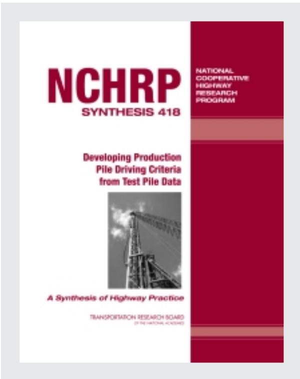

Developing Production Pile Driving Criteria from Test Pile Data

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP SYNTHESIS 418

Developing Production Pile Driving Criteria from Test Pile Data

A Synthesis of Highway Practice

CONSULTANTS

DAN A. BROWN

and

W. ROBERT THOMPSON, III

Dan Brown and Associates

Sequatchie, Tennessee

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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The Transportation Research Board of the National Academies was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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Cover figure: A 36-in. concrete pile being driven for the I-10 bridges over Escambia Bay in Florida (Credit: Dan Brown).

FOREWORD

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-05, "Synthesis of Information Related to Highway Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice*.

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

By Jon M. Williams
Program Director
Transportation
Research Board

This report provides information on the current practices used by state transportation agencies to develop pile driving criteria, with special attention paid to the use of test pile data in the process. The information collected shows high variability in the level and sophistication of the practices being used. A significant component of the variation in pile driving criteria may be related to the pace of implementation of new approaches for pile testing and differences between agencies in training, experience, and acceptance of new technologies.

Information was gathered through a literature review, a survey of all state transportation agencies, and selected interviews.

Dan A. Brown and W. Robert Thompson, III, of Dan Brown and Associates, Sequatchie, Tennessee, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

CONTENTS

APPENDIXES B AND C OF THIS REPORT CAN BE FOUND AT WWW.TRB.ORG, SEARCH ON "NCHRP SYNTHESIS 418."

DEVELOPING PRODUCTION PILE DRIVING CRITERIA FROM TEST PILE DATA

SUMMARY

Although exploratory borings and engineering studies during design are an integral part of foundation engineering, the axial resistance of a driven pile foundation is ultimately determined by the criteria used to decide when to stop driving the pile during construction. The use of test piles for the purpose of developing the pile installation criteria can be instrumental in building driven pile foundations that are reliable and cost-effective. Nationwide practices for developing pile driving criteria range from the use of very simple formula without any test pile verification to the use of pre-production test piles with dynamic measurements during installation and static load testing. Many agencies employ a range of technologies and methods based on the size of the project, the type of pile, and the predominant ground conditions. However, this issue is handled differently from state to state based on local experience, economics, and other factors.

This synthesis provides a survey of the current practices used by transportation agencies to develop pile driving criteria, with special attention placed on the use of test pile data. The survey consists of questionnaires sent to all 50 state departments of transportation plus the District of Columbia and Puerto Rico; 44 of the 52 agencies provided responses. In addition, a Phase II Survey was performed by telephone interview with nine agencies representing a broad geographical distribution of large states that have extensive pile foundation construction projects.

The information collected indicated that practices used by transportation agencies to develop pile driving criteria for production pile installation can be described as highly variable in terms of the level and sophistication of the testing performed. To some extent, such variability in test pile requirements may reflect the inherent variety in project size, complexity, ground conditions, pile type, etc. However, a significant component of the variation in pile driving criteria may be related to the pace of implementation of new approaches to pile testing and variation among agencies with respect to training, experience, and acceptance of new technology.

Practices include the following:

- Constructing the foundations without any test piles, using driving criteria based on a simple pile driving formula or a wave equation analysis. This practice is widespread for routine projects or simple situations such as steel piles driven to bear on rock or a hard bearing layer. The wave equation analysis provides a more rigorous and comprehensive model of the pile installation process and offers numerous advantages over the use of a simple formula. The results are typically provided to an inspector in tabular or graphical form, which can include provisions to account for varying hammer energy. The results can also include an allowance for a time-dependent increase in resistance as the pile "sets up" so that restrike measurements can be used to verify that a pile has the required resistance after some period if the required resistance was not observed during initial driving. However, the time required to perform these analyses and the greater level of education and training required to employ this technology is an impediment to more widespread use. The benefits may be insignificant on small or very simple projects.
- The number and types of test piles varies according to predominant pile type, ground conditions, size of project, and agency practice. Many agencies evaluate the costs versus

benefits on a project-specific basis, and this evaluation includes the consideration of the increased values of the resistance factor for design that is provided in the AASHTO code. There is a greater tendency to use test piles:

- In coastal states;
- In projects with larger piles, longer piles, or a greater numbers of piles;
- Where piles derive a majority of axial resistance through side resistance;
- Where ground conditions are more variable;
- Where concrete or large pipe piles are used, as opposed to steel H- or smaller diameter (18 in. or less) pipe piles; and
- Where design-build project delivery is used.

• Developing a driving criteria based on test pile measurements using a High Strain Dynamic Test (HSDT). This practice is most often employed using test piles that serve as production piles and become part of the permanent foundation. The measurements obtained from the HSDT are often used to refine the results of a wave equation analysis so that improved reliability in the driving criteria is achieved. The capabilities of the equipment used to perform an HSDT have improved significantly in the last 20 years and the capability of agencies and consultants to reliably perform such tests has become much more widespread. Signal-matching analysis is routinely employed to obtain more detailed information about the test pile behavior and soil response.

• Using pre-production test piles with HSDT measurements and/or static load tests (SLTs) to develop driving criteria based on a more reliable determination of the axial resistance of a test pile. Pre-production test piles, installed in advance of foundation construction, allow restrike measurements to be performed over time to measure setup. SLT measurements provide the most reliable indication of the static axial resistance of the pile and, in some circumstances, are used to overcome uncertainties associated with dynamic test measurements. Rapid load tests (RLTs) are used on rare occasions in lieu of a SLT. The use of pre-production test piles also allows for a more reliable estimate of the length of production piles in advance, which is particularly valuable to agencies that routinely use prestressed concrete piles. Hindrances to the use of pre-production piles typically include the time and costs associated with performing the tests before production pile installation, as well as restrictions to site access prior to construction by environmental or other permits.

Useful practices are described in chapter five, with descriptions of the practical approaches several agencies use to integrate a range of technologies to develop pile driving criteria under typical conditions. Each of the practices identified have limitations and impediments to implementation. In several cases, the most common limitation to improvements in practice is the perception of limited benefits relative to costs associated with technologies that require a significant commitment of resources or time. For small or routine projects with relatively simple foundation conditions these perceptions may be accurate. In some cases, improved reliability and economy may be difficult to quantify or there may be resistance to changing long-standing practices even though they may be inefficient. Other limitations to increased use of test piles include a lack of equipment and/or trained staff or consultants available to employ advanced technology. In addition, several knowledge gaps have been identified relating to technical issues for which research could potentially improve practice.

CHAPTER ONE

INTRODUCTION

BACKGROUND

Nationwide practices vary widely for developing and using production pile driving criteria, particularly from test pile data obtained from static load testing (ASTM D1143-07e1), rapid load testing (ASTM D7383-08), or high-strain dynamic testing with (or without) signal-matching analysis (ASTM D4985-08). The FHWA pile design/construction manual (Hannigan et al. 2006) and the AASHTO *LRFD Bridge Design Specifications* (AASHTO 2010) provide some information and guidance on this issue. However, this issue is handled differently from state to state based on local experience, economics, and other factors.

This report gathered and synthesized the current practices various states use, allowing other states/agencies to identify the common elements as well as the differences, advantages, and disadvantages of each approach, especially as applied to specific situations or site conditions.

DEFINITION OF TERMS

The following terms are defined as used in this synthesis:

Beginning of Redrive (BOR): The first few restrike blows after a period of setup.

Blow count: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (*b*/*f*), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

Driving resistance: Axial resistance at the time of driving.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The pile driving analyzer (PDA) is a commonly used apparatus for dynamic monitoring.

End-of-driving (EOD): The last few blows during the installation of a driven pile at initial drive, a restrike, or a redrive.

End-of-Initial Drive (EOID): The last few blows at which the initial driving of a pile is stopped.

High Strain Dynamic Test (HSDT): The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance as described by ASTM Standard D 4945-00.

Indicator pile: See Probe pile.

Maximum driving resistance: The maximum amount of axial resistance that must be overcome to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance that must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Pile driving criteria: A specific set of requirements used to define the conditions that must be met during the installation of a production pile. This usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Pile driving formula: A closed form equation, such as the Gates or *Engineering News Record* (ENR) formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Probe pile: A pile that is installed before installation of production piles to aid in the determination of pile length variations across the site. Probe piles may or may not be incorporated into the permanent structure.

Production pile: A pile that will become part of the permanent foundation for the structure.

Rapid load test (RLT): The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a RLT.

Refusal: A blow count at which the effective energy of the hammer blow is no longer sufficient to cause penetration of the pile into the soil. The criteria are specific to a given driving system operating at a specific energy.

Relaxation: A reduction in the axial pile resistance after a period of time.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time, ranging from hours to days, during which the pile is not actively driven. Restrike blows are applied to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Signal matching: The use of numerical modeling of a pile and pile driving system back-correlated to the results of a high-strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Static load test (SLT): The application of a static force to perform a load test of a deep foundation element as described by ASTM D1143.

Substructure unit: The foundation unit supporting a pier or abutment. It may consist of a pile bent or a single pile footing, or a series of pile footings each supporting a single column.

Test pile: A pile that is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. The test data may influence the driving criteria. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment used to evaluate behavior of the pile and driving equipment for a specific project. The WEAP (Wave Equation Analysis of Piles) program is an example of a computer code used for wave equation analysis.

PRIMARY ISSUES

From a review of the available literature outlined in chapter two, and from a review of several state agency specifications, the following are the important issues with respect to developing pile driving criteria.

Methods for Developing Pile Driving Criteria

Pile driving criteria can be developed in different ways and often are developed using a combination of two or more individual techniques. The methods used to develop the driving criteria can vary according to pile type, soil type, and installation technique. The common elements for developing criteria that are the focus of this synthesis, used alone or in various combinations, are:

- Drive to a minimum tip elevation based on static analysis with little or no regard to driving resistance (blow count).
- Drive to a minimum tip elevation and minimum blow count based on the correlation of blow count to axial resistance from a pile driving formula.
- Drive to a blow count that constitutes practical refusal.
- Drive to a minimum tip elevation and minimum blow count based on the correlation of blow count to axial resistance from a wave equation analysis (numerical model).
- Drive to a minimum blow count based on the correlation of blow count to axial resistance from high-strain dynamic testing with (or without) signal matching. Testing may be performed on pre-production piles or on production piles.
- Drive to a minimum blow count based on the correlation of blow count to axial resistance from RLTs.
- Drive to a minimum blow count based on the correlation of blow count to axial resistance from SLTs.

Methods of Selecting the Driving System

Because different types (diesel, air, hydraulic, etc.) or sizes of hammers will influence the driving resistance for a given static axial resistance, the selection of the pile driving system will have an influence on the driving criteria. The selection of the pile driving system may be influenced by several factors:

- Local practice and availability,
- Regulatory restrictions (such as noise, vibrations, use of diesel), and
- Driving stresses and appropriateness of hammer for pile type and size or for soil conditions.

The minimum requirements for the driving system, usually requiring hammer energy, are developed by the design engineer and included in the project plans or called out from standard specifications. Pile driving formulas or wave equation analysis are the most common methods for establishing the minimum required hammer energy.

Economics are a major consideration in the selection of the driving system by the contractor. For instance, hammer size can affect crane size requirements, and air or hydraulic hammers may require substantial support equipment compared with simpler diesel hammers. Productivity and schedule requirements are a major consideration to the contractor. In the case of design-build project delivery, the design and construction partners typically have additional economic incentive to work collaboratively to find the optimal pile driving system. Wave equation analysis is a common technique to evaluate drivability and productivity.

Varying Types of Contractor Submittals Required for the Installation of Piles

In most cases, the minimum required hammer energy is specified in either the project plans or the standard specifications. In such cases, the minimum contractor submittal for pile installation is the proposed hammer and supporting equipment (pile leads, power supply, cranes, etc.) that meets the minimum required hammer energy. In some cases, particularly in the design-build project environment, a contractor-performed wave equation analysis is required to demonstrate that the hammer can drive the proposed piles to the correct resistance without damage. Additional submittals can occasionally include installation sequence or procedure, procedures for testing or restrikes, and procedures for remediation of piles that are suspect or do not meet the planned driving criteria.

Degree of Soil Setup or Relaxation and Its Effect on Driving Criteria

Soil setup can have a major impact on driving criteria. Although restrikes or load tests may be performed after setup has occurred to document that the pile has the design resistance, the driving criteria are set for the conditions at the time of driving. By reliably quantifying setup before or at the start of production pile driving, its effect can be factored into the driving criteria by determining an acceptable end of drive blow count that includes an allowance for the setup, or by establishing an acceptable end of drive resistance as measured by a PDA. If setup is not accounted for, the criteria would be established for a pile resistance that cannot be achieved at the end of drive, causing delays, disputes, overruns in pile quantities, or excessive restrike tests to confirm that piles have the required resistance for the design.

Setup can be quantified based on local experience by a program of restrike measurements at a range of times after initial driving, by static load tests, or another systematic manner. With appropriate conservatism in setting pile tip elevations, the risk of delays owing to questions regarding pile axial resistance and the need for set checks or splices can be reduced when setup is accounted for. Piles driven to satisfy the established criteria that accounts for setup are assured to ultimately achieve the required axial resistance.

Relaxation, or the loss of resistance over time, can also have an impact on driving criteria. Although relaxation is a rare occurrence, it needs to be considered in those soil and rock formations where it typically occurs. Failure to account for relaxation when it does occur results in nonconservative driving criteria.

Methods of Determining the Number and Distribution of Pile Tests for Use in a Pile Testing Program

The number and distribution of pile tests in a testing program can be selected either with a rigidly specified procedure or by guidelines that call for individual judgment of the project conditions. Rigid specifications often require that certain tests be performed at a specific interval. Examples of specified intervals are: a static load test every *X* linear feet of pile, a HSDT every *Y*% of piles, or a HSDT required for all projects with friction piles. Some agencies use the AASHTO specifications as a rigid specification, whereas others use their own specifications. Some agencies use the AASHTO specifications as a guide, with engineering judgment and a cost–benefit analysis providing input into the determination of test pile quantities.

In design-build projects, economic and schedule decisions are significant influences, as are the potential to reduce uncertainty. Sometimes the benefits of additional test piles, manifested in higher resistance factors, confirmation of driving system performance, or confirmation of setup can more than offset the additional cost for the test piles.

Use of Data Collected During the Testing Program with Regard to Developing Production Pile Driving Criteria

Data collected from test piles can be used in several ways to develop production pile criteria. Some of these uses include:

- Verification of hammer performance and drivability of the piles.
- Measurements to indicate axial resistance at specific blow counts.
- Verification of axial resistance of a driven pile from SLTs. Site-specific SLTs may be used to correlate dynamic test results with static axial resistance to increase the reliability of dynamic test measurements.
- Measurements to demonstrate that setup will occur and to verify long-term axial resistance so that lesser initial driving resistance may be determined to be acceptable.
- Confirming or modifying design lengths based on test results.
- Signal matching of HSDT results to provide refined soil resistance models for wave equation analysis for production piles.

Varying Soil Conditions Across a Project and Its Effect on Driving Criteria

Because soil conditions can often vary significantly across a site, the development of driving criteria can be impacted not only the by location of tests or observations for criteria development, but also by the frequency of tests on a site. The definition of what constitutes a “site” needs to be clear when discussing variable subsurface conditions: is a site the entire bridge or is the bridge location divided up into two or more sites with similar subsurface conditions.

Where significant changes in soil type occur, different criteria need to be developed (e.g., separate criteria for piles in clay versus piles in sand). The presence of refusal driving conditions (with an adequately sized hammer) may vary significantly across the site, requiring differing criteria to cover areas of potential pile refusal and areas where piles will not achieve refusal.

Piles driven to a driving resistance as determined by a PDA are often associated with a specific minimum blow count at the desired tip elevations. The variation of soil strength estimated or measured for axial design, as well as the variation in hammer energy and efficiency, can mean that achieving something less than *X* blows per foot in a certain clay strata does not necessarily mean a pile does not provide the required resistance. Although blow counts can be indicators, trying to achieve a certain blow count value of *X* can create difficulties if variations in soil strength are not taken into account. If only one test is done and the blow count is 10 blows per foot when the required resistance is met, then all piles will be subject to those criteria if an allowance for soil variation is not considered.

Effects of Production Pile Driving Criteria on the Resistance Factor Chosen for Design

The selection of production pile criteria can affect the design resistance factor through the methods used to determine the criteria. Both the FHWA *Driven Pile Manual* (Hannigan et al. 2006) and AASHTO LRFD (Load and Resistance Factor Design) 2010 (AASHTO 2010) provide guidance for selecting the design resistance factor. The selection is based on the type and frequency of testing performed before and during production pile installation. In general, higher resistance factors are allowed as the frequency of testing increases, resulting in positive effects on the design. If little or no verification testing is used to establish or confirm driving criteria or pile performance, the design is impacted by the requirement to utilize lower resistance factors.

SURVEY PROCESS

The survey was conducted in two phases. The first phase (Phase I) consisted of a written survey to all state geotechnical engineers (or equivalent). The second phase (Phase II) consisted of telephone interviews with selected agencies based on the responses to the written survey. The Phase I Survey (Appendix A) was developed to gather information on how the surveyed agencies were developing and utilizing pile driving criteria. Special attention was focused on the use of test pile data for developing driving criteria. The goal of the survey was to enable the collection of information in such a way that the current practices by various states could be synthesized and evaluated to include some areas of best practices and some areas that need improvement. It is also intended that the results be used by others to identify common elements as well as the advantages and disadvantages of each approach, especially as applied to specific situations or site conditions.

Information was also gathered by a literature review, including sources from industry organizations [such as the Pile Driving Contractors Association (PDCA) and the Deep Foundations Institute], other government agencies (such as the U.S. Army Corp of Engineers), and industry design publications (FHWA and AASHTO).

SYNTHESIS ORGANIZATION

This synthesis is organized as follows:

- This introduction (chapter one) provides the background on the issues, defines terms, and identifies the primary issues.
- A literature review summarizing published information on developing and utilizing pile driving criteria (chapter two).
- A summary and discussion of the Phase I Survey of the state agencies (chapter three).
- A summary and discussion of the Phase II Survey of telephone interviews with selected agencies (chapter four).
- A summary of the essential components of good practice identified in the literature review and the survey responses, and a conclusion that summarizes the assessment of the current state of practice and identifies knowledge gaps to be considered for additional research (chapter five).

The individual written survey responses, notes from the telephone interviews, and summary tables of the survey responses are included in the appendixes. A bibliography of references from the literature review is also included.

CHAPTER TWO

LITERATURE REVIEW

Pile driving criteria can be developed through several means, usually a combination of two or more individual techniques. Often the criteria can vary according to pile type, soil type, and installation technique. This chapter provides the results of a comprehensive literature review on the range of practices included in test pile programs and their use in developing production pile driving criteria.

Most information concerning requirements for pile driving criteria are included in design manuals, construction manuals, and construction specifications of various agencies and some industry groups. A search of research databases was also done, including the TRB Transportation Research Information Service (TRIS), TRB Research in Progress (RiP), the American Society of Civil Engineers Research Library, and Deep Foundations Institute publications.

Each of the following sections of this chapter describes a specific organization or published reference with respect to information concerning the development and/or use of pile driving criteria. The terminology used by each reference has been retained in the summaries of each reference.

AASHTO 2010 *LOAD AND RESISTANCE FACTOR DESIGN BRIDGE DESIGN SPECIFICATIONS*

The 2010 *LRFD Bridge Design Specifications* is the guiding document for bridge design. At the time of this report, not all state departments of transportation (DOTs) have completed the transition from Allowable Stress Design. The AASHTO manual contains both specifications and commentary. Items concerning pile driving criteria from both are listed in this section.

Resistance Factors—Strength Limit States—Driven Piles (10.5.5.2.3)

- Resistance factors for calculating geotechnical limit state resistance (Table 10.5.5.2.3-1) vary according to the analysis method used and the type of testing employed during installation.
- When driving criteria are based on a SLT it is important that the potential for site variability be considered. Variability can be addressed through multiple load tests or site characterization.
- Local experience or site-specific test results could be used to refine wave equation soil input values or increase the confidence in the values selected. Field verification of analyses could be performed.

Strength Limit State Design—General (10.7.3.1)

- It is important that minimum pile penetration only be specified if needed to ensure that uplift, lateral stability, depth to resist downdrag, depth to resist scour, and depth for structural lateral resistance are met for the strength limit state, in addition to similar requirements for the service and extreme event limit states.
- A minimum pile penetration alone should not be used to ensure that the required nominal pile bearing has been met.

Determination of Axial Pile Resistance in Compression—Static Load Test (10.7.3.8.2)

- Refers to Design and Construction of Driven Pile Foundations, FHWA NHI-05-042, NHI Courses 132021 and 132022 (Hannigan et al. 2006) for considering SLT results when developing driving criteria.

Determination of Axial Pile Resistance in Compression—Dynamic Testing (10.7.3.8.3)

- If dynamic test data are used to establish driving criteria, signal-matching analysis would always be used to determine the nominal axial resistance.
- Restrike testing could be used if setup or relaxation is anticipated.
- Dynamic measurements with signal matching may not always match SLT results, particularly where pile set is very low.
- In cases of significant soil setup where the pile set at the beginning of restrike is less than 0.1 in., the nominal resistance of the pile can be estimated using the signal match analysis tip resistance from the end of drive with the side resistance at beginning of restrike.

Determination of Axial Pile Resistance in Compression—Wave Equation Analysis (10.7.3.8.4)

- Considerable judgment is required when using wave equation analysis in the absence of dynamic testing with signal matching and/or SLT data. The soil input values (quake, damping, and distribution between skin and tip resistance) and the hammer performance can be measured/determined from the tests.

- The resistance factor listed for use with wave equation analysis was determined based on calibrations that used the default values for hammer and soil input values. Higher resistance factors may be used when hammer and soil input values are refined using local experience and previous test data.

Determination of Axial Pile Resistance in Compression—Dynamic Formula (10.7.3.8.5)

- More accurate methods such as wave equation or dynamic testing with signal matching are preferred over the pile driving formula for establishing driving criteria. Formulas are provided as an option because of their long history of use.
- Two formulas are provided: FHWA Modified Gates Formula (Modified Gates) and the *Engineering News* Formula (ENR). The Modified Gates Formula is preferred over the ENR formula. If another formula is used, it shall be calibrated to measured load test results.
- Pile drivability could be evaluated to confirm that the pile can be driven to the resistance determined by the formula without overstress or damage, otherwise design stresses are limited to values listed in Article 6.15.2.
- It is important that driving formulas only be used to determine end of drive blow count criteria.
- The reliability of dynamic formulas tends to decrease as the required nominal bearing resistance increases.
- Dynamic formulas are not to be used for required nominal resistance of more than 600 kips.

Determination of Minimum Pile Penetration (10.7.6)

- A minimum pile penetration would only be specified if necessary to ensure that all of the applicable limit states are met. A minimum pile penetration is not to be specified solely to meet axial compression resistance.

AMERICAN PETROLEUM INSTITUTE: RECOMMENDED PRACTICE 2A-WSD

The American Petroleum Institute (API) is a national trade association that represents all aspects of the U.S. oil and natural gas industry. The API sponsors research and publishes design guides and specifications concerning all aspects of exploration and production, including design and construction of facilities. In its publications the API addresses pile foundations concerning design of offshore platforms (American Petroleum Institute 2000). Such structures are often supported on large-diameter steel pipe piles. Although not necessarily applicable to most transportation projects, large-diameter pipe piles are used on large-span bridge structures. API’s recommended practices concerning pile driving criteria include:

- Use of wave equation analysis to analyze driving stresses.
- Pile penetration based on static design methods and not a correlation of pile capacity with the number of blows for penetration.

DEPARTMENT OF DEFENSE

In recent years the U.S. Department of Defense has consolidated the various design manuals, technical publications, design guides, and construction specifications published by each of the service branches into unified publications. Most documents are now published under the Unified Facilities Criteria (UFC) program. All UFC documents can be obtained through the *Whole Building Design Guide* (WBDG) run by the National Institute of Building Sciences. The *Whole Building Design Guide* is a web-based portal run for building-related guidance, criteria, and technology.

Some UFC documents are new or revised publications written and formatted under the UFC document guidelines. Others are existing documents published by one of the services that have been given a UFC designation without revision.

UFC 3-220-01A Deep Foundations

This is U.S. Army Corps of Engineers publication *TI 818-02 Technical Instructions—Design of Deep Foundations* and provides information with respect to the selection and design of deep foundations. Information or recommendations concerning pile driving criteria include:

- Perform an initial wave equation analysis before driving piles.
- Drive indicator piles, typically 2% to 5% of the production piles.
- Perform additional wave equation analyses using actual hammer performance and adjust for changes in soil strength.
- Drive to various depths and determine penetration resistances with the PDA using the case method to determine the static ultimate bearing capacity.
- Restrike the piles after a minimum waiting period; usually 1 day.
- Perform CAPWAP analysis to correlate wave equation analysis and to verify field test results.
- Perform SLTs to confirm the dynamic test results, particularly on large projects.
- Additional piles could be dynamically tested during driving or restruck throughout pile installation as required by changes in soil conditions, load requirements, pile types, or changes in pile driving behavior.

UFC 3-220-02 Pile Driving Equipment

This is U.S. Army Corps of Engineers publication *TI 818-03 Technical Instructions—Pile Driving Equipment.* The document provides information to assist with the preparation of specifications for pile installation and for the assessment of installation operations. Information or recommendations concerning pile driving criteria include:

- Contains a pile driving formula method, Preliminary Method for Sizing Hammers for Concrete and Steel Piles, SI units (after Florida DOT Specification, Section 455).
- Recommends field check of the design consisting of a feasibility analysis, installation of indicator piles with PDA equipment, and wave equation analysis.
- Indicator piles will be driven before load testing.
- Pile load tests are recommended and can be completed for economically significant projects.
- Driving of indicator piles and load tests could be handled in a separate contract from the construction project or at a minimum accomplished before the ordering of the bulk of the production piles. Pile lengths could be determined based on final results from the indicator and pile load tests.

FEDERAL HIGHWAY ADMINISTRATION: DESIGN AND CONSTRUCTION OF DRIVEN PILE FOUNDATIONS, FHWA NHI-05-042, NHI COURSES 132021 AND 132022

This is the current FHWA design manual for pile foundations. It covers the following with respect to pile driving criteria:

- Chapter 11 Contract Documents (p. 11-4) states that good practice includes the use of wave equation analysis and dynamic pile testing to replace the use of dynamic formulas to monitor piles (e.g., driving criteria).
- The Sample Specification, Construction Methods Commentary (pp. 11-24–11-25) includes additional discussion on the preference of wave equation analysis and moving away from pile driving formulas. The *Engineering News Record* (ENR) formula is recognized as the least accurate of all of the formulas. The commentary (pp. 11-28–11-29) also recommends that dynamic tests be done on at least half of the reaction piles for a SLT to help adjust the test equipment for the site soil conditions. Dynamic testing of the static test pile during installation and restrike after the SLT can help correlate the static test with dynamic tests. This section also recommends that the first pile in each substructure foundation be tested when dynamic tests are specified for production piles.
- Chapter 14, Section 14.3 Driving Criteria provides the following:
  - Driving criteria usually consist of a specified penetration resistance at a given hammer stroke, with a minimum pile penetration in some cases.
  - The method to determine the criteria could be selected and specified by the foundation designer.
  - Driving criteria could consider time-dependent changes in pile resistance (setup and relaxation).
  - Driving criteria could be substantiated by SLTs whenever possible.
  - Pile driving formulas do not provide information on pile stresses and have in some cases been shown to be unreliable.
  - Wave equation analysis and dynamic testing are appropriate for establishing and evaluating driving criteria.
  - Practical refusal is typically defined as 20 blows per inch.
- Chapter 15 covers pile driving formulas, again stressing that they could be used in limited circumstances with substantial correlation to test data.
- Chapter 16 provides a detailed discussion of wave equations analysis, including methodology, example problems, and procedures for comparing with dynamic measurements.
- Chapter 17 covers dynamic testing and analysis, including basic wave mechanics, testing equipment and methods, and analyzing results.
- Chapter 18 covers static load testing, including test methods, equipment, and analysis of results.
- Chapter 20 covers rapid load testing, including test methods, equipment, and analysis of results.

INTERNATIONAL BUILDING CODE

Many state, county, and local governments use the International Building Code (IBC) (2009) for their regulatory building code. As with many codes, the requirements within the IBC are relatively broad so as to apply to most normal construction situations. The requirements contained in the code that pertain to foundations are typically guidance for minimum design and/or construction requirements. The IBC, and many other codes, allow for the discretion and judgment of the engineer to evaluate the basic requirements of the code when applied to specific projects. Information concerning pile driving criteria found in the IBC includes:

- For allowable loads of more than 40 tons, wave equation analysis shall be used to estimate pile drivability of both driving stresses and net displacement per blow at ultimate load.
- Allowable loads shall be verified by load tests.
- A load test of at least one pile per uniform soil condition.
- Remaining piles shall be deemed having a support capacity equal to the control (test) pile where such piles are the same type, size, and relative length as the test pile; are installed with the same or comparable equipment and methods; are installed in similar soil conditions as the test pile; and where the rate of penetration (distance per blow) is equal to or less than that of the test pile.

PILE DRIVING CONTRACTORS OF AMERICA: INSTALLATION SPECIFICATION FOR DRIVEN PILES, PDCA SPECIFICATION 102-07

The PDCA is an industry association that promotes the pile driving industry. The PDCA supports research on driven pile foundations and has member-run technical committees. The recommended practices pertaining to pile driving criteria contained in their guide specification are:

- Ultimate capacity can be determined by SLTs, RLTs, dynamic tests, wave equation analysis, or dynamic formula.
- A wave equation analysis could be performed to evaluate the driving system and ensure it can install the piles. This analysis could be done for piles where the ultimate capacity is determined by SLTs, RLTs, dynamic tests, or wave equation analysis. Verification of the driving system by wave equation analysis is not necessary if the ultimate capacity is determined by dynamic formula.
- To determine driving stresses to ensure that they do not exceed recommended parameters.
- Piles could be driven to the required ultimate pile capacity, the required ultimate pile capacity and minimum tip elevation, or the specified tip elevation.
- The ultimate pile capacity is usually confirmed by achieving the specified blow count.

PRECAST/PRESTRESSED CONCRETE INSTITUTE: RECOMMENDED PRACTICE FOR DESIGN, MANUFACTURE, AND INSTALLATION OF PRESTRESSED CONCRETE PILING

The Precast/Prestressed Concrete Institute (PCI) promotes research, construction best practices, and structural design of prestressed, precast concrete. It has a staff of technical and marketing professionals, as well as several member-run technical committees. PCI's recommended practices concerning pile driving criteria include:

- Wave equation analysis may be used to help with hammer and drive system selection.
- Dynamic testing may be helpful in evaluating the effectiveness of the drive system. It is also useful for evaluating pile hammer performance, cushion adequacy, driving stresses, and pile load capacity.
- No recommendations on test frequency, testing programs, etc.

STATE DEPARTMENTS OF TRANSPORTATION

A review of several state DOT specifications and design documents was included in the literature review to obtain a sampling of current practices. Agencies that typically use a pile driving formula, such as the Minnesota DOT (Mn/DOT), Nebraska Department of Roads (NDOR), or the California DOT (Caltrans), will list the specific formulas within the construction specification. The use of HSDT and SLT is typically addressed from a procedural standpoint in specifications. Guidance or requirements for test frequency and evaluation are often included in agency design manuals or documents.

California Department of Transportation

Pile driving criteria for Caltrans are governed by the following documents:

- State of California Department of Transportation Standard Specifications 2006 Edition—Section 49.
- State of California Department of Transportation Bridge Design Specifications 2003 Edition—Section 4.

The Caltrans specification states that the nominal resistance for driven piles shall be determined by the use of dynamic formulas listed in the specifications. Piles are driven to a required tip elevation and bearing value. For piles of more than 18 in., other project-specific special provisions govern pile criteria and testing. The bridge manual directs that test piles shall be considered for each substructure unit. The piles may be tested by static or dynamic test methods. Where previous experience exists with the same pile type, same required resistance, and similar subsurface conditions, test piles may not be required.

Florida Department of Transportation

Pile driving criteria for the Florida DOT (FDOT) are governed by the following document:

- Florida Department of Transportation Standard Specifications for Road and Bridge Construction 2010 Edition, Section 455.

FDOT's specification lists the requirements for determining pile acceptance criteria, including the requirement of the HSDT. The use of a blow count criteria (based on the HSDT) or practical refusal (defined) is directed, along with directives on when to use restrikes or set checks to verify pile resistance for acceptance.

Minnesota Department of Transportation

Pile driving criteria for Mn/DOT are governed by the following documents:

- Mn/DOT Standard Specifications for Construction 2005 Edition—Division II Construction Details.
- Mn/DOT *Bridge Construction Manual*, 2005 Edition.

Mn/DOT requires that piles be driven to substantial refusal or to a specified penetration and resistance. Resistance is determined by the dynamic formulas listed in the specification and the bridge construction manual. The bridge construction manual allows for the use of HSDT in lieu of the dynamic formula to determine pile resistance.

Nebraska Department of Roads

Pile driving criteria for NDOR are governed by the following document:

- NDOR Standard Specifications for Highway Construction 2007 edition—Division 700 Section 703.

The NDOR standard specifications state that the pile resistance is determined by the dynamic formulas listed in the specifications. Piles will be driven to a depth specified in the plans or to practical refusal. When SLTs are performed, each test pile will be monitored by a PDA during installation and will have a restrike test. Production piles are used as load test piles.

New York State Department of Transportation

Pile driving criteria for the New York State DOT (NYSDOT) are governed by the following documents:

- State of New York Department of Transportation Standard Specifications 2008 edition—Section 551.
- New York State Department of Transportation *Bridge Manual*, 4th Edition—Section 11.1.4.
- New York State Department of Transportation, *Highway Design Manual*, 2009—Chapter 9.

The NYSDOT specifications state that piles will be driven to the criteria determined by the Deputy Chief Engineer Structures. The criteria are not provided in the specifications or the *Bridge Manual*. Chapter 9 of the *Highway Design Manual* indicates that the type and frequency of HSDT or SLT will be determined by the Geotechnical Engineering Bureau.

North Carolina Department of Transportation

Pile driving criteria for the North Carolina DOT (NCDOT) are covered by the following documents:

- *LRFD Driven Pile Foundation Design Policy*, 2010 Revision 2.
- NCDOT Standard Specifications, 2002.
- LRFD Pile Special Provision, March 2010.

The LRFD Design Policy provides minimum, maximum, and refusal blow counts for pile driving. Minimum blow count indicates that the selected hammer is too large, whereas maximum blow count indicates that the hammer is too small. The design policy also provides guidance on selection of resistance factors based on the frequency of HSDT. The LRFD Pile Special Provision indicates that the engineer will determine the acceptance criteria and provide the blows per foot, equivalent set for 10 blows, and minimum tip elevation as the pile criteria.

Ohio Department of Transportation

Pile driving criteria for the Ohio DOT (ODOT) are governed by the following documents:

- ODOT 2010 Construction and Materials Specification Section 507 Driven Piles.
- ODOT 2010 Construction and Materials Specification Section 523 Dynamic Load Tests.
- ODOT *Bridge Design Manual* (2007), Sections 202.2.3.2 Pile Design.

ODOT requires that the driving criteria be determined to achieve the “ultimate bearing value” of the pile. The criteria may consist of a minimum blow count with a minimum hammer stroke, a minimum depth of penetration, or both. Criteria are established using HSDT for friction piles. Piles driven to refusal on bedrock do not require HSDT. The specifications do not include a specific refusal criterion.

For friction piles, ODOT requires a SLT if the total order length of a single pile type on a project exceeds 10,000 ft. One SLT is required for each increment of 10,000 ft of pile. Two dynamic tests are required to be performed with each SLT, with each dynamic test consisting of two dynamic test piles and one restrike.

Washington State Department of Transportation

Pile driving criteria for the Washington State DOT (WSDOT) are governed by the following documents:

- WSDOT *Geotechnical Design Manual*, M 46-03.01, January 2010.
- 2010 Standard Specifications for Road, Bridge, and Municipal Construction (M 41-10)

Both the *Geotechnical Design Manual* and the specifications provide the WSDOT pile driving formula used for pile driving criteria on most piles. The *Geotechnical Design Manual* mandates that the formula could not be used for piles with a nominal resistance of greater than 500 tons or a pile diameter greater than 30 in. Field testing (HSDT with signal matching or SLT) is recommended for resistance values of more than 500 tons and diameters greater than 30 in.

The design manual provides guidance for selecting appropriate resistance factors for design based on the intended acceptance criteria. Guidance is also provided for selecting pile type and pile size considering required nominal pile resistance. A table is provided that lists the typical pile types and sizes for typical nominal pile resistance values.

TRB RESEARCH IN PROGRESS DATABASE

A search was performed of the TRB Research in Progress (RiP) database for current research that may be related to this synthesis. This search found several research projects related to pile driving criteria. They are listed with the source organization and the scheduled completion date, as well as a brief summary (if provided) of the project. Some of the projects listed in RiP have a stated completion date that has already passed, but are still listed as current projects with no published reports. The listings found in RiP are:

- Analysis of the Alaska DOT & PF (Public Facilities) Pile Driving and Dynamic Pile Test Results (December 2009): Compiled and analyzed Alaska DOT & PF dynamic pile driving testing results and synthesized the results of the analysis into a format useful to geotechnical and bridge foundation engineers.
- Calibration of LRFD Resistance Factor for the Wave Equation Analysis of Pile Driving Program, Oregon DOT (June 2010): To calibrate resistance factors based on practice and conditions for Oregon DOT projects.
- Embedded Data Collector (EDC) Evaluation Phase II—Comparison with Instrumented Static Load Tests, FDOT (December 2011): Evaluation of EDC estimates of static resistance when compared with SLT; development of LRFD resistance factors for EDC pile monitoring; establishment of high-quality static skin friction and end-bearing database; evaluation of EDC estimation of pile stresses and damping; and use of EDC data in combination with load tests and in situ testing to improve pile freeze predictions as well as cone penetration test axial pile prediction software.
- Establishing a Dynamic Formula for Pile Design & Construction Control of Pile Driving, Iowa DOT (June 2009): The objective of this project is to develop dynamic formulas, consistent with LRFD specifications, to design piles and control their installation in the field, focusing on methods suitable for Iowa soil conditions.
- Field Testing of Piles & Development of a Wave Equation Method for Pile Design in Iowa, Iowa DOT (February 2011): The project team will conduct 12 field tests on steel H-piles and obtain a complete set of data that will include: (1) a detailed soil profile from soil borings, together with appropriate soil parameters; (2) driving data including strain and acceleration measurements and the associated dynamic analysis method; and (3) static pile load test data. From this database, a suitable wave equation analysis method for pile design will be developed.
- Implementation of Pile Drivability Methods, Indiana DOT (October 2010): No summary provided.
- Improved Design for Driven Piles Based on a Pile Load Test Program in Illinois, Illinois DOT (September 2010): Collecting/interpreting information on SLT, driving performance, and restrike performance in Illinois and the Midwest to assess and improve methods for limiting driving stresses and methods for predicting pile capacity.
- Pile Driving Analysis for Pile Design and Quality Assurance, Indiana DOT (December 2012): No summary provided.
- Resistance Factors for 100% Dynamic Testing, with and without Static Load Tests, Florida DOT (June 2011): Establish LRFD values for design based on number of piles dynamically monitored in a group.

OTHER REFERENCES

Current Practices and Future Trends in Deep Foundations, *Geotechnical Special Publication 125* (ASCE 2004)

Several papers in *Geotechnical Special Publication 125* (*GSP 125*) cover general topics pertaining to this synthesis (Komurka 2004; Rausche et al. 2004; Stevens 2004). Although these papers do not cover specifics on the development of pile driving criteria, it is worth noting that they mention information that is important to pile driving operations and pile driving criteria. Komurka explains the phenomenon of soil set-up and how properly accounting for it can lead to the use of smaller hammers, smaller pile sections, shorter piles, higher capacities/allowable loads, and therefore more economical installations than otherwise possible. This paper also includes two case histories that involve soil set-up. Rausche et al. discusses the derivation of the Case Method and the assumptions used in the governing equations. Stevens explains how even if a pile driving hammer selected for a particular installation may be large enough to drive the piles to design penetration, it may not be large enough to overcome the long-term static capacity that is caused by soil set-up over time. By using a signal-matching program such as CAPWAP, it is possible to proof test a pile without the expense of mobilizing a larger hammer to the site by superimposing the CAPWAP results of EOID and after a given set-up period.

"Development of a New Pile Driving Formula and Its Calibration for Load and Resistance Factor Design" (Allen 2005)

The WSDOT conducted a research program to develop its own dynamic formula for accepting driven piles and to calibrate it to LRFD methodology. A database of 131 pile load tests was used to develop the WSDOT formula using the original Gates Formula as the starting point. The resulting formula was calibrated to a resistance factor of $\Phi = 0.55$ for design of pile foundations. The WSDOT formula has been used with much success by the WSDOT since. The information contained in this paper is also contained in the report *Development of the WSDOT Pile Driving Formula and Its Calibration for Load and Resistance Factor Design* (*LRFD*), WA-RD 610.1 (WSDOT 2005).

***Dynamic Pile Testing Technology: Validation and Implementation,* Report FHWA/OH-2007-08 (Liang and Yang 2007)**

This report, produced for ODOT, covers several issues related to implementation of LRFD for pile design and construction. One of the objectives of the study that related to pile driving criteria was to develop reliability-based quality control criteria for driven pile installation. Chapter three presents the developed reliability-based quality control method on driven piles, particularly regarding the criteria for the number of dynamic pile tests and the acceptable measured capacity. Tables 3-2 and 3-3 list the recommended number of load tests to be conducted for quality control of driven piles. These recommendations are obtained from a statistical analysis approach based on the desired level of reliability. Factors considered included the type of test, site variability, number of piles, and the timing of the test (EOID, restrike, etc.). Note that the Technical Note, "Quality Control Method for Pile Driving" (Liang and Yang 2006) is a summary of the information presented in chapter three of this report.

SUMMARY

This chapter provided a brief review of the various codes and specifications used to define the requirements of pile driving criteria. This review suggests that a wide range of approaches is used in the construction industry and in transportation agencies. The approaches for developing driving criteria range from using an existing driving formula, to developing a dynamic formula specific to an agency's geographic area and methods of practice, to using dynamic testing alone, to incorporating static load testing with dynamic testing.

The AASHTO code provides a comprehensive treatment of the subject and includes guidance for design based on a broad range of potential strategies to develop pile driving criteria. The application of test data to pile driving criteria is mostly incorporated into the selection of the resistance factor based on the type and quantity of testing used for establishing driving criteria or for quality control in the field, or both.

Among other guidelines and codes, the U.S. Army Corps of Engineers utilizes similar test methods as AASHTO, with perhaps less latitude for installation based on pile driving formula alone. The FHWA design guidelines and NHI courses are generally consistent with AASHTO, but have not been updated to LRFD format as of the time of this writing. These documents attempt to steer agencies away from using dynamic formula and rely more on dynamic and static testing for pile acceptance criteria. Other codes used for commercial and industry projects, as well as industry group guide documents, are generally less specific in their requirements for the development of pile driving criteria. These documents tend to be focused on providing guidance on equipment and installation techniques rather than specific acceptance criteria.

Several state DOTs have publications that define their own requirements in more specific terms than provided by the AASHTO code. Such publications specify resistance factors for design, test location selection, test type selection, and test frequency. The guidance provided is based on the AASHTO code, agency experience, and/or research (both internal and external). Other states either utilize unpublished internal guidelines or have not developed specific requirements separate from the AASHTO requirements.

Chapters three and four present a survey of individual transportation agencies to better determine and document current practices.

CHAPTER THREE

RESULTS OF THE PHASE I SURVEY

INTRODUCTION

The Phase I Survey (Appendix A) was developed to gather information on how the surveyed agencies were developing and using pile driving criteria. Special attention was focused on the use of test pile data for developing driving criteria. The goal of the survey was to collect information that shows the current practices by various states that could be synthesized and evaluated as well as to include suggested areas of useful practices and some areas that need improvement. It is also intended that the results can be used by others to identify common elements as well as the advantages and disadvantages of each approach, especially as applied to specific situations or site conditions.

The questionnaires were sent to the geotechnical engineer (or equivalent) in all 50 state DOTs, plus the District of Columbia and Puerto Rico. The following is a list of the states that responded. Of the 52 agencies surveyed, 44 (87%) provided responses to the survey, including Arizona and Hawaii, where driven piles are not used.

Alabama	Mississippi
Alaska	Missouri
Arkansas	Nebraska
California	Nevada
Colorado	New Hampshire
Connecticut	New Jersey
Delaware	New Mexico
Florida	New York
Georgia	North Carolina
Idaho	North Dakota
Illinois	Ohio
Indiana	Oregon
Iowa	South Carolina
Kansas	South Dakota
Kentucky	Tennessee
Louisiana	Utah
Maine	Vermont
Maryland	Virginia
Massachusetts	Washington
Michigan	Wisconsin
Minnesota	Wyoming

Tables summarizing some of the response questions are included in the following sections of this chapter. Not all of the questions lend themselves to summarization in table format. All of the responses received to the Phase I Survey are in Appendix B in alphabetical order by state. This chapter will discuss each question and the responses.

Some of the Phase I Survey responses summarized in this chapter include information derived from discussions with selected agencies through the follow-up telephone interviews. The telephone interviews were done as the Phase II Survey and provided an opportunity for agencies to explain and/or elaborate on the responses from the Phase I Survey. Notes from the telephone interviews are included in Appendix C.

At the time of the survey, some states were not aware of the errors in Chapter 10 of the initial publication of the AASHTO 2010 *LRFD Bridge Design Specifications*. Many of the errors were on the subject of resistance factors and pile testing frequency. The answers included by the states reflect their understanding of the 2010 specification as they understood it at the time of the survey.

QUESTIONNAIRE FORMAT

The survey questionnaire was organized with the questions generally arranged in groups pertaining to a certain subject, and generally organized as follows:

- Questions 1 and 2—area of geographic practice and the volume of pile projects.
- Questions 3 and 4—installation plan submittals and the agency review.
- Questions 5–9—current practice of the respondent with regard to pile driving criteria.
- Questions 10–13—establishing the use and frequency of various types of pile tests and how to determine the axial resistance of test piles.
- Questions 14–16—use of high-strain dynamic testing.
- Questions 17–19—use of load tests (rapid and static).
- Question 20—additional quality assurance measures.
- Question 21—impact of driving criteria on design.

Some questions required a free-form written response, whereas others had numerical answers. Some questions asked respondents to assign a percentage of projects to several different options. In some cases, respondents gave answers that sum to greater than 100%, as they believed that there may have been overlap where some projects could be classified in more than one option.

TABLE 1
Q2. PLEASE ESTIMATE (to the best of your ability) APPROXIMATELY HOW MANY OF THE FOLLOWING OCCUR WITHIN YOUR AGENCY ON AN ANNUAL BASIS:

a. Number of projects with driven pile foundations

No. of Projects Annually	States		
<20	Alaska Connecticut Delaware Idaho Maryland	Massachusetts Nevada New Hampshire New Jersey New Mexico	North Dakota South Dakota Vermont Washington Wyoming
20–49	Alabama Arkansas California Colorado Georgia	Kansas Kentucky Maine Mississippi Missouri	New York Oregon South Carolina Utah
50+	Florida Illinois Indiana	Iowa Louisiana Michigan	North Carolina Ohio Virginia Wisconsin

In the following discussions where respondents were asked to provide numerical answers an attempt has been made to utilize answers that indicate a majority. That is, when an agency had values among several options, the option with the majority was typically taken as the “predominate” method or answer.

SUMMARY DISCUSSION OF SURVEY RESPONSES

Questions 1 and 2: Volume of Piles Installed

1. **What is your general geographic area (location & extent) of practice?**
2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**
   a. **Number of projects with driven pile foundations**
   b. **Number of individual driven piles installed**
   c. **Lineal feet of driven piles installed**

Tables 1–3 group the responding agencies according to the responses to Question 2. The annual linear feet of pile varied from under 10,000 to 400,000. The quantity of piles driven can vary among the states for several reasons, yet two are more significant than others: (1) some states do not use many or any piles, such as Nevada and Arizona, and (2) the size of transportation programs varies in general relationship with the size of the population. States such as Vermont and Alaska do not have many projects in a given year, whereas states such as California or Ohio have many pile projects every year.

Questions 3 and 4: Submittals and Review

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires**

TABLE 2
Q2. PLEASE ESTIMATE (to the best of your ability) APPROXIMATELY HOW MANY OF THE FOLLOWING OCCUR WITHIN YOUR AGENCY ON AN ANNUAL BASIS:

b. Number of individual driven piles installed

No. of Individual Piles	States		
<500	Alaska Arkansas Colorado Delaware	Maine Nevada New Mexico South Dakota	Vermont Washington Wyoming
500–2,999	Alabama Connecticut Florida Georgia Idaho Kansas	Kentucky Maryland Massachusetts Missouri New Hampshire	New Jersey New York North Dakota Oregon South Carolina
3,000+	California Illinois Indiana Iowa	Louisiana Michigan North Carolina Ohio	Utah Virginia Wisconsin

TABLE 3
Q2. PLEASE ESTIMATE (to the best of your ability) APPROXIMATELY HOW MANY OF THE FOLLOWING OCCUR WITHIN YOUR AGENCY ON AN ANNUAL BASIS:

c. Lineal feet of driven piles installed

No. of Pile-Feet	States		
<20,000	Alaska Delaware Nevada	New Mexico South Dakota Vermont	Washington Wyoming
20,000–99,999	Alabama Arkansas Colorado Connecticut Georgia Idaho Kansas	Kentucky Maine Maryland Massachusetts Missouri New Hampshire New Jersey	North Dakota New York Oregon South Carolina Utah
100,000+	California Florida Illinois Indiana	Iowa Louisiana Michigan North Carolina	Ohio Tennessee Virginia Wisconsin

the contractor to submit an installation plan for driven piles that includes the following:

a. **No submittal required**
50% to 100%, with 3 of 42 states listing as primary method.

b. **List of pile driving equipment only**
10% to 100%, with 27 of 42 states listing as primary method.

c. **List of pile driving equipment plus wave equation analysis**
5% to 100%, with 13 of 42 states listing as primary method.

d. **Specific information regarding the driving sequence**
2% to 100%, with 4 of 42 states listing as primary method.

e. **Other information specifically related to pile driving criteria, please explain**
One state (Oregon—depends on method used to calculate pile resistance).

By far, most states (27 of 42) require only a submittal of the pile driving equipment by the contractor. Most of the remaining states require the contractor to submit a wave equation analysis of the proposed hammer(s). The survey answers for Question 3 are listed in Table 4.

4. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. **No evaluation is performed**
   50% to 100%, with 5 of 42 states listing as primary method.

TABLE 4
Q3. PLEASE PROVIDE YOUR BEST ESTIMATE OF THE PERCENTAGE OF DRIVEN PILES (e.g., out of the total number of driven piles used for transportation structures on an annual basis) FOR WHICH YOUR AGENCY REQUIRES THE CONTRACTOR TO SUBMIT AN INSTALLATION PLAN FOR DRIVEN PILES WHICH INCLUDES THE FOLLOWING:

a. No submittal required

b. List of pile driving equipment only

c. List of pile driving equipment plus wave equation analysis

d. Specific information regarding the driving sequence

e. Other information specifically related to pile driving criteria, please explain

State	3a	3b	3c	3d	3e
Alabama		100%			
Alaska			100%	100%	
Arkansas		100%			
California		90%	10%		
Colorado		20%			
Connecticut			100%	10%	
Delaware			100%	20%	Drivability
Florida		100%		100%	
Georgia		99%	1%		

TABLE 4
(*continued*)

State	3a	3b	3c	3d	3e
Idaho		100%			
Illinois	90%		10%		
Indiana		100%	60%	10%	
Iowa		100%			
Kansas		100%			
Kentucky		95%	5%		
Louisiana		100%		100%	Load test frame and reaction system when test piles are included
Maine			100%		
Maryland		90%	10%	0%	
Massachusetts			90%	10%	
Michigan		90%	10%		
Minnesota		10%	90%		
Mississippi		100%			
Missouri		90%	10%		
Nebraska		All projects			We perform wave equation analysis
Nevada			100%		
New Hampshire		100%			100%—pile splice and pile point details, preboring details (if required)
New Jersey			100%		At least two test piles are required to be driven first for each foundation. The test piles are to be monitored with PDA w/CAPWAP. The production pile order length and the driving criteria will be issued based on the test pile driving data and PDA/CAPWAP report. The production piles can only be driven with the same hammer used for the test piles driving.
New Mexico		100%			
New York		96%		4%	Jetting criteria for prestressed concrete piles
North Carolina		90%	10% (D/B)		
North Dakota		100%	3%	3%	
Ohio		100%			Minimum of 30 blows/ft for hammer selection
Oregon		30%	70%		
South Carolina		100%		100%	Method to determine potential hammer energy, template details, and any jetting, spudding, or predrilling details if warranted
South Dakota	100%				
Tennessee	50%	50%			
Utah			100%		None
Vermont		2%	98%		
Virginia		40%	60%		
Washington		10%	90%		-
Wisconsin	5%	90%	5%		
Wyoming		100%			

D/B = design-build.

b. Specified hammer energy included in specifications
5% to 100%, with 12 of 42 states listing as primary method.

c. Evaluate using a pile driving formula (please specify which formula is used)
10% to 100%, with 7 of 42 states listing as primary method.

d. Evaluate using a wave equation analysis
1% to 100%, with 27 of 42 states listing as primary method.

e. Other, please explain
5%; depends on how pile resistance was calculated.

Evaluation and approval of hammers again were the majority, with 27 of 42 utilizing a wave equation analysis of the contractor's submittal, although some of these used the analysis submitted by the contractor. The remainder of the respondents was generally equally distributed between utilizing specified hammer energy in their standard specification and using a pile driving formula for the evaluation. The survey answers for Question 4 are listed in Table 5.

TABLE 5
Q4. PLEASE PROVIDE YOUR BEST ESTIMATE OF THE PERCENTAGE OF DRIVEN PILES (e.g., out of the total number of driven piles used for transportation structures on an annual basis) FOR WHICH YOUR AGENCY EVALUATES THE SUITABILITY OF THE PROPOSED HAMMER AND DRIVING SYSTEM AS FOLLOWS:

a. No evaluation is performed

b. Specified hammer energy included in specifications

c. Evaluate using a pile driving formula (please specify which formula is used)

d. Evaluate using a wave equation analysis

e. Other, please explain

State	4a	4b	4c	4d	4e
Alabama			100%		
Alaska				100%	
Arkansas		72%		28%	
California			90% (Gates Formula)	10%	
Colorado		20%		20%	
Connecticut		100%		100%	
Delaware		10%		100%	
Florida					100% evaluated based on wave equation analysis and satisfactory performance in the field during dynamic monitoring of test piles
Georgia	75%		24% (S-Pile)	1% (WEAP)	
Idaho				100%	
Illinois			90% (WSDOT formula)	10%	
Indiana			40%	60%	
Iowa				100%	
Kansas		100%	100% Modified ENR	50%	All of our inspectors must conduct a drivability calculation. Based on the contractor's equipment, the inspector then inputs the data into a spread sheet that will calculate the required blows needed for the required bearing.
Kentucky		95%		5%	
Louisiana		30%		70%	
Maine				100%	
Maryland		100%		10%	
Massachusetts		1%	24%	75%	
Michigan			90%	10%	
Minnesota		5%	10%	85%	
Mississippi		20%		100%	
Missouri				10%	90%—minimum hammer energy included in specifications
Nebraska				All projects	
Nevada		100%		100%	
New Hampshire		5%		100%	
New Jersey				100%.	The contractor is required to submit WEAP for approval for each hammer that is proposed to be used.
New Mexico		100%		100%	Pile dynamic testing, 50%

TABLE 5
(*continued*)

State	4a	4b	4c	4d	4e
New York				100%	
North Carolina		10%		100%	
North Dakota		100%	97% (Modified ENR)	3%	
Ohio	100%				
Oregon					The method for determining the suitability of hammers depends on the method being used to determine bearing. Either dynamic formula (FHWA Gates), wave equation, or PDA/CAPWAP is typically used. If dynamic formula is specified then a range of hammer energies is provided to the contractor in the contract specifications to evaluate hammer acceptance for a given bearing resistance. This is about 25% of total annual pile driving projects. If wave equation is used to determine bearing, the contractor does the WEAP analysis using specified soil input values to evaluate and submit hammers for use that meet specified driving stress and resistance criteria (about 70% of pile projects). Hammer acceptance based on PDA/CAPWAP is determined based on preliminary WEAP analysis and verified in the field using measured data (about 5% of projects).
South Carolina	100%	90%		100%	Please note that our group is in preconstruction and the Bridge Maintenance office may use different criteria.
South Dakota					A minimum energy of the hammer is stated in the plans to use in order to drive the pile.
Tennessee	50%	50% (Minimum specified)	50% (ENR)		
Utah		100% (minimum hammer energy specified in plans)		100%	None
Vermont				100%	
Virginia		5%	40% ENR (the Gates Formula is now used for LRFD projects).	60%	
Washington		20%	10% (WSDOT formula)	90%	
Wisconsin	90%			5% (Only on mega-projects)	5% (when driving issues arise)
Wyoming				95%	WYDOT hires a consultant to perform PDA testing on about 5% of bridges

Questions 5–9: Current Practice

Question 5—Predominant Criteria

5. **Please estimate the percentage of driven pile projects for which the predominant method your agency uses as a criteria for installation of production piles is the following:**
   a. **Drive the pile to a specified tip elevation**
   1% to 100%, with 4 of 42 states listing as primary method.
   b. **Drive the pile to practical refusal**
   5% to 100%, with 7 of 42 states listing as primary method.
   c. **Drive the pile to a specified driving resistance (blow count) based on a pile driving formula**
   1% to 100%, with 14 of 42 states listing as primary method.
   d. **Drive the pile to a specified driving resistance (blow count) based on a wave equation analysis (WEAP or similar)**
   2% to 100%, with 9 of 42 states listing as primary method.
   e. **Drive the pile to driving resistance (blow count) based on correlation to the driving resistance of another pile that had previously been subjected to high-strain dynamic measurements (such as with a PDA or similar device)**
   5% to 100%, with 16 of 42 states listing as primary method.
   f. **Drive the pile to driving resistance (blow count) based on correlation to the driving resistance of another pile that had previously been subjected to static or rapid load test measurements**
   2% to 50%; Tennessee uses load tests on all "friction" piles (50% of total piles).
   g. **A combination of both "e" and "f"**
   1% to 40%.

The use of high-strain dynamic testing (HSDT) and the use of a pile driving formula were almost equally the most common criteria (14 of 42 and 16 of 42, respectively). The use of wave equation analysis alone followed (9 of 42). Only a few states used a specified tip elevation or refusal criteria as the predominant criteria, typically owing to favorable driving conditions in their state (such as shallow bedrock). For those states that used a pile driving formula as the primary criteria, the Gates and ENR formulas were the most often cited, although several states used their own formulas or in-house modifications to the existing formulas. The survey answers for Question 5 are shown in Table 6.

Question 6—Use of Restrikes—Question 6 aimed to understand how agencies were utilizing restrike measurements to verify axial resistance.

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**
   a. **Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer**
   5% to 97%.
   b. **Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance**
   1% to 10%.
   c. **Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location**
   1% to 95%.
   d. **Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive**
   5% to 100%.
   e. **Would restrike every pile that does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance**
   5% to 100%.
   f. **Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive**
   1% to 100%.

Although many agencies use restrikes in some capacity, most restrikes tend to be used to check piles that do not meet the acceptance criteria during initial drive. Several agencies also routinely use restrikes to demonstrate pile set up, but this application is not always used in all situations where setup occurs. Some agencies factor the setup into the initial drive criteria without verifying with a restrike. The survey answers for Question 6 are listed in Table 7.

Question 7—Use of Dynamic Monitoring on Production Piles

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

TABLE 6
Q5. PLEASE ESTIMATE THE PERCENTAGE OF DRIVEN PILE PROJECTS FOR WHICH THE PREDOMINATE METHOD YOUR AGENCY USES AS A CRITERIA FOR INSTALLATION OF PRODUCTION PILES IS THE FOLLOWING:

a. Drive the pile to a specified tip elevation

b. Drive the pile to practical refusal

c. Drive the pile to a specified driving resistance (blow count) based on a pile driving formula

d. Drive the pile to a specified driving resistance (blow count) based on a wave equation analysis (WEAP or similar)

e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile that had previously been subjected to high-strain dynamic measurements (such as with a PDA or similar device)

f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile that had previously been subjected to static or rapid load test measurements

g. A combination of both “e” and “f”

State	5a	5b	5c	5d	5e	5f	5g
Alabama		60%					40%
Alaska				30%	70%		
Arkansas	1%		71%	23%	5%		
California	90% (both a and c)		90% (both a and c)		4%		6%
Colorado					100%		
Connecticut				40%	40%		20%
Delaware	30%			100%	10%	10%	
Florida					97%		3%
Georgia	100%		98%		1%	1%	
Idaho		20%		50%	30%		
Illinois	1%		99%				
Indiana	0%—Only if scour a minimum tip	5%	35%		60%		
Iowa	Full penetration when achievable						
Kansas			93%	2%	5%		5%
Kentucky		75%; “Practical refusal” is often defined according to a driving formula	95%		5%		
Louisiana		5%	60%		10%	30%	40%
Maine	30%				100%		
Maryland			90%		10%		0%
Massachusetts		10%	1%	15%	64%	10% or less	
Michigan			90%		10%		1%
Minnesota	5%		75%		20%		
Mississippi	10%		20–25% (being phased out with LRFD)		60%+ (will be 100% when ASD projects are complete)	20%	75%+

(continued on next page)

TABLE 6
(*continued*)

State	5a	5b	5c	5d	5e	5f	5g
Missouri		75%—Modified Gates Verified	15%—Modified Gates Controlled		10%—Modified Gates Verified		
Nebraska			All projects		If we specify test piles on the project		
Nevada	100%, also must meet required blow count			100%, also must meet tip elevation requirements	90%	<10%	<5%
New Hampshire					100%	2%	100%
New Jersey					95% of production piles driving criteria are based on the test piles driving data that are subjected to PDA/CAPWAP measurements.	5% of production pile driving criteria may be based on data from SLT and PDA/CAPWAP performed to the test piles. Generally the SLT is considered for the larger size diameter piles. The larger diameter piles commonly used are 36, 48, and 54 in. precast prestressed concrete piles.	
New Mexico	13%	12%		25%	50%		
New York		35% (use WEAP for stresses)		45%	20%		2%
North Carolina	15%	20%		80% (including Questions a & e)	15%		
North Dakota		97%	97%		3%		
Ohio	1%	10%			89%		
Oregon			25%	70%	5%		
South Carolina				70%	28%	1%	1%
South Dakota			100%				
Tennessee		50%				50 (minimum tip elevation may be required)	
Utah				2%	94%		4%
Vermont				2%	98%		
Virginia	10%	35%	30% (H-pile pract. ref.) 10% (friction piles)	5%	45%	<5%	<5%
Washington	1%		80%		20%		5%
Wisconsin		55%	35%		10 (due to 2 large mega-projects)		
Wyoming	We always use the planned length as a guide.	85%; for the other 15% WEAP and/or PDA testing is used.		100%, we run WEAP on all pile projects	5 to 10% of projects		

TABLE 7
Q6. PLEASE ESTIMATE THE PERCENTAGE OF DRIVEN PILE PROJECTS FOR WHICH YOUR AGENCY WOULD UTILIZE RESTRIKE MEASUREMENTS TO VERIFY AXIAL RESISTANCE OR DRIVING RESISTANCE ON PRODUCTION PILES AFTER SOIL SETUP

a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

State	6a	6b	6c	6d	6e	6f
Alabama	60%				100%	
Alaska	80%		10%			10%
Arkansas	44%	1%			28%	0%
California				90%		10%
Colorado			90%			10%
Connecticut	85%		15%			
Delaware			30%	100%	100%	
Florida			10%	75%	15%	
Georgia	50%		50%			
Idaho					Restrike minimum of 2 that don't make it	
Illinois	30%		50%	10%	10%	
Indiana			10%			
Iowa	5%		95%		100%	40%
Kansas	40%			20%	80%	20%
Kentucky	75%		5%	20%		1%
Louisiana	10%	5%	50%	25%	15%	75%
Maine					5%	5%
Maryland	95%			5%		
Massachusetts	80%		20%	100%	50%	20%
Michigan	99%		1%			
Minnesota	75%			25%		
Mississippi	95%			5%		
Missouri	10%	10%	70%+	10–20%		
Nebraska					15%	
Nevada	97%		3%			
New Hampshire						
New Jersey	90%		10%	10%		
New Mexico				100%		
New York	10%		25%	65%		
North Carolina				100%		100%
North Dakota	40%		8%	50%		2%
Ohio						
Oregon	80%			20%		

(continued on next page)

TABLE 7
(*continued*)

State	6a	6b	6c	6d	6e	6f
South Carolina			25%	5%		
South Dakota					5%	
Tennessee	50%					
Utah	10%			90%		
Vermont	35%		55%			<1%
Virginia	50%			50%		
Washington			10%	5%		
Wisconsin	90%			10%		
Wyoming			10%			

This question required a narrative answer from the respondents. The survey answers for Question 7 are listed in Table 8.

Most states appear to be using dynamic monitoring of production piles before establishing final driving criteria on at least some projects. Although the question was worded to consider production piles prior to establishing final criteria, some states gave answers that reflected their total construction monitoring percentages.

Most of the states that consistently use dynamic monitoring require that at least one pile on each substructure unit be tested to develop final criteria specific to that foundation unit. A few states use dynamic monitoring under limited circumstances,

TABLE 8
Q7. PLEASE ESTIMATE THE PERCENTAGE OF DRIVEN PILE PROJECTS FOR WHICH YOUR AGENCY WOULD UTILIZE DYNAMIC MONITORING (with PDA or similar) OF PRODUCTION PILES PRIOR TO ESTABLISHMENT OF FINAL PRODUCTION PILE DRIVING CRITERIA. PLEASE COMMENT ON FACTORS AFFECTING YOUR AGENCY'S DECISION TO UTILIZE THIS TECHNOLOGY (e.g., pile types and/or ground conditions)

State	
Alabama	Presently, the test piles set up for PDA monitoring are production piles. Thus, the production pile criteria are determined by the test pile results. Production piles failing to meet the criteria are tested individually. This occurs on the 40% of the projects that are not drive to refusal (DTR) projects. Test piles are not set up on DTR projects.
Alaska	I estimate 70% of projects utilize PDA. This is when we anticipate high driving stresses and are concerned with pile damage, or if we are in a friction pile with little end bearing, where we are trying to get as much capacity out of a pile as possible (by utilizing a higher resistance factor). Other times we use simple economics to determine if the PDA will pay for itself by allowing us to use fewer piles.
Arkansas	5% 1. Large number of piles such that significant savings could be achieved. 2. Higher required driving resistance than that typically required.
California	10%. Most typically, the pile size is the largest determinant. Piles over 20 in. in diameter are required to have site-specific PDA production pile criteria. Piles larger than 36 in. in diameter receive PDA dynamic measures, but capacity values are determined by site-specific static axial pile load testing. Few piles less than 20 in. in diameter receive dynamic testing.
Colorado	CDOT utilizes the PDA on all (100%) pile driving projects to establish the pile driving criteria. CDOT uses end bearing criteria for its driven pile and 90% of our pile are H-pile and driven into bedrock.
Connecticut	See attached excerpt from our geotech manual ... I've also attached our current pile standard specifications.
Delaware	100%
Florida	100%. FDOT normally requires dynamic monitoring of about 10–20% of piles to evaluate the driving system, determine the final pile lengths, establish the required installation criteria, and confirm bearing resistance. Sometimes it is desirable to utilize dynamic monitoring on a larger percentage of piles in order to increase confidence at a particular location or in a portion of the structure. All dynamically tested piles are normally incorporated into the structure.
Georgia	1%. Used on large friction pile projects where wave equation or PDA could help save pile lengths.
Idaho	40%. Determine need of PDA testing based on pile type, pile design capacity, and soil conditions.
Illinois	2%—(use on very big projects with friction piles where many lineal feet of piling can be saved).
Indiana	60%. Ground conditions and the costs of piling
Iowa	0%. Production pile criteria may be changed based on PDA results but PDA is not used to establish production driving criteria.
Kansas	Currently we are monitoring approximately 5% of the piles with a PDA. This number will decrease as we build up our database.

TABLE 8
(*continued*)

State	
Kentucky	5%; ground conditions, project size; LRFD implementation is a factor affecting decision to use technology
Louisiana	Approximately 50% of LADOTD driven pile projects utilize PDA to establish driving criteria. For highly competent soil conditions the Gates Dynamic formula may be used for capacity verification.
Maine	100%
Maryland	10%. This is used for bridges that use large piles (>18 in. diameter) installed as friction piles or for projects with a large volume of friction piles where the increased cost of PDA can be justified. For bridges with a small amount of linear feet of piling, we find it cheaper and quicker to take a conservative approach and install additional piling rather than performing testing.
Massachusetts	75%
Michigan	Estimate 10% of future projects to use PDA testing. PDA testing specified on projects where engineers estimate for piling pay item is over $300,000.
Minnesota	25%. Generally only used for test piles. Factors: Capacity—lower or higher than typical. If high-energy hammers are expected to be used. Questionable soils (unsure where and how bearing to expect). Expect significant set-up. Generally don't test H-piles (end-bearing piles) with the PDA.
Mississippi	Currently approximately 60%; future 100%. As ASD projects are phased out, all future pile projects will utilize dynamic testing of "test" piles prior to establishing production pile lengths and driving criteria. This is especially important when driving steel H-piles in sand, variable soils (soft clays over/underlying sands), or where piles are driven through a thick scour zone. Note: MDOT's "test" piles are driven in-place and are used as production piles.
Missouri	PDA would be specified on 10% of pile projects. PDA would routinely be specified on friction piles and rarely on end-bearing piles where difficult driving or highly variable depth to rock is anticipated.
Nebraska	Historically about 10% of projects; however, with the implementation of LRFD will test more piles.
Nevada	100%. NDOT requires that PDA, pile restrikes, and CAPWAP be utilized at each foundation location (piers and abutments) to confirm pile capacity. Information gained through this process is used to establish final pile driving criteria.
New Hampshire	100%. NHDOT has owned and operated a PDA since 1996, so it is convenient to perform PDA testing as required to provide the necessary quality control.
New Jersey	PDA/CAPWAP monitoring is required for all test piles. Test piles are the index piles and at least two piles are required for each piled foundation. Test piles are to be driven first prior to issuing the order length and driving criteria for the production piles.
New Mexico	50%— based on soil conditions at a depth where there is no defined bottom and where the number of piles is significant (~50 plus) with lengths in the 60 ft to 90 ft length.
New York	20%. Usually for friction piles where the amount of end-bearing capacity is hard to predict, on prestressed concrete piles to evaluate tension stresses, and H-piles in sands and gravels where the pile length has a tendency to run longer than predicted.
North Carolina	10%. PDA will be utilized if— 1. Concern about overstressing piles such as prestressed concrete piles (PCP) driving through high blow count soils or long PCP piles. 2. Concern about achieving required resistance. PDA may be utilized if— 1. Special piles such as composite piles (steel H-pile on bottom connected with prestressed concrete pile) are used. 2. Piles are designed for very high resistance.
North Dakota	3%
Ohio	100% of friction piles being driven to a specified resistance. Dynamic testing of piles being driven to refusal is not required.
Oregon	Dynamic monitoring is used on less than about 5% of driven pile projects overall and almost always in conjunction with signal-matching analysis (typically CAPWAP). PDA/CAPWAP is typically used when there are sufficient numbers of friction piles on the project to justify the expense, taking into account the higher resistance factor that may be used to optimize the number, size, and/or lengths of piling on a project. It is also used to monitor high driving stress conditions (reducing pile damage potential), to verify hammer performance, and for large, high-capacity piles.
South Carolina	We would use test piles that are also production piles on about 25% of our projects. Main reason is ground conditions and pile stresses owing to high loading during driving.
South Dakota	1%. A consultant may on occasion set up PDA on a non-state government project that the SDDOT is not involved in.
Tennessee	We do not use PDAs.
Utah	100%. We typically test one of the first production piles driven and base pile driving criteria on that dynamic test for the rest of the piles in the foundation. Depending on the number of piles in a given foundation, more tests may be performed (as per AASHTO criteria).
Vermont	Our standard protocol is to test one pile at each substructure prior to production driving. From this, we develop a driving criteria, which we use to confirm resistance of production piles. All test piles are restriked, unless they are driven to bedrock. We feel this is the most efficient way to ensure we are getting the resistance we need (and what we pay for) at the best price.

(continued on next page)

TABLE 8
(*continued*)

State	
Virginia	50%. VDOT has been using PDA to establish pile capacity for over 25 years. Most projects with friction piles will have driving test piles that are driven and dynamically monitored. A restrike is performed 5 days after initial drive. Driving test piles are usually driven at production pile locations, which are designated in the bid documents. Some H-piles that are driven to refusal are dynamically monitored if special conditions exist. About 10% of our H-piles in end-bearing projects require dynamic monitoring.
Washington	20%—Size of project or potential for significant setup.
Wisconsin	We currently have two mega-projects that are using PDA to set drive criteria, but this is not common. Normally we only use PDA if drive issues arise or the use of PDA is considered when there is a large number of friction piles (100+) on a project.
Wyoming	5 to 10%. Shallow bedrock, < 80 ft deep is common in Wyoming and piles are often driven to a plan length with refusal blow counts and/or to a blow count and stroke based on WEAP.

such as very large projects, certain soil conditions, or other special circumstances. Some states that have had limited use of dynamic monitoring indicated that they foresee increased use of the technology as they fully transition to LRFD design to take advantage of the higher resistance factors associated with dynamic monitoring.

Questions 8 and 9—Use of Pre-Production Test or Probe Piles

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**
   a. **Would not perform any load tests on pre-production piles**
   15% to 100%, with 28 of 42 states stating no pre-production tests are used.
   b. **Would install pre-production (probe) piles without dynamic monitoring**
   15% to 98%, with 4 of 42 states listing as primary method.
   c. **Would install pre-production test piles with dynamic monitoring (PDA or similar) only**
   5% to 100%, with 8 of 42 states listing as primary method.
   d. **Would install pre-production test piles for static or rapid load testing only**
   Tennessee is the only state to routinely do this (50% of projects).
   e. **Would install pre-production test piles with both "c" and "d"**
   85% to 100% (only two states: New Hampshire and Louisiana).
9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

A large majority of states (28 of 42) do not perform pre-production load tests to aid in developing the driving criteria. A few states do routinely use pre-production probe piles without dynamic monitoring or test piles with dynamic monitoring, with only three states using an occasional pre-production SLT or RLT. For those not using pre-production test piles, there do not appear to be any additional measures being used beyond the wave equation analysis or driving formulas cited as normal practice for developing criteria. The survey answers for Questions 8 and 9 are listed in Tables 9 and 10, respectively.

Questions 10–13: Use and Frequency of Pile Tests

10. **On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?**
    a. **High strain dynamic testing only (PDA or similar)**
    1% to 100%.
    b. **High strain dynamic testing with signal matching only (CAPWAP or similar)**
    5% to 100%.
    c. **Static load tests only**
    1% to 10% (with Tennessee listing 50%).
    d. **Rapid load tests (Statnamic or similar) only**
    <1% for three states that answered.
    e. **Combinations of the above**
    1% to 100%.
    f. **Other (please explain)**
    (see Table 11).

Of the states that use HSDT on a regular or exclusive basis, three-fourths (13 of 17) use signal-matching analyses. The remaining fourth do not use signal matching. Very few states utilize SLT or RLT methods on a regular basis. The survey answers for Question 10 are listed in Table 11.

11. **Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.**

Most states do not make modification to their prescribed number and types of tests based on pile type. In many cases,

TABLE 9
Q8. PLEASE ESTIMATE THE PERCENTAGE OF DRIVEN PILE PROJECTS FOR WHICH YOUR AGENCY WOULD UTILIZE TESTING OF PRE-PRODUCTION (test or probe) PILES PRIOR TO ESTABLISHMENT OF FINAL PRODUCTION PILE DRIVING CRITERIA AS FOLLOWS:

a. Would not perform any load tests on pre-production piles

b. Would install pre-production (probe) piles without dynamic monitoring

c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only

d. Would install pre-production test piles for static or rapid load testing only

e. Would install pre-production test piles with both “c” and “d”

State	8a	8b	8c	8d	8e
Alabama	60%		1%	1%	38%
Alaska	100%				
Arkansas	100%		5%		
California	99%				1%: Rare to have pre-production tests
Colorado	<1%		<1%		<1%
Connecticut	20%		70%		10
Delaware			100%	Special projects only	
Florida			99%		1%
Georgia	99%				1%
Idaho		60%	40%		
Illinois		98%	2%		
Indiana			60%		
Iowa					1%
Kansas	<1%		100%		
Kentucky	99%		5%		
Louisiana	15%		15%		85%
Maine					
Maryland	98%		2%		
Massachusetts			5%		10%
Michigan		90%	10%		1%
Minnesota		Test piles (not probe piles) without dynamic monitoring 75%	25%		
Mississippi	75–80%				20–25%
Missouri	100%				
Nebraska	Never done any				
Nevada					
New Hampshire			100%	2%	100%
New Jersey					See items 5 & 7. Test piles monitored with PDA/CAPWAP are required for all pile foundations. Additionally, 5% of test piles may be subjected to static load test due to size of pile diameter (36 in. or larger).
New Mexico					

(continued on next page)

TABLE 9
(*continued*)

State	8a	8b	8c	8d	8e
New York	96%		2%		2%
North Carolina			One every other year		
North Dakota	100%		3%		
Ohio	100%				
Oregon					<1%
South Carolina	99%				1%
South Dakota					
Tennessee	50%			50%	
Utah	98%				2%
Vermont			98%		
Virginia	30%—These are end-bearing piles driven to refusal.	15%	55%	5%—This would always include a PD.	5%
Washington					
Wisconsin	98%		2% (mega-projects only)		
Wyoming			5%–10%		

TABLE 10
Q9. IF YOUR AGENCY DOES NOT USE A TEST PILE PROGRAM TO DEVELOP PRODUCTION PILE DRIVING CRITERIA, WHAT ADDITIONAL PROCEDURES ARE USED BY YOUR AGENCY TO ESTABLISH PRODUCTION PILE DRIVING CRITERIA?

9. If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?

State	
Alabama	
Alaska	We either use the wave equation or PDA on every project.
Arkansas	A test pile program is not used for piling that is expected to be driven to rock or practical refusal. In this case, the piles are driven to the required driving resistance. Otherwise, a test pile program is used to establish production pile driving criteria.
California	
Colorado	The use of wave equation analysis such as WEAP or DRIVEN to establish a minimum tip elevation. Then the use of the PDA to determine the final driving criteria using end-bearing capacity.
Connecticut	
Delaware	N/A
Florida	When test piles are not needed to determine final pile lengths, the initial production piles are dynamically monitored to determine the required installation criteria or reliable wave equation analysis parameters for determining the required installation criteria.
Georgia	After minimum tip elevation has been achieved, drive the piles to driving resistance using ENR. However, due to LRFD requirements, this will be changing to the use of PDA or load tests to establish production pile driving criteria.
Idaho	
Illinois	
Indiana	Gates formula is used for test piles on other 40% of projects.
Iowa	History of static load tests to establish soil friction and end-bearing factors
Kansas	
Kentucky	When dynamic testing is not performed we typically use a driving formula, effectively without pre-production piles.

TABLE 10
(*continued*)

State	
Louisiana	
Maine	Drivability analysis during design stage.
Maryland	Our typical procedure is to use the first production pile in a substructure unit as the test pile. This test pile is used primarily for estimating pile lengths for ordering correct pile lengths. The test pile and all production piles are driven to a designated capacity verified by a pile driving formula.
Massachusetts	WEAP, PDA
Michigan	We use test pile program.
Minnesota	We use test piles
Mississippi	
Missouri	End-bearing piles to hard rock would be designed based on the structural capacity of the pile and boring information would be utilized by the construction inspectors to estimate the pile lengths anticipated during driving. For friction piles, we would commonly use PDA/CAPWAP on first pile driven in each substructure element to establish driving criteria for additional piles. The modified Gates formula would likely be checked as supplement to PDA. The modified Gates formula would be used if PDA was not specified.
Nebraska	If we do not specify test pile, then we use NDOR-modified ENR formula
Nevada	1. Site-specific geotechnical investigation. 2. AASHTO static pile capacity established to develop minimum and maximum pile tip elevations, and estimated maximum driving resistance. 3. In-house WEAP done to confirm equipment availability and pile drivability. 4. Maximum anticipated driving resistance provided to contractor in Geotech Reports and Plans. 5. Require contractor to submit all proposed driving equipment along with independent WEAP showing his equipment is appropriate for approval. 6. Require PDA, CAPWAP, and restrikes at each substructure support location to verify pile capacity versus dynamic EOD blow counts. 7. Final pile driving criteria is based on the results of these tests for each substructure unit (pier, abutment).
New Hampshire	N/A
New Jersey	N/A
New Mexico	N/A
New York	We rarely have used test programs during the design stage of the project; in fact, I can only think of one project where we did this. During construction we will do dynamic pile testing on selected projects, usually on pile per substructure and on all other projects WEAP is used exclusively.
North Carolina	1. Wave equation is used to establish driving criteria for all production piles. 2. PDA is used along with wave equation to establish driving criteria for approximately 10% of all production piles. Currently, no additional procedures other than those stated above are used to establish production pile driving criteria.
North Dakota	We do not
Ohio	None
Oregon	Standard criteria require all piles to be driven to a minimum tip elevation and a required bearing resistance based on either dynamic formula, wave equation analysis, or PDA/CAPWAP. Full-scale static load tests are rarely performed. See answer to Question 4 regarding criteria used to determine bearing resistance of production piles.
South Carolina	On non-test pile projects, we use static analysis methods to estimate pile length and then WEAP during construction on contractor's hammer for verification. Geotechnical Engineer is contacted if lengths vary from plan lengths.
South Dakota	SDDOT uses test piles
Tennessee	
Utah	We typically do a static design coupled with a WEAP analysis to determine minimum hammer energy and required pile type and section. Dynamic monitoring during construction (including CAPWAP analysis) is used to verify/modify the static design.
Vermont	Driving tests are not required for H-piles driven to refusal unless special circumstances require PDA testing. H-piles are driven to practical refusal. Practical refusal has been defined as double blow count as obtained from ENR (the Gates formula is now used for LRFD projects).
Virginia	
Washington	
Wisconsin	Driving criteria based on FHWA modified Gates formula.
Wyoming	

TABLE 11
Q10. ON WHAT PERCENTAGE OF PROJECTS WOULD THE FOLLOWING TYPES OF TESTS BE PERFORMED OR REQUIRED OR UTILIZED BY YOUR AGENCY IN ORDER TO DETERMINE THE AXIAL RESISTANCE OF A TEST PILE?

a. High strain dynamic testing only (PDA or similar)

b. High strain dynamic testing with signal matching only (CAPWAP or similar)

c. Static load tests only

d. Rapid load tests (Statnamic or similar) only

e. Combinations of the above

f. Other (please explain)

State	10a	10b	10c	10d	10e	10f
Alabama					90%	
Alaska		70%				
Arkansas		5%				
California	1%	5%	1%		Both a & c = 6%	
Colorado	100%	20%	<1%			
Connecticut		85%			15%	
Delaware	100%	100%	Special projects only—When >100 piles on project			
Florida		99%			1% c or d used to confirm dynamic measurements	
Georgia						
Idaho		100%				
Illinois						
Indiana		60%	<1%			
Iowa						PDA and CAPWAP are used to address hammer performance issues and unusual driving results
Kansas	5%	5%				
Kentucky		5%				
Louisiana		10%	10%	<1%	90%	A static load test is performed on all test piles unless we determine that the applied test load will not fail the soil. PDA and signal matching (CAPWAP) are performed on all test piles.
Maine		100%				
Maryland		2%				
Massachusetts						WEAP + PDA 74% WEAP + PDA + static 1%; this is broken out from Question 7
Michigan	10%	10%	1%		10%	

TABLE 11
(*continued*)

State	10a	10b	10c	10d	10e	10f
Minnesota		25%	2%	Have only used on one project, but will use in the future.		
Mississippi		80			20%	These percentages are for pile projects where ENR alone is not used to determine pile capacity (ENR being phased out by LRFD).
Missouri						
Nebraska		10%				
Nevada		99%			<10%	
New Hampshire	100%	10%	2%		100%	
New Jersey		100%				
New Mexico	25%	25%	1%			
New York		20%			2%	
North Carolina		10%				
North Dakota						
Ohio	89	45			5% (static, dynamic, and restrike load test)	
Oregon		<5%				
South Carolina		25%			1%	
South Dakota	1%					
Tennessee			50%			
Utah		98%			2%	2% (WEAP only if for planned refusal)
Vermont					98%	
Virginia		55%	<1%	<1%	5%—All piles to be static load tested are PDA'd	
Washington		20%				
Wisconsin						
Wyoming	5–10%					

a single pile type is exclusively used or is very predominate in the particular states.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc.)? If so, please explain.

The few instances of modifications are based on either pile size (e.g., larger than typical, requiring more tests) or soil conditions (e.g., test only friction piles). For example, California, the pile size (diameter) usually dictates the types of tests and the frequency is controlled by soil conditions, whereas in New York the soil conditions typically control both type and frequency of tests. Virginia will omit restrikes when piles are bearing on rock. Ohio and Tennessee are examples of agencies that distinguish between "end bearing piles" and "friction piles" for purposes of test piles.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

There are some states where economics and project size is the primary consideration to perform tests or modify the frequency. The states that do not routinely use test programs typically have small projects or a low volume of piles on an annual basis. Such states typically responded that they consider tests on very large projects, but do not necessarily require them. For states that have used or routinely use test programs, the potential cost savings associated with higher resistance factors is usually considered to evaluate the suitability of using pile tests for large projects.

Questions 14–16: Use of High Strain Dynamic Testing

Question 14—Circumstances and Frequency of HSDT and Signal Matching

14. If your agency uses high-strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

The consensus among those agencies using HSDT is that one pile per substructure unit is generally tested with HSDT. Those agencies that use test piles outside of production pile locations typically require HSDTs on all test piles. Sometimes circumstances such as significant changes to subsurface conditions, suspected pile damage, or low-resistance measurements result in additional HSDTs being performed. Examples of the circumstances and frequency decisions are:

- The FDOT uses HSDT test piles for every project, placing them in production pile locations, with one test pile per pier.
- For those projects that the Louisiana Department of Transportation and Development (LADOTD) use HSDT test piles, they typically use a nonproduction pile location.
- Caltrans determines the frequency of HSDT piles based on pile size and site stratigraphy, using control zones with one test pile per control zone. Caltrans also considers economic factors of costs of tests versus benefits to the design.
- The Utah DOT uses the HSDT on the first production pile in each substructure to verify the criteria (blow count at minimum energy at specified tip elevation) established by wave equation analysis.
- The NCDOT utilizes HSDTs, but does not routinely use HSDTs for monitoring piles or for developing criteria. The HSDT is mostly used if there is a concern that the pile did not achieve bearing, concern with pile stresses, or damage during driving.
- Some states, such as Louisiana, Minnesota, Mississippi, and Oregon look at the cost-effectiveness of an HSDT test pile program when determining the frequency of tests.

The use of signal-matching analysis is usually required on all HSDT piles by most agencies. There are some circumstances when signal matching may not be performed, such as:

- Multiple HSDTs in a single substructure unit.
- Production pile HSDTs that are used for confirmation of resistance when there are test piles that have had signal-matching analysis performed.
- SLT data are available that the HSDT has been correlated with.

In cases where HSDT is performed on nonproduction test piles or on piles driven for SLTs, signal matching is typically performed on all such piles.

Question 15—Restrikes with HSDT

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

There appear to be two common circumstances for performing restrikes. The most common is when a pile does not meet the required resistance at the end of the drive. In such cases, restrikes are not part of the HSDT requirements. The other circumstance is that restrikes are required by the agency, either on all dynamically tested piles or only in certain soil profiles that are known to exhibit significant increases in pile resistance over time.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

Required setup times varied, but tend to be 1 to 2 days after initial drive. Some states require a second restrike at 7 days in clay and silt soil profiles. In a few select cases, the standard requirements require three restrikes (typically 1, 3, and 7 days) to better document the relationship of setup with time.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

The restrike blow for analyses is selected based mostly on the blow with highest energy transferred or highest measured resistance. A few states have a specified selection such as the average of 10 blows. A few others leave the selection solely to the judgment of the engineer performing the analysis.

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

Of the 35 agencies that provided an answer to this question, two-thirds (23 of 35) of the respondents reported that they do not consider or allow the addition of base resistance from one blow with the side resistance of a different blow. There are cases where such an analysis may be warranted, such as when the hammer does not sufficiently move the pile during a restrike to be confident that the full pile resistance was mobilized. Sometimes it is appropriate to add the base resistance from the EOID to the side resistance measured during the restrike. Those agencies that said they consider or follow this analysis stressed the need to carefully evaluate the data and the appropriateness for each project. The survey answers for Question 15 are listed on Tables 12 and 13.

Question 16—Developing Driving Criteria from Select Signal Matching Analyses

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

There are a few different approaches to utilizing dynamic testing/signal-matching data to develop production pile criteria. In most cases, the agencies use the HSDT and signal matching to develop bearing graphs and/or inspectors charts. Some agencies use the data to refine the wave equation analysis performed

TABLE 12
Q15. IF YOUR AGENCY USES HIGH STRAIN DYNAMIC TESTING:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

State	15a	15b
Alabama	Settlement during the static load test	Within 48 h of the static load test. Times range from a minimum of 36 h to 7 days or longer in some of the over-consolidated clays and silts.
Alaska	If setup is expected, yet driving capacity is not being met at anticipated EOD, then we will wait 24 h or so to see if setup has occurred enough such that capacity is met.	Generally we wait 24 h, but if necessary or deemed beneficial we will wait longer.
Arkansas	Restrike measurements are only performed on production piles and only if the driving resistance was not achieved.	Setup is only allowed on production piles and, if a restrike measurement is performed, the restrike measurement may be done any time after 24 h.
California	Restrike measurements are typically performed in soils with cohesive content, sometimes several restrikes at different lengths of time after the initial drive.	Different setup times are used in different soil types. Silt may be 1 to 3 days, but a fat clay may require 28 days.
Colorado	Yes. 95% of CDOT PDA testing is performed as restrikes.	Usually 1 h with no difference in setup time due to different geology.
Connecticut	Restrikes are routinely performed.	Nothing prescribed....it's all based on judgment/experience.
Delaware	Yes, just perform 10 blows after 48 h	No, generally 48 h
Florida	When reasonable shortfalls in initial drive resistances are measured, restrike tests are typically performed at the tip elevation required for lateral stability and at the anticipated bearing layer.	Setup times of 1 to 24 h are normally investigated. When required, times up to 7 days are investigated.
Georgia		
Idaho	Soil type	1 to a few days for silt or sand; 1 to several weeks for clay
Illinois		
Indiana	Restrikes are performed on all HSDT piles.	24 h for sands and hard rock to 7 days for clays and shales
Iowa		
Kansas	Restrikes are performed on all friction piles and rarely on end-bearing piles.	We conduct 15-min, 1-h, 4-h, and 18-h restrikes to plot set-up or relaxation verses time graphs. This gives a picture of what amount of set-up will occur.
Kentucky	Yes, if setup occurs	1 to 7 days depending on soil type

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TABLE 12
(*continued*)

State	15a	15b
Louisiana	In general, when the target capacity is achieved on the initial drive, restrikes are not performed. 24-h restrikes are performed on piles to verify capacity in set-up situations.	Typically a 24-h restrike is performed; however, if ample restrike data are available/collected earlier we may allow restrikes of less than 24 h.
Maine	Restrike tests are performed to gauge relaxation or setup effects in friction piles and displacement piles, and piles bearing on certain meta-sedimentary bedrock formations.	24-h minimum; 48- and 72-h restrikes may be warranted on rare occasion
Maryland	Yes, soil conditions dictate if restrikes will be performed. If we believe increases in capacity will be seen over time, we will perform restrikes.	48 h
Massachusetts	Yes, standard specifications, number of days	48 h, longer setup time specified on individual basis in silt and clay
Michigan	Typically restrike is avoided unless piles are in silts and/or silty clays. Restrike is problematic due to scheduling and production issues.	48 h is specified.
Minnesota	About 50–60% of the time. Looking for set-up to reduce pile length.	24 h for granular soils, 48 h for cohesive soils.
Mississippi	Yes. The PDA test pile pay item includes a 1 and 7 day restrike. Often in sands, the 7 day restrike is eliminated.	For clays and silts, the 1 and 7 day restrikes are performed.
Missouri		
Nebraska	It will be based on the soil type	36 h
Nevada	Yes, typically required for all projects.	24 hours unless otherwise specified by Geotech Engineer. Longer times may be specified for clayey soils.
New Hampshire	Would run restrike if we did not achieve the required nominal resistance for the test piles.	3 days for sand/silt; 7 days if clayey soils
New Jersey	Restrike is performed for the test pile that does not reach the required resistance at the estimated pile tip elevation. Programmed restrike may arise to realize potential setup benefits.	Normally 24-h wait is minimum required. A longer period; e.g., 7 days has been practiced.
New Mexico	1. Soil type and moisture/H_20 level; 2. clay layers	Uses 24 h $\geq$ 4 days depending on clay type, PI/H_20 level
New York	Restrike tests are performed on all piles with high-strain dynamic testing.	We mostly use a 24-h setup period, but on some projects with clayey soils we may increase that up to 72 h
North Carolina	Restrike is used if we don't get the required resistance from the initial driving.	Waiting time is varied depending on field conditions.
North Dakota		
Ohio	Only if static load test is being specified	7 days
Oregon	If there is concern for relaxation, restrikes are performed. If pile setup is required, piles are driven to a specified tip elevation, allowed to set for a specified period of time, and then restruck. Standard specifications allow for a minimum 24-h wait period before restrike and so if piles do not reach bearing there is an option to restrike, if necessary.	Standard specification allows for a minimum 24-h set period. This set period may be modified by special provision depending on the soil conditions, pile design, and other factors.

TABLE 12
(*continued*)

State	15a	15b
South Carolina	Yes, in clay and silt profiles	Typically 1 day or 3 to 7 days, depending on fines content of soils
South Dakota		
Tennessee	No	
Utah	If we do not achieve required ultimate capacity at EOID, then we will perform a restrike. Many times we only perform restrike testing because we are sure we will not achieve capacity during initial drive.	A minimum of 24 h is required. At times we attempt to achieve more set-up time based on a soil profile.
Vermont	Yes, see answers to Question 14.	48 h is stated in our specifications
Virginia	Our Special Provision for Dynamic Pile Testing requires a 5-day restriking and signal matching. About 75% of friction pile projects have dynamic pile testing.	Our Special Provision for Dynamic Pile Testing requires a 5-day restriking. This maybe modified to as little as 3 days or as many as 7 days if conditions dictate. Default initial drive capacity is 80% of nominal pile resistance shown on the plans. The geotech involved in the testing will usually modify this to 50% of nominal.
Washington	In such cases, restrike is performed about 70% of the time; however, we might not do restrike if in relatively clean sands or gravels.	Setup time varies based on soil type and possibly contract constraints.
Wisconsin		
Wyoming	All piles that are PDA tested are restruck. If PDA testing is not conducted, restriking may be completed for piles that do not reach capacity.	Generally 24 h

TABLE 13
Q15. IF YOUR AGENCY USES HIGH STRAIN DYNAMIC TESTING:

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

State	15c	15d
Alabama	Highest energy/measured resistance within ½ in. movement	No
Alaska	Depends, but we generally take last inch or whatever is a useful measurement.	No, we take the restrike blow and use whatever capacity is calculated from that last blow.
Arkansas	Restrike measurements are not performed with high-strain dynamic testing. Restrike measurements are evaluated with a bearing graph with penetration after 20 blows.	No
California	Wave traces are examined with regard to quality and suitability of data. One or more blows are selected accordingly in the first tenths of a foot of a restrike to establish the value.	No. Hammers are usually sized such that the scenario described (partial refusal case) does not occur, thus removing the need to perform this compilation.
Colorado	A single blow that represents an average of the first 10 blows.	No, we use end-bearing capacity only and use only one blow, not a combination of blows.
Connecticut	Highest resistance	That has not been a consideration
Delaware	10 blows after 48 h	Ratio of tip resistance to skin friction is taken from static analysis

(continued on next page)

TABLE 13
(*continued*)

State	15c	15d
Florida	Restrike blows are analyzed individually based on the quality of the data, the energy transferred into the pile, and the measured resistance.	The reliability of the pile is evaluated using the highest resistance blow and the resistance of the next five blows. If there is very little set during the restrike, it is generally assumed the tip resistance is not fully mobilized, so the tip resistance measured at initial drive is assumed to still be present but not mobilized by the restrike; great care is needed when evaluating analyses with this assumption.
Georgia		
Idaho		
Illinois		
Indiana	Highest quality and high-resistance blow from the BOR, generally within the first 5 blows is selected for CAPWAP.	No
Iowa		
Kansas	Restrikes are conducted in 5 blow increments for 20 blows.	No we do not allow that interpretation.
Kentucky	Usually leave that to the tester	We have not considered doing this.
Louisiana	Take a high energy blow; not the first couple of blows.	No
Maine		No
Maryland	None	No
Massachusetts	Nothing specified	Nothing specified, nothing specific in specs
Michigan	First 3 in. of restrike drive using a hammer warmed up on a pile at least 25 ft away.	No
Minnesota	Generally 2nd or 3rd blow—by local practice, not per required specifications	No
Mississippi	Generally use one of the early “high energy” blows	No
Missouri		
Nebraska	Average of 10 blows	No
Nevada	Warm up hammer on different pile for a minimum of 20 blows. Drive pile with a minimum of 15 blows when PDA/load testing is not required (in the past PDA was not required so this spec. is old, since we now require PDA and CAPWAP for all projects). When PDA is used the maximum penetration allowed during a restrike is 6 in. or 50 blows, whichever occurs first.	No, not that I'm aware of
New Hampshire	Use highest if data look good, otherwise use average or select good data points	No
New Jersey	Highest resistance is selected. Restrike is terminated when capacity is reached, when amount of penetration reaches 6 in., or when the total number of hammer blows reaches 50, whichever occurs first.	Generally this practice is considered for those larger size diameter piles. The base resistance from EOD and the skin resistance from restrike may be used to assess the overall resistance.
New Mexico	1st 10 blows, pick good strikes, good record	We have not done so, but might consider
New York	Take the blow with the highest energy and resistance.	Yes, this is done on occasion where the end of initial drive end bearing is combined with the beginning of restrike shaft resistance. On very long piles we will also use superposition where shaft resistance from one blow is combined with another.
North Carolina	Take the highest resistance.	No

TABLE 13
(*continued*)

State	15c	15d
North Dakota		
Ohio	Specific blow data from the first 5 blows	No
Oregon	Generally defer to the PDA operator to take one of the blows with the highest transfer of energy.	Yes, toe resistance mobilized during end of initial driving may be considered for addition to the friction resistance mobilized during restrike. Sometimes the hammer is not large enough to mobilize the full end-bearing (toe) resistance during restrike. However, relaxation of base resistance must be considered.
South Carolina	Usually one of the first blows with highest resistance	Yes, if we think the base resistance was not mobilized during restrike
South Dakota		
Tennessee		
Utah	We typically will chose the highest capacity blow if we feel it is representative of true ultimate capacity. If a high blow seems anomalous, we may choose a lower-capacity blow.	Yes. We use this method often and feel it is conservative because quite a bit of the shaft friction is not even included when adding initial drive toe capacity to restrike skin friction.
Vermont	The hammer must be warmed up on another pile and resistance must be maintained for 2 in. or 20 blows, whichever comes first.	No
Virginia	20 blows or 3 in. whichever occurs first (or as directed by the Engineer).	VDOT does not do dynamic testing in-house. PDAs are a bid item and the contractor will hire a qualified Professional Engineer to provide a wave equation of his driving system and to conduct the dynamic testing. The results are provided to VDOT for review. Signal matching of several blows may have been used to develop capacities presented in the final report. On occasion VDOT after review will ask for an additional blow to be processed.
Washington		We have considered this when we are having difficulty making things match up properly.
Wisconsin		
Wyoming	Yes, average of 10 blows per (measurement)	No

during design or submittal review to produce the criteria. Some utilize criteria of blow count versus resistance based on the test results, whereas others calculate a minimum blow count for a minimum hammer energy or stroke. Following are some examples of specific procedures obtained from the responses to the survey.

Caltrans' approach to developing and using driving criteria varies according to the pile size and subsurface conditions, with the site divided into control zones of consistent subsurface conditions. When HSDT with dynamic monitoring is used to develop acceptance criteria, a minimum of one test pile will be included in each control zone. Signal-matching analysis is performed on the HSDT results for use in a revised wave equation analysis. The inspectors in the field are provided acceptance graphs with a family of curves from the revised wave equation analysis that relate blow count, hammer stroke, and pile resistance for the specific hammer and pile size. When restrikes are used to verify setup, a second graph is included showing the relationship of resistance over time.

FDOT performs a signal match analysis on all HSDTs and the resulting data are put back into the WEAP model. A WEAP analysis will be performed that reflects the resistance for the particular blow selected for the signal match analysis, comparing the results with the HSDT results to make sure they are compatible and adjusted if necessary. A WEAP analysis will then be performed using the production pile length and required nominal resistance to develop the production pile driving criteria. Inspectors are given a table of blows per foot for different stroke heights or energy transfer levels. A project will typically have a set of criteria for each pier location based on the test pile at that location. Several pier locations can be grouped together if they are consistent enough.

When the NYSDOT uses HSDT to establish the driving criteria for cast-in-place or H-piles, one test pile (a production pile) per substructure is tested at initial drive and with a 24-h restrike. Piles will be driven to estimated length on the initial drive. The inspector is provided the acceptance blow count and hammer performance criteria based on the HSDT results.

When the Mn/DOT utilizes the HSDT, it is used to determine the pile resistance at the EOID or restrike. This resistance is used to evaluate pile acceptance in lieu of the results of the dynamic formula. Once the resistance is verified by the HSDT, production piles are driven to the same tip elevation and hammer energy/blow count. The pile driving formula is not used for acceptance. Data from the signal-matching analysis is not used to modify wave equation analyses or the dynamic formula to adjust the driving criteria.

The Utah DOT utilizes HSDT with signal matching on the first pile in each substructure unit to verify the criteria (minimum blow count at specified hammer energy and tip elevation) as specified by wave equation analysis. The dynamic monitoring data and signal-matching analysis are not used to perform revised WEAP analyses.

WSDOT uses the wave equation analysis to estimate the blow count required using the HSDT and signal match analysis to refine the wave equation input parameters to develop the blow count acceptance criteria. The inspectors will have a series of curves for blow count as a function of stroke to achieve the required resistance. Production piles are driven to the blow count criteria predicted by the correlated wave equation analysis.

Questions 17–19: Use of Load Tests (Rapid and Static)

17. **If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?**
18. **If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?**

The use of RLT methods is very rare among the responding states. Those few that have used it have done so only on an experimental basis or on very large projects. SLT is used more frequently than RLTs, but still on a very limited basis on very large projects that can justify the costs. Exceptions to this include Tennessee, where SLTs are required for use of friction piles, and Ohio, where an SLT is required if the quantity of a specific pile exceeds 10,000 linear feet on a project. SLTs are also used for situations outside of an agency's normal practice, such as very large piles or uncommon (to them) pile types or unfamiliar geologic conditions. For example, both California and Minnesota use SLT for large-diameter, open-ended high-capacity pipe piles.

19. **How are rapid or static load test results used in the development of driving criteria for production piles?**

With respect to using RLT or SLT results to develop driving criteria, the few states that utilize one or both take advantage of the higher resistance factors available when such tests are used. Some agencies use SLT and RLT solely to verify the pile resistance as installed or confirm the dynamic measurements (Alabama, Ohio, and Vermont), not using the data to modify pile tip elevations or driving criteria. Some states use SLT and RLT results to correlate HSDT on production piles (Mississippi, New Jersey, New York, and South Carolina). Following are some specific examples of the uses of SLT and RLT data obtained from the survey responses.

Caltrans requires SLT for developing driving criteria of piles with a diameter of more than 36 in. A minimum of one SLT is performed per control zone, with a HSDT and signal-matching analysis also performed to measure pile stresses, hammer energy, and the magnitude of setup. The results of the SLT and the HSDT signal-matching analysis are used to generate a site-specific wave equation analysis and determine final driving criteria. The SLT provides a set point where the pile resistance is known for a given stroke and blow count. The signal match analysis data provides the magnitude of the setup as well as starting values for quake, damping, etc. The resistance values from signal-match analysis are not used in the analysis. WEAP analyses are performed, adjusting parameters to get a match with the SLT results and then developing a family of curves of blow count versus resistance that are correlated to the SLT. These curves are used by the inspector in the field.

FDOT uses SLT and RLT to check the reasonableness of the pile resistance and load transfer distributions that are estimated with the signal match analysis. The resistance values obtained from the signal-match analysis are not scaled by the SLT or RLT results. The SLT or RLT may be used to fine tune the signal-matching analysis, particularly the load transfer characteristics. Production pile order lengths are rarely changed as a result of SLT or RLT results.

Although the LADOTD does not use SLT and HSDT on all projects, they are commonly used and are always performed together. The test piles are typically sacrificial, nonproduction piles. Once the testing is complete, a revised WEAP analysis is performed using the results of the signal match analysis (quake, damping, energy, etc.) from the HSDT and the pile resistance from the SLT. The WEAP results establish the driving criteria (blow count and hammer energy), with the pile tip elevations established based on the results of the SLT.

The Tennessee DOT uses SLT to correlate blow counts during driving to an actual pile resistance. The required blow count to achieve the required resistance is used for the driving criteria.

WSDOT uses SLT on large diameter piles, using the data to back correlate soil parameters and then adjust the static pile analysis. Piles are then driven to a design tip elevation based on the revised static analysis, rather than to a criteria established by formula or HSDT.

Question 20: Additional Quality Assurance Measures

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

In addition to the driving criteria, quality assurance measures used to evaluate production piles include:

- Acceptable pile plumbness,
- Checking for heave of soil or adjacent piles,
- Assuring that the pile driving equipment is working properly,
- Observations of hammer stroke,
- Hammer cushion as per the submittal or specifications,
- Evaluations by the inspector with driving formulas,
- Dynamic testing to monitor driving stresses, and
- Use of a saximeter to monitor hammer performance.

Question 21: Impact of Driving Criteria on Design

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

The states that responded are generally following the AASHTO Bridge Design Specifications with respect to selection of resistance factors based on the level of testing (none, HSDT, SLT, etc.) or the specified driving criteria (formula, wave equation, etc.). At the time of the survey, some states were not aware of the errors in Chapter 10 of the initial publication of the AASHTO 2010 LRFD Bridge Design Specifications. Many of the errors were on the subject of resistance factors and pile testing frequency, including Tables 10.5.5.2.3-2 and 10.5.5.2.3-3 as presented in the initial 2010 publication. The answers in this survey included by the states reflect their understanding of the 2010 specification as they understood it at the time of the survey. As the June 2010 Errata of the 2010 specification is circulated, the recommendations of Table 10.5.5.2.3-1 will be adopted by most agencies.

Some states such as Louisiana, Indiana, and Ohio have slightly adjusted the resistance factors based on their own experience and/or calibration of design methods with load test data. These three states are using a resistance factor of 0.7 for dynamically tested piles. Florida has a range of resistance factors based on the combinations of SLTs and HSDTs utilized on the project.

There are also some agencies that are conducting research to address resistance factor selection. MnDOT has an open research project with Dr. Sam Paikowsky (University of Massachusetts–Lowell) to establish resistance factors. FDOT has an internal research project that is developing a guidance document for assessing and applying site variability to selection of resistance factors for soil conditions typical to Florida.

CHAPTER FOUR

RESULTS OF THE PHASE II SURVEY

INTRODUCTION

The Phase II Survey consisted of telephone interviews of selected agencies based on their responses to the Phase I Survey. The goal of the Phase II Survey was to explore in more detail some of the practices highlighted in the survey responses, obtain more details about the experiences of the interviewees, and provide information concerning potential problems and difficulties in the interpretation of pile test results and their application to developing pile driving criteria. With the broad format of a survey it is often difficult to glean details on the nuances of local practices. The interviews were approached as an open forum covering one or more of the following general areas:

- Current Practices
- Perceived Concerns, Problems, or Challenges in Current Practices
- Suggested Topics or Practices for Evaluation.

The interviews were loosely structured to allow the discussions to follow any appropriate course based on the Phase I Survey responses of the agency being interviewed or subjects that came up during the interviews themselves.

The states selected for Phase II Surveys are listed in Table 14 with notes on the basis of the selection. In addition to attempting to select agencies based on a range of practices, an attempt was made to sample different geographical and subsurface conditions across the country. The person interviewed at each agency was designated by the agency in the Phase I Survey and was typically the state geotechnical engineer, a senior level geotechnical design engineer, or other design engineer or engineering manager considered by the agency to be responsible for or familiar with the development and/or review of pile driving criteria.

The records of the Phase II Surveys are included in Appendix C in alphabetical order. The remainder of this chapter will discuss the information obtained in the interviews.

SURVEY RESULTS

California (Caltrans)

Caltrans' approach to developing and using driving criteria varies according to the pile size and subsurface conditions. A site will be divided into control zones where the subsurface conditions are consistent such that a single pile would be representative of the control zone (not greatest resistance, but representative). Information from the static pile analysis model can be consulted to help select control zones.

There are three typical pile sizes and associated processes: (1) standard pile size: small diameter piles, typically less than 20 in. in width and 100 tons or less required resistance; (2) intermediate size pile (20 in. to 36 in.); and (3) large diameter piles (36 in. and above). The standard pile size is typically a precast prestressed concrete pile, with the occasional use of other pile types. Piles larger than standard sizes are almost exclusively open end pipe piles and Cast-in-Steel-Shell piles.

Acceptance of standard pile size piles is based on a minimum tip plus bearing criteria—drive to planned tip and check with Gates Formula. Caltrans has a long history on the use of and confidence in performance of the standard pile size when judged by the Gates equation. If a pile encounters refusal before minimum tip with an appropriately sized hammer, the pile can be accepted based on the formula alone (or some specified multiple of the formula), provided that the minimum tip elevations for tension and lateral have been achieved. In the rare case that a pile does not have the required resistance at the minimum tip elevation, restrikes are performed after setup. If capacity is still not achieved or difficult driving exists, dynamic analysis or static testing can be requested. If there are issues such as nontypical behavior during driving or suspected damage, HSDTs with PDA or equivalent are performed.

For intermediate size piles (20 in. to 36 in.), HSDT with PDA is used to develop acceptance criteria. A minimum of one test pile will be included in each control zone. Signal-matching analysis is performed on the HSDT results for use in a revised wave equation analysis. The inspectors in the field are provided acceptance graphs with a family of curves from the revised WEAP analysis that relate blow count, hammer stroke, and pile resistance for the specific hammer and pile size. When restrikes are used to verify setup, a second graph is included showing the relationship of resistance over time.

For large diameter piles (36 in. and above), a full SLT is required for developing driving criteria. A minimum of one SLT is performed per control zone, with HSDT and signal-matching analysis also done to measure pile stresses, hammer energy, and the magnitude of the setup. The results of the SLT

TABLE 14
PARTICIPANTS IN PHASE II SURVEY

State	Geographic Area	Notes on Selection
California	West Coast	Uses pile driving formula for criteria development on 90% of projects; load testing on large piles.
Florida	Gulf Coast and Atlantic Coast	Regularly uses pre-production HSDT for criteria development.
Louisiana	Gulf Coast	Regularly uses pre-production SLTs for criteria development.
Minnesota	North	Uses pile driving formula for criteria development on 75% of projects; uses HSDT on remainder.
New York	Northeast	Uses wave equation analysis on all, with HSDT for selected projects.
North Carolina	East Coast	Uses wave equation analysis for criteria development; limited use of HSDT.
Ohio	Midwest	Uses HSDT for friction piles only; SLT use based on size of project.
Utah	West	Uses HSDT on all pile projects to confirm criteria established by wave equation.
Washington	West Coast	Uses WSDOT pile driving formula and some HSDT.

and the HSDT signal-matching analysis are used to generate a site-specific wave equation analysis and determine final driving criteria. The SLT provides a set point where the pile resistance is known for a given stroke and blow count. The CAPWAP data provide the magnitude of the setup, as well as starting values for quake, damping, etc. The resistance values from CAPWAP are not used in the analysis. WEAP analyses are performed, adjusting parameters to get a match with the SLT results, and then develop the family of curves that are correlated to the SLT.

Additional HSDTs may be performed on indicator piles within a control zone during production pile installation to monitor pile stresses and hammer performance, but not as an indicator of pile resistance. Based on its experience, Caltrans believes that there are some scaling issues with large diameter piles with the PDA in both the measurement of the waves in the pile and how the wave signals are analyzed to calculate a pile resistance.

Florida (FDOT)

Prestressed concrete pile is the predominate pile type used by FDOT. Driving criteria are established in a test pile program at the beginning of each project. The test pile lengths are estimated by adding 15 ft to the estimated production pile lengths determined by static analysis.

Test piles are always in a production pile location, but almost always done in advance of approval to starting production piles. Design phase testing programs with HSDT are occasionally used. SLT are not used very often; when they are used, it is typically on design-build projects where a larger resistance factor provides economy.

HSDT is performed on all test piles with the results used to perform wave equation analysis to develop final driving criteria. The hammer and driving system performance are also evaluated during the test pile program. Because of its extensive experience with HSDT, FDOT has a high level of confidence that when done properly, the HSDT test results are not routinely over-predicting the static resistance of the piles.

After completion of the HSDT, a signal-match analysis is performed using CAPWAP. The information on the load distribution (tip vs. side), soil variables (quake and damping), energy transfer, pile stresses, etc., is put into the WEAP model. A WEAP analysis is performed that reflects the resistance for the particular blow selected for the CAPWAP analysis. The results are compared with the HSDT results to make sure they are compatible and are adjusted if necessary. A WEAP analysis is then run using the production pile length and required nominal resistance to develop the production pile driving criteria.

A project typically has a set of criteria for each pier location based on the test pile at that location. Several pier locations can be grouped together if they are consistent enough. Small bridges may have a single criteria set for all piers. Inspectors are given a table of blows per foot for different stroke heights or energy transfer levels. Because FDOT drives mostly precast concrete piles, additional instructions are also provided concerning fuel settings and other items for easy or hard driving conditions. All inspectors are required to complete a qualification course to be approved as pile inspectors.

Piles are typically driven to plan lengths. Although a pile can be accepted if it has achieved minimum penetration, the blow counts are generally increasing and it has met the minimum blow count criteria for 24 consecutive inches. Piles may also be stopped for practical refusal (20 blows per inch, no more than ¼ inch pile rebound, for at least 2 consecutive inches).

If a pile does not meet specified resistance criteria at end of drive, the pile will be allowed to set for up to 2 h and then a set check is performed (restrike), either with or without dynamic testing. If the pile does not meet the criteria after setup, the District Geotechnical Engineer will determine whether to perform additional set checks or to splice. When a splice is done, the contractor may pull the pile and drive a longer pile.

SLT and RLT are used to check the reasonableness of the pile resistance and load transfer distributions that are estimated with the CAPWAP analysis. The CAPWAP resistance values are not scaled by the SLT or RLT results. The SLT or RLT may be used to fine tune the signal-matching analysis, particularly the load transfer characteristics. Production pile order lengths are rarely changed because of SLT or RLT results.

FDOT will combine EOID base resistance with restrike side resistance on occasions when the setup has exceeded the capacity of the hammer to demonstrate resistance. FDOT's approach when doing this is to verify that the required resistance is available (after accounting for side resistance), rather than assuming the EOID base resistance is the full base resistance.

FDOT has a short-term trial evaluation (through September 2010 lettings) of using embedded sensors in all prestressed concrete piles. The sensors near the pile tips (within 1 pile width) appear to be providing a good measurement of tip stress and estimates of static tip resistance.

The design-build project environment is slightly different than normal practice for driving criteria in that FDOT requires the engineer who designed the foundation and the engineer who performed/approved dynamic testing (if different entities) to both approve and seal the driving criteria. The designer provides pile driving inspectors and certifies that piles were installed according to the criteria and meet all project requirements.

One issue that FDOT has is the frequency of required testing for utilizing AASHTO resistance factors in design. It is FDOT's opinion that the code provides resistance factors for two cases: a minimal amount of testing (10%) or complete testing of all foundations (100%). It is the opinion of FDOT that there may be room for something in between these two levels. To aid the selection of resistance factors, FDOT is working on an internal guidance document for assessing and applying site variability to the selection of resistance factors for soil conditions typical to Florida.

Louisiana (LADOTD)

Prestressed concrete pile is the most common pile type used by LADOTD. The computer program DRIVEN is used for analysis of static axial resistance with the subsurface model based on soil borings. The pile tip elevations are set using LRFD resistance factors.

Although not used on all projects, SLT and HSDT are commonly used by LADOTD. All test piles are installed with both HSDT and SLT. The feasibility of using test piles is determined using a cost–benefit analysis comparing the cost savings of using a higher resistance factor with a load test to the cost of the piles using the lower resistance factor without testing. The decision is not solely based on cost. Sometimes, even if the shorter piles and a load test costs slightly more than the longer piles without a load test, test piles will be included in a project to obtain data for future use. The slight extra cost is deemed worth the data obtained.

For small bridges with no SLT piles or no dynamic tests/monitoring, pile tip elevations are set during the axial analysis using a resistance factor $\Phi = 0.5$. The piles are typically driven to grade with the resistance checked with Gates Formula using $\Phi = 0.4$:

$$\text{Gates Formula } R \geq \frac{\text{Factored Load}}{\Phi}$$

When test piles are used, they are typically sacrificial nonproduction piles. Once the testing is complete, a revised WEAP analysis from the HSDT and CAPWAP data are used to establish driving criteria (blow count and hammer energy). The pile tip elevations are usually based on the results of the SLT. Test pile tip elevations are estimated using $\Phi = 0.7$, then installed to the estimated tip elevation and load tested. Results of the CAPWAP analysis (quake, damping, energy, etc.) are used to refine the WEAP analysis using the resistance from the SLT and not the CAPWAP resistance.

Tables of blow count and hammer stroke are provided to inspectors to verify end of drive conditions, along with additional instructions for changing stroke (fuel setting) for the start of driving, other easy driving conditions, or at hard driving conditions. If it is believed that refusal conditions could be encountered, the criteria will have an allowance for stopping driving within 5 to 10 ft of planned tip and cutting off the pile if refusal is encountered early.

In some locations, the contractor is allowed the option of predrilling to start the piles. It is not always known if the contractor will predrill or not. WEAP analyses are performed for both cases and the inspector's charts are prepared for both, with or without predrilling.

Production piles are typically driven to a target tip elevation. If the blow count criteria are not met at end of drive, restrikes may be performed. When setup is investigated, test piles will have restrikes over a range of times up to 14 days after initial drive. HSDT with CAPWAP would be performed for each restrike. The results of the CAPWAP analysis are used to develop a setup curve.

Some of the challenges that LADOTD noted were defining refusal in a consistent manner with respect to hammer energy, selecting appropriate design resistance factors, and the reuse of pile cushions without risking damage to piles. LADOTD also noted an interesting condition common to the central part of the state where there is high toe quake at refusal blow counts. When a restrike is performed the following day, the piles drive down. It is speculated that high negative pore pressures may be developing in the more sandy/silty soils in this area. LADOTD hopes to investigate this condition further to better understand establishing pile criteria for projects in this area.

Minnesota (Mn/DOT)

The most common pile type used by Mn/DOT is the cast-in-place shell (closed-end pipe pile filled with concrete) displacement pile. These piles are reported to work better in the glacial deposits and plastic clay soils present in Minnesota. H-piles are used when driving to bear on rock.

A dynamic formula is used as acceptance criteria on most piles. One to two test piles are driven for each substructure. Test piles are almost always production piles. If the test piles drive to the required resistance as demonstrated by the driving formula, authorization is given to drive production piles.

HSDT with PDA is used on larger projects and larger diameter piles with very low or high resistance values outside of the range of the driving formula. HSDT is also used for projects where a restrike is necessary to demonstrate pile resistance (when significant setup is expected), particularly when the piles are expected to “break free” within a few blows of the start of the restrike. When a restrike occurs where the pile does not move, Mn/DOT does not typically evaluate adding EOID base resistance with restrike side resistance as measured by the PDA. The evaluation of the restrike in such instances is based more on judgment than a strict formula analysis.

When HSDT with a PDA is performed, it is used to determine the pile resistance at EOID or restrike. This resistance is used to evaluate pile acceptance in lieu of the results of the dynamic formula. Once the resistance is verified by the HSDT, production piles are driven to the same tip elevation and hammer energy/blow count. The pile driving formula is not used for acceptance. Data from the signal-matching analysis with CAPWAP are not used to modify wave equation analyses or the dynamic formula to adjust the driving criteria.

As Mn/DOT completes the implementation of LRFD, the HSDT is being used more frequently to help “calibrate” the existing driving formulas. There is a current research project being led by Dr. Sam Paikowsky (University of Massachusetts–Lowell) to evaluate selection of appropriate resistance factors during design that are compatible with the Mn/DOT pile acceptance process.

SLT are not typically performed, although some recent large bridge projects with large diameter piles have included a SLT owing to the high loads and inadequate Mn/DOT experience with such large piles. A research project recently began conducting 12 load tests over a two to three year period to provide SLT data for HSDTs and driving formula correlation.

Recent limited experiences with large diameter open-end pipe piles bearing in soil (above bedrock) indicated that the PDA does not typically provide a reliable measurement of the pile resistance. Such large diameter piles are typically designed for a required resistance well above the range of resistance values that can be reliably evaluated by the driving formula. In many cases, the pile does not move sufficiently to provide reliable measurements with a PDA. Other than SLT or RLT, Mn/DOT is considering how to evaluate and approve piles in such situations.

With a large part of the state being extremely rural, performing evaluations with PDA or other devices is not economical. This is mostly owing to the limited availability of qualified consultants in the rural areas and the resulting schedule impact, as well as the limited gain in design efficiency for the small projects typical of the rural areas of the state. Using a pile driving formula continues to be the most economical method of approving piles in these areas.

New York (NYSDOT)

The most common piles used by NYSDOT are cast-in-place piles (closed-end pipe piles filled with concrete) and H-piles. Cast-in-place piles are typically 12 in. to 14 in. in diameter, with sizes up to 24 in. being used on occasion. These piles can be designed as either combined base resistance and side resistance, or side resistance only. H-piles are usually driven to refusal on rock. Other pile types that are occasionally used are Monotube piles (when a tapered cast-in-place pile is needed) and precast prestressed concrete cylinder piles (in coastal and tidal deposits on Long Island or upstate).

All pile designs, submittal reviews, and pile criteria development are done in-house by NYSDOT personnel. Pile driving criteria are usually established by wave equation analysis for the cast-in-place piles and H-piles for normal soil conditions or typical sized projects. For unusual soil conditions, large projects, or large piles, HSDT are used to set the driving criteria. NYSDOT performs signal-matching analysis on all HSDT data.

A wave equation analysis is used to evaluate the contractor’s drive system submittal. When the wave equation is used to set the driving criteria, the inspectors are provided an acceptance blow count and minimum hammer energy or stroke. Restrike blows are only used if piles do not achieve the desired resistance at the estimated drive length. Restrikes are typically performed after 24 h.

HSDTs are performed on projects built using precast prestressed cylinder piles. The piles are either ordered to the length designated on the plans and then the HSDT is used on the first production piles to establish criteria, or a pre-production test pile program is conducted to set pile order lengths and determine the driving criteria. Evaluation of tensile and compressive stresses in the piles during driving is also a major part of dynamic testing of these piles.

When HSDT is used to establish the driving criteria for cast-in-place piles or H-piles, one test pile (a production pile) per substructure is tested at initial drive and with a 24-h restrike. Piles will be driven to estimated length on the initial drive. The inspector is provided the acceptance blow count and hammer performance criteria based on the HSDT results.

When evaluating restrike HSDT data with signal matching, NYSDOT will often use the base resistance from the EOID with the side resistance from restrike blows to estimate the static pile resistance. In very long piles (100 to 140 ft), the side resistance from several blows is superimposed to develop a single model of the side shear resistance for the pile. This is done to account for the side resistance not developing along the full length of the piles during early restrike blows.

The most significant challenge for NYSDOT is developing good estimates of soil setup in some of the clay soils found in certain parts of the state. Their experience indicates that for these soils the setup times can range from 24 h to one month. On a typical sized project, the schedule is often set such that there is not enough time to allow a test program to fully investigate piles set up in clay soils. Piles tend to be over-driven (driven to higher resistance than necessary if setup was better defined) in order to meet the schedule.

North Carolina (NCDOT)

NCDOT utilizes two main pile types: H-piles and prestressed concrete piles. H-piles are commonly used throughout the state; prestressed concrete piles are used primarily in the coastal plain. H-piles are driven to refusal on rock or in residual soils, and are also used as friction piles in the coastal plain. Both open-end and closed-end pipe piles are occasionally used on state projects.

The approach to driving criteria for NCDOT is to perform a wave equation analysis for all hammer submittals from contractors. NCDOT will provide the driving criteria, typically a minimum tip elevation (as stated in the contract plans), and a required blow count (blows per foot) and equivalent set for 10 blows to achieve the required driving resistance at a minimum stroke/energy based on the wave equation analysis. Refusal is usually defined as 240 blows per foot or any equivalent set.

If the required bearing is not achieved at the estimated tip elevation, restrikes can be performed after a set time ranging from 4 h to 1 day. Increasing the pile length rather than performing restrikes is usually an option available to the contractor. Restrikes are used generally 35% to 40% of the time for friction piles (H- or open-ended pipe piles) in the coastal plain, typically to check piles that do not achieve resistance at end of drive. Restrikes, in general, are not used for displacement piles (prestressed concrete piles or closed-ended pipe piles). Also, restrikes are not used in the piedmont residual soils.

HSDT with PDA is not routinely used for monitoring piles or for developing criteria. HSDT is primarily used if there is a concern that a pile did not achieve bearing, or there is a concern with pile stresses or damage during driving. When PDA tests are performed, signal matching with CAPWAP is also performed.

If there is a concern with pile bearing or constructability issues (such as overstressing the piles) during the design phase, HSDT will be specified. Tests are done on the first production pile. Nonproduction test piles, in general, are not used. On larger projects on the east coast of the state where concrete piles are used, a design phase testing program may be performed to assist in establishing pile order lengths, as well as the driving criteria.

If the piles do not meet initial driving criteria during installation, HSDT may be used to verify that the bearing has been achieved or to adjust the driving criteria. Depending on the test results, the engineer may decide to lower the required bearing (lower driving resistance in LRFD or lower factor of safety in Allowable Stress Design) or to drive the pile deeper (pile splicing may be required).

When HSDT is performed, the pile resistance and soil parameters from the CAPWAP analysis are used to perform adjusted wave equation analyses to provide the driving criteria (blow count and minimum stroke/energy at the minimum tip elevation). If setup is anticipated for clay soils, restrikes with HSDT may be used to verify bearing and provide a restrike blow count for acceptance when production piles do not meet target resistance and are checked after setup has occurred.

Ohio (ODOT)

ODOT typically uses either H-piles driven to refusal on rock as bearing piles, or cast-in-place piles (closed-end pipe piles filled with concrete) used as friction piles. Other pile types are used very infrequently.

H-piles are designed for bearing on rock with the specified resistance based on the limiting structural resistance of the pile. For piles bearing on competent rock, the pile tip elevation is specified. For piles bearing in weathered rock, a refusal criterion of 20 blows per inch is specified instead of the pile tip elevation.

Cast-in-place pipe piles are closed-end steel pipes that are filled with concrete. The pipes are typically 12, 14, or 16 in. in diameter, with wall thickness ranging from ¼ to ½ inch. These piles are designed for friction resistance using a resistance factor of $\Phi = 0.7$ based on HSDT. The piles are driven to a specified resistance, not a specified length. The resistance of cast-in-place pipe piles is a specified effective geotechnical resistance for a given pile diameter and wall thickness. The effective geotechnical resistance values are based on an evaluation of the hammers typically used by the contractors in Ohio.

HSDT with signal-matching analysis (CAPWAP) is required for all friction piles. A minimum of two HSDTs per pile size and resistance are required at each bridge structure. The CAPWAP analysis or other HSDT data are not used to adjust wave equation analyses; only to determine resistance and hammer performance for the driv-ing criteria.

The driving criteria for friction piles are established for the EOID conditions. The criteria consist of a blow count at a minimum hammer energy/stroke for each pile size and resistance. Setup is not usually considered when establishing the EOID criteria; however, when setup is considered, piles are driven to a specified tip elevation. Setup is confirmed through restrike tests.

SLTs are only used if the quantity of pile (each size and resistance combination) exceeds 10,000 linear feet for a project. SLT data are only used for confirmation of resistance.

Site variability is addressed by requiring a soil boring at each substructure and requiring the piles at the substructure to be designed according to that boring. Site variability is also addressed during installation by basing the pile criteria on driving to the required resistance as determined by the HSDT, rather than driving to a specified length.

ODOT has had one recent project with large diameter open-ended pipe piles. An interior ring was installed in the piles to encourage plugging to allow for reliance on end bearing. All piles were subjected to HSDT with restrikes to evaluate setup. The required resistance was not achieved at EOID, but was demonstrated to be achieved after setup. No SLTs were performed on this project.

One challenge that ODOT is working through is the issue of making sure design consultants evaluate the constructability of pile designs. Currently the piles may be designed by a consultant, but the WEAP analysis is performed by the contractor to select the hammer. Design consultants are not always considering drivability in their designs, including performing WEAP analyses. ODOT is working toward increasing consultant knowledge and the use of WEAP to perform drivability analysis during design.

Utah (UDOT)

When piles are used in Utah, UDOT predominately uses 12-in. diameter closed-end concrete-filled pipe piles in alluvial soils (layered sands, gravels, and clays) and lake bottom clays. Setup is often relied on to achieve the required resistance, and piles are usually designed for the tip to bear in a dense layer for some base resistance.

Typical driving criteria are to drive to an estimated length (with minimum length) with blow count for stroke (diesel) or hammer energy (hydraulic) when the pile reaches tip elevation. One HSDT test is usually performed on the first pile in each substructure unit. Minimum hammer energy is always specified as part of the criteria. If the minimum blow count at the specified hammer energy/stroke is not achieved, a restrike test is done. The PDA data and signal-matching analysis are not used to perform revised WEAP analyses.

Restrikes with PDA measurements are also usually performed to verify setup. In recent years, a common observation has been that verification of setup cannot be demonstrated with the PDA. Many of the local contractors do not have hammers large enough to verify resistance if the design is for a large resistance. In such cases, UDOT will combine EOID base resistance with restrike side resistance (CAPWAP for both) to estimate the pile resistance.

SLTs are rare for UDOT. The subsurface conditions are so variable that there is concern with extrapolating the results of a load test to a broader area. The use of HSDT with signal matching has provided an economical approach for the projects and conditions in Utah.

A significant issue for UDOT is the assessment of downdrag on piles. UDOT does not agree with the AASHTO code process, believing it leads consultants to overestimate (often doubling) downdrag effects. UDOT uses the neutral plane method (Fellenius 1988) for settlement calculations and believes this provides a more rational basis for estimating downdrag loads on piles.

Washington (WSDOT)

The most common pile type used by WSDOT is a cast-in-place steel shell (closed-end pipe) pile, 24 in. in diameter (the diameter range can be from 18 in. to 36 in.). The marine division typically uses 30- to 36-in. diameter open-ended pipe piles, and 18-in. precast concrete piles for trestles and docks.

The WSDOT driving formula is used to determine pile resistance during driving for most piles. The formula is correlated to wave equation predictions and field test data (WSDOT

2005; Allen 2007). If the WSDOT formula is the acceptance criteria, the inspector uses the formula in the field. The required blow counts are developed as a function of hammer stroke.

HSDT with CAPWAP is used in the marine division where there are significant uplift requirements and often difficult driving conditions. HSDT is also typically used for land structures for piles larger than 30 in. in diameter, as well as on very large projects. The use of HSDT plus CAPWAP is more likely when using friction piles, especially if significant setup is anticipated. WSDOT also uses HSDT, but without CAPWAP, to monitor energy transfer into the pile head if swinging leads are used to detect alignment problems. When HSDT is used, it is typically performed on the first production pile in a pier, and then periodically used to monitor hammer performance. For bridge piers, one to two piles per pier are tested. For marine structures/terminals, HSDT plus CAPWAP are performed on all piles where uplift resistance is needed. However, in most cases for this situation, bearing resistance is usually not critical, and checking bearing resistance using the WSDOT driving formula is adequate.

When wave equation and HSDT plus CAPWAP are used for acceptance, the inspectors are provided with a series of curves for blow count as a function of stroke to achieve the required resistance. The most common practice is to use the wave equation analysis to estimate the blow count required, using HSDT and CAPWAP to refine the wave equation input parameters to develop the blow count acceptance criteria. The parameters used in the wave equation analysis are adjusted to match, as much as possible, the resistance predicted by the CAPWAP analysis and the transferred energy measured by the PDA. The resistance as given by the PDA is not relied on to directly determine acceptance. In some cases HSDT plus CAPWAP computed resistance may be relied upon for acceptance. Typically, when significant setup is anticipated, the EOID CAPWAP resistance is used to establish the end-bearing resistance of the pile, and the Beginning of Redrive (BOR) CAPWAP resistance is used to establish the skin friction resistance for correlating to the wave equation for the development of driving criteria. Production piles are driven to the blow count criteria predicted by the correlated wave equation analysis.

If the required resistance is met during driving after achieving the required minimum tip elevation, driving is stopped. Piles are not usually driven to grade once the required resistance is achieved. If the required resistance is not met at the estimated design tip elevation, a restrike may be used after allowing the pile to set, or the pile will be spliced and driven deeper. Contractual issues are taken into consideration when using pile splices.

In the Bellingham Drift (an area of mostly clay soils in the northern part of the state) where significant setup is anticipated, restrike tests are typically performed and the test data are used to determine acceptance. WSDOT has historical load test data demonstrating the approximate relationship of setup with time in this formation. For current projects where such deposits are present, the historical data along with restrikes with PDA and CAPWAP are typically used at each pier to adjust acceptance.

Static load testing is not commonly used by WSDOT at this time. Projects with large diameter piles will typically have one SLT. It may also be used for very large projects, unusual pile types/sizes, or unusual conditions. SLT data can be used to back correlate soil parameters and then adjust the static pile analysis. Piles are then driven to a design tip elevation based on the revised static analysis. The blow count is ignored for pile acceptance in these cases. This approach would only be used where piles are driven into deposits that are likely to have a lot of setup that takes a long time to develop.

If HSDT data are available with SLT data, the wave equation analysis is adjusted using the CAPWAP results (soil resistance distribution, quake, damping, etc.) to correlate to the SLT resistance. A blow count and stroke relationship is then provided to the inspector. If the SLT resistance is significantly greater than the resistance determined by CAPWAP from HSDT data, the dynamic results will usually be scaled up to correlate to the SLT results. If the dynamic results are significantly higher than the SLT, the results may or may not be scaled.

If more than one SLT is done, then the data may or may not be averaged, depending on the consistency of subsurface conditions at the site. If multiple SLTs are done, it is more likely that the results of each test would be applied to a given portion of the site that has a stratigraphy that is consistent with the stratigraphy at the SLT site.

CHAPTER FIVE

CONCLUSIONS: A SUMMARY OF USEFUL PRACTICES

The practices used by transportation agencies to develop pile driving criteria for production pile installation as identified in the previous two chapters can be described as highly variable in terms of the level and sophistication of the testing performed. To some extent, such variability in test pile requirements may reflect the inherent variety of project size, complexity, ground conditions, pile type, etc. However, a significant component of the variation in pile driving criteria may be related to the pace of implementation of new approaches to pile testing and variation among agencies with respect to training, experience, and acceptance of new technology. This variation is also reflected in the pace of implementation of Load and Resistance Factor Design practices and terminology.

A test pile is defined for purposes of this study (see chapter one) as a pile that is installed for the primary purpose of performing a test of the pile, including the behavior during installation and/or during subsequent testing to determine the axial resistance. The test data may influence the driving criteria. Test piles may or may not be incorporated into the structure as production piles.

This chapter summarizes the components of useful practice that have been identified based on the literature review and the agency surveys. In addition, limitations of these practices are identified along with impediments to implementation. Some examples of integrated approaches obtained from the surveys are included as well.

PILE DRIVING CRITERIA DEVELOPED WITHOUT TEST PILE DATA

Many driven pile projects are completed without the use of any site-specific test pile data, and this practice is accepted as an effective approach where conditions warrant. The most common circumstances where this practice may be effective include small projects with relatively few piles, projects where piles are driven to bear on rock, and projects where local experience suggests that the costs and time involved in performing test pile measurements are not justified. In these situations, the driving criteria are established in advance and the pile installation begins with production piles driven to meet the pre-established criteria.

More than one-third of the states that responded to the survey indicated that they use a dynamic formula for their pile driving criteria. Some of these states are using a formula for all pile installations, whereas some use a formula for a selected portion of the pile projects (based on pile type, size, quantity, etc.). About one-fourth use wave equation analysis as the sole criteria, with more than half using wave equation analysis as a part of criteria development. Some agencies use a wave equation analysis to evaluate drivability and acceptance of a hammer, but still rely on a formula for field verification of axial resistance.

The primary justification for the use of a formula for field verification of axial resistance is the simplicity of use, which is attractive for small projects or routine situations such as steel H-piling driven to bear on rock. In the latter situation, the piles may typically be driven to practical refusal and the installed length of pile is not particularly sensitive to the criteria. A formula can be incorporated into standard specifications so that it becomes the default setting for routine projects. The use of a wave equation analysis in such circumstances typically requires significant effort by more highly trained staff who may have limited availability.

Another justification for the use of a formula is the experience an agency may have developed over many years of use for routine practice in a local area. Some states have developed correlations and/or modifications to a formula to incorporate local conditions. Washington State has developed its own formula based on pile test data for its specific conditions. Other agencies, such as Kansas, Missouri, and North Dakota, have modified the existing *Engineering News* or Gates Formulas to better correlate to the specific conditions in its area. Resistance factors used for design may reflect an agency's experience.

A significant issue with the use of dynamic formulas is the method of accounting for pile setup. Dynamic formulas typically rely on empirical correlations of driving resistance at the end of initial drive (EOID) with static resistance from load tests. This correlation therefore incorporates an average amount of setup reflecting the data from which the correlation was developed. The use of such a formula with a restrike blow would therefore be inappropriate. An agency could develop a correlation of a formula based on a "beginning-of-restrike," blow but no such published correlations are known to exist.

Wave equation analysis is often used to evaluate pile drivability as well as to establish driving criteria. About half of the agencies that responded to the survey indicated that wave equation analysis was used to evaluate the contractor's driving system to determine if it was adequate to install the piles to the specified resistance. In some cases, this drivability analysis was performed by the agency post-bid, when the contractor made its equipment submittals. In other cases, the contractor provides the drivability analysis as part of its submittal.

Wave equation analysis provides a more rigorous method for relating driving resistance to the axial resistance of a pile. The wave equation can consider all of the components of the driving system, such as pile cushions and hammer cushions, and a more sophisticated model of the hammer energy delivered to the pile. The soil resistance is distributed along the length of the pile and to the pile toe, and setup can be incorporated by the user to perform analyses based on EOID or beginning-of-restrike driving resistance.

The results of a wave equation analysis as driving criteria are often provided to the inspector or field engineer in the form of a table or bearing graph that indicates axial resistance as a function of driving resistance for a range of observed hammer stroke. Driving criteria from wave equation analysis may also include instructions for hammer operation to avoid pile damage, as in the event of a reduced fuel setting or hammer energy that might be used with a prestressed concrete pile at low driving resistance. A bearing graph or table from a wave equation analysis that has been computed without any setup can be used to provide a means to "set check" a production pile with a restrike measurement for verification of axial resistance if the driving resistance on initial drive is low.

In spite of the many obvious benefits to the use of numerical modeling of the pile driving process with the wave equation, many agencies do not utilize wave equation analyses as often as might be justified. The impediments to greater implementation of the wave equation model over a dynamic formula include the following:

- Use of the wave equation requires a greater level of education and training compared with a simple formula.
- On small or simple projects, for example piles driven to bear on shallow rock, the benefits of this more sophisticated analysis technique may be small or insignificant.
- Use of the wave equation on simple or small projects requires additional engineering effort on the part of the agency, and trained staff and other resources may be limited.
- There may be inertia with respect to changing long-established practices where the limitations of the established practice may not be evident.
- The costs of underutilized pile capacity may be unrecognized or considered relatively unimportant.

Although either the wave equation or simple formulas have been used effectively to establish driving criteria, the use of any purely computational approach is limited as compared with direct field measurements on test piles. The actual performance of the hammer is not known in advance of construction. Important soil parameters such as setup and damping are not known and may have significant impact on the computed resistance and correlation to long-term static resistance. Although the application of the wave equation is recognized as a useful practice, the use of this technology alone without field measurements would not be the preferred approach for many significant projects.

The following sections of this chapter address issues relative to the use of test piles to develop driving criteria for use with production pile installation.

TYPES AND NUMBER OF TEST PILES AND SITE VARIABILITY

The numbers and types of test piles are subject to judgment on the part of the agency and designer, and can affect the resistance factor used for design per the AASHTO code, Section 10. The code notes that a site may be only a portion of the area in which the structure is located, and could be limited to a single pier where conditions are highly variable.

Where static load testing (SLT) is utilized, the challenge of interpretation of the load test measurements and applying the results across a broad area typically requires careful consideration of site stratigraphy. Where the California Department of Transportation (DOT) (Caltrans) uses SLT, its practice is to divide a site into control zones where a single test pile would be representative of the subsurface conditions within each control zone. This approach uses the different criteria in each control zone as developed from the test pile within each zone to address the site variability. The Louisiana Department of Transportation and Development often uses SLT on larger projects and selects nonproduction locations for test piles to be performed pre-production. The Ohio DOT uses SLT on large projects, with one load test per 10,000 linear feet of pile.

Because of the issue of site variability and the challenge of extrapolating results from a load test across the project, dynamic testing is the predominant method used by most agencies to determine axial resistance of test piles on a routine basis. Substructure units may be combined to define a site based on the engineer's evaluation of ground conditions. Caltrans' practice of dividing a site into control zones uses a single test pile in a production location to represent the subsurface conditions within each control zone. Another approach is that taken by the Florida DOT where a pre-production test pile (usually in a production pile location) is utilized at each pier location. By performing tests at each pier location, site variability is evaluated and accounted for in the process of establishing the driving criteria at each location. Similarly, the Utah DOT also uses the first production pile in each substructure unit as a test pile, with a high strain dynamic test (HSDT).

USE OF PRE-PRODUCTION VERSUS PRODUCTION TEST PILES

Most state transportation agencies do not routinely utilize pre-production test piles. A typical practice is to use a production pile as a test pile, sometimes the first production pile at a given location. This practice has the advantage in that it minimizes schedule impacts and costs associated with moving pile installation equipment around the site to install test piles separately from the remainder of the production piles in a given substructure unit. If there are uncertainties related to final production pile length requirements, this practice can result in the need for cutoffs or splices. For those agencies who primarily use steel piles (either H sections or pipe), the impacts associated with pile length adjustments may be modest.

With the use of production test piles, many agencies establish a driving criteria in advance of the installation of the test pile, and then use the test pile to either verify that the established criteria is suitable or to make modifications to the criteria. With production test piles there are often time pressures on the agency to make decisions and finalize the driving criteria as expeditiously as possible.

Some agencies find it useful to install and test piles in advance of finalizing pile driving criteria. This practice offers the following advantages:

- The final pile length can be more reliably determined before ordering or starting installation of production piles. This issue may be particularly important for precast concrete piles.
- The installation of test piles well in advance of production allows for the opportunity to perform tests after significant setup has occurred, thereby allowing setup to more readily be incorporated into the final design.

Transportation agencies in Florida, Mississippi, New Jersey, Virginia, Delaware, and Louisiana routinely use pre-production test piles to not only develop production pile driving criteria but also to more reliably estimate production pile lengths. These agencies also frequently use prestressed concrete piles for bridge structures. Besides the need for verification of axial resistance, an important component of the pile installation criteria for these piles is the need to control driving stresses, and these test piles help establish hammer operation procedures and pile cushion requirements. Although Florida, Mississippi, and New Jersey most often allow placement of pre-production test piles at production pile locations, Louisiana most often places tests piles at nonproduction locations.

Kansas, Connecticut, Michigan, Minnesota, and Vermont are states that predominantly use steel piles, but also frequently utilize pre-production test piles to develop driving criteria. Other agencies have included the use of pre-production test piles on selected (usually large) projects.

USE OF HIGH-STRAIN DYNAMIC TESTING

Most agencies have determined HSDT to be a useful practice on at least some, if not most, projects involving driven pile foundations. A common useful practice is to utilize HSDT on at least one pile per substructure to develop and/or verify driving criteria, and often using signal-matching analysis to estimate static resistance. The major benefits of HSDT with respect to establishing pile driving criteria are:

- The hammer performance is verified on a regular basis. The measurements can also identify problems with hammer/pile alignment or other problems related to equipment and installation methods.
- The controls on pile overstressing are verified on a regular basis.
- Pile damage can often be detected.
- The tests are relatively fast and economical compared with static load testing.
- HSDT provides a more reliable basis for estimating static resistance based on driving resistance than wave equation analyses alone because the input forces are better known and the pile response is more fully characterized.
- AASHTO and many agencies allow the use of a significantly higher resistance factor for pile design when HSDT is used ($\Phi = 0.65–0.75$) than when only wave equation analysis is used ($\Phi = 0.5$), depending on the quantity of testing and the volume of piles driven. This higher resistance factor offers economic advantages.
- Restrike measurements can easily be performed to evaluate setup, and can readily be employed to verify performance of a production pile that has exhibited low driving resistance during initial installation.

The Florida DOT has developed such reliance on HSDT for driven prestressed concrete piling that this agency has sponsored the development of technology to routinely utilize wireless-embedded sensors on production piles. This technology has the potential to make every production pile a tested pile, at least at the time of initial installation.

When HSDT is used, an effective and widespread practice is to utilize signal-matching analysis (e.g., CAPWAP) with all HSDT. Signal-matching analysis provides the means to back-calibrate the results of HSDT to determine static axial resistance. The waves measured by HSDT and the waves computed by wave equation theory are matched through analysis of the relative soil resistance distribution, soil quake, and soil damping characteristics. This provides a more rigorous evaluation of the static pile resistance than the HSDT data alone.

With respect to the use of signal matching, a further useful practice that has been acknowledged by several agencies is the use of superposition to combine the back-calculated base resistance from a pile on initial drive or from a blow on redriving the pile with the back-calculated side resistance from the early blows at the beginning of restrike. This practice is perceived to overcome the limitations of HSDT related to the reduction in side resistance observed during driving that may occur before full mobilization of the base resistance.

In spite of the benefits of HSDT described previously, many agencies do not include HSDT as a routine part of pile installation. The impediments to greater implementation of HSDT include:

- Performing such tests requires equipment and trained engineering staff or consultants, and therefore the resources needed to perform the testing in a timely manner on a routine basis may be unavailable or the availability difficult to ensure.
- Poorly trained or inexperienced operators may not recognize poor quality measurement data, leading to misleading indications of pile performance.
- On small or simple projects, the benefits of this testing relative to the costs and schedule impact may be small or insignificant. Examples include steel piles that are relatively easy to drive without damage or piles driven to bear on shallow rock, where the axial resistance is relatively reliable.
- There may be inertia with respect to changing long-established practices, where the limitations of the established practice may not be evident.
- The costs of underutilized pile capacity owing to long-established conservative practice may go unrecognized or considered relatively unimportant.

Although HSDT offers advantages over purely computational methods without direct measurements of pile and/or hammer performance, any dynamic load test has undeniable limitations as an indicator of static axial pile resistance compared with conventional SLT. Some agencies have identified circumstances where correlations of dynamic load tests with static resistance were either poor or suspect, most notably with large pile sizes. Some factors that are known or suspected to influence HSDT correlation with static resistance include:

- The effect of soil plugging within pipe piles, cylinder piles, or steel H-piles. The inertial resistance of the soil mass within a pile may result in a different behavior during a dynamic test than would be observed during a static loading, when the inertial resistance of the plug to downward displacement is not a factor.
- The effect of strain compatibility between side and base resistance during HSDT, whereby side resistance is diminished after several blows before base resistance is fully mobilized. The aforementioned practice of superposition represents an attempt to address this limitation.
- The effect of large toe quake, which can exacerbate the issue cited earlier. Larger values of toe quake mean that larger displacements are required to fully mobilize the base resistance, increasing the difference of the displacements for mobilizing side and base resistances.
- The potential for differences between different engineers or testing agencies in the interpretation of HSDT measurements as an indication of static resistance.
- The potential inability of the driving system to fully mobilize the axial resistance of the pile. If a hammer used to perform HSDT does not fully mobilize the axial resistance of the pile the test can only be interpreted as a lower bound on the resistance.
- There may be other unknown factors such as unusual soil behavior, damping, or other parameters that deviate from typical experience that can affect HSDT correlations with static resistance in a manner not foreseen in advance. Although HSDT is a relatively mature technology, experience in local geology with similar pile types and hammers is understood to be of great value.

A useful practice used by some agencies to overcome many of the limitations cited earlier is to include one or more conventional SLTs on a project to provide a site-specific calibration of the HSDT correlations to static resistance. Rapid load testing (RLT) has also been employed to address some of the limitations, such as soil plugging or strain compatibility. Calibrating HSDT to SLT allows for a higher resistance factor ($\Phi = 0.8$) for design than HSDT ($\Phi = 0.65$–0.75) or SLT alone ($\Phi = 0.75$). It also provides insights to the effects of site-specific conditions on the dynamic behavior of the soil/pile system when comparing with a static model. Although not always practical or economical on all projects, the data and experience collected when it is feasible can be used to evaluate and "ground truth" HSDT programs over time.

In addition, the accumulation of correlated SLTs can provide value as a long-term resource for future reference in a local area or geologic formation, if the test results are carefully documented and the information publicized in a useful way.

Some of the perceived limitations of HSDT represent knowledge gaps that could be eliminated or mitigated with additional research. Another area of research or improvement for HSDT includes development of a more automated and rigorous methodology for signal-matching analysis; if this technique could be automated and employed in real time (or even nearly so) whereby the results were immediately available, the implementation of this technique in practice would be significantly enhanced.

USE OF RESTRIKE MEASUREMENTS

The time-dependent development of static resistance appears to be generally well understood by engineers within transportation agencies, and restrike measurements are often recognized as a useful practice for both the evaluation of setup or for verification of pile resistance and integrity. Restrike measurements with HSDT over a period of time after initial drive can establish the relationship of resistance increase with time (setup) for a given site. If the relationship is established prior to or early in production driving, the end of drive criteria can be set to incorporate the anticipated increase in axial resistance through setup.

By incorporating setup into the EOID criteria, the need for subsequent restrikes on production piles to verify resistance can be significantly reduced or eliminated. The use of signal-matching analysis with restrikes provides valuable information on the distribution of pile resistance and provides a more meaningful comparison with the static resistance of the pile. Restrikes can also be used to verify pile resistance, either with a blow count alone (set check) or by measurement with a pile driving analyzer (PDA).

The most significant impediment to the use of restrike measurements to develop pile driving criteria is the time required to relocate the hammer or test apparatus onto a pile and the impact this operation has on the schedule. For many routine projects in ground conditions that provide significant increased axial resistance with increased pile length, it appears that agencies may choose to simply drive a longer pile to avoid the need for verifying setup. Where long-term restrike measurements are not used, a restrike may often be made with a setup period ranging from a few hours to overnight to derive the benefit from at least some of the available setup.

Another method to overcome the schedule impact of restrikes during production pile installation on a large project is to incorporate a program of restrike measurements over an extended period of time at a number of locations. These measurements could be used in advance to determine the setup of production for a range of soil conditions. However, this approach requires a consideration of the variability in soil conditions and anticipated setup.

The subject of time-dependent change in static axial resistance of driven piles has been the subject of numerous scholarly papers and research. However, there remains an insufficient understanding of the fundamental nature of the development of axial resistance of driven piles with time in different soils. This topic continues to represent a knowledge gap and an area that needs research.

USE OF STATIC LOAD TESTING OR RAPID LOAD TESTING

Although most agencies employ SLT infrequently, such tests are recognized to be a useful technology by providing the most direct measure of the pile static resistance. SLT can be conducted to mimic anticipated loading schemes (such as cyclic loading or staged loading), or be performed according to standard procedures. Static load testing (alone or with HSDT) provides the highest available resistance factors ($\Phi = 0.75–0.8$) for design, thereby offering the potential for more efficient and economical designs than would otherwise be available.

In many cases, particularly small projects, SLT may not be economical; however, for large projects, the costs of the test are often recouped by the savings from more efficient foundation designs. SLT may also be included as a long-term benefit as a means to improve methods for static computations, evaluate long-term setup, and improve correlations with dynamic tests.

Some agencies use static load testing for large diameter pipe piles because of concerns relating to the reliability of HSDT as indicative of axial resistance. Caltrans reported that they always require SLT for piles that are greater than 36 in. in diameter. Minnesota has used SLT and RLT owing to concerns about the reliability of HSDT on 42-in.-diameter pipe piles and has an ongoing test pile program designed to evaluate this issue. Projects in Washington State with large diameter piles will typically have an SLT.

The most significant impediments to the use of SLT are:

- The cost associated with the installation of a test pile, reaction system, test setup, etc.
- The time required to set up and perform the test, particularly where the test may require a separate mobilization of pile driving equipment.
- The difficulty inherent in applying the results of one or a few tests across a large site to establish pile driving criteria. The Utah DOT reported that its subsurface conditions are typically so variable that there is concern with extrapolating the results of a single SLT to a broader area.
- The ability to address environmental permit issues, particularly if the SLT is done as a separate preconstruction contract or if the load test and all production piles must be completed within a relatively short permitted time (e.g., a “fish window” or other specified period of time).

As a means to overcome some of these limitations, some agencies employ static load testing as a control on a large project, with a more widespread use of HSDT as described in Use of High Strain Dynamic Testing in this chapter.

A few agencies recognize RLT as a useful and cost-effective alternative to conventional SLT. For large capacity piles, the RLT offers cost advantages over conventional SLT. Other perceived advantages of RLT are that the test closely replicates the behavior of a pile during static loading and therefore overcomes some limitations of HSDT with respect to large displacements and soil plugging. The high rate of loading associated with RLT compared with a static loading represents a limitation, because the static resistance derived from the test measurement must account for rate-of-loading effects.

INTEGRATED APPROACH TO DEVELOPING PILE DRIVING CRITERIA FROM TEST PILE DATA

The survey and interviews indicated that agencies commonly employ a variety of technologies to develop a pile driving criteria using the information from test piles. Most agencies integrate combinations of dynamic formulas and/or wave equations with measurements from test piles that often include HSDT (usually with signal-matching analyses), and sometimes SLT to arrive at final criteria for production pile installation. Some of the details of the approaches to using test data for developing pile driving criteria were presented in the summaries of the telephone interviews in chapter four. This section contains four examples selected from those interviews that illustrate four different integrated approaches. These approaches integrate two or more types of testing into the development of pile driving criteria.

Reliance on Dynamic Formula, with Some HSDT (Washington State DOT—WSDOT)

The WSDOT driving formula is used to determine pile resistance during driving for most piles. The formula is correlated to wave equation predictions and field test data. HSDT with signal matching (CAPWAP) is used in the marine division where there are significant uplift requirements and often difficult driving conditions. HSDT is also typically used for land structures for piles larger than 30 in. in diameter, as well as on very large projects. SLT is used by WSDOT on occasion, especially if there is significant uncertainty in the amount of setup likely to occur, if large diameter piles (e.g., 48-in. piles) are planned, or if there are unusual features regarding the piles. The WSDOT approach is as follows:

- If the WSDOT formula is the acceptance criteria, the inspector uses the formula. Required end-of-driving blow counts are developed as a function of hammer stroke. The piles are then driven to the required blow count, and to at least a specified minimum tip elevation to address downdrag, uplift, lateral resistance, etc.
- If wave equation and/or HSDT are used for acceptance criteria, the inspectors will have a series of curves for blow count as a function of stroke to achieve the required resistance. If the wave equation is used, it is typically used in combination with HSDT and signal-matching analysis (CAPWAP).
- When wave equation and HSDT plus signal-matching analysis are used for acceptance, the wave equation analysis is used to estimate the blow count required, using HSDT and information from the signal-matching analysis to refine the wave equation input parameters to develop driving criteria. Then the production piles are driven to that blow count. The resistance as given by the PDA is not relied on to determine acceptance; however, HSDT plus resistance computed using the signal-matching analysis may be relied on for acceptance. The input parameters in the wave equation model are adjusted so that the computed resistance from the wave equation will agree reasonably closely with the resistance predicted by the signal-matching analysis and the transferred energy will agree with that measured using the PDA. Production piles are driven to the blow count criteria predicted by the correlated wave equation analysis.
- When significant setup is anticipated, it is common practice that the EOID resistance indicated from the signal-matching analysis is used to establish the end-bearing resistance of the pile, and the Beginning of Redrive resistance from the signal-matching analysis is used to establish the side resistance. These values of side and base resistance are used in the wave equation model for the development of driving criteria.

Wave Equation with HSDT (Utah DOT)

The Utah DOT relies on wave equations to develop the driving criteria. Piles are driven to an estimated length with a minimum blow count for a minimum stroke or hammer energy. The criteria are verified by performing HSDT on the first pile in each substructure unit. Minimum hammer energy is always specified as part of the criteria. If the minimum blow count at the specified hammer energy/stroke is not achieved, a restrike test is performed. The HSDT data and signal-matching analysis are not used to perform revised wave equation analyses.

HSDT with SLT (Louisiana Department of Transportation and Development—DOTD)

Although not used on all projects, SLT and HSDT are commonly used by the Louisiana DOTD. All test piles are nonproduction piles and are installed with both HSDTs and SLTs. The approach used by the Louisiana DOTD is:

- Test pile tip elevations are estimated using a resistance factor of $\Phi = 0.7$, then installed with HSDT and signal match analysis (CAPWAP). Piles are driven to the estimated tip elevation and load tested.
- Results of the signal-matching analysis (quake, damping, energy, etc.) are used to refine the wave equation analysis using the resistance from the SLT and not the resistance from the signal-matching analysis.
- Revised wave equation analysis from the HSDT and signal-matching analysis are used to establish driving criteria where the pile tip elevation is based on the SLT.
- Tables of blow count and stroke are provided to inspectors to verify end-of-drive conditions, along with additional instructions for changing stroke (fuel setting) for the start of driving, other easy driving conditions, or for hard driving conditions.
- If a production pile does not achieve the required resistance, restrikes (both set checks and HSDT) can be performed, or an SLT is performed to verify resistance.
- During production pile installation, typically one to two piles per bridge (more on larger projects) will be monitored piles with HSDT and signal-matching analysis. Data will be used during the initial drive to check pile stresses and integrity; restrikes are used to check setup.

Graduated Approach: Formula–HSDT–SLT (California DOT—Caltrans)

There are three typical pile sizes and associated processes: (1) standard pile size: small diameter piles, typically less than 20 in. and 100 tons or less required resistance; (2) intermediate size pile (20 in. to 36 in.); and (3) large diameter piles (36 in. and above). The standard pile size is typically a precast prestressed concrete pile, with the occasional use of other pile types. Piles larger than standard sizes are almost exclusively open-end pipe piles and cast-in-steel shell piles. Caltrans approach is as follows:

- Standard pile size (less than 20 in.):
  - Use specified tip plus bearing criteria—drive to planned tip and check with Gates Formula.
  - When pile encounters refusal before planned tip with appropriately sized hammer (uncommon occurrence, although sometimes expected owing to geology), pile can be accepted based on formula (or some specified multiple of the formula), provided that the minimum tips for tension and lateral have been achieved.
  - When pile does not have required resistance at minimum tip (a rare occurrence, except in cohesive soils), restrikes are done after setup. If resistance is still not achieved or difficult driving exists, dynamic analysis or SLT can be requested.
- Intermediate piles (20 in. to 36 in.):
  - Number and frequency of test piles will be site-specific based on soil and geology conditions. The site will be divided into control zones where the subsurface conditions are consistent such that a single pile would be representative of the control zone (not greatest resistance, but representative). Information from the static pile analysis model can be brought in to help select control zones.
  - A minimum of one test pile per control zone using HSDT at EOID and a restrike. CAPWAP is performed on the test data. The results of the CAPWAP analysis (resistance, quake, damping, etc.) are put into a wave equation analysis (GRL WEAP). The WEAP analysis develops a family of curves relating blow count, stroke, and pile resistance. An additional plot representing setup over time is also generated using the restrike data.
  - The developed curves are used for accepting piles in the control zone and for the specific hammer and pile size that were developed. If the hammer is changed, a new set of curves must be developed.
- Large diameter piles (36 in. and above):
  - Site divided into control zones as for intermediate-sized piles.
  - A minimum of one SLT is performed per control zone. HSDT is also done for monitoring pile stresses, hammer performance, and to determine magnitude of setup.
  - The pile acceptance curves are developed from the SLT and signal-matching analysis from the HSDT. The SLT provides a set point where the pile resistance is known for a given stroke and blow count. The signal-matching analysis provides the magnitude of the setup, as well as starting values for quake, damping, etc. The resistance values from signal-matching analysis are not used as an indication of static resistance. Wave equation analyses are performed, adjusting parameters to get a match with the SLT results and then develop the family of curves that are correlated to the SLT.
  - The developed curves are used for accepting piles in the control zone and for the specific hammer and pile size for which they were developed. If the hammer is changed, a new set of curves must be developed.
  - Additional HSDT may be performed on indicator piles in a control zone to check stresses during hard driving, or other issues, but not for acceptance.
  - In some instances, the data can be used to reevaluate the static model(s) to possibly shorten pile lengths.

RESEARCH NEEDS

As noted in the previous sections, there are limitations to each of the technologies and methods described in this report. Some of these limitations indicated areas where there is need for additional research to close some of the knowledge gaps that can hinder implementation of a certain method or technique. Some areas or concepts that need research are:

- Continued research and development of technology to utilize wireless-embedded sensors routinely on production piles.
- Some of the perceived limitations of HSDT described earlier in this chapter represent knowledge gaps that could be eliminated or mitigated with additional research.
- Development of a more automated and rigorous methodology for signal-matching analysis, allowing for “real time,” or nearly so, availability of results.
- The effect of soil plugging within pipe piles, cylinder piles, or steel H-piles on HSDT results.
- The effect of strain compatibility between side and base resistance during HSDT, whereby side resistance is diminished after several blows before base resistance is fully mobilized. The aforementioned practice of superposition represents an attempt to address this limitation.
- The effects of large toe quake during HSDT.
- Understanding of the fundamental nature of the development of the axial resistance of driven piles with time in different soils.
- Collection of comparison tests of SLT and RLT to better understand and determine the rate-of-loading effects when analyzing RLT data.

SUMMARY

This chapter summarized a number of useful practices identified and employed by transportation agencies to develop pile driving criteria from test piles, and described limitations and impediments to more widespread application of these useful practices. The most common limitation to improvements in practice for many cases is the perception of limited benefits relative to costs associated with technologies that require significant commitment of resources or time. For small or routine projects with relatively simple foundation conditions, these perceptions may be accurate. In some cases, improved reliability and economy may be difficult to quantify or there may be simple resistance to changing long-standing practices even though they may be inefficient. In almost all cases there are cost and schedule impacts associated with making measurements on test piles and interpreting the results so as to refine pile driving criteria.

Other limitations to increased use of test piles include lack of equipment and/or trained staff or consultants available to employ advanced technology. Several knowledge gaps have been identified relating to technical issues for which research could potentially improve practice. The most readily apparent need is for research leading to clear guidelines on the need for test piles and the level of testing that is appropriate to develop pile driving criteria and that cover the broad spectrum of project size, complexity, pile type, and ground conditions.

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APPENDIX A

Survey Questionnaire

Dear State Geotechnical or Bridge Engineer:

The Transportation Research Board is preparing a synthesis on "Developing Production Pile Driving Criteria from Test Pile Data." This is being done for the National Cooperative Highway Research Program (NCHRP), under the sponsorship of the American Association of State Highway and Transportation Officials in cooperation with the Federal Highway Administration.

Practices vary widely nationwide for developing production pile driving criteria from test pile data obtained from static load testing, rapid load testing, or high strain dynamic testing with (or without) signal matching analysis. This synthesis will gather and synthesize the current practices various states use.

We request your assistance in completing this survey, which is being sent to all State Departments of Transportation. Your cooperation in completing the questionnaire will help ensure the success of this effort. <u>We request that this questionnaire be completed and returned by April 28, 2010.</u> Note that if your state is <u>not</u> using test pile programs to develop production pile driving criteria, you will only need to respond to questions 1–9.

When it is completed, please save it and email it to our consultant Dan Brown at <u>dbrown@danbrownandassociates.com</u>. If you have any questions about the survey, you may contact Dr. Brown at 423-942-6861.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name

Title

Agency

Address

Email

Phone

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of-driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which is installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. What is your general geographic area (location & extent) of practice? (e.g., Louisiana, Missouri, New Orleans district, etc.)

2. Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:

- **a.** Number of projects with driven pile foundations
- **b.** Number of individual driven piles installed
- **c.** Lineal feet of driven piles installed

3. Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:

- **a.** No submittal required
- **b.** List of pile driving equipment only

c. List of pile driving equipment plus wave equation analysis

d. Specific information regarding the driving sequence

e. Other information specifically related to pile driving criteria, please explain

4. Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:

a. No evaluation is performed

b. Specified hammer energy included in specifications

c. Evaluate using a pile driving formula (please specify which formula is used)

d. Evaluate using a wave equation analysis

e. Other, please explain

5. Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:

a. Drive the pile to a specified tip elevation

b. Drive the pile to practical refusal

c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)

f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

g. A combination of both **e.** and **f.**

6. Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:

a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

7. Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).

8. Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:

a. Would not perform any load tests on pre-production piles

b. Would install pre-production (probe) piles without dynamic monitoring

c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only

d. Would install pre-production test piles for static or rapid load testing only

e. Would install pre-production test piles with both **c.** and **d.**

9. If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)

b. High strain dynamic testing with signal matching only (CAPWAP or similar)

c. Static load tests only

d. Rapid load tests (Statnamic or similar) only

e. Combinations of the above

f. Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc.)? If so, please explain.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

19. How are rapid or static load test results used in the development of driving criteria for production piles?

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Thank you for completing this survey.

APPENDIX B

Phase I Survey Responses: Responses to Questionnaire

Dear State Geotechnical or Bridge Engineer:

The Transportation Research Board is preparing a synthesis on "Developing Production Pile Driving Criteria from Test Pile Data." This is being done for the National Cooperative Highway Research Program (NCHRP), under the sponsorship of the American Association of State Highway and Transportation Officials in cooperation with the Federal Highway Administration.

Practices vary widely nationwide for developing production pile driving criteria from test pile data obtained from static load testing, rapid load testing, or high strain dynamic testing with (or without) signal matching analysis. This synthesis will gather and synthesize the current practices various states use.

We request your assistance in completing this survey, which is being sent to all State Departments of Transportation. Your cooperation in completing the questionnaire will help ensure the success of this effort. We request that this questionnaire be completed and returned by April 28, 2010. Note that if your state is not using test pile programs to develop production pile driving criteria, you will only need to respond to questions 1 - 9.

When it is completed, please save it and email it to our consultant Dan Brown at dbrown@danbrownandassociates.com If you have any questions about the survey, you may contact Dr. Brown at 423-942-6861.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Kaye Chancellor Davis

Title Asst. Geotechnical Engineer

Agency Alabama Department of Transportation

Address 3700 Fairground Road, Montgomery, AL 36110

Email chancellork@dot.state.al.us

Phone 334.206.2277

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Alabama

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   Approximately 40 per year

   b. Number of individual driven piles installed
   Approximately 1600

   c. Lineal feet of driven piles installed
   Approximately 48,200

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required

   b. List of pile driving equipment only
   100% of state projects

   c. List of pile driving equipment plus wave equation analysis
   15% of county projects

   d. Specific information regarding the driving sequence

   e. Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed

   b. Specified hammer energy included in specifications

   c. Evaluate using a pile driving formula (please specify which formula is used)
   Some county projects

   d. Evaluate using a wave equation analysis
   100% of state projects

   e. Other, please explain

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation

   b. Drive the pile to practical refusal
   60%

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

   g. A combination of both **e.** and **f.**
   40%

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   60% as noted in 5b above

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   100% of test piles

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   100% of production piles

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   Presently, the test piles set up for PDA monitoring are production piles. Thus the production pile criteria is determined by the test pile results. Production piles failing to meet the criteria are tested individually. This occurs on the 40% of the projects which are not drive to refusal (DTR) projects. Test piles are not set upon DTR projects.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**

    a. Would not perform any load tests on pre-production piles
    60% - DTR projects

    b. Would install pre-production (probe) piles without dynamic monitoring

    c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only

    d. Would install pre-production test piles for static or rapid load testing only

    e. Would install pre-production test piles with both **c.** and **d.**
    95% of non-DTR, the other 5% would be c or d

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)

b. High Strain dynamic testing with signal matching only (CAPWAP or similar)

c. Static load tests only

d. Rapid load tests (Statnamic or similar) only

e. Combinations of the above
90%

f. Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

Yes - with respect to design loads, soil types, pile type, and size. Require one test pile for each different pile size and/or loading on the bridge.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

Yes - require more test piles where expect the load transfer to be in skin friction. Sometimes require more test piles in cohesive soil profiles where the expectation of soil setup could result in shorter piles.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

If the project is a very long bridge, often will request more test piles.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

High strain dynamic testing is performed for all test piles on all projects which are not set up to be drive to refusal. Signal matching computations are rarely performed on these measurements. A restrike is usually performed instead.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

Settlement during the static load test

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

Within 48 hours of the static load test. Times range from a minimum of 36 hours to 7days or longer in some of the over-consolidated clays and silts.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

Highest energy/measured resistance within 1/2" movement

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

No

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Typically after each initial dynamic test

19. How are rapid or static load test results used in the development of driving criteria for production piles?

Determination of ultimate resistance for bearing charts to be used by field inspectors.

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

- Saximeter records height of stroke and serves as a check on hammer efficiency
- Bearing charts indicate hammer settings and acceptable stroke/bpf combinations
-ALDOT Form C-16 records driven pile data for review

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

Still utilizing ASD at this time. Will change to LRFD by 11/2011

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name David A Hemstreet

Title State Foundation Engineer

Agency State of Alaska DOT/PF

Address 5800 E Tudor Road
Anchorage, Alaska 99507

Email dave.hemstreet@alaska.gov

Phone 907.269.6233

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Alaska

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   4

   b. Number of individual driven piles installed
   80

   c. Lineal feet of driven piles installed
   8000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required
   0

   b. List of pile driving equipment only
   0

   c. List of pile driving equipment plus wave equation analysis
   100

   d. Specific information regarding the driving sequence
   100

   e. Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed
   0

   b. Specified hammer energy included in specifications
   0

   c. Evaluate using a pile driving formula (please specify which formula is used)
   0

   d. Evaluate using a wave equation analysis
   100

   e. Other, please explain

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation

   0

   b. Drive the pile to practical refusal

   0

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

   0

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

   30

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)

   70

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

   0

   g. A combination of both **e.** and **f.**

   0

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   80

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   0

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   10

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   0

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   0

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

   10

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   I estimate 70% of projects utilize PDA. This is when we anticipate high driving stresses and we are concerned with pile damage, or if we are in a friction pile with little end bearing, where we are trying to get as much capacity out of a pile as possible (by utilizing a higher resistance factor). Other times we use simple economics to determine if the PDA will pay for itself by allowing us to use fewer piles.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**
   - **a.** Would not perform any load tests on pre-production piles

     100
   - **b.** Would install pre-production (probe) piles without dynamic monitoring
   - **c.** Would install pre-production test piles with dynamic monitoring (PDA or similar) only
   - **d.** Would install pre-production test piles for static or rapid load testing only
   - **e.** Would install pre-production test piles with both **c.** and **d.**

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

   We either use the wave equation or PDA on every project.

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

- **a.** High strain dynamic testing only (PDA or similar)
  0
- **b.** High Strain dynamic testing with signal matching only (CAPWAP or similar)
  70
- **c.** Static load tests only
  0
- **d.** Rapid load tests (Statnamic or similar) only
  0
- **e.** Combinations of the above
  0
- **f.** Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

No

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

Yes. We may test more piles if we feel driving stresses are very high such as when we drive to hard bedrock. We also use dynamic testing when driving in loose materials so that we have a higher degree of confidence that required capacities have been met, and so that we can utilize a higher resistance factor.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

Generally follow AASHTO unless there is a very small number of piles to be driven, such as on a pedestrian bridge.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

Generally one test per substructure unless high stresses are expected and we want to monitor more than one pile per substructure.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

If setup is expected, yet driving capacity is not being met at anticipated EOD, then we will wait 24 hours or so to see if setup has occurred enough such that capacity is met.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

Generally we wait 24 hours, but if necessary or deemed beneficial, we will wait longer.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

Depends, but we generally take last inch or whatever is a useful measurement.

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

No, we take the restrike blow and use whatever capacity is calculated from that last blow.

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

Generally, each test is applied to the adjacent piles. The driving criteria established is used for the adjacent piles.

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

N/A

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

N/A

19. How are rapid or static load test results used in the development of driving criteria for production piles?

N/A

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

Welding inspections, driveability analysis, etc?

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

We follow AASHTO. Resistance factor is 0.40 when using wave equation only, and it is 0.65 when using dynamic testing with signal matching.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes, Dave Hemstreet at 907 269 6233

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Carl Fuselier

Title Assistant Division Head, Bridge Division

Agency Ark. Hwy. & Transportation Dept.

Address P.O. Box 2261, Little Rock, AR 72203-2261

Email Carl.Fuselier@arkansashighways.com

Phone 501-569-2363

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Arkansas, All answers below with regard to percentage of driven piles are based on the last 5 years.

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**
   - **a.** Number of projects with driven pile foundations
     99%
   - **b.** Number of individual driven piles installed
     Difficult to determine
   - **c.** Lineal feet of driven piles installed
     75,000 ft.

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**
   - **a.** No submittal required
   - **b.** List of pile driving equipment only
     100%
   - **c.** List of pile driving equipment plus wave equation analysis
   - **d.** Specific information regarding the driving sequence
   - **e.** Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**
   - **a.** No evaluation is performed
   - **b.** Specified hammer energy included in specifications
     72%
   - **c.** Evaluate using a pile driving formula (please specify which formula is used)
   - **d.** Evaluate using a wave equation analysis
     28%
   - **e.** Other, please explain

5. Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:

- **a.** Drive the pile to a specified tip elevation
  1%
- **b.** Drive the pile to practical refusal
- **c.** Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula
  71%
- **d.** Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)
  23%
- **e.** Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)
  5%
- **f.** Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements
- **g.** A combination of both **e.** and **f.**

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   44%

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   1%

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   0%

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   0%

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   28%

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

   0%

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   5%

   1. Large number of piles such that significant savings could be achieved.

   2. Higher required driving resistance than that typically required.

8. Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:

a. Would not perform any load tests on pre-production piles

100%

b. Would install pre-production (probe) piles without dynamic monitoring

0%

c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only

5%

d. Would install pre-production test piles for static or rapid load testing only

0%

e. Would install pre-production test piles with both **c.** and **d.**

0%

9. If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?

A test pile program is not used for piling that is expected to be driven to rock or practical refusal. In this case, the piles are driven to the required driving resistance.

Otherwise, a test pile program is used to establish production pile driving criteria.

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)
0%

b. High Strain dynamic testing with signal matching only (CAPWAP or similar)
5%

c. Static load tests only
0%

d. Rapid load tests (Statnamic or similar) only
0%

e. Combinations of the above
0%

f. Other (please explain)
0%

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

No.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

No.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

No.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

Signal matching is always used in conjunction with high strain dynamic testing.

High strain dynamic testing with signal matching would be used every few bents within a structure or wherever ground conditions or driving conditions change.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

Restrike measurements are only performed on production piles and only if the driving resistance was not achieved.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

Setup is only allowed on production piles and if a restrike measurement is performed, the restrike measurement may be performed any time after 24 hours.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

Restrike measurements are not performed with high strain dynamic testing. Restrike measurements are evaluated with a bearing graph with penetration after 20 blows.

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

No.

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

A hammer blow count relationship is developed in the form of a bearing graph. The hammer blow relationship is derived from a wave equation analysis that uses data from signal matching and fiels results from the test pile.

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

N/A

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

N/A

19. How are rapid or static load test results used in the development of driving criteria for production piles?

N/A

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

None.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

The production pile driving criteria method is established during plan development and the applicable resistance factor is used during design.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Carl Fuselier, Assistant Division Head, Bridge Division
(501) 569-2363 Carl.Fuselier@arkansashighways.com

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Brian Liebich, P.E.

Title Chief, Foundation Testing

Agency California Department of Transportation

Address 5900 Folsom Blvd. MS#5,
Sacramento, CA 95819-4612

Email brian.liebich@dot.ca.gov

Phone (916) 227-1000

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   California

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   30-40

   b. Number of individual driven piles installed
   3000-3500

   c. Lineal feet of driven piles installed
   150,000-200,0000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required

   b. List of pile driving equipment only
   90%

   c. List of pile driving equipment plus wave equation analysis
   10%

   d. Specific information regarding the driving sequence

   e. Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed

   b. Specified hammer energy included in specifications

   c. Evaluate using a pile driving formula (please specify which formula is used)
   90% <Gates Formula>

   d. Evaluate using a wave equation analysis
   10%

   e. Other, please explain

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation
   90% (both a and c)

   b. Drive the pile to practical refusal

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula
   90% (both a and c)

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)
   4%

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

   g. A combination of both **e.** and **f.**
   6%

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   90%

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

   Other: 10%. Establish Setup Curves for project

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   10%. Most typically, the pile size is the largest determinant. Piles over 20-inches in diameter are required to have site specific PDA production pile criteria. Piles larger than 36-inches in diameter receive PDA dynamic measures, but capacity values are determined by site specific static axial pile load testing. Few piles under 20-inches in diameter receive dynamic testing.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**
   - **a.** Would not perform any load tests on pre-production piles
     99%
   - **b.** Would install pre-production (probe) piles without dynamic monitoring
   - **c.** Would install pre-production test piles with dynamic monitoring (PDA or similar) only
   - **d.** Would install pre-production test piles for static or rapid load testing only
   - **e.** Would install pre-production test piles with both **c.** and **d.**
     1%: Rare to have Pre-production tests

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

- **a.** High strain dynamic testing only (PDA or similar)
  1%
- **b.** High Strain dynamic testing with signal matching only (CAPWAP or similar)
  5%
- **c.** Static load tests only
  1%
- **d.** Rapid load tests (Statnamic or similar) only
- **e.** Combinations of the above
  Both a & c = 6%
- **f.** Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

Size of Pile. See explanation in Question 7.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

End bearing directly upon competent rock may eliminate uncertainty about capacity, leading to static load tests or CAPWAP not being required.

Number of pile tests will be related to the number of control zones present at a project site. The project will be broken down into regions that have relatively low geotechnical variability, with a minimum of one test per control zone.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

Cost effectiveness of pile testing program always considered as part of the total project cost. When uneconomical, pile types may be altered from driven piles.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

High Strain dynamic testing is performed, at minimum one per control zone, on all piles above 20 inches. CAPWAP is performed unless capacity information is obtained by other means, such as a static pile load test.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

Restrike measurements are typically performed in soils with cohesive content, sometimes several restrikes at different lengths of time after the initial drive.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

Different setup times are used in different soil types. Silt may be 1-3 days, but a fat clay may require 28 days.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

Wave traces are examined with regard to quality and suitability of data. One or more blows are selected accordingly in the first tenths of a foot of a restrike to establish the value.

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

No. Hammers are usually sized such that the scenario described (partial refusal case) does not occur, thus removing the need to perform this compilation.

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

Results from dynamic analysis and signal matching are used to calibrate a site-specific WEAP analysis for that control zone, pile type and hammer. Inspector charts are produced, along with time setup charts.

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Minimum of 1 per control zone when requested by the Geotechnical Designer. Most typically, this is associated with the requirement associated with pile size (>36" in diameter), geologic conditions that are difficult to accurately quantify, an unrpoven design methodology, an alternative pile type or a significant economic savings.

19. How are rapid or static load test results used in the development of driving criteria for production piles?

Dynamic measurements from dynamic analysis such as energy and blow count are combined with measured capacity information from static axial pile load testing in a calibrated WEAP model. The process tends to be iterative. The resultant model is site-specific for that control zone, pile type and hammer. Inspector charts are produced, along with time setup charts.

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

Visual Observations of pile behavior or damage. Additionally, certain minimum specified tip elevations are required, especially for tension, lateral or scour/liquefaction considerations.
Additional dynamic monitoring performed if pile do not behave as expected.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

At present, not considered. Changes are expected.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Brian Liebich, P.E. 916-227-1000.

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Alan Hotchkiss

Title Research Scientist III

Agency Colorado Dept. of Transportation

Address 4670 Holly Street, Denver, CO 80216

Email alan.hotchkiss@dot.state.co.us

Phone 303-398-6587

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Colorado

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**
   - **a.** Number of projects with driven pile foundations
     20
   - **b.** Number of individual driven piles installed
     400
   - **c.** Lineal feet of driven piles installed
     24,000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**
   - **a.** No submittal required
     0
   - **b.** List of pile driving equipment only
     20
   - **c.** List of pile driving equipment plus wave equation analysis
     0
   - **d.** Specific information regarding the driving sequence
     0
   - **e.** Other information specific related to pile driving criteria, please explain
     0

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**
   - **a.** No evaluation is performed
     0
   - **b.** Specified hammer energy included in specifications
     20
   - **c.** Evaluate using a pile driving formula (please specify which formula is used)
     0
   - **d.** Evaluate using a wave equation analysis
     20
   - **e.** Other, please explain

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation

   b. Drive the pile to practical refusal

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)
   100

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

   g. A combination of both **e.** and **f.**

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   0

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   0

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   90

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   0

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   0

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

   10

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   CDOT utilizes the PDA on all (100%) pile driving projects to establish the pile driving criteria. CDOT uses end bearing criteria for it's driven pile and 90% of our pile are H - Pile and driven into bedrock.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**
    - **a.** Would not perform any load tests on pre-production piles
      <1%
    - **b.** Would install pre-production (probe) piles without dynamic monitoring
      0
    - **c.** Would install pre-production test piles with dynamic monitoring (PDA or similar) only
      <1%<1%
    - **d.** Would install pre-production test piles for static or rapid load testing only
    - **e.** Would install pre-production test piles with both **c.** and **d.**
      <1%

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

    The use of wave equation analysis such as WEAP or DRIVEN to establish a minimum tip elevation. Then the use of the PDA to determine the final driving criteria using end bearing capacity.

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

- **a.** High strain dynamic testing only (PDA or similar)
  100
- **b.** High Strain dynamic testing with signal matching only (CAPWAP or similar)
  20%
- **c.** Static load tests only
  <1%
- **d.** Rapid load tests (Statnamic or similar) only
  0
- **e.** Combinations of the above
  0
- **f.** Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

No

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

Yes. Typically H pile into shallow bedrock (<100') and pipe or friction pile in areas where bedrock is too deep to encounter. Both types of pile are chosen dependent upon the geology encountered in the boring logs and structural requirements.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

Yes. CDOT provides PDA testing on 20% of the piling being driven on a project with a minimum of 1 PDA test per bent. Smaller projects can exceed 20% testing while larger projects are usually at or above 20%.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

PDA testing is required on all CDOT projects, either provided by CDOT personnel or a qualified PDA consultant. Minimum PDA testing is 20% of the total number of pile on the project as well as a minimum of 1 test per bent.

CDOT rarely performs signal matching, CAPWAP. This is due to CDOT performing PDA testing during re-strike, usually within 1 hour of the EOID (End of Initial Drive). All pile are driven to the required capacity and though set up occurs, it is not figured into the final end bearing capacity.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

Yes. 95% of CDOT PDA testing is performed as re-strikes.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

Usually 1 hour with no difference in setup time due to different geology.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

A single blow that represents an average of the first 10 blows.

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

No, we use end bearing capacity only and use only 1 blow, not a combination of blows.

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

Driving criteria is established by measurement of inches/10 blows prior to EOID. A re-strike is then performed, usually within an hour of the EOID, with a minimum of 30 blows recorded and marked in inches/10 blows. Then the end bearing capacity determined. Stroke of the piston, fuel setting, and inches/10 blows data is collected and compared to the EOID inches/10 blows.

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

N/A

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

N/A

19. How are rapid or static load test results used in the development of driving criteria for production piles?

N/A

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

Instrumentation is calibrated once a year and equipment is verified using a second independent PDA at least once per year.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

The ultimate resistance is derived using a resistance factor of 0.7 (AASHTO LRFD Bridge Design Specifications, 1994) for design. The driving criteria for the production pile is adjusted in the field using the PDA to ensure that the bearing capacity is reached and the piles are not over stressed during installation.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes,
Alan Hotchkiss 303-398-6587

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Leo Fontaine

Title Trans. Principal Engineer

Agency Connecticut DOT

Address 2800 Berlin Turnpike
Newington, CT 06131

Email leo.fontaine@ct.gov

Phone 860.594.3180

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Connecticut

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   5

   b. Number of individual driven piles installed
   500

   c. Lineal feet of driven piles installed
   25000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required

   b. List of pile driving equipment only

   c. List of pile driving equipment plus wave equation analysis
   100%

   d. Specific information regarding the driving sequence
   10%

   e. Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed

   b. Specified hammer energy included in specifications
   100%

   c. Evaluate using a pile driving formula (please specify which formula is used)

   d. Evaluate using a wave equation analysis
   100%

   e. Other, please explain

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

    a. Drive the pile to a specified tip elevation

    b. Drive the pile to practical refusal

    c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

    d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)
    40%

    e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)
    40%

    f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

    g. A combination of both **e.** and **f.**
    20%

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   85%

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   15%

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   See attached excerpt from our geotech Manual...I've also attached our current pile standard spec.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**

   a. Would not perform any load tests on pre-production piles

   20%

   b. Would install pre-production (probe) piles without dynamic monitoring

   c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only

   70

   d. Would install pre-production test piles for static or rapid load testing only

   e. Would install pre-production test piles with both **c.** and **d.**

   10

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

- **a.** High strain dynamic testing only (PDA or similar)
- **b.** High Strain dynamic testing with signal matching only (CAPWAP or similar)
  85
- **c.** Static load tests only
- **d.** Rapid load tests (Statnamic or similar) only
- **e.** Combinations of the above
  15
- **f.** Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

Nothing prescribed....it's all based on judgement/experience

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

Nothing prescribed....it's all based on judgement/experience

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

On rare occasions, a preconstruction pile load test program may be performed.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

CAPWAP is always done with our dynamic testing....Our philosophy on the testing

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

restrikes are routinely performed

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

Nothing prescribed....it's all based on judgement/experience

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

highest resistance

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

that has not been a consideration

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

No set procedure, but the results of the test(s) are strongly considered when establishing the driving criteria.

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Not frequently done anymore, generally only done when the resistance factor needs to be maximized.

19. How are rapid or static load test results used in the development of driving criteria for production piles?

Nothing prescribed....it's based on many factors in addition to the load test results...subsurface conditions (friction, end bearing-till/igm, end bearing-rock), test pile driving record, pile freeze/relaxation, judgement/experience

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

dynamic monitoring is occasionally used if there is a question regarding capacity or integrity

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

See attached Manual excerpt

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

you may contact me....

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Jiten Soneji/Jason Hastings

Title Bridge Design Engineer/Project Manager

Agency Delaware Department of Transportation

Address PO Box 778
800 Bay Road
Dover, DE 19903

Email jiten.soneji@state.de.us/jason.hastings@state.de.us

Phone 302-760-2299

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Delaware - Statewide

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   5

   b. Number of individual driven piles installed
   200

   c. Lineal feet of driven piles installed
   10000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required
   0

   b. List of pile driving equipment only
   0

   c. List of pile driving equipment plus wave equation analysis
   100

   d. Specific information regarding the driving sequence
   20

   e. Other information specific related to pile driving criteria, please explain

   Driveability

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed
   0

   b. Specified hammer energy included in specifications
   10

   c. Evaluate using a pile driving formula (please specify which formula is used)
   0

   d. Evaluate using a wave equation analysis
   100

   e. Other, please explain

5. Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:

a. Drive the pile to a specified tip elevation

30

b. Drive the pile to practical refusal

0

c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

0

d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

100

e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)

10

f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

10

g. A combination of both **e.** and **f.**

6. Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:

- **a.** Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

  0
- **b.** Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

  0
- **c.** Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

  30
- **d.** Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

  100
- **e.** Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

  100
- **f.** Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

  0

7. Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).

100%

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**
   - **a.** Would not perform any load tests on pre-production piles
     0
   - **b.** Would install pre-production (probe) piles without dynamic monitoring
     0
   - **c.** Would install pre-production test piles with dynamic monitoring (PDA or similar) only
     100
   - **d.** Would install pre-production test piles for static or rapid load testing only
     Special Projects Only
   - **e.** Would install pre-production test piles with both **c.** and **d.**
     0

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

   N/A

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)
100

b. High Strain dynamic testing with signal matching only (CAPWAP or similar)
100

c. Static load tests only
Special Projects Only - When >100 Piles on Project

d. Rapid load tests (Statnamic or similar) only
0

e. Combinations of the above

f. Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

N/A

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

N/A

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

Yes, if the soils are consistent and the lengths could be reduced

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

Yes, just perform 10 blows after 48 hours

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

No, generally 48 hours

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

10 blows after 48 hours

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

Ratio of tip resistance to skin friction is taken from static analysis

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

Number of blows per foot established as a result of PDA and CAPWAP analysis

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

N/A

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Yes, when there are more than 100 piles

19. How are rapid or static load test results used in the development of driving criteria for production piles?

N/A

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

Stay within the driving tolerances, plumb, etc.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

Follow AASHTO criteria

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes if necessary

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Larry Jones

Title State Geotechnical Engineer

Agency Florida Department of Transportation

Address 605 Suwannee Street
Tallahassee, FL 32399

Email Larry.Jones@dot.state.fl.us

Phone 850 414-4305

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Florida

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   100

   b. Number of individual driven piles installed
   2200

   c. Lineal feet of driven piles installed
   181000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required

   b. List of pile driving equipment only
   100

   c. List of pile driving equipment plus wave equation analysis

   d. Specific information regarding the driving sequence
   100

   e. Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed

   b. Specified hammer energy included in specifications

   c. Evaluate using a pile driving formula (please specify which formula is used)

   d. Evaluate using a wave equation analysis

   e. Other, please explain

   100 percent evaluated based on wave equation analysis and satisfactory performance in the field during dynamic monitoring of test piles.

5. Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:

a. Drive the pile to a specified tip elevation

b. Drive the pile to practical refusal

c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)

97

f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

g. A combination of both **e.** and **f.**

3

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location
   10

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive
   75

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance
   15

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   100. FDOT normally requires dynamic monitoring of about 10-20% of piles to evaluate the driving system, determine the final pile lengths, establish the required installation criteria, and confirm bearing resistance. Sometimes it is desirable to utilize dynamic monitoring on a larger percentage of piles in order to increase confidence at a particular location or in a portion of the structure. All dynamically tested piles are normally incorporated into the structure

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**

   a. Would not perform any load tests on pre-production piles

   b. Would install pre-production (probe) piles without dynamic monitoring

   c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only
   99

   d. Would install pre-production test piles for static or rapid load testing only

   e. Would install pre-production test piles with both **c.** and **d.**
   1

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

   When test piles are not needed to determine final pile lengths, the initial production piles are dynamically monitored to determine the required installation criteria or determine reliable wave equation analysis parameters for determining the required installation criteria.

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)

b. High Strain dynamic testing with signal matching only (CAPWAP or similar)
99

c. Static load tests only

d. Rapid load tests (Statnamic or similar) only

e. Combinations of the above
1% c or d used to confirm dynamic measurements

f. Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

no

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

no

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

Yes. The use of static or Statnamic load tests or 100% dynamic testing is based on the economic advantages of using increased resistance factors for the project.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

Dynamic monitoring tests are performed on all test piles, including piles for subsequent static or Statnamic testing. Test piles are often installed at every bent for larger span bridges. For small bridges at least two test piles per bridge is required.

Signal matching analysis is always required for test piles monitored with the Pile Driving Analyzer.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

When reasonable shortfalls in initial drive resistances are measured, restrike tests are typically performed at the tip elevation required for lateral stability and at the anticipated bearing layer.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

Setup times of one to 24 hours are normally investigated. When required, times up to 7 days are investigated.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

Restrike blows are analyzed individually based on the quality of the data, the energy transferred into the pile, and the measured resistance.

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

The reliability of the pile is evaluated using the highest resistance blow and the resistance of the next five blows. If there is very little set during the restrike, it is generally assumed the tip resistance is not fully mobilized, so the tip resistance measured at initial drive is assumed to still be present but not mobilized by the restrike; great care is needed when evaluating analyses with this assumption.

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

Dynamic testing and signal matching is used to determine the most appropriate soil response, pile cushion response and hammer efficiency parameters for use in wave equation analyses to determine driving criteria for production piles.

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Rapid load tests are used when the costs of justifying the resistance factor FDOT uses for rapid load testing is considered cost effective. Testing frequency is similar to static load testing. Horizontal rapid load tests are considered an effective means of evaluating foundation response to vessel impact loading.

Currently FDOT uses only Statnamic rapid load tests (ASTM D7383 Procedure A) because the results of the analysis method for Stanamic tests were statistically calibrated to the results of static load tests, and we are not aware such calibrations for the other methods of analyzing Procedure B type tests.

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Static load tests are used when the costs of justifying the resistance factor for static load testing is considered cost effective.

19. How are rapid or static load test results used in the development of driving criteria for production piles?

Rapid or static load tests increase the confidence in the results of dynamic testing; they are used to verify signal matching analyses do not over estimate the static capacity of the pile. With proper instrumentation, they are used to verify the load transfer characteristics determined in the dynamic testing method.

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

Monitor blow count vs. hammer energy (stroke, bounce pressure, etc.) of every pile.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

The resistance factor chosen for design is based on the level of confidence in the driving criteria, resulting from dynamic testing w/ signal matching or closed form solution (SM) as follows:
100% dynamic testing w/ SM verified by static load testing - use 0.85
100% dynamic testing w/ SM verified by Statnamic load testing - use 0.80
100% dynamic testing w/ SM without static or Statnamic tests - use 0.75
≥10% dynamic testing w/ SM verified by static load testing - use 0.75
≥10% dynamic testing w/ SM verified by Statnamic load testing - use 0.70
≥10% dynamic testing w/ SM without static or Statnamic tests - use 0.65

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes.
Larry Jones (850) 414 - 4305

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Thomas Scruggs

Title State Geotechnical Engineer

Agency Georgia DOT

Address 15 Kennedy Drive, Forest Park, GA 30297

Email tscruggs@dot.ga.gov

Phone 404-363-7548

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Georgia

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   40-50

   b. Number of individual driven piles installed
   >1200

   c. Lineal feet of driven piles installed
   >70,000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required

   b. List of pile driving equipment only
   99%

   c. List of pile driving equipment plus wave equation analysis
   1%

   d. Specific information regarding the driving sequence

   e. Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed
   75%

   b. Specified hammer energy included in specifications

   c. Evaluate using a pile driving formula (please specify which formula is used)
   24% (S-pile)

   d. Evaluate using a wave equation analysis
   1% (GRL Weap)

   e. Other, please explain

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation
   100%

   b. Drive the pile to practical refusal

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula
   98%

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)
   100%

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)
   1%

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements
   1%

   g. A combination of both **e.** and **f.**

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer
   50%

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location
   50%

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   1%- used on large friction pile projects where wave equation or PDA could help save pile lengths.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**

   a. Would not perform any load tests on pre-production piles
   99%

   b. Would install pre-production (probe) piles without dynamic monitoring

   c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only

   d. Would install pre-production test piles for static or rapid load testing only

   e. Would install pre-production test piles with both **c.** and **d.**
   1%

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

   After minimum tip elevation has been achieved, drive the piles to driving resistance using ENR. However, due to LRFD requirements, this will be changing to the use of PDA or load tests to establish production pile driving criteria.

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

- **a.** High strain dynamic testing only (PDA or similar)
- **b.** High Strain dynamic testing with signal matching only (CAPWAP or similar)
- **c.** Static load tests only
- **d.** Rapid load tests (Statnamic or similar) only
- **e.** Combinations of the above
- **f.** Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

15. If your agency uses high strain dynamic testing:

- **a.** Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

- **b.** If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

- **c.** What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

- **d.** In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

19. How are rapid or static load test results used in the development of driving criteria for production piles?

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Tri Buu

Title Geotechnical Engineer

Agency Idaho Transportation Dept.

Address PO Box 7129, Boise, ID 83707

Email tri.buu@itd.idaho.gov

Phone 208 334 8448

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Idaho

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**
   - **a.** Number of projects with driven pile foundations
     15
   - **b.** Number of individual driven piles installed
     500
   - **c.** Lineal feet of driven piles installed
     30000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**
   - **a.** No submittal required
   - **b.** List of pile driving equipment only
     100
   - **c.** List of pile driving equipment plus wave equation analysis
   - **d.** Specific information regarding the driving sequence
   - **e.** Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**
   - **a.** No evaluation is performed
   - **b.** Specified hammer energy included in specifications
   - **c.** Evaluate using a pile driving formula (please specify which formula is used)
   - **d.** Evaluate using a wave equation analysis
     100
   - **e.** Other, please explain

5. Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:

a. Drive the pile to a specified tip elevation

b. Drive the pile to practical refusal

20

c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

50

e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)

30

f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

g. A combination of both **e.** and **f.**

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   30

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   50

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   10

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   10

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   40%. Determine need of PDA testing based on pile type, pile design capacity and soil conditions.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**
   - **a.** Would not perform any load tests on pre-production piles
   - **b.** Would install pre-production (probe) piles without dynamic monitoring
     60
   - **c.** Would install pre-production test piles with dynamic monitoring (PDA or similar) only
     40
   - **d.** Would install pre-production test piles for static or rapid load testing only
   - **e.** Would install pre-production test piles with both **c.** and **d.**

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

- **a.** High strain dynamic testing only (PDA or similar)
- **b.** High Strain dynamic testing with signal matching only (CAPWAP or similar) 100
- **c.** Static load tests only
- **d.** Rapid load tests (Statnamic or similar) only
- **e.** Combinations of the above
- **f.** Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

CAPWAP is always required.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

Soil type

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

1 to few days for silt or sand. 1 to several weeks for clay

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

The test results are used to calibrate the pile driving criteria developed by wave equation analysis.

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

19. How are rapid or static load test results used in the development of driving criteria for production piles?

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

Use resistance factor of 0.55 when production piles are driven with criteria developed by wave equation analysis. Use resistance factor of 0.65 if the number of pile dynamic tests meets the minimum required as in Table 10.5.5.2.3 of the AASHTO LRFD Bridge Design Specifications.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name William Kramer

Title State Foundations and Geotechnical Engineer

Agency IL DOT

Address 2300 South dirksen parkway, Springfield IL. 62764

Email william.kramer@illinois.gov

Phone 217-782-7773

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Illinois

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   400/yr

   b. Number of individual driven piles installed
   6000/yr

   c. Lineal feet of driven piles installed
   300,000 lin. ft/yr

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required
   90%

   b. List of pile driving equipment only

   c. List of pile driving equipment plus wave equation analysis
   10%

   d. Specific information regarding the driving sequence

   e. Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed

   b. Specified hammer energy included in specifications

   c. Evaluate using a pile driving formula (please specify which formula is used)
   90% (WSDOT formula)

   d. Evaluate using a wave equation analysis
   10

   e. Other, please explain

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation
   1%

   b. Drive the pile to practical refusal

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula
   99%

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

   g. A combination of both **e.** and **f.**

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location
   10%

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   2% (use on very big projects with friction piles where many lineal ft. of piling can be saved).

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**
   - **a.** Would not perform any load tests on pre-production piles
   - **b.** Would install pre-production (probe) piles without dynamic monitoring
     98%
   - **c.** Would install pre-production test piles with dynamic monitoring (PDA or similar) only
     2%
   - **d.** Would install pre-production test piles for static or rapid load testing only
   - **e.** Would install pre-production test piles with both **c.** and **d.**

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

- **a.** High strain dynamic testing only (PDA or similar)
- **b.** High Strain dynamic testing with signal matching only (CAPWAP or similar)
- **c.** Static load tests only
- **d.** Rapid load tests (Statnamic or similar) only
- **e.** Combinations of the above
- **f.** Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

15. If your agency uses high strain dynamic testing:

- **a.** Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

- **b.** If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

- **c.** What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

- **d.** In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

19. How are rapid or static load test results used in the development of driving criteria for production piles?

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name MIR A. ZAHEER

Title GEOTECHNICAL ENGINEER

Agency INDIANA DEPT. OF TRANSPORTATION

Address 120 S. SHORTRIDGE ROAD, INDIANAPOLIS, IN 46219

Email MZAHEER@INDOT.IN.GOV

Phone (317) 610 - 7251 EXT. 224

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   INDIANA

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   117

   b. Number of individual driven piles installed
   7800 approx.

   c. Lineal feet of driven piles installed
   393,000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required
   0%

   b. List of pile driving equipment only
   100%

   c. List of pile driving equipment plus wave equation analysis
   60%

   d. Specific information regarding the driving sequence
   10%

   e. Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed
   0%

   b. Specified hammer energy included in specifications
   0%

   c. Evaluate using a pile driving formula (please specify which formula is used)
   40%

   d. Evaluate using a wave equation analysis
   60%

   e. Other, please explain

5. Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:

- **a.** Drive the pile to a specified tip elevation
  0% - Only if scour a minimum tip
- **b.** Drive the pile to practical refusal
  5%
- **c.** Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula
  35%
- **d.** Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)
  0%
- **e.** Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)
  60%
- **f.** Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements
  0%
- **g.** A combination of both **e.** and **f.**

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   5%

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   0%

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   95%

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   0%

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   100%

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

   40%

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   60% - Ground conditions and the costs of piling

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**
   - **a.** Would not perform any load tests on pre-production piles
     0%
   - **b.** Would install pre-production (probe) piles without dynamic monitoring
     0%
   - **c.** Would install pre-production test piles with dynamic monitoring (PDA or similar) only
     60%
   - **d.** Would install pre-production test piles for static or rapid load testing only
     0%
   - **e.** Would install pre-production test piles with both **c.** and **d.**
     0%

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

   Gates formula is used for test piles on other 40% projects

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

- **a.** High strain dynamic testing only (PDA or similar)
  0%
- **b.** High Strain dynamic testing with signal matching only (CAPWAP or similar)
  60%
- **c.** Static load tests only
  <1%
- **d.** Rapid load tests (Statnamic or similar) only
  0
- **e.** Combinations of the above
  0
- **f.** Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

NO

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

YES. Varying site geology across the bridge structures. Or H-piles in sandy strata.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

YES. On small projects with a fewer number of piles and smaller factored loads, we do not use PDA

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

Depending on the site geology variation we require at least 2 tests for a 2 span bridge. All HSDT projects require CAPWAP.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

Restrikes are performed on all HSDT piles.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

24 hrs for sands and hard rock to 7 days for clays and shales.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

Highest quality and high resistance blow from the BOR, generally within the first 5 blows is selected for CAPWAP.

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

NO

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

Refined WEAP analyses are performed to develop driving criteria.

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

N/A

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

On very large projects and on projects with piles driven carry higher factored loads and a high structural resistance factor for axial compression is used e.g. phi(c) >0.42

19. How are rapid or static load test results used in the development of driving criteria for production piles?

SLT are always done with HSDT and CAPWAP.

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

Is pile as per design and specs
Restrike of piles.
Acceptable Plumbness
Check all piles for heave.
Pile driving equipment working properly
Hammer cushion as per the submittal
Pile tip/closure requirements

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

With Static Load Tests the Resistance factors used are 0.75
With PDA w/CAPWAP the RF's used are 0.70
With Gates Formula the RF's used are 0.55

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

YES. Mir Zaheer

Thank you for completing this survey.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Iowa

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**
   - **a.** Number of projects with driven pile foundations
     50
   - **b.** Number of individual driven piles installed
     3,000
   - **c.** Lineal feet of driven piles installed
     180,000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**
   - **a.** No submittal required
   - **b.** List of pile driving equipment only
     100%
   - **c.** List of pile driving equipment plus wave equation analysis
   - **d.** Specific information regarding the driving sequence
   - **e.** Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**
   - **a.** No evaluation is performed
   - **b.** Specified hammer energy included in specifications
   - **c.** Evaluate using a pile driving formula (please specify which formula is used)
   - **d.** Evaluate using a wave equation analysis
     100%
   - **e.** Other, please explain

5. Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:

a. Drive the pile to a specified tip elevation
Full penetration when achievable

b. Drive the pile to practical refusal

c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)

f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

g. A combination of both **e.** and **f.**

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance
   Restrike min. of 2 that don't make it

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   0% Production pile criteria may be changed based on PDA results but PDA is not used to establish production driving criteria.

8. Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:

a. Would not perform any load tests on pre-production piles

b. Would install pre-production (probe) piles without dynamic monitoring

c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only

d. Would install pre-production test piles for static or rapid load testing only

e. Would install pre-production test piles with both **c.** and **d.**

1%

9. If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?

History of static load tests to establish soil friction and end bearing factors

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)

b. High Strain dynamic testing with signal matching only (CAPWAP or similar)

c. Static load tests only

d. Rapid load tests (Statnamic or similar) only

e. Combinations of the above

f. Other (please explain)

PDA and CAPWAP are used to address hammer performance issues and unusual driving results

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Bob Henthorne

Title Chief Geologist

Agency Kansas Dept. of Transportation

Address 2300 Van Buren Topeka, KS 66611

Email roberth@ksdot.org

Phone 785-291-3860

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Kansas

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**
   a. Number of projects with driven pile foundations
      25
   b. Number of individual driven piles installed
      1250
   c. Lineal feet of driven piles installed
      67,000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**
   a. No submittal required
      0
   b. List of pile driving equipment only
      100
   c. List of pile driving equipment plus wave equation analysis
      0
   d. Specific information regarding the driving sequence
      0
   e. Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**
   a. No evaluation is performed
      0
   b. Specified hammer energy included in specifications
      100
   c. Evaluate using a pile driving formula (please specify which formula is used)
      100 Modified ENR
   d. Evaluate using a wave equation analysis
      50
   e. Other, please explain

      All of our inspectors must conduct a driveability calculation. Based on the contractors equipment. The inspector then inputs the data into a spread sheet that will calculate the required blows needed for the required bearing.

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation

      0

   b. Drive the pile to practical refusal

      0

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

      93

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

      2

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)

      5

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

      0 we conducted only a handful of these tests

   g. A combination of both **e.** and **f.**

      5

6. Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:

a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

40

b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

0

c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

0

d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

20

e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

80

f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

20

7. Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).

Currently we are monitoring approximately 5 percent of the piles with a PDA. This number will decrease as we build up our database.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**
   a. Would not perform any load tests on pre-production piles
      less than 1
   b. Would install pre-production (probe) piles without dynamic monitoring
      0
   c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only
      100
   d. Would install pre-production test piles for static or rapid load testing only
      0
   e. Would install pre-production test piles with both **c.** and **d.**
      0

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)
   5
b. High Strain dynamic testing with signal matching only (CAPWAP or similar)
   5
c. Static load tests only
   0
d. Rapid load tests (Statnamic or similar) only
   0
e. Combinations of the above

f. Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

We may increase or decrease the number of PDA test conducted at a specific site depending upon the results.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

Yes most of our PDA test are conducted in the deep sand friction situations. Usually 1 per foundation element. When in an end bearing situation we may test only 1 pile for the structure.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

No

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

Capwap is run on all PDA tests.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

Restrikes are performed on all friction piles and rarely on endbearing piles.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

We conduct 15 min. 1 hour, 4 hour and 18 hour restrikes to plot set-up or relaxation verses time graphs. This gives a picture of what amount of set-up will occur.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

Restrikes are conducted in 5 blow increments for 20 blows.

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

No we don't allow that interpretation.

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

After the PDA is finished we give recommended blow count and penetration recommendations to the inspectors. They also continue to monitor the drive with the Modified ENR formula.

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

19. How are rapid or static load test results used in the development of driving criteria for production piles?

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

Continued monitoring of the pile driving operation by the inspector and modified ENR calculations.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

By utilizing a PDA we typically increase the phi factor by as much as 20 percent.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Bob Henthorne or Carrie Ridley at 785-291-3862

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Darrin Beckett, P.E.

Title Transportation Engineer Specialist (Geotech Branch)

Agency Kentucky Transportation Cabinet, Division of Structural Design, Geotechnical Branch

Address 1236 Wilkinson Blvd., Frankfort, KY, 40601

Email darrin.beckett@ky.gov

Phone 502-564-2374 ext 293

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Kentucky

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   ~30

   b. Number of individual driven piles installed
   ~1500

   c. Lineal feet of driven piles installed
   ~75,000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required
   0%

   b. List of pile driving equipment only
   95%

   c. List of pile driving equipment plus wave equation analysis
   5%

   d. Specific information regarding the driving sequence
   0%

   e. Other information specific related to pile driving criteria, please explain

   0%

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed
   0%

   b. Specified hammer energy included in specifications
   95%

   c. Evaluate using a pile driving formula (please specify which formula is used)
   0%

   d. Evaluate using a wave equation analysis
   5%

   e. Other, please explain

5. Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:

a. Drive the pile to a specified tip elevation

0%

b. Drive the pile to practical refusal

75%, "Practical Refusal" is often defined according to a driving formula.

c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

95%

d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

0%

e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)

5%

f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

0%

g. A combination of both **e.** and **f.**

0%

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   75%

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   0%

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   5%

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   20%

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   0%

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

   1%

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   - 5%
   - ground conditions, project size
   - LRFD implementation is a factor affecting decision to use technology

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**

   a. Would not perform any load tests on pre-production piles
   99%

   b. Would install pre-production (probe) piles without dynamic monitoring
   0%

   c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only
   5%

   d. Would install pre-production test piles for static or rapid load testing only
   0%

   e. Would install pre-production test piles with both **c.** and **d.**
   0%

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

   When dynamic testing is not performed we typically use a driving formula, "effectively without pre-production piles.

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)
0%

b. High Strain dynamic testing with signal matching only (CAPWAP or similar)
5%

c. Static load tests only
0%

d. Rapid load tests (Statnamic or similar) only
0%

e. Combinations of the above
0%

f. Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

No

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

Typically intend to perform more dynamic testing on friction piles not driven to bedrock.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

If we use dynamic testing, we will generally test 1 to 2 piles per substructure unit and meet or exceed requirements in LRD specs.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

See #13 Signal matching generally not performed on every pile tested, but enough to meet LRFD criteria.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

Yes, if setup occurs.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

1 to 7 days depending on soil type.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

Usually leave that to the tester.

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

We have not considered doing this

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

We typically evaluate a group of test results and select a blow count and stroke that correspond to the required resistance. In some cases we have used refined wave equation analyses.

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

We have not used these methods. Although we're not adamently opposed we haven't seriously considered circumstances and frequency.

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

We would likely use static load tests on very large projects where they could result in significant cost savings and/or if we question the results of dynamic testing.

19. How are rapid or static load test results used in the development of driving criteria for production piles?

Applicable phi factors per LRFD would be used to determine the required nominal resistance.

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

Check driving stresses & pile damage.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

The applicable phi factor per LRFD specs would be used to determine the required nominal capacity.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes, Darrin Beckett, 502-564-2374 ext 293

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Chris Nickel

Title Geotechnical Engineer Manager

Agency LA. D.O.T.D.

Address 1201 Capitol Access Road, Baton Rouge, LA 70804

Email chris.nickel@la.gov

Phone 225-379-1016

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Louisiana

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   100

   b. Number of individual driven piles installed
   3,000

   c. Lineal feet of driven piles installed
   200,000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required
   0

   b. List of pile driving equipment only
   100

   c. List of pile driving equipment plus wave equation analysis
   0

   d. Specific information regarding the driving sequence
   100

   e. Other information specific related to pile driving criteria, please explain

   Load test frame and reaction system when test piles are included.

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed
   0

   b. Specified hammer energy included in specifications
   30

   c. Evaluate using a pile driving formula (please specify which formula is used)
   0

   d. Evaluate using a wave equation analysis
   70

   e. Other, please explain

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation

   0

   b. Drive the pile to practical refusal

   5

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

   60

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

   0

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)

   10

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

   30

   g. A combination of both **e.** and **f.**

   40

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   10

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   5

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   50

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   25

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   15

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

   75

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   Approximately 50% of LA DOTD driven pile projects utilize PDA to establish driving criteria. For highly competent soil conditions the Gates Dynamic formula may be used for capacity verification.

8. Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:

- **a.** Would not perform any load tests on pre-production piles

  15
- **b.** Would install pre-production (probe) piles without dynamic monitoring

  0
- **c.** Would install pre-production test piles with dynamic monitoring (PDA or similar) only

  15
- **d.** Would install pre-production test piles for static or rapid load testing only

  0
- **e.** Would install pre-production test piles with both **c.** and **d.**

  85

9. If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

- **a.** High strain dynamic testing only (PDA or similar)
  0
- **b.** High Strain dynamic testing with signal matching only (CAPWAP or similar)
  10
- **c.** Static load tests only
  10
- **d.** Rapid load tests (Statnamic or similar) only
  <1
- **e.** Combinations of the above
  90
- **f.** Other (please explain)
  A static load test is preformed on all test piles unless we determine that the applied test load will not fail the soil. PDA and signal matching (CAPWAP) are performed on all test piles.

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

If multiple pile sizes are to be used, LA DOTD may require instrumenting one size test pile (embedded strain gages). However, if the test pile is not instrumented than multiple size test piles may be required. Example: for production pile sizes 16, 24, 30 one 24" instrumented test pile will suffice. If no instrumented than a 16" and 30" test pile will be needed.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

No

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

Based on economic feasibility we determine the number of test piles.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

All high strain dynamic testing is accompanied by CAPWAP.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

In general, when the target capacity is achieved on the initial drive, restirkes are not performed. 24hour restirkes are performed on piles to verify capacity in set-up situations.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

Typically a 24hr restrike is performed; however, if ample restrike data is available/collected earlier we may allow restrikes less than 24 hours.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

Take a high energy blow. Not the first couple of blows.

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

No.

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

We perform a CAPWAP analysis and a refined GRLWEAP analysis in order to create an inspectors table.

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Very few Statnamic load tests have been performed and it is usually when very high loads are anticipated.

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

We conduct a feasibility analysis utilizing applicable soil resistance factors to determine the need for test piles. We also look a construct ability where driving conditions may be an issue.

19. How are rapid or static load test results used in the development of driving criteria for production piles?

Static load tests are generally used in determining production pile lengths. Static load tests are compared to CAPWAP results for calibration purposes.

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

We would generally restrike a few other selected production piles and make adjustments to the driving criteria as necessary.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

If a test pile is used the the appropriate resistance factors are used. this is accordance with LRFD AASHTO, which depends upon soil site variability. In general we use 0.70 and verify driving criteria/capacity with pile restrikes. When test piles are not used we design based on locally collaborated resistance factors.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes, please contact Chris Nickel at 225-379-1016

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Laura Krusinski, P.E.

Title Snr. Geotechnical Engineer

Agency MaineDOT

Address 16 State House Station, Augusta, ME, 04333-0016

Email laura.krusinski@maine.gov

Phone 207-624-3441

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Maine, statewide

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**
   - **a.** Number of projects with driven pile foundations
     25
   - **b.** Number of individual driven piles installed
     398
   - **c.** Lineal feet of driven piles installed
     23,000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**
   - **a.** No submittal required
     0
   - **b.** List of pile driving equipment only
     0
   - **c.** List of pile driving equipment plus wave equation analysis
     100%
   - **d.** Specific information regarding the driving sequence
     0
   - **e.** Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**
   - **a.** No evaluation is performed
     0
   - **b.** Specified hammer energy included in specifications
     0
   - **c.** Evaluate using a pile driving formula (please specify which formula is used)
     0
   - **d.** Evaluate using a wave equation analysis
     100%
   - **e.** Other, please explain

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation
   30

   b. Drive the pile to practical refusal
   0

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula
   0

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)
   0

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)
   100

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements
   0

   g. A combination of both **e.** and **f.**

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   80%

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   20

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   100

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   50

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

   20

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   100

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**
    - **a.** Would not perform any load tests on pre-production piles
      0
    - **b.** Would install pre-production (probe) piles without dynamic monitoring
      0
    - **c.** Would install pre-production test piles with dynamic monitoring (PDA or similar) only
      0
    - **d.** Would install pre-production test piles for static or rapid load testing only
      0
    - **e.** Would install pre-production test piles with both **c.** and **d.**
      0

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

   Drivability analysis during design stage.

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

- **a.** High strain dynamic testing only (PDA or similar)
  0
- **b.** High Strain dynamic testing with signal matching only (CAPWAP or similar)
  100
- **c.** Static load tests only
  0
- **d.** Rapid load tests (Statnamic or similar) only
  0
- **e.** Combinations of the above
  0
- **f.** Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

No. Only we tend to include provisions for restrike tests more for displacement piles, such as pipe piles.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

We include provisions for restrike tests for friction piles.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

Number of pile tests specified are a function of site subsurface variablity, level of risk, and the variability of pile types on the project.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

MaineDOT pile QC requirements are: Dynamic testing with signal matching of at least 1 pile per substructure, but not less than 2 dynamic tests from opposite corners for substructures longer than 40 feet or with more than 15 piles, and no less than 2% of the production piles at any one site, and up to 5% of the production piles for sites with moderate to highly variable subsurface conditions or an higher level of risk.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

Restrike tests are performed for to gage relaxation or setup effects in friction piles and displacement piles, and piles bearing on certain metasedimentary bedrock formations.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

24-hour minimum. 48- and 72-hour restrikes may be warranted on rare occasions.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

No.

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

Driving criteria for production piles at a particular foundation is established by the results of a dynamic test on the first production pile driven at the foundation, and may be subsequently refined by the results of the signal matching analysis. For substructures with more than 20, a third pile test is added to the QC program, and that test is conducted mid-production after approximately one half of the piles have been installed.

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

In the past 15 years, we included provisions for static load tests on one pile high-risk foundation project in case anomolies in test results from the dynamic load testing program occurred.

19. How are rapid or static load test results used in the development of driving criteria for production piles?

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

Pile driving logs are maintained.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

We typically employ a resistance factor of 0.65 considering our standard of practice is to require dynamic testing with signal matching.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes. Laura Krusinski

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Jeff Robert

Title Project Manager

Agency Maryland State Highway Administration - Office of Structures

Address 707 N. Calvert St., Baltimore, MD 21202

Email jrobert@sha.state.md.us

Phone 410-545-8327

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Maryland

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
      8
   b. Number of individual driven piles installed
      650
   c. Lineal feet of driven piles installed
      25,000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required
      0%
   b. List of pile driving equipment only
      90%
   c. List of pile driving equipment plus wave equation analysis
      10%
   d. Specific information regarding the driving sequence
      0%
   e. Other information specific related to pile driving criteria, please explain

      0%

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed
      0%
   b. Specified hammer energy included in specifications
      100%
   c. Evaluate using a pile driving formula (please specify which formula is used)
      0%
   d. Evaluate using a wave equation analysis
      10%
   e. Other, please explain

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation
   0%

   b. Drive the pile to practical refusal
   0%

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula
   90%

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)
   0%

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)
   10%

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements
   0%

   g. A combination of both **e.** and **f.**
   0%

6. Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:

- **a.** Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer
  95%
- **b.** Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance
  0%
- **c.** Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location
  0%
- **d.** Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive
  5%
- **e.** Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance
  0%
- **f.** Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive
  0%

7. Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).

10% - This is used for bridges that use large piles (>18" diameter) installed as friction piles or for projects with a large volume of friction piles where the increased cost of PDA can be justified. For bridges with a small amount of LF of piling, we find it cheaper and quicker to take a conservative approach and install additional piling rather than performing testing.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**

   a. Would not perform any load tests on pre-production piles
   98%

   b. Would install pre-production (probe) piles without dynamic monitoring
   0%

   c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only
   2%

   d. Would install pre-production test piles for static or rapid load testing only
   0%

   e. Would install pre-production test piles with both **c.** and **d.**
   0%

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

   Our typical procedure is to use the first production pile in a substructure unit as the test pile. This test pile is used primarily for estimating pile lengths for ordering correct pile lengths. The test pile and all production piles are driven to a designated capacity verified by a pile driving formula.

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

Our agency does not use dynamic monitoring frequently; however, I have responded to the following questions based on our limited use.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)
0%

b. High Strain dynamic testing with signal matching only (CAPWAP or similar)
2%

c. Static load tests only
0%

d. Rapid load tests (Statnamic or similar) only
0%

e. Combinations of the above
0%

f. Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

No, typically 2 or 3 piles are designated at each substructure unit.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

We would not use high strain dynamic testing for end bearing piles.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

No.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

This type of testing is used for bridges utilizing large piles (>18" diameter) or projects involving a large volume of piles where our level of certainty of estimated pile capacity is low due to poor soil conditions. Signal matching would be performed in all cases that dynamic monitoring is used.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

Yes, soil conditions dictate if restrikes will be performed. If we believe increases in capacity will be seen over time, we will perform restrikes.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

48 hours

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

None.

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

No.

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

Once capacity is achieved with a test pile, production piles are driven to match the test pile. If capacity of a production pile is suspect, a restrike with dynamic monitoring will be performed.

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Rapid load testing is not used.

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Very rare situation - on special bridges only

19. How are rapid or static load test results used in the development of driving criteria for production piles?

There is no established procedure since it is rarely performed.

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

None.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

We follow the guidelines set forth in AASHTO. Increased testing would raise the resistance factor.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes, Jeff Robert (410-545-8327)

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Peter J Connors

Title Geotechnical Engineer

Agency MASSDOT

Address 10 Park Plaza, Boston, MA 02116

Email Peter.connors@state.ma.us

Phone

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Massachusetts

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
      10-15

   b. Number of individual driven piles installed
      500

   c. Lineal feet of driven piles installed
      25500

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required
      0

   b. List of pile driving equipment only
      0

   c. List of pile driving equipment plus wave equation analysis
      90

   d. Specific information regarding the driving sequence
      10

   e. Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed
      0

   b. Specified hammer energy included in specifications
      1

   c. Evaluate using a pile driving formula (please specify which formula is used)
      24

   d. Evaluate using a wave equation analysis
      75

   e. Other, please explain

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation
   0%

   b. Drive the pile to practical refusal
   10%

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula
   1%

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)
   15%

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)
   64%

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements
   10% or less

   g. A combination of both **e.** and **f.**

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   0

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   0%

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   0

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   0%

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   5

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

   5

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   75

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**
   a. Would not perform any load tests on pre-production piles
   0%
   b. Would install pre-production (probe) piles without dynamic monitoring
   0
   c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only
   5
   d. Would install pre-production test piles for static or rapid load testing only
   0%
   e. Would install pre-production test piles with both **c.** and **d.**
   10%

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**
   WEAP, PDA

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)
0

b. High Strain dynamic testing with signal matching only (CAPWAP or similar)
0%

c. Static load tests only
0

d. Rapid load tests (Statnamic or similar) only
0%

e. Combinations of the above

f. Other (please explain)
WEAP + PDA 74%
WEAP+PDA+static 1%
this is broken out form question 7

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

Nothing Prescribed but it would be based upon specific project evaluation.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

Nothing Prescribed but it would be based upon specific project evaluation.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

Nothing Prescribed but it would be based upon specific project evaluation.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

Friction Piles, integrity testing
capwap on 100% of PDA based upon standard spec

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

Yes, standard spec, # days

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

48 hrs, longers setup time specified on individual basis in silt and clay

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

nothing specified

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

nothing specified, nothing specific in spec

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

Recommendations in PDA report

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

N/A

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

limited frequency, nothing Prescribed but it would be based upon specific project evaluation.

19. How are rapid or static load test results used in the development of driving criteria for production piles?

Production piles driven to criteria and/or tip similar to test pile/recommendation in SLT report. Test pile subject to WEAP and PDA

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

WEAP, PDA, SLT

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

AASHTO LRFD SPECs

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Peter J Connors

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Richard Endres

Title Supervising Engineer-Geotechnical Services Section

Agency Michigan Department of Transportation

Address P.O. Box 30049
Lansing Mi. 48909

Email endresr@michigan.gov

Phone 517-322-1207

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Michigan

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   70

   b. Number of individual driven piles installed
   3000

   c. Lineal feet of driven piles installed
   325000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required
   0

   b. List of pile driving equipment only
   90

   c. List of pile driving equipment plus wave equation analysis
   10

   d. Specific information regarding the driving sequence
   0

   e. Other information specific related to pile driving criteria, please explain

   0

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed

   b. Specified hammer energy included in specifications

   c. Evaluate using a pile driving formula (please specify which formula is used)
   90

   d. Evaluate using a wave equation analysis
   10

   e. Other, please explain

5. Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:

a. Drive the pile to a specified tip elevation

0

b. Drive the pile to practical refusal

0

c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

90

d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

0

e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)

10

f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

g. A combination of both **e.** and **f.**

1

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   99

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   0

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   1

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   Estimate 10 % of future projects to use PDA testing. PDA testing specified on projects where engineers estimate for piling pay item is over $300000.00

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**
   - **a.** Would not perform any load tests on pre-production piles
   - **b.** Would install pre-production (probe) piles without dynamic monitoring

     90
   - **c.** Would install pre-production test piles with dynamic monitoring (PDA or similar) only

     10
   - **d.** Would install pre-production test piles for static or rapid load testing only

     0
   - **e.** Would install pre-production test piles with both **c.** and **d.**

     1

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

   We use test pile program.

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

- **a.** High strain dynamic testing only (PDA or similar)
  10
- **b.** High Strain dynamic testing with signal matching only (CAPWAP or similar)
  10
- **c.** Static load tests only
  1
- **d.** Rapid load tests (Statnamic or similar) only
  0
- **e.** Combinations of the above
  10
- **f.** Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

No

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

No

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

Yes- PDA testing with signal matching specified on projects where engineers estimate for piling pay item is over $300000.00

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

Signal matching specified on all PDA projects.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

Typically restrike is avoided unless piles are in silts and/or silty clays. Restrike is problematic due to scheduling and production issues.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

48 hrs is specified.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

First 3 inches of restrike drive using a hammer warmed up on a pile at least 25 feet away.

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

no

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

Refined GRLWeap

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Don't use rapid load testing.

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Case by case based on soil conditions and $ value of the pile to be installed.

19. How are rapid or static load test results used in the development of driving criteria for production piles?

Pile set is measured at end of drive on load test pile. Load test capacity is correlated to pile set.

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

Saximeter is used to monitor hammer performance and count blows.

Estimated pile length from static analysis is shown on closest boring log.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

Resistance factor used for determination of factored pile capacity is selected based on quality control methods specified for construction.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes-Contact Ryan Snook (Foundation Analysis Engineer)

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Paul Rowekamp

Title Bridge Standards Engineer

Agency Minnesota DOT

Address Minnesota DOT Bridge Office
3485 Hadley Ave North
Oakdale, MN 55128

Email paul.rowekamp@state.mn.us

Phone 651-366-4484

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Minnesota

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   50

   b. Number of individual driven piles installed
   1700

   c. Lineal feet of driven piles installed
   115,000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required

   b. List of pile driving equipment only
   10%

   c. List of pile driving equipment plus wave equation analysis
   90%

   d. Specific information regarding the driving sequence

   e. Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed

   b. Specified hammer energy included in specifications
   5%

   c. Evaluate using a pile driving formula (please specify which formula is used)
   10%

   d. Evaluate using a wave equation analysis
   85%

   e. Other, please explain

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation
   5%

   b. Drive the pile to practical refusal

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula
   75%

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)
   20%

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

   g. A combination of both **e.** and **f.**

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer
   75%

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive
   25%

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   25%
   Generally only used for test piles
   Factors:
   Capacity - lower or higher than typical
   If high energy hammers are expected to be used
   Questionable soils (unsure where & how bearing to expect)
   Expect significant set-up
   Generally don't test H piles (end bearing piles) w/ the PDA

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**
   - **a.** Would not perform any load tests on pre-production piles
   - **b.** Would install pre-production (probe) piles without dynamic monitoring
     test piles (not probe piles) w/o dynamic monitoring 75%
   - **c.** Would install pre-production test piles with dynamic monitoring (PDA or similar) only
     25%
   - **d.** Would install pre-production test piles for static or rapid load testing only
   - **e.** Would install pre-production test piles with both **c.** and **d.**

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

   We use test piles

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)

b. High Strain dynamic testing with signal matching only (CAPWAP or similar)
25%

c. Static load tests only
2%

d. Rapid load tests (Statnamic or similar) only
Have only used on one project, but will use in the future.

e. Combinations of the above

f. Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

Yes - usually don't use PDA for end bearing (H piles)

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

Yes - see question #7, questionable soils, expect significant set-up, don't use PDA for end bearing piles.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

More likely to use static load tests on very large projects to justify the cost and benefit from potential savings.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

We always use capwap. See #7 for when used. Generally use 1 PDA per substructure.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

About 50-60% of the time. Looking for set-up to reduce pile length.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

24 hrs for granular soils, 48 hours for cohesive soils.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

Generally 2nd or 3rd blow - by local practice, not per required specifications.

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

No

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

Always use CAPWAP
Use blowcount vs. resistance and/or PDA inspector chart

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Only used 1 time. Will consider in the future on a very limited basis.

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Very high capacity piles expected to be used.
On very large projects where we will realize savings by using a load test program.

19. How are rapid or static load test results used in the development of driving criteria for production piles?

Capacity charts and graphs developed through the testing. Penetration resistance criteria. Depth vs. EOID.

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

No specific QA process. Often compare driving formula to PDA inspector charts and vice versa.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

Currently studying this w/ Prof Sam Paikowsky. We use phi of 0.65 for PDA and phi = 0.40 for dynamic formula. Unsure of design side process.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Paul Rowekamp 651-366-4484

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Sean Ferguson

Title State Geotechnical Engineer

Agency Mississippi Dept. of Transportation

Address 412 E. Woodrow Wilson Drive, Jackson, MS, 39216

Email sferguson@mdot.state.ms.us

Phone 601-359-1795

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   State of Mississippi

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   20+

   b. Number of individual driven piles installed
   4000+

   c. Lineal feet of driven piles installed
   200,000+

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required
   0%

   b. List of pile driving equipment only
   100%

   c. List of pile driving equipment plus wave equation analysis
   Wave Equation performed in-house

   d. Specific information regarding the driving sequence
   0%

   e. Other information specific related to pile driving criteria, please explain

   0%

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed
   0%

   b. Specified hammer energy included in specifications
   20%

   c. Evaluate using a pile driving formula (please specify which formula is used)
   0%

   d. Evaluate using a wave equation analysis
   100%

   e. Other, please explain

   -

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation

   10%

   b. Drive the pile to practical refusal

   0%

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

   20-25% (Being phased out with LRFD)

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

   0%

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)

   60%+ (Will be 100% when ASD projects are complete)

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

   20%

   g. A combination of both **e.** and **f.**

   75%+

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   10%

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   10%

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   70%+

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   10-20%

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   0%

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

   0%

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   Currently approx. 60%, future 100%. As ASD projects are phased out, all future pile projects will utilize dyamic testing of "test" piles prior to establishing production pile lengths and driving criteria. This is especially important when driving steel H-piles in sand, variable soils (soft clays over/underlying sands), or where piles are driven through a thick scour zone.

   Note: MDOT's "test" piles are driven in-place and are used as production piles.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**

    a. Would not perform any load tests on pre-production piles
    75-80%

    b. Would install pre-production (probe) piles without dynamic monitoring
    0%

    c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only
    0%

    d. Would install pre-production test piles for static or rapid load testing only
    0%

    e. Would install pre-production test piles with both **c.** and **d.**
    20-25%

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

    -

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

- **a.** High strain dynamic testing only (PDA or similar)
- **b.** High Strain dynamic testing with signal matching only (CAPWAP or similar)
  80%
- **c.** Static load tests only
  0%
- **d.** Rapid load tests (Statnamic or similar) only
  0%
- **e.** Combinations of the above
  20%
- **f.** Other (please explain)

  These percentages are for pile projects where ENR alone is not used to determine pile capacity (ENR being phased out by LRFD).

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

No.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

Generally, no.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

Yes. On larger pile projects or where it's expected that substantial cost savings may be realized by reducing estimated pile lengths during test pile installation, a combination of PDA and static load tests are performed.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

Where PDA is used to verify capacity during test pile installation, all test piles are driven with PDA monitoring. CAPWAP / GRLWEAP is used on each test pile to determine capacity and pile driving criteria.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

Yes. The PDA test pile pay item includes a 1 and 7 day restrike. Often in sands, the 7 day restrike is eliminated.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

For clays and silts, the 1 and 7 day restrikes are performed.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

Generally use one of the early "high energy" blows.

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

No.

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

Driving criteria for production piles is developed based on location to the nearest test pile in similar soil conditions.

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Rarely used.

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

On larger projects or where required pile capacity was not achieved during initial drive or restrike(s).

19. How are rapid or static load test results used in the development of driving criteria for production piles?

They are used for correlating capacity results from PDA test piles.

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

Pile cushions must be replaced for each production pile, inspectors verify stroke / hammer performance.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

Where PDA with CAPWAP will be used during test pile installation a resistance factor of 0.65 is used for design.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes. You can contact me.

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Thomas W. Fennessey

Title Geotechnical Engineer

Agency Missouri Department of Transportation

Address 1617 Missouri Boulevard
Jefferson City, MO 65109

Email thomas.fennessey@modot.mo.gov

Phone

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Missouri

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   45

   b. Number of individual driven piles installed
   1400

   c. Lineal feet of driven piles installed
   70000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required

   b. List of pile driving equipment only
   90

   c. List of pile driving equipment plus wave equation analysis
   10

   d. Specific information regarding the driving sequence

   e. Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed

   b. Specified hammer energy included in specifications

   c. Evaluate using a pile driving formula (please specify which formula is used)

   d. Evaluate using a wave equation analysis
   10

   e. Other, please explain

   90 - minimum hammer energy included in specifications

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

    a. Drive the pile to a specified tip elevation

    b. Drive the pile to practical refusal

    75 - Modified Gates Verified

    c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

    15 - Modified Gates Controlled

    d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

    e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)

    10 - Modified Gates Verified

    f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

    g. A combination of both **e.** and **f.**

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   95

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   5

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   PDA would be specified on 10% of pile projects. PDA would routinely be specified on friction piles and rarely on end-bearing piles where difficult driving or highly variable depth to rock is anticipated.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**
   - **a.** Would not perform any load tests on pre-production piles
     100
   - **b.** Would install pre-production (probe) piles without dynamic monitoring
   - **c.** Would install pre-production test piles with dynamic monitoring (PDA or similar) only
   - **d.** Would install pre-production test piles for static or rapid load testing only
   - **e.** Would install pre-production test piles with both **c.** and **d.**

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

   End bearing piles to hard rock would be designed based on the structural capacity of the pile and boring information would be utilized by the construction inspectors to estimate the pile lengths anticipated during driving.

   For friction piles, we would commonly use PDA/CAPWAP on first pile driven in each substructure element to establish driving criteria for additional piles. The modified Gates formula would likely be checked as supplement to PDA. The modified Gates formula would be used if PDA was not specified.

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)

b. High Strain dynamic testing with signal matching only (CAPWAP or similar)

c. Static load tests only

d. Rapid load tests (Statnamic or similar) only

e. Combinations of the above

f. Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

19. How are rapid or static load test results used in the development of driving criteria for production piles?

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Omar Qudus

Title Geotechnical Engineer

Agency Nebraska Department of Roads

Address 1400 HWY II Lincoln NE

Email omar.qudus@nebraska.gov

Phone 402-479-4394

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Nebraska

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations

   we work in a lot of project and don't keep track of

   b. Number of individual driven piles installed

   same

   c. Lineal feet of driven piles installed

   same

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required

   b. List of pile driving equipment only

   All projects

   c. List of pile driving equipment plus wave equation analysis

   d. Specific information regarding the driving sequence

   e. Other information specific related to pile driving criteria, please explain

   we preform wave equation analysis

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed

   b. Specified hammer energy included in specifications

   c. Evaluate using a pile driving formula (please specify which formula is used)

   d. Evaluate using a wave equation analysis

   All projects

   e. Other, please explain

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation

   b. Drive the pile to practical refusal

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula
   All projects

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)
   if we specify test piles on the project.

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

   g. A combination of both **e.** and **f.**

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   All projects

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   Historically about 10% of projects, however with the implementation of LRFD will test more piles

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**

   a. Would not perform any load tests on pre-production piles

   Never done any

   b. Would install pre-production (probe) piles without dynamic monitoring

   c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only

   d. Would install pre-production test piles for static or rapid load testing only

   e. Would install pre-production test piles with both **c.** and **d.**

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

   if we do not specify test pile, then we use NDOR modified ENR formula.

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)

b. High Strain dynamic testing with signal matching only (CAPWAP or similar)
10%

c. Static load tests only

d. Rapid load tests (Statnamic or similar) only

e. Combinations of the above

f. Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

No our decision for test piles are based on the size of the bridge

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

No

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

yes, it is based on the number of piles on each substructure.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

if test pile program was specified then we use PDA and CAPWAP measurement for at least one pile per substructures.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

it will be based on the soil type

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

36 Hours

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

Average 10 blows

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

No

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

we adjust ENR formula accordingly

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

We have not used it.

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

we have not used static load test in the past 25 years

19. How are rapid or static load test results used in the development of driving criteria for production piles?

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

if bearing is not achieved than we use combination of ENR and PDA

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

we adjusted ENR formula to use the same resistance factor.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

yes

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name J. Mark Salazar

Title Chief Geotechnical Engineer

Agency Nevada Dept of Transportation

Address Materials Division
1263 South Stewart Street
Carson City, Nevada 89712

Email msalazar@dot.state.nv.us

Phone 775.888.7875

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Nevada

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**
   a. Number of projects with driven pile foundations
      1 or less
   b. Number of individual driven piles installed
      20 or less
   c. Lineal feet of driven piles installed
      less than 800'

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**
   a. No submittal required
      0%
   b. List of pile driving equipment only
      0%
   c. List of pile driving equipment plus wave equation analysis
      100%
   d. Specific information regarding the driving sequence
      0% (governed by our standard specs)
   e. Other information specific related to pile driving criteria, please explain
      0%

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**
   a. No evaluation is performed
      0%
   b. Specified hammer energy included in specifications
      100%
   c. Evaluate using a pile driving formula (please specify which formula is used)
      0%
   d. Evaluate using a wave equation analysis
      100%
   e. Other, please explain

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation
   100% also must meet required blow count

   b. Drive the pile to practical refusal
   0%

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula
   0%

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)
   100% also must meet tip elevation requirements

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)
   90%

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements
   <10%

   g. A combination of both **e.** and **f.**
   < 5 %

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

      0 %

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

      0%

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

      0%

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

      100%

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

      0%

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

      100%. Restrikes done at all substructures.

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   100%. NDOT requires that PDA, pile restrikes, and CAPWAP be utilized at each foundation location (piers and abutments) to confirm pile capacity. Information gained through this process is used to establish final pile driving criteria.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**

   a. Would not perform any load tests on pre-production piles
      0% NDOT doesn't use probe piles
   b. Would install pre-production (probe) piles without dynamic monitoring
      0%
   c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only
      0%
   d. Would install pre-production test piles for static or rapid load testing only
      0%
   e. Would install pre-production test piles with both **c.** and **d.**
      0%

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

   1. Site specific geotechnical investigation
   2. AASHTO static pile capacity established to develop minimum and maximum pile tip elevations, and estimated maximum driving resistance.
   3. In house WEAP done to confirm equipment availability and pile driveablility.
   4. Maximum anticipated driving resistance provided to Contractor in Geotech Report and Plans.
   5. Require Contractor to submit all proposed driving equipment along with independent WEAP showing his equipment is appropriate for approval.
   6. Require PDA, CAPWAP, and restrikes at each substructure support location to verify pile capacity versus dynamic EOD blow counts.
   7. Final pile driving criteria is based upon the results of these test for each substructure unit (pier, abutment).

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

- **a.** High strain dynamic testing only (PDA or similar)
  0%
- **b.** High Strain dynamic testing with signal matching only (CAPWAP or similar)
  99%
- **c.** Static load tests only
  0%
- **d.** Rapid load tests (Statnamic or similar) only
  0%
- **e.** Combinations of the above
  <10%
- **f.** Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

No.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

No.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

No not typically. However, rarely we have waved PDA testing at sites where NDOT is widening existing structures that have performed well if similar foundation types are being used.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

We typically use PDA and CAPWAP on every pile driving project at a minimum rate of 1 test per substructure unit.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

Yes. Typically required for all projects.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

24 hours unless otherwise specified by Geotech Engineer. Longer times may be specified for clayey soils.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

Warm up hammer on different pile a minimum of 20 blows. Drive pile with a maximum of 15 blows when PDA/load testing isn't required (In the past PDA wasn't required so this spec is old since we now require PDA and CAPWAP for all projects). When PDA is used the maximum penetration allowed during a restrike is 6 inches or 50 blows, whichever occurs first.

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

No not that I'm aware of.

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

PDA and CAPWAP are required for all project at a rate of one per substructure unit. If it is determined that the specified ultimate pile capacity is attained for each pile that is restruck, then the remaining piles in that bent will be considered satisfactory when driven to at least the same penetrations and EOD resistance as the restruck piles.

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Rapid load testing has not been used at NDOT as far as I know.

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

NDOT used to use static load testing commonly to confirm driven pile capacities (up to the early 1990's). We very rarely use them now. PDA, CAPWAP, and restrikes is our current standard.

19. How are rapid or static load test results used in the development of driving criteria for production piles?

In the past static load tests results would be correlated to EOD blow counts to establish final driving criteria on a project by project basis.

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

1. We inspect the pile driving equipment to make sure it is in good condition and matches the Contractor's submittals.
2. We conduct in house WEAP runs to insure the pile is drivable with commonly available pile hammers and require the Contractor to submit an independent WEAP that shows his equipment is appropriate.
3. We have construction inspectors on the job to verify that proper equipment and procedures are followed, to inspect the pile heads, alignments, and interior condition in pipe piles. We provide inspectors information regarding minimum and maximum pile tip elevations as well as a target blow counts to reach the design capacities and or to limit driving stresses.
4. We require CAPWAP and restrikes at every substructure location to verify dynamic EOD criteria. Initial driving criteria will be modified using this information if necessary.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

NDOT follows current AASHTO's LRFD guidelines regarding the choice of resistance factors.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Sure. Contact Mark Salazar at 775.888.7875

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Thomas F. Cleary

Title Soils Engineer

Agency NHDOT - Materials and Research Bureau

Address PO Box 483
Concord, NH 03302

Email tcleary@dot.state.nh.us

Phone (603) 271-1654

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   New Hampshire

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
      10
   b. Number of individual driven piles installed
      1000
   c. Lineal feet of driven piles installed
      50,000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required
      0
   b. List of pile driving equipment only
      100
   c. List of pile driving equipment plus wave equation analysis
      0
   d. Specific information regarding the driving sequence
      0
   e. Other information specific related to pile driving criteria, please explain
      100 - pile splice and pile point details, preboring details (if req'd)

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed
      0
   b. Specified hammer energy included in specifications
      5
   c. Evaluate using a pile driving formula (please specify which formula is used)
      0
   d. Evaluate using a wave equation analysis
      100
   e. Other, please explain

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation

   0

   b. Drive the pile to practical refusal

   0

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

   0

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

   0

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)

   100

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

   2

   g. A combination of both **e.** and **f.**

   100

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   90

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   0

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   10

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   10

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   0

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

   0

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   100 - NHDOT has owned and operated a PDA since 1996, so it is convenient to perform PDA testing as required to provide the necessary quality control.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**

   a. Would not perform any load tests on pre-production piles

   0

   b. Would install pre-production (probe) piles without dynamic monitoring

   0

   c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only

   100

   d. Would install pre-production test piles for static or rapid load testing only

   2

   e. Would install pre-production test piles with both **c.** and **d.**

   100

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

   N/A

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)
100

b. High Strain dynamic testing with signal matching only (CAPWAP or similar)
10

c. Static load tests only
2

d. Rapid load tests (Statnamic or similar) only
0

e. Combinations of the above
100

f. Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

No

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

Yes - would use static load test if primarily a friction pile in loose to medium dense soil

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

Yes - for a small project would use a longer pile length to reach a competent end bearing strata instead of a static load test (e.g., $25K to $40K), if the overall cost is less with the longer piles.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

Typically, would conduct at least one PDA per substructure on the first pile driven within the substructure. Would use CAPWAP, if the RMX prediction is borderline in comparison to the required nominal bearing resistance (10 percent).

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

Would run restrike if did not achieve the required nominal resistance for the test piles.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

3 days for sand/silt. 7 days if clayey soils

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

use highest if data looks good, otherwise use average, or select good data points

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

No

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

Record blows per foot and blows per inch at EOD and corresponding stroke for OED for the PDA test piles. Compare this data with the WEAP analysis using the EMX recorded in the field. Then develop the driving criteria based on this information.

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

have not used

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Would be used for friction piles with limited end bearing resistance. Would be one test for a particular project.

19. How are rapid or static load test results used in the development of driving criteria for production piles?

not used to date.

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

Have full time inspection to verify that the driving criteria is met, and to record installed pile length. Use PDA on test pile to verify that the pile stress is acceptable. Use saxmeter for OED for each pile to make sure that the hammer is not malfunctioning. Inspector can easily request PDA testing of a questionable production pile, or if any concerns of pile damage.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

With the procedures described above (i.e., PDA testing, WEAP analysis, saxmeter, full time inspection), would generally use phi = 0.65 divided into the maximum factored load to determine the target nominal resistance for the PDA testing during the construction phase (would also add scour depth resistance, if applicable). Would use higher phi, if static load test included in the project. The design phase phi is based on the static analysis method. The static analysis is used primarily to determine an estimated pile length for bidding purposes, and to assess whether the maximum factored pile load should be limited by the nominal structural or geotechnical capacity.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name: Kuang-Yu Yang

Title: Supervising Engineer

Agency: New Jersey State Department of Transportation

Address: P.O. Box 600, 1035 Parkway Avenue Trenton NJ 08625

Email: kuangyu.yang@dot.state.nj.us

Phone:609-530-5302

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   New Jersey includes parts of two geographic provinces, the Coastal Plain and the Appalachian. The Appalachian is subdivided into the Piedmont Plateau, the Highlands, and Appalachian Valley.

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**
   - **a.** Number of projects with driven pile foundations: *10 projects*
   - **b.** Number of individual driven piles installed: *1200 piles*
   - ***c.*** Lineal feet of driven piles installed: *84,000 L.F.*

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**
   - **a.** No submittal required: N/A
   - **b.** List of pile driving equipment only: N/A
   - ***c.*** List of pile driving equipment plus wave equation analysis: *100%*
   - **d.** Specific information regarding the driving sequence: N/A
   - **e.** Other information specific related to pile driving criteria, please explain

     At least two test piles are required to be driven first for each foundation. The test piles are to be monitored with PDA w/ CAPWAP. The production pile order length and the driving criteria will be issued based on the test pile driving data and PDA/CAPWAP report. The production piles can only be driven with the same hammer used for the test piles driving.

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**
   - **a.** No evaluation is performed
   - **b.** Specified hammer energy included in specifications
   - **c.** Evaluate using a pile driving formula (please specify which formula is used)

d. Evaluate using a wave equation analysis

100%. The Contractor is required to submit WEAP for approval for each hammer that is proposed to be used.

e. Other, please explain

5. Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:

a. Drive the pile to a specified tip elevation

b. Drive the pile to practical refusal

c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)

95% of production piles driving criteria are based on the test piles driving data that are subjected to PDA/CAPWAP measurements.

f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

5% of production pile driving criteria may be based on data from static load test and PDA/CAPWAP performed to the test piles. Generally the static load test is considered for the larger size diameter piles. The larger diameter piles commonly used are 36", 48" and 54" precast prestressed concrete piles.

g. A combination of both **e.** and **f.**

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   100%. Generally restrike is performed on the test piles that do not reach the resistance at the anticipated tip elevation. Restrike is to be monitored with PDA/CAPWAP to assure the increased resistance through setup. The production driving criteria will be based on driving resistance blow count obtained from the test piles. Additional restrikes will be performed for those production piles that do not reach required blow count.

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   PDA/CAPWAP monitoring is required for all test piles. Test piles are the index piles and at least two piles are required for each piled foundation. Test piles are to be driven first prior to issuing the order length and driving criteria for the production piles.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**

   a. Would not perform any load tests on pre-production piles

   b. Would install pre-production (probe) piles without dynamic monitoring

   c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only

   d. Would install pre-production test piles for static or rapid load testing only

   e. Would install pre-production test piles with both **c.** and **d.**

   See item#5 &7. Test piles monitored with PDA/CAPWAP are required for all piled foundations. Additionally, 5% of test piles may be subjected to static load test due to size of pile diameter (36" or larger)

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

   N/A

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)

b. High Strain dynamic testing with signal matching only (CAPWAP or similar)

100%

c. Static load tests only

d. Rapid load tests (Statnamic or similar) only

e. Combinations of the above

f. Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

Generally all test piles are monitored with PDA/CAPWAP. Additional static load test may be performed for those larger size diameter piles.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

PDA/CAPWAP will be always required. Increased number of test piles and addition tests may be adjusted based on site condition and pile size.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

I would not think economic/project size would be reasons to modify the test pile requirement.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

PDA and CAPWAP are always required for each test pile.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

Restrike is performed for the test pile that does not reach the required resistance at the estimated pile tip elevation. Programmed restrike may arise to realize potential setup benefits.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

Normally 24 hours wait is minimum required. A loner period, e.g . 7 days has been practiced.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

Highest resistance is selected. Restrike is to terminate when capacity is reached, when amount of penetration reaches 6 inches, or when the total number of hammer blows reaches 50, whichever occurs first.

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

Generally this practice is considered for those larger size diameter piles. The base resistance from EOD and the skin resistance from restrike may be used to assess the overall resistance.

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

The profile PDA data, CAPAWP capacity, and associated blow count are used to determine the required pile driving.

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Load test, STN has not been used for the bridge foundations. However, STN has been used to verify the capacity for vibro concrete columns and controlled modulus columns that support the embankment.

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Mainly for the larger diameter piles.

19. How are rapid or static load test results used in the development of driving criteria for production piles?

The data resulted from the static load test, PDA/CAPWAP tests, and blow count recorded for the test piles are used to determine the driving criteria.

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

Generally the required blow count is to observe for a required penetration. The criteria will also describe the hammer setting that was used for the test pile driving. Th e inspector is to assure that hammer is been operated normally as per manufacturer's specification.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

The resistance factor of 0.65 is normally selected. Our piled foundation required subsurface exploration (boring and/or CPT), site condition analysis for design parameters, pile resistance calculation for the estimated length(tip elevation) , driveability analysis, WEAP analysis for the selected hammer, test pile driving with PDA/CAPWAP measurements.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes.

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name RECTOR, EDWARD

Title GEOTECH DESIGN UNIT MANAGER

Agency NMDOT

Address POB 1149, SANTA FE, NM 87501

Email EDWARD.RECTOR@STATE.NM.US

Phone 505 827-5211

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   STATE OF NEW MEXICO

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**
   a. Number of projects with driven pile foundations → 10

   b. Number of individual driven piles installed → 300

   c. Lineal feet of driven piles installed 18,000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**
   a. No submittal required

   b. List of pile driving equipment only 100 %

   c. List of pile driving equipment plus wave equation analysis

   d. Specific information regarding the driving sequence

   e. Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**
   a. No evaluation is performed

   b. Specified hammer energy included in specifications 100 %

   c. Evaluate using a pile driving formula (please specify which formula is used)

   d. Evaluate using a wave equation analysis 100 %

   e. Other, please explain PILE DYNAMIC TESTING 50%

5. Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:

a. Drive the pile to a specified tip elevation 13 %

b. Drive the pile to practical refusal 12 %

c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar) 25%

e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device) 50 %

f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

g. A combination of both **e.** and **f.**

6. Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:

10% a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

25% c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

65% d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

7. Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).

50% – BASED ON SOIL CONDITIONS at DEPTH WHERE NO THERE IS NO DEFINE BOTTOM & WHERE the # OF PILES IS SIGNIFICANT => (50 PLUS W/ LENGTHS IN THE 60'–90' LENGTH.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**

   a. Would not perform any load tests on pre-production piles

   b. Would install pre-production (probe) piles without dynamic monitoring

   c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only

   d. Would install pre-production test piles for static or rapid load testing only

   e. Would install pre-production test piles with both **c.** and **d.**

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

N/A

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

- **a.** High strain dynamic testing only (PDA or similar) 25%
- **b.** High Strain dynamic testing with signal matching only (CAPWAP or similar) 25%
- **c.** Static load tests only 1%
- **d.** Rapid load tests (Statnamic or similar) only
- **e.** Combinations of the above
- **f.** Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

No

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

No

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

(Soil Type & Moisture/H_2O Level, Clay Layers

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)? Use 24 hrs ⟶ 4 days depending on clay type, PI/ H_2O Level

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

1st 10 blows, Pick good strike, good Record

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

We have not done so, but might consider

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

CREATE A WEAP CHART FOR OTHER PILE

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

N/A

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

1 test PER SOIL type, WITH PROJECTS W/ LARGE Number of PILES, & W/ LONG LENGTHS. -> (80' - 100')

19. How are rapid or static load test results used in the development of driving criteria for production piles?

RUN a PDA TEST IN CONJUNCTION, & MATCH to CAPWAP.

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

NONE

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

BASED ON the LRFD CRITERIA, DESIGN PROCEDURES

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

BOB MEYERS 505-8275466 W
490-2619 C

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Stephen Borg

Title CE II

Agency New York State Department of Transportation

Address Geotechnical Engineering Bureau
50 Wolf Road Albany N.Y. 12232

Email sborg@dot.state.ny.us

Phone (518) 457-4770

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   New York State

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**
   - **a.** Number of projects with driven pile foundations
     40
   - **b.** Number of individual driven piles installed
     Difficult number to estimate
   - **c.** Lineal feet of driven piles installed
     164000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**
   - **a.** No submittal required
     0%
   - **b.** List of pile driving equipment only
     96%
   - **c.** List of pile driving equipment plus wave equation analysis
     0%
   - **d.** Specific information regarding the driving sequence
     2%
   - **e.** Other information specific related to pile driving criteria, please explain
     2% (Jetting criteria for prestressed concrete piles)

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**
   - **a.** No evaluation is performed
     0%
   - **b.** Specified hammer energy included in specifications
     0%
   - **c.** Evaluate using a pile driving formula (please specify which formula is used)
     0%
   - **d.** Evaluate using a wave equation analysis
     100%
   - **e.** Other, please explain

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation
   3%

   b. Drive the pile to practical refusal
   35% (Use WEAP for stresses)

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula
   0%

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)
   40%

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)
   20%

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements
   0%

   g. A combination of both **e.** and **f.**
   2%

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer
   40%

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance
   0%

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location
   8%

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive
   50%

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance
   0%

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive
   2%

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   20% - Usually for friction piles with where the amount of end bearing capacity is hard to predict, on prestressed concrete piles to evaluate tension stresses and H-piles in sands and gravels where the pile length has a tendency to run longer than predicted.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**
   - **a.** Would not perform any load tests on pre-production piles
     96%
   - **b.** Would install pre-production (probe) piles without dynamic monitoring
     0%
   - **c.** Would install pre-production test piles with dynamic monitoring (PDA or similar) only
     2%
   - **d.** Would install pre-production test piles for static or rapid load testing only
     0%
   - **e.** Would install pre-production test piles with both **c.** and **d.**
     2%

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

   We rarely have used test programs during the design stage of the project in fact I can only think of one project where we did this. During construction we will do dynamic pile testing on selected projects usually one pile per substructure and on all other projects WEAP is used exclusively.

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)
0%

b. High Strain dynamic testing with signal matching only (CAPWAP or similar)
20%

c. Static load tests only
0%

d. Rapid load tests (Statnamic or similar) only
0%

e. Combinations of the above
2%

f. Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

The typical piles to be tested are cast-in-place concrete piles where a closed end pipe is driven and the resistance is predominantly from the shaft. We also test prestressed concrete piles for capacity and driving stresses and H-piles in sands and gravels. A static pile load test would be conducted on a very large project or where an unusual pile size is used such as a 24 inch diameter cast-in-place concrete pile.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

Yes ground conditions control whether testing is to be done and the number of tests required. If pile terminated in bedrock we will not test and if there cohesive material, silts and sandy soil restrike tests with dynamic monitoring are done to determine pile set-up.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

Yes on a very large project we will use static pile load tests in combination with dynamic monitoring.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

We use dynamic pile testing on about 20% of our driven pile projects and the frequency is one test per substructure with signal matching performed on all tests.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

Restrike tests are performed on all piles with high strain dynamic testing.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

We mostly use a 24 hour setup period but on some projects with clayey soils we may increase that up to 72 hours.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

Take the blow with the highest energy and resistance.

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

Yes this is done on occasion where the end of initial drive end bearing is combined with the beginning of restrike shaft resistance. On very long piles we will also use superposition where shaft resistance from one blow is combined with another.

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

If the required resistance is achieved on the selected test pile the blow count at that resistance is used on the production piles.

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

We do not use rapid load testing.

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

It will be used on very large projects and one test will be performed.

19. How are rapid or static load test results used in the development of driving criteria for production piles?

The static load test results are used to correlate the dynamic measurements. If the test results correlate additional dynamic monitoring is used to develop blow count criteria at other locations.

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

The hammer stroke or blow rate is observed. The closed-end cast-in-pace concrete pipe is visually inspected to check for water leakage or pipe damage.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

When dynamic monitoring is used we use a higher resistance factor to calculate the nominal resistance of the pile in the LRFD code. This allows us to drive the pile to a lower resistance than if only WEAP was used.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes
Stephen Borg
(518) 457-4770
sborg@dot.state.ny.us

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Njoroge Wainaina

Title State Geotechnical Engineer

Agency NCDOT Geotechnical Engineering Unit

Address 1020 Birch Ridge Drive, Raleigh, NC 27610

Email nwainaina@ncdot.gov

Phone 919-250-4088

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   North Carolina (coastal, piedmont and mountain regions)

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   180

   b. Number of individual driven piles installed
   6,000

   c. Lineal feet of driven piles installed
   250,000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required

   b. List of pile driving equipment only
   90%

   c. List of pile driving equipment plus wave equation analysis
   10% (D/B)

   d. Specific information regarding the driving sequence

   e. Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed

   b. Specified hammer energy included in specifications
   10%

   c. Evaluate using a pile driving formula (please specify which formula is used)

   d. Evaluate using a wave equation analysis
   100%

   e. Other, please explain

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation
   15%

   b. Drive the pile to practical refusal
   20%

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)
   80% (including Questions a & e)

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)
   15%

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

   g. A combination of both **e.** and **f.**

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance
   15%

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   10%.
   PDA will be utilized if -
   1. Concern about over stressing piles such as prestressed concrete piles (PCP) driving through high blow count soils or long PCP piles.
   2. Concern about achieving required resistance.

   PDA may be utilized if -
   1. Special piles such as composite piles (steel H pile on bottom connected with prestressed concrete pile) are used.
   2. Piles are designed for very high resistance.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**

   a. Would not perform any load tests on pre-production piles

   b. Would install pre-production (probe) piles without dynamic monitoring

   c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only

   one every other year

   d. Would install pre-production test piles for static or rapid load testing only

   e. Would install pre-production test piles with both **c.** and **d.**

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

   1. Wave equation is used to establish driving criteria for all production piles.
   2. PDA is used along with wave equation to establish driving criteria for approximately 10% of all production piles.

   Currently, no additional procedures other than those stated above are used to establish production pile driving criteria.

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)

b. High Strain dynamic testing with signal matching only (CAPWAP or similar)
10%

c. Static load tests only

d. Rapid load tests (Statnamic or similar) only

e. Combinations of the above

f. Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

No. But, if necessary, Engineer can make modifications.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

No. But, if necessary, Engineer can make modifications.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

No. But, if necessary, Engineer can make modifications.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

1. NCDOT will utilize PDA tests under the situations as indicated in the previous responses.

2. NCDOT always uses CAPWAP analysis with PDA tests.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

Restrike is used if we don't get the required resistance from the initial driving.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

Waiting time is varied depending upon field conditions.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

Take the highest resistance.

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

No.

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

We determine skin and toe quake and damping; use those factors for wave equation analysis to establish driving criteria.

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

NCDOT does not use rapid load testing on piles.

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

N/A.

19. How are rapid or static load test results used in the development of driving criteria for production piles?

N/A.

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

NCDOT Geotechnical's Operations Engineer will provide services if any one of the the following situations happen:
1. minimum tip elevation not achieved,
2. estimated pile length not achieved,
3. piles out of locations,
4. piles damaged during driving,
5. hammer is not working right,
6. pile driving encountered obstructions, and
7. other situations to be resolved.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

1. A higher resistance factor will be used if PDA testing is recommended and AASHTO requirement are met.

2. A higher resistance factor will not be used if PDA testing is recommended but AASHTO requirement are not met.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Chris Chen (phone: 919-250-4088)

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Jon Ketterling

Title Geotechnical Engineer

Agency North Dakota Department of Transportation

Address Materials & Research Division
300 Airport Road
Bismarck, ND 58504

Email jketterl@nd.gov

Phone 701-328-6908

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   North Dakota

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   10

   b. Number of individual driven piles installed
   600

   c. Lineal feet of driven piles installed
   48,000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required
   0

   b. List of pile driving equipment only
   100

   c. List of pile driving equipment plus wave equation analysis
   3

   d. Specific information regarding the driving sequence
   3

   e. Other information specific related to pile driving criteria, please explain

   3

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed
   0

   b. Specified hammer energy included in specifications
   100

   c. Evaluate using a pile driving formula (please specify which formula is used)
   97 Modified Engineering News

   d. Evaluate using a wave equation analysis
   3

   e. Other, please explain

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation

   0

   b. Drive the pile to practical refusal

   97

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

   97

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

   0

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)

   3

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

   0

   g. A combination of both **e.** and **f.**

   0

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

    a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

    97

    b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

    0

    c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

    3

    d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

    0

    e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

    0

    f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

    0

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

    3

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**
   - **a.** Would not perform any load tests on pre-production piles
     100
   - **b.** Would install pre-production (probe) piles without dynamic monitoring
     0
   - **c.** Would install pre-production test piles with dynamic monitoring (PDA or similar) only
     3
   - **d.** Would install pre-production test piles for static or rapid load testing only
     0
   - **e.** Would install pre-production test piles with both **c.** and **d.**
     0

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

   We don't

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)

b. High Strain dynamic testing with signal matching only (CAPWAP or similar)

c. Static load tests only

d. Rapid load tests (Statnamic or similar) only

e. Combinations of the above

f. Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

19. How are rapid or static load test results used in the development of driving criteria for production piles?

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Jawdat Siddiqi, P.E

Title Assistant Administrator/Foundation Engineer

Agency Ohio Department of Transportation

Address 1980 West Broad St. Columbus, Ohio 43223

Email Jawdat.Siddiqi@dot.state.oh.us

Phone 614-728-2057

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Ohio

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**
   - **a.** Number of projects with driven pile foundations
     70
   - **b.** Number of individual driven piles installed
     10,000
   - **c.** Lineal feet of driven piles installed
     400,000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**
   - **a.** No submittal required
   - **b.** List of pile driving equipment only
     100%
   - **c.** List of pile driving equipment plus wave equation analysis
   - **d.** Specific information regarding the driving sequence
   - **e.** Other information specific related to pile driving criteria, please explain
     Min. of 30 Blows/ft. for Hammer Selection

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**
   - **a.** No evaluation is performed
     100%
   - **b.** Specified hammer energy included in specifications
   - **c.** Evaluate using a pile driving formula (please specify which formula is used)
   - **d.** Evaluate using a wave equation analysis
   - **e.** Other, please explain

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation
   1%

   b. Drive the pile to practical refusal
   10%

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)
   89%

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

   g. A combination of both **e.** and **f.**

6. Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:

a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

g. Restrike dynamic testing is specified only when a static Load test is being performed.

7. Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).

100% of friction piles being driven to a specified resistance. Dynamic testing of piles being driven to refusal is not required.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**

   a. Would not perform any load tests on pre-production piles
   100%

   b. Would install pre-production (probe) piles without dynamic monitoring

   c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only

   d. Would install pre-production test piles for static or rapid load testing only

   e. Would install pre-production test piles with both **c.** and **d.**

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

   None

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

- **a.** High strain dynamic testing only (PDA or similar)
  89%
- **b.** High Strain dynamic testing with signal matching only (CAPWAP or similar)
  45%
- **c.** Static load tests only
- **d.** Rapid load tests (Statnamic or similar) only
- **e.** Combinations of the above
  5% (Static , Dynamic and Restrike Load test
- **f.** Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

H-Piles driven to refusal on bedrock are not tested using high strain measurements and are not tested using static load test method.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

End bearing vs. friction piles

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

Static load test is only performed when the estimated pile length exceeds 10,000 linear foot on a specific project.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

- Pile size
- Ultimate bearing value

signal matching is done 50% of the dynamic tests performed

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

Only if static load test is being specified

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

7 days

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

specific blow data from the first 5 blows

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

No

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

Number of blows per ft. and minimum stroke of the hammer

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Quick static load test is generally accepted method by the department.

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Static load test is only performed when the estimated pile length exceeds 10,000 linear foot on a specific project.

19. How are rapid or static load test results used in the development of driving criteria for production piles?

Static load test results are only used as a verifications of pile capacity. Driving Criteria is based on dynamic measurements. Restrike data is used as further verification of static load test data.

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

Training of construction personnel

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

Ohio DOT has established resistance factor of 0.7 for friction piles which is not subject to revision on project bases.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes,

Jawdat Siddiqi, P.E.
Assistant Administrator/Foundation Engineer
Office of Structural Engineering, Ohio Department of Transportation
Ph.: 614-728-2057 Fax.: 614-752-4824

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Jan Six

Title Senior Geotechnical Engineer

Agency Oregon DOT

Address 355 Capitol St NE, Room 301
Salem, Oregon 97301

Email jan.l.six@odot.state.or.us

Phone 503-986-3377

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Oregon (state-owned bridges only)

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**
   a. Number of projects with driven pile foundations
      31
   b. Number of individual driven piles installed
      1100
   c. Lineal feet of driven piles installed
      59000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**
   a. No submittal required
   b. List of pile driving equipment only
      30
   c. List of pile driving equipment plus wave equation analysis
      70
   d. Specific information regarding the driving sequence
   e. Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**
   a. No evaluation is performed
   b. Specified hammer energy included in specifications
   c. Evaluate using a pile driving formula (please specify which formula is used)
   d. Evaluate using a wave equation analysis
   e. Other, please explain

      The method for determining the suitability of hammers depends on the method being used to determine bearing. Either dynamic formula (FHWA Gates), Wave Equation or PDA/CAPWAP are typically used. If dynamic formula is specified then a range of hammer energies is provided to the contractor in the contract specifications to evaluate hammer acceptance for a given bearing resistance. This is about 25% of total annual pile driving projects. If wave equation is used to determine bearing, the contractor does the WEAP analysis using specified soil input values to evaluate and submit hammers for use that meet specified driving stress and resistance criteria (about 70% of pile projects). Hammer acceptance based on PDA/CAPWAP is determined based on preliminary WEAP analysis and verified in the field using measured data (about 5% of projects).

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**
    - **a.** Drive the pile to a specified tip elevation
    - **b.** Drive the pile to practical refusal
    - **c.** Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula
      25
    - **d.** Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)
      70
    - **e.** Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)
      5
    - **f.** Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements
    - **g.** A combination of both **e.** and **f.**

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

   g. Restrike dynamic testing is specified only when a static Load test is being performed.

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   100% of friction piles being driven to a specified resistance. Dynamic testing of piles being driven to refusal is not required.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**

   a. Would not perform any load tests on pre-production piles

   b. Would install pre-production (probe) piles without dynamic monitoring

   c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only

   d. Would install pre-production test piles for static or rapid load testing only

   e. Would install pre-production test piles with both **c.** and **d.**
   Would utilize this option, <1%

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

   Standard criteria requires all piles to be driven to a minimum tip elevation and a required bearing resistance based on either dynamic formula, wave equation analysis or PDA/CAPWAP. Full scale static load tests are rarely performed. See answer to question 4 regarding criteria used to determine bearing resistance of production piles.

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)
0

b. High Strain dynamic testing with signal matching only (CAPWAP or similar)
<5

c. Static load tests only
0

d. Rapid load tests (Statnamic or similar) only
0

e. Combinations of the above

f. Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

No

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

The number of dynamic test piles will vary depending on the uniformity of the soil conditions at a given bridge site. Soil "zones" with uniform, similar soil conditions and properties are defined along the length of the bridge. Uniformity is determined by compiling information on the subsurface material properties (insitu and lab testing) combined with engineering judgement. At least one PDA/CAPWAP test is performed in each zone.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

Dynamic testing is typically not performed unless economically justified (with some exceptions). A project with a large number of friction piles (especially high capacity piles) may benefit from dynamic testing which would lead to more accurate estimated resistances (pile lengths required) and allow the use of a higher resistance factor. The number of tests is typically not altered based on economics once it is determined that dynamic testing is economically reasonable or justified in the first place. The number of tests is a function of the size of the project, (generally the larger the project the more tests, even under relatively uniform soil conditions).

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

PDA/CAPWAP the first production pile driven in each Pile Zone (as defined by uniformity of soil conditions). Restrikes may be required depending on ground conditions. A Pile Zone may be a single bent or multiple bents depending on soil uniformity and judgement. Additional dynamic testing may be performed on other production piles in a given zone depending on the consistency of driving resistances observed during installation. CAPWAP is always performed in conjunction with PDA testing unless the concern is just about pile damage or hammer performance during the project.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

If there is a concern for relaxation restrikes are performed. If pile setup is required, piles are driven to a specified tip elevation, allowed to set for a specified period of time, and then restruck. Standard specifications allow for a minimum 24-hour wait period before restrike and so if piles do not reach bearing there is an option to restrike if necessary.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

Standard specification allows for a minimum 24-hour set-period. This set period may be modified by special provision depending on the soil conditions, pile design and other factors.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

Generally defer to the PDA operator to take one of the blows with the highest transfer energy.

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

Yes; Toe resistance mobilized during end of initial driving may be considered for addition to the friction resistance mobilized during restrike. Sometimes the hammer is not large enough to mobilized the full end bearing (toe) resistance during restrike. However, relaxation of base resistance must be considered.

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

Hammer and soils data from the signal matching (CAPWAP) analysis is used to modify parameters in the wave equation program until key outputs of the wave equation (such as ENTHRU, stresses, blow count and stroke) match the field measured values. Once the WEAP is matched to CAPWAP the specified pile bearing resistance can be input and the required resistance and hammer stroke determined for the remaining production pile.

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

N/A

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

N/A

19. How are rapid or static load test results used in the development of driving criteria for production piles?

N/A

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

Pile hammer and equipment data sheet (form) is required to be filled out and submitted by contractor for approval prior to beginning work.

Geotechnical engineer provides pile driving criteria in the form of an inspectors graph or table to project manager's office along with the approved Hammer and Equipment Data Sheet. Inspector is on site during pile driving operations to record and document pile driving data including hammer and pile type, pile lengths, tip elevations, splices, driving resistance, hammer stroke (saximeter), restrike resistance and other data. Inspector meets with geotechnical engineer prior to start of operations to discuss pile driving criteria and any potential problems or issues that may be anticipated.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

Use the resistance factors for driven piles specified in AASHTO for the method chosen.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes, Jan Six, 503-986-3377

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Jeff Sizemore

Title Geotechnical Design Support Engineer

Agency SCDOT

Address P.O. Box 191 Columbia, SC 29202

Email sizemorejc@scdot.org

Phone 803-737-1571

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   SC

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   20

   b. Number of individual driven piles installed
   1000

   c. Lineal feet of driven piles installed
   50000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required
   0

   b. List of pile driving equipment only
   100

   c. List of pile driving equipment plus wave equation analysis
   0, WEAP completed by DOT or DOT's representative.

   d. Specific information regarding the driving sequence
   100

   e. Other information specific related to pile driving criteria, please explain
   method to determine potential hammer energy, template details, and any jetting or spudding or predrilling details if warranted

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed
   100

   b. Specified hammer energy included in specifications
   90

   c. Evaluate using a pile driving formula (please specify which formula is used)
   0

   d. Evaluate using a wave equation analysis
   100

   e. Other, please explain

   Please note that our group is in Preconstruction and the Bridge Maintenance office may use different criteria.

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation
   0
   b. Drive the pile to practical refusal
   0
   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula
   0
   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)
   70
   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)
   28
   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements
   1
   g. A combination of both **e.** and **f.**
   1

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   0

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   0

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   25

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   5

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   0

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

   0

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   We would use test piles which are also production piles on about 25% of our projects. Main reason is ground conditions and pile stresses due to high loading during driving.

8. Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:

a. Would not perform any load tests on pre-production piles

99

b. Would install pre-production (probe) piles without dynamic monitoring

0

c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only

0

d. Would install pre-production test piles for static or rapid load testing only

0

e. Would install pre-production test piles with both **c.** and **d.**

1

9. If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?

On non test pile projects, we use static analysis methods to estimate pile length and then WEAP during construction on Contractor's hammer for verification. Geotechnical Engineer is contacted if lengths vary from plan lengths.

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

- **a.** High strain dynamic testing only (PDA or similar)
  0
- **b.** High Strain dynamic testing with signal matching only (CAPWAP or similar)
  25
- **c.** Static load tests only
  0
- **d.** Rapid load tests (Statnamic or similar) only
  0
- **e.** Combinations of the above
  1
- **f.** Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

Yes, if any pile size were to exceed 36", we would do a rapid or static load test in conjunction with PDA and CAPWAP. If the pile type was differnet from our typical types we would probably do PDA/CAPWAP testing as a minimum.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

NO

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

No

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

Our frequency is based on AASHTO recommendations, and our PDA testing is always paired with signal matching.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

Yes, in clay and silt profiles

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

typically 1 day or 3-7 days, depending fines content of soils

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

usually one of the first blows with highest resistance

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

Yes, if we think the base resistance was not mobilized during restrike

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

calibration with the WEAP in accordance with AASHTO

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Economics and difficult soil conditions, frequency same as static load test in AASHTO.

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Same as # 17.

19. How are rapid or static load test results used in the development of driving criteria for production piles?

Also used in conjunction with PDA/CAWPAP/WEAP to develop criteria.

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

Hammer energy estimation using stroke or pressure control as predicted by WEAP. Unusual results are investigated by engineer.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

AASHTO resistance factors used based on method used to monitor installation.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes, Jeff Sizemore, 803-737-1571

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Dan Vockrodt

Title Foundation Engineer

Agency South Dakota Department of Transportation

Address 700 Broadway Ave. East, Pierre, South Dakota 57501

Email dan.vockrodt@state.sd.us

Phone 605.773.4466

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   South Dakota

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   15 projects

   b. Number of individual driven piles installed
   250 piles

   c. Lineal feet of driven piles installed
   12,000 linear feet

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required
   100%

   b. List of pile driving equipment only

   c. List of pile driving equipment plus wave equation analysis

   d. Specific information regarding the driving sequence

   e. Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed

   b. Specified hammer energy included in specifications

   c. Evaluate using a pile driving formula (please specify which formula is used)

   d. Evaluate using a wave equation analysis

   e. Other, please explain

   A minimum energy of the hammer is stated in the plans to use in order to drive the pile.

5. Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:

- **a.** Drive the pile to a specified tip elevation

- **b.** Drive the pile to practical refusal

- **c.** Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula
  100%

- **d.** Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

- **e.** Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)

- **f.** Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

- **g.** A combination of both **e.** and **f.**

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance
   5%

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   1%, A consultant may on occasion set up PDA on a non-state government project that the SDDOT is not involved in.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**
    - **a.** Would not perform any load tests on pre-production piles
      0%
    - **b.** Would install pre-production (probe) piles without dynamic monitoring
    - **c.** Would install pre-production test piles with dynamic monitoring (PDA or similar) only
    - **d.** Would install pre-production test piles for static or rapid load testing only
    - **e.** Would install pre-production test piles with both **c.** and **d.**

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

   SDDOT uses test piles

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)
1%

b. High Strain dynamic testing with signal matching only (CAPWAP or similar)

c. Static load tests only

d. Rapid load tests (Statnamic or similar) only

e. Combinations of the above

f. Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

No

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

No

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

No

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

None

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

None

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

None

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

None

19. How are rapid or static load test results used in the development of driving criteria for production piles?

None

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

None

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

Right now it does not.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes, Dan Vockrodt, Foundation Engineer

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Houston Walker

Title Civil Engineering Manager 2

Agency Tennessee DOT

Address 505 Deaderick St.,
1100 James K. Polk Bldg.
Nashville, TN 37243-0339

Email houston.walker@tn.gov

Phone 615-741-3351

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Tennessee

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   Not easily obtainable

   b. Number of individual driven piles installed
   Not easily obtainable

   c. Lineal feet of driven piles installed
   Approx. 183,000 (2009 amount)

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required
   50

   b. List of pile driving equipment only
   50

   c. List of pile driving equipment plus wave equation analysis
   0

   d. Specific information regarding the driving sequence
   0

   e. Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed
   50

   b. Specified hammer energy included in specifications
   50 (Minimum specified)

   c. Evaluate using a pile driving formula (please specify which formula is used)
   50 ENR

   d. Evaluate using a wave equation analysis
   0

   e. Other, please explain

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation

   0

   b. Drive the pile to practical refusal

   50

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

   0

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

   0

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)

   0

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

   50 (Min. tip elev. may be required)

   g. A combination of both **e.** and **f.**

   0

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   50

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   0

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   0

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   0

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   0

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

   0

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   We do not use PDA's.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**
   - **a.** Would not perform any load tests on pre-production piles
     50
   - **b.** Would install pre-production (probe) piles without dynamic monitoring
     0
   - **c.** Would install pre-production test piles with dynamic monitoring (PDA or similar) only
     0
   - **d.** Would install pre-production test piles for static or rapid load testing only
     50
   - **e.** Would install pre-production test piles with both **c.** and **d.**
     0

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

- **a.** High strain dynamic testing only (PDA or similar)
  0
- **b.** High Strain dynamic testing with signal matching only (CAPWAP or similar)
  0
- **c.** Static load tests only
  50
- **d.** Rapid load tests (Statnamic or similar) only
  0
- **e.** Combinations of the above
  0
- **f.** Other (please explain)
  0

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

Yes. We only use test piles and load test friction piles, which are common in about 1/3 of the state. We drive steel point bearing piles to refusal.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

Yes. As stated above we do not use any tests for point bearing steel piles. Friction piles use test piles with blow counts correlated to a static load test, usually a quick load test.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

For a long bridge with friction piles, we may use multiple load tests in order to keep all production piles no further than 500 ft from a load test.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

N/A

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

No.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

N/A

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

N/A

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

All friction pile projects use a static load test, usually one per bridge per pile size/type unless bridge is very long as mentioned in #13 above.

19. How are rapid or static load test results used in the development of driving criteria for production piles?

Static load tests are used to correlate blow counts to an actual pile bearing capacity. The required tons of bearing required is then determined.

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

None, although the load test is a proof load, if only for one pile.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

The use of a static load test in lieu of a dynamic test causes a reduced resistance factor to be used.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes. Contact Houston Walker.

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Keith Brown

Title State Geotechnical Engineer

Agency Utah Department of Transportation

Address

Email kebrown@utah.gov

Phone

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Utah

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   20

   b. Number of individual driven piles installed
   3,000

   c. Lineal feet of driven piles installed
   25,000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required
   0

   b. List of pile driving equipment only
   0

   c. List of pile driving equipment plus wave equation analysis
   100

   d. Specific information regarding the driving sequence
   0

   e. Other information specific related to pile driving criteria, please explain

   none

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed
   0

   b. Specified hammer energy included in specifications
   100 (minimum hammer energy specified in plans)

   c. Evaluate using a pile driving formula (please specify which formula is used)
   0

   d. Evaluate using a wave equation analysis
   100

   e. Other, please explain

   none

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation

   0

   b. Drive the pile to practical refusal

   0

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

   0

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

   2

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)

   94

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

   0

   g. A combination of both **e.** and **f.**

   4

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   10

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   0

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   0

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   90

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   0

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

   0

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   100 - We typically test one of the first production piles driven and base pile driving criteria on that dynamic test for the rest of the piles in the foundation. Depending on the number of piles in a given foundation, more tests may be performed (as per AASHTO criteria).

8. Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:

a. Would not perform any load tests on pre-production piles
98

b. Would install pre-production (probe) piles without dynamic monitoring
0

c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only
0

d. Would install pre-production test piles for static or rapid load testing only
0

e. Would install pre-production test piles with both **c.** and **d.**
2

9. If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?

We typically do a static design coupled with a WEAP analysis to determine minimum hammer energy and required pile type and section. Dynamic monitoring during construction (including CAPWAP analysis) is used to verify/modify the static design.

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)
0

b. High Strain dynamic testing with signal matching only (CAPWAP or similar)
98

c. Static load tests only
0

d. Rapid load tests (Statnamic or similar) only
0

e. Combinations of the above
2

f. Other (please explain)
2 (WEAP only for planned refusal conditions)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

No (we use only steel pipe and H-pile and don't treat them differently)

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

The only exception to not using dynamic measurements on at least 1 pile per foundation would be known driving to bedrock conditions where only WEAP analysis is used (very rare, maybe 2% of all piles).

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

No

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

We test at least one pile per foundation using PDA with signal matching.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

If we do not achieve required ultimate capacity at EOID, then we will perform a restrike. Many times we only perform restrike testing because we're sure we will not achieve capacity during initial drive.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

A minimum of 24 hours is required. At times we attempt to achieve more set-up time based on a soil profile.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

We typically will chose the highest capacity blow if we feel it is representative of true ultimate capacity. If a high blow seems anomalous, we may choose a lower-capacity blow.

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

Yes. We use this method often and feel it is conservative because quite a bit of the shaft friction isn't even included when adding initial drive toe capacity to restrike skin friction.

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

Based on the test pile, we will typically require a minimum blow count/stroke/delivered energy. We may also require that a minimum elevation be reached (based on design criteria such as settlement, uplift, etc.).

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

We've used rapid load testing (Statnamic) only in a research capacity.

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

We rarely use static load testing.

19. How are rapid or static load test results used in the development of driving criteria for production piles?

We would follow current AASHTO criteria for static load testing. Rapid load testing is still in a research phase in our state.

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

An inspector keeps a driving record for each pile including stroke (or delivered hammer energy), blow count, plumbness, alignment and visible pile damage.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

We use the appropriate resistance factor prescribed in the current AASHTO specs (typically 0.65 for PDA w/ signal matching).

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes. (801)965-4326. Jon Bischoff

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Nicholas Meltzer

Title Geotechnical Engineer

Agency Vermont Agency of Transportation

Address One National Life Drive, Materials & Research
Montpelier, VT 05633

Email Nick.Meltzer@state.vt.us

Phone 802-828-6911

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   The entire state of Vermont

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   8

   b. Number of individual driven piles installed
   98

   c. Lineal feet of driven piles installed
   6860

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required

   b. List of pile driving equipment only
   2 %

   c. List of pile driving equipment plus wave equation analysis
   98%

   d. Specific information regarding the driving sequence

   e. Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed

   b. Specified hammer energy included in specifications

   c. Evaluate using a pile driving formula (please specify which formula is used)

   d. Evaluate using a wave equation analysis
   100%

   e. Other, please explain

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation

   b. Drive the pile to practical refusal

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)
   2%

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)
   98%

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

   g. A combination of both **e.** and **f.**

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   50%

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   50%

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   Our standard protocol is to test one pile at each substructure prior to production driving. From this, we develop a driving criteria, which we use to confirm resistance of production piles. All test piles are restriked, unless they are driven to bedrock. We feel this is the most efficient way to insure we are getting the resistance we need (and what we pay for) at the best price

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**
   a. Would not perform any load tests on pre-production piles

   b. Would install pre-production (probe) piles without dynamic monitoring

   c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only
   98%

   d. Would install pre-production test piles for static or rapid load testing only

   e. Would install pre-production test piles with both **c.** and **d.**

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)

b. High Strain dynamic testing with signal matching only (CAPWAP or similar)

c. Static load tests only

d. Rapid load tests (Statnamic or similar) only

e. Combinations of the above
98%

f. Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

We primarily use H-Piles, but our means and methods do not change when we use other types of piles.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

Yes. We will waive the restrike if the piles are end bearing on bedrock. Our standard protocol is to restrike after 48 hours, however we may extend this to gain resistance in cohesive soils. If cobbles and boulders exist, we may test multiple piles to insure they are not damaged.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

No.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

One test pile (with dynamic testing) is done per substructure unit, per project. CAPWAP is done on all test piles to confirm field measured data.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

Yes, see explanation above.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

48 hours is stated in our specifcations

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

The hammer must be warmed up on another pile and resistance must be maintained for 2 inches, or 20 blows, whichever comes first.

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

No.

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

Blows per inch are recorded during dynamic testing, while measuring stroke height with a saximeter. Once resistance is reached based on dynamic testing, it is maintained for 3 inches. From this, the blows per inch are compared with the PDA results to come up with a blows per inch and minimum stroke height (measured by the saximeter) criteria. This criteria is used to confirm resistance on production piles

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

N/A

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

To verify design assumptions (skin friction), static load tests are commonly performed on larger projects to calibrate dynamic testing and take advantage of higher resistance factors.

19. How are rapid or static load test results used in the development of driving criteria for production piles?

See above.

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

Wave equation submitted by the contractor is checked, pile driving and equipment data sheet is required, and confirmed with equipment brought on site. The saximeter results are compared with the PDA stroke height. A CAPWAP analysis is performed for each test pile after PDA testing.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

Reduction factors are applied to the nominal axial resistances to attain the factored axial geotechnical bearing resistances. Geotechnical resistance is defined as the resistance provided by the in-situ soil. The nominal bearing resistance is factored using the resistance factors, in Table 10.5.5.2.3-1 of the AASHTO LRFD code. The resistance factor 0.65 requires a minimum of 3 dynamic tests performed during installation in accordance with Table 10.5.5.2.3-3 of AASHTO. No less than 1 test is performed at each abutment/pier. The remaining piles are calibrated by wave equation analysis.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes, contact me, Nick Meltzer, at 802-828-6911

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name D. Ashton Lawler

Title Program Manager for the Geotechnical Design of Structures

Agency Virginia Department of Transportation

Address 1401 E Broad Street
Richmond, VA 23219

Email ashton.lawler@vdot.virginia.gov

Phone 804-786-2355

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Virginia

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   50 to 60

   b. Number of individual driven piles installed
   >4000

   c. Lineal feet of driven piles installed
   >100,000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required
   0%

   b. List of pile driving equipment only
   40%

   c. List of pile driving equipment plus wave equation analysis
   60%

   d. Specific information regarding the driving sequence
   0%

   e. Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed
   0%

   b. Specified hammer energy included in specifications
   5%

   c. Evaluate using a pile driving formula (please specify which formula is used)
   40% ENR (the Gates Formula is now used for LRFD projects).

   d. Evaluate using a wave equation analysis
   60%

   e. Other, please explain

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation
   10%

   b. Drive the pile to practical refusal
   35%

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula
   30%(H-Pile pract ref) 10%(Fric Piles)

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)
   5%

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)
   45%

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements
   <5%

   g. A combination of both **e.** and **f.**
   <5%

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   35%

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   0%

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   55%

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   PDA & restrike based on subsurface variation not substr units.

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   Rarely(only if EOID of production pile blow count was less than that of test pile)

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

   <1%

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   50%
   VDOT has been using PDA to establish pile capacity for over 25 years. Most projects with friction piles will have driving test piles that are driven and dynamically monitored. A restrike is performed 5 days after initial drive. Driving test pile are usually driven at production pile locations, which are designated in the bid documents.

   Some H-Piles that are driven to refusal are dynamically monitored if special conditions exist. About 10% of our H-Piles in end bearing projects require dynamic monitoring.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**

    a. Would not perform any load tests on pre-production piles
    30% These are end bearing piles driven to refusal.

    b. Would install pre-production (probe) piles without dynamic monitoring
    15%

    c. Would install pre-production test piles with dynamic monitoring (PDA or similar) only
    55%

    d. Would install pre-production test piles for static or rapid load testing only
    5% This would always include a PDA.

    e. Would install pre-production test piles with both **c.** and **d.**
    5%

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

    Driving test are not required for H-Piles driven to refusal unless special circumstances require PDA testing.

    H-Piles are driven to practical refusal. Practical refusal has been defined as double blow count as obtained from ENR (the Gates Formula is now used for LRFD projects).

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)
0%

b. High Strain dynamic testing with signal matching only (CAPWAP or similar)
55%

c. Static load tests only
<1%

d. Rapid load tests (Statnamic or similar) only
<1%

e. Combinations of the above
5% All piles to be static load tested are PDA'd

f. Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

H-Piles are driven to practical refusal. Practical refusal has been defined as double blow count as obtained from ENR (the Gates Formula is now used for LRFD projects). Driving test are not usually required. On about 10% of the end bearing pile projects dynamic testing on the initial drive of the first production pile will be required where pile capacity is increased above 9000 psi or hard driving is expected.

Friction pile projects always have at least one driving test. Wave Equ only is on 10% of the friction pile projects; wave equ and dynamic testing on 75%.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

H-Piles are driven to practical refusal. Practical refusal has been defined as double blow count as obtained from ENR (the Gates Formula is now used for LRFD projects). Wave Equ may be used in the hammer approval stage if over stressing the pile issues exist. Driving test are not usually required. On about 10% of the end bearing pile projects wave equ and dynamic testing on the initial drive of the first production pile will be required where pile capacity is increased above 9000 psi or hard driving is expected or over driving is required to achieve a good toe in.

The location and number of driving test for friction piles is evaluated for each project based on subsurface conditions, pile capacity requirements, potential for soil setup and potential for high driving stresses. Smaller/non-complex project may only require ENR(the Gates Formula is now used for LRFD projects). Most friction pile projects require hammer approval by wave equ and dynamic pile testing on designated piles. Driving test piles are usually shown done at production pile locations and piles are restruck 5 days after initial drive. CAPWAP's are required. After the results are received and reviewed by the Engineer an order this for the remaining production piles will be issued.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

Smaller/non-complex project may only require ENR(the Gates Formula is now used for LRFD projects). Small projects are evaluated for the complexity of driving conditions and possible economic gain from the use of dynamic testing. On very large (mega) projects pre-design deep foundation testing programs may be considered.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

Our Special Provision for Dynamic Pile Testing requires a 5 day restriking and signal matching.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

Our Special Provision for Dynamic Pile Testing requires a 5 day restriking and signal matching. About 75% of friction pile projects have dynamic pile testing.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

Our Special Provision for Dynamic Pile Testing requires a 5 day restriking. This maybe modified to as little as 3 days or as many as 7 days if conditions dictate. Default initial drive capacity is 80% of nominal pile resistance shown on the plans. The geotec involved in the testing will usually modify this to 50% of nominal.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

20 blows or three inches which ever occurs first (or as directed by the Engineer).

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

VDOT does not do dynamic testing in house. PDA's are a bid item and the Contractor will hire a qualified Professional Engineer to provide a wave equ of his driving system and to conduct the dynamic testing. The results are provided to VDOT for review. Signal matching of several blows may have been used to develop capacities presented in the final report. On occasion VDOT after review will ask for an additional blow to be processed.

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

The signial matching results are evaluated and a tip elevation and production pile length set. Pile driving inspectors will be told to drive the pile to the tip elevation unless the blow count for the next to last foot is less than that achieved on the initial drive of the test pile; leave the pile one foot high and contact the Engineer for guidance.

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

VDOT has only used rapid pile testing on experimental projects.

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Static load test may be required on major projects where larger than normal pile capacities are desired to maximize pile economy or in areas where static load test correlation with dynamic testing have not been established.

19. How are rapid or static load test results used in the development of driving criteria for production piles?

Static load test are always used with dynamic pile testing. Restrikes with dynamic testing help establish soil setup and production pile lengths. The static load test validates the reliability of the dynamic testing results.

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

VDOT will approve or modify the Contractor's production pile order list and furnish the pile driving inspector a minimum blow count that is to be met or exceeded for the last three feet of driving. If that blow count is not met for the initial two feet of final driving the piles is left one foot high and the Engineer contacted for direction on when to redrive. If on restriking the pile still fails to meet the Engineer's requirements, a second restrike may be required after an extended period set by the Engineer. This second restrike may include dynamic testing. Dynamic Testing may also be required for an installed production pile if there is any concern the pile may have been damaged during driving.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

VDOT has just begun LRFD design and the transition from ASD to LRFD is a work in progress. We have already switched from ENR to Gates and will probably switch to requiring wave equ for most projects not dynamically tested. LRFD criteria that no less that 2% of production piles be dynamically tested to achieve the 0.65 resistance factor would require us to do more dynamic testing than we have been. We will probably not do additional test up to 2% since we feel our current practice has been quite sucessful.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes. Please feel free to contact Ashton Lawler at 804-786-2355

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Tony M. Allen

Title State Geotechnical Engineer

Agency WSDOT

Address State Materials Laboratory
P.O. Box 47365
Olympia, WA 98504-7365

Email allent@wsdot.wa.gov

Phone 360-709-5450

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   State of Washington

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   5 to 10

   b. Number of individual driven piles installed
   ???

   c. Lineal feet of driven piles installed
   ???

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required
   0

   b. List of pile driving equipment only
   10%

   c. List of pile driving equipment plus wave equation analysis
   90%

   d. Specific information regarding the driving sequence
   ??

   e. Other information specific related to pile driving criteria, please explain
   ??

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed
   0

   b. Specified hammer energy included in specifications
   20%

   c. Evaluate using a pile driving formula (please specify which formula is used)
   10% - WSDOT formula

   d. Evaluate using a wave equation analysis
   90%

   e. Other, please explain

5. Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:

- **a.** Drive the pile to a specified tip elevation
  1%
- **b.** Drive the pile to practical refusal
  0
- **c.** Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula
  80%
- **d.** Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)
  0
- **e.** Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)
  20%
- **f.** Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements
  0
- **g.** A combination of both **e.** and **f.**
  5%

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   0

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   0

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   10%

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   5%

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   0

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

   0

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   20% - Size of project, or potential for significant setup.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**
   - **a.** Would not perform any load tests on pre-production piles
     ?
   - **b.** Would install pre-production (probe) piles without dynamic monitoring
     ?
   - **c.** Would install pre-production test piles with dynamic monitoring (PDA or similar) only
     ?
   - **d.** Would install pre-production test piles for static or rapid load testing only
     ?
   - **e.** Would install pre-production test piles with both **c.** and **d.**
     ?

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

- **a.** High strain dynamic testing only (PDA or similar)
  0
- **b.** High Strain dynamic testing with signal matching only (CAPWAP or similar)
  20
- **c.** Static load tests only
  0
- **d.** Rapid load tests (Statnamic or similar) only
  0
- **e.** Combinations of the above
- **f.** Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

No

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

Possibly; depends on complexity of subsurface conditions.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

Possibly, but not a primary consideration once we decide to do that tyupe of testing.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

On one project we actually tested 100% of the piles. But normally, we would test 2 piles per pier and have a few other test piles available to deal with problem areas.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

In such cases, restrike is performed about 70% of the time. But we might not do restrike if in relatively clean sands or gravels.

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

Setup time varies based on soil type and possibly contract constraints.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

???

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

We have considered this when we are having difficulty making things match up properly.

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

We use the PDA/CAPWAP testy results to help "calibrate" the wave equation analyses (e.g., to adjust quake and damping values, % skin friction, transferred energy, etc.). Then we use the wave equation to develop the final driving criteria. Alternatively, if we feel that for each pier the conditions are uniform enough, we may use the PDA/CAPWAP to establish the pile resistance directly for a minimum hammer energy/stroke, etc.).

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

generally don't use.

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

Generally it would only be on the biggest projects, and we would look at the site variability and provide one load test per portion of the site that we can consider adequately consistent for application of the load test results.

19. How are rapid or static load test results used in the development of driving criteria for production piles?

Used to enable us to adjust wave equation results to match the pile load test results. Wave equation is then used to develop the final driving criteria.

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

Hammer performance observations, such as stroke, to help assess energy being delivered to pile, and of course the blow count.

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

We are generally consistent with AASHTO.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Tony Allen 360-709-5450

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Bob Arndorfer

Title Foundation and Pavement Engineering Supervisor

Agency Wisconsin DOT

Address 3502 Kinsman Blvd.
Madison, WI 53704

Email robert.arndorfer@dot.wi.gov

Phone 608-246-7940

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   State of Wisconsin

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**
   - **a.** Number of projects with driven pile foundations
     200
   - **b.** Number of individual driven piles installed
     4500
   - **c.** Lineal feet of driven piles installed
     350,000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**
   - **a.** No submittal required
     5
   - **b.** List of pile driving equipment only
     90
   - **c.** List of pile driving equipment plus wave equation analysis
     5
   - **d.** Specific information regarding the driving sequence
   - **e.** Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**
   - **a.** No evaluation is performed
     90
   - **b.** Specified hammer energy included in specifications
   - **c.** Evaluate using a pile driving formula (please specify which formula is used)
   - **d.** Evaluate using a wave equation analysis
     5 (Only on mega projects.)
   - **e.** Other, please explain

     5 (When driving issues arise.)

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation

   b. Drive the pile to practical refusal
   55

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula
   35

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)
   10 (Due to 2 large mega-projects.)

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

   g. A combination of both **e.** and **f.**

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   90

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   10

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency’s decision to utilize this technology (e.g., pile types and/or ground conditions).**

   We currently have two mega-projects that are using PDA to set drive criteria, but this is not common. Normally only use PDA if drive issues arise, or the use of PDA is considered when there is a large number of friction piles (100+) on a project.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**
   - **a.** Would not perform any load tests on pre-production piles
     98
   - **b.** Would install pre-production (probe) piles without dynamic monitoring
   - **c.** Would install pre-production test piles with dynamic monitoring (PDA or similar) only
     2 (Mega projects only)
   - **d.** Would install pre-production test piles for static or rapid load testing only
   - **e.** Would install pre-production test piles with both **c.** and **d.**

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

   Driving criteria based on FHWA modified Gates formula.

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

a. High strain dynamic testing only (PDA or similar)

b. High Strain dynamic testing with signal matching only (CAPWAP or similar)

c. Static load tests only

d. Rapid load tests (Statnamic or similar) only

e. Combinations of the above

f. Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

15. If your agency uses high strain dynamic testing:

- **a.** Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

- **b.** If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

- **c.** What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

- **d.** In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

19. How are rapid or static load test results used in the development of driving criteria for production piles?

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes, Bob Arndorfer (Author of these responses.)

Thank you for completing this survey.

Thank you for completing this survey on Synthesis Topic 41-10, Developing Production Pile Driving Criteria from Test Pile Data. Please provide your name and contact information below and complete the questionnaire that follows.

Name Jim Coffin

Title Chief Engineering Geologist

Agency Wyoming Department of Transportation

Address 5300 Bishop Blvd.

Email jim.coffin@dot.state.wy.us

Phone 307-777-4205

Definition of terms

For purposes of this questionnaire, the following definitions of terms are provided:

Pile driving criteria: A specific set of requirements used to define the conditions which must be met during the installation of a production pile. Usually involves some combination of minimum embedment and/or driving resistance, the latter related to specific installation equipment.

Wave equation analysis: Numerical model of the specific pile, soil conditions, and installation equipment, used to evaluate behavior of the pile and driving equipment for a specific project.

Pile driving formula: A closed form equation, such as the Gates or Engineering News formulas, used to relate pile hammer characteristics and driving resistance to the axial static resistance of the pile.

Driving resistance: A measure of the resistance to penetration of the pile during driving. May be expressed as blows per foot (b/f or blow count), blows per inch (bpi), or set per blow (inches).

Drivability analysis: An analysis of the maximum driving resistance and the installation equipment in order to evaluate whether a hammer and driving system will likely install the pile in a satisfactory manner.

End-of- driving (EOD): The last few blows during the installation of a driven pile.

Restrike: A hammer blow or series of hammer blows applied to a pile after a period of time ranging from hours to days during which the pile is not actively driven. Restrike blows are applied in order to provide a measure of setup or relaxation after the initial driving of the pile.

Setup: An increase in the nominal axial resistance of a pile that develops over time.

Relaxation: A reduction in the axial pile resistance after a period of time.

Beginning of redrive (BOR): The first few restrike blows after a period of setup.

Dynamic monitoring: A measure of the behavior of the pile during one or more hammer blows in which instrumentation on the pile is used to obtain measurements of strain and acceleration. The Pile Driving Analyzer® (PDA) is a commonly used apparatus for dynamic monitoring.

High strain dynamic test: The procedure for using dynamic monitoring to test deep foundations and determine static axial resistance is described by ASTM Standard D 4945-00.

Signal matching: The use of numerical modeling of the pile and pile driving system, back-calibrated to the results of a high strain dynamic test to determine static axial resistance. The CAPWAP (CAse Pile Wave Analysis Program) is an example of a computer code used for signal matching.

Rapid load test: The application of a force pulse to perform a load test of a deep foundation element as described by ASTM Standard D-7383-08. The Statnamic® (STN) loading device is a commonly used method for performing a rapid load test.

Static load test: The application of a static force to perform a load test of a deep foundation element as described by ASTM Standard D-1143.

Production pile: A pile which will become part of the permanent foundation for the structure.

Probe pile: A pile which installed prior to installation of production piles in order to aid in the determination of pile length variations across the site. Probe piles are typically not incorporated into the permanent structure.

Test pile: A pile which is installed for the primary purpose of performing a test of the pile including the behavior during installation and/or during subsequent testing to determine the axial resistance. A test pile may or may not be incorporated into the permanent foundation as a production pile.

Nominal bearing resistance: The resistance of a pile to static axial compression loading at the strength limit state.

Maximum driving resistance: The maximum amount of axial resistance which must be overcome in order to install the pile to the minimum pile penetration and to achieve the nominal bearing resistance. In addition to the nominal bearing resistance, the axial resistance which must be overcome may include axial resistance within zones of soil that may be removed by scour or that may be subject to downdrag.

1. **What is your general geographic area (location & extent) of practice? (e.g. Louisiana, Missouri, New Orleans district, etc.)**

   Wyoming

2. **Please estimate (to the best of your ability) approximately how many of the following occur within your agency on an annual basis:**

   a. Number of projects with driven pile foundations
   6 to 10

   b. Number of individual driven piles installed
   200

   c. Lineal feet of driven piles installed
   8,000

3. **Please provide your best estimate of the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency requires contractor to submit an installation plan for driven piles which includes the following:**

   a. No submittal required

   b. List of pile driving equipment only
   100%

   c. List of pile driving equipment plus wave equation analysis
   WYDOT performs the WEAP

   d. Specific information regarding the driving sequence

   e. Other information specific related to pile driving criteria, please explain

4. **Please provide your best estimate the percentage of driven piles (e.g., out of the total number of driven piles used for transportation structures on an annual basis) for which your agency evaluates the suitability of the proposed hammer and driving system as follows:**

   a. No evaluation is performed

   b. Specified hammer energy included in specifications

   c. Evaluate using a pile driving formula (please specify which formula is used)

   d. Evaluate using a wave equation analysis
   95%

   e. Other, please explain

   WYDOT hires a consultant to perform PDA Testing on about 5% of bridges

5. **Please estimate the percentage of driven pile projects for which the predominate method your agency uses as a criteria for installation of production piles is the following:**

   a. Drive the pile to a specified tip elevation

   We always use the planned length as a guide.

   b. Drive the pile to practical refusal

   85%, the other 15% WEAP and/or PDA Testing is used.

   c. Drive the pile to a specified driving resistance (blow count) based upon a pile driving formula

   d. Drive the pile to a specified driving resistance (blow count) based upon a wave equation analysis (WEAP or similar)

   100%, we run WEAP on all projects.

   e. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to high strain dynamic measurements (such as with a PDA or similar device)

   5 to 10% of projects

   f. Drive the pile to driving resistance (blow count) based upon correlation to the driving resistance of another pile which had previously been subjected to static or rapid load test measurements

   0%

   g. A combination of both **e.** and **f.**

6. **Please estimate the percentage of driven pile projects for which your agency would utilize restrike measurements to verify axial resistance or driving resistance on production piles after soil setup:**

   a. Would not use restrike measurements because piles would be driven to the required driving resistance or practical refusal, for example, because the piles are designed to provide resistance from end bearing on rock or a hard layer

   b. Would not use restrike measurements because piles are installed to a specified tip elevation without regard to driving resistance

   c. Would restrike a few selected piles on the project to demonstrate setup through increased driving resistance, but not necessarily one at every foundation location
   10%

   d. Would restrike at least one pile at each foundation location to demonstrate setup through increased driving resistance if all of the piles at the foundation location do not achieve the required driving resistance on initial drive

   e. Would restrike every pile which does not achieve the required driving resistance on initial drive to demonstrate setup through increased driving resistance

   f. Would restrike selected piles on the project to evaluate potential relaxation in axial resistance, even if piles were driven to achieve the required driving resistance on initial drive

7. **Please estimate the percentage of driven pile projects for which your agency would utilize dynamic monitoring (with PDA or similar) of production piles prior to establishment of final production pile driving criteria. Please comment on factors affecting your agency's decision to utilize this technology (e.g., pile types and/or ground conditions).**

   5 to 10%. Shallow bedrock, < 80 feet deep is common in Wyoming and pile are often driven to a plan length, with refusal blow counts and/or to a blow count and stroke based on WEAP.

8. **Please estimate the percentage of driven pile projects for which your agency would utilize testing of pre-production (test or probe) piles prior to establishment of final production pile driving criteria as follows:**
   - **a.** Would not perform any load tests on pre-production piles
   - **b.** Would install pre-production (probe) piles without dynamic monitoring
   - **c.** Would install pre-production test piles with dynamic monitoring (PDA or similar) only
     5-10%
   - **d.** Would install pre-production test piles for static or rapid load testing only
   - **e.** Would install pre-production test piles with both **c.** and **d.**

9. **If your agency does not use a test pile program to develop production pile driving criteria, what additional procedures are used by your agency to establish production pile driving criteria?**

If your agency's procedures frequently include dynamic monitoring or load testing to develop pile driving criteria, please continue the survey. Otherwise, please stop here and return the survey.

10. On what percentage of projects would the following types of tests be performed or required or utilized by your agency in order to determine the axial resistance of a test pile?

- **a.** High strain dynamic testing only (PDA or similar)
- **b.** High Strain dynamic testing with signal matching only (CAPWAP or similar)
  5-10%
- **c.** Static load tests only
- **d.** Rapid load tests (Statnamic or similar) only
- **e.** Combinations of the above
- **f.** Other (please explain)

11. Does your agency make modifications to the prescribed number and types of pile tests described above based on pile type? If so, please explain.

12. Does your agency make modifications to the prescribed number and types of pile tests described above based on ground conditions (e.g., end bearing vs. friction piles, rock vs. soil, sandy soil profiles vs. cohesive soil profiles, etc)? If so, please explain.

Generallly, we conduct PDA Testing when we use friction pile and when the pile tips will be founded in weathered or soft bedrock or soils.

13. Does your agency make modifications to the prescribed number and types of pile tests described above based on economics/project size? If so, please explain.

The number of pile driven on a project usually dictate the number of PDA tests.

14. If your agency uses high strain dynamic testing, under what circumstances and with what frequency (on a particular project) would such tests be performed? Under what circumstances and with what frequency would signal matching computations (e.g., CAPWAP or similar) be performed on these measurements?

Usually one to two PDA tests per bridge. Average bridges are 3 span, with two to four pile foundation locations (abutments or bents). CAPAWAP is run on all PDA testing.

15. If your agency uses high strain dynamic testing:

a. Are restrike measurements typically performed, and what factors are considered in deciding to perform restrike measurements?

All pile that are PDA tested are restruck. If PDA testing is not conducted, restriking may be completed for pile that do not reach capacity

b. If so, what setup time is normally used and do you use different setup time in different soil conditions (e.g., piles in predominantly clay profiles vs. silt or sand)?

Generally 24 hours.

c. What additional procedures are used for selecting a restrike blow for analysis (e.g., take the highest resistance, average 10 blows, etc.)?

Yes, average of 10 blows per (measurement)

d. In interpreting restrike measurements to determine axial resistance, does your agency ever consider (or allow) the addition of base resistance from one blow with the side resistance from a different blow? If so, what factors are considered in utilizing this interpretation?

No

16. If only dynamic testing/signal matching is performed on selected test piles, what procedures are used by your agency to develop driving criteria for production piles using these results?

17. If your agency uses rapid load testing, under what circumstances and with what frequency (on a particular project) would such tests be performed?

18. If your agency uses static load tests, under what circumstances and with what frequency (on a particular project) would such tests be performed?

19. How are rapid or static load test results used in the development of driving criteria for production piles?

20. What quality assurance measures are used in combination with the driving criteria to evaluate production piles?

21. Please describe how the production pile driving criteria methods used by your agency affect the resistance factor chosen for design.

22. Would your agency be willing to respond to a telephone interview and if so, who should we contact for this interview?

Yes, Jim Coffin, 307-777-4205

Thank you for completing this survey.

APPENDIX C

Phase II Survey Responses: Interview Notes

Agency:	California DOT
Participants:	Brian Liebich, P.E. – Chief, Foundation Testing
Interview Date:	August 24, 2010; September 21, 2010

Current practices:

- The process of developing and using driving criteria varies according to the pile size. There are three typical processes: 1) Standard Pile Size: small diameter piles, typically less than 20in and 100tons or less required resistance; 2) Above Standard Pile Size / Intermediate Size (20in to 36in); and 3) High Capacity / Large Diameter (36in and above).
- For Standard Pile Size, typically use pre-cast pre-stressed concrete piles, with some use of open-end pipe piles and H-piles. For larger sizes, almost exclusively open end pipe piles and Cast in Steel Shell (CISS) piles.
- Gates equation is used for acceptance of Standard Pile Size. For other sizes, the inspectors in the field are provided acceptance graphs with a family of curves relating blow count, hammer stroke, and pile resistance. When restrikes are used to verify setup, a second graph is included showing the relationship of resistance over time.
- Standard Pile Size (less than 20in)
    - Caltrans has a long history of use and confidence in performance of the Standard Pile Size. Most contractors have appropriate equipment for these piles.
    - Acceptance is by Gates pile driving equation with a minimum tip elevation. Pile lengths are usually ordered based on minimum tip or small amount extra. Typical contractor practice is to drive to grade (if pile won't be damaged) rather than cut off if bearing is achieved at minimum tip with a longer pile.
    - When hard driving is anticipated, refusal is defined as some multiple of the Gates resistance criteria, typically 2 to 3 times the calculated blows.
    - If there are issues such as atypical behavior during driving, low resistance, or suspected damage, HSDT with PDA or equivalent will be performed.
- Above Standard Pile Size / Intermediate (20in to 36in)
    - HSDT with PDA is used for acceptance criteria. Signal matching analysis (CAPWAP) is performed on the HSDT results for use in a revise wave equation analysis.
    - Test piles are typically production piles.

- Pre-production pile test programs are extremely rare. It is difficult to get additional environmental permits for design phase or pre-construction testing in a timely manner before the start of construction.

- High Capacity / Large Diameter (36in and above)
    - Full static load test (SLT) is required for developing driving criteria. The results of the SLT are used to calibrate the wave equation analysis and determine final driving criteria.
    - HSDT is used for monitoring pile stresses and hammer performance, but has been a poor predictor of pile resistance. HSDT predictions of static resistance have ranged from 2x over to 6x under. Based on their experience, Caltrans believes that there are some scaling issues with the PDA in both the measurement of the waves in the pile and how the wave signals are analyzed to calculate a pile resistance.

<u>Concerns, problems, or challenges in current practices:</u>

- Continue with questions concerning verifying resistance for large diameter pipe piles. Requiring SLT will continue for foreseeable future.
- Difficulty reconciling LRFD resistance factors between design methods and field acceptance methods, wanting to make sure that the design is verifiable in the field – that a more conservative design factor is being verified with a higher testing factor.

<u>Specific Techniques:</u>

- Standard Pile Size (less than 20in):
    - Use specified tip plus bearing criteria – drive to planned tip and check with Gates formula. When pile encounters refusal before minimum tip with appropriately sized hammer (uncommon occurrence, although sometime expected due to geology), pile can be accepted based on formula (or some specified multiple of the formula), provided that the minimum tips for tension and lateral have been achieved. When pile does not have required resistance at minimum tip (rare occurrence, except in cohesive soils), restrikes are performed after setup. If capacity is still not achieved or difficult driving exists, dynamic analysis or static testing can be requested.
- For Above Standard Pile Size / Intermediate Piles (20in to 36in):
    - Number / Frequency of test piles will be site specific based on soil/geology conditions. The site will be divided into control zones where the subsurface conditions are consistent such that a single pile would be representative of the

control zone (not greatest resistance, but representative). Information from the static pile analysis model can be brought in to help select control zones.

- A minimum of one test pile per control zone using HSDT at end of initial drive (EOID) and a restrike. CAPWAP is performed on the test data. The results of the CAPWAP analysis (resistance, quake, damping, etc.) are put into a wave equation analysis (GRL WEAP). The WEAP analysis develops a family of curves relating blow count, stroke, and pile resistance. An additional plot representing setup over time is also generated using the restrike data. These curves are provided to the inspectors in the field to use as pile acceptance criteria.
- The developed curves are used for accepting piles in the control zone and for the specific hammer and pile size that they were developed. If the hammer is changed, a new set of curves must be developed.

- High Capacity / Large Diameter (36in and above):
  - Site divided into control zones as for intermediate sized piles above.
  - A minimum of one SLT is performed per control zone. HSDT is also performed for monitoring pile stresses, hammer performance, and to determine magnitude of setup.
  - The pile acceptance curves are developed from the SLT and CAPWAP data from HSDT. The SLT provides a set point where the pile resistance is known for a given stroke and blow count. The CAPWAP data provides the magnitude of the setup, as well as starting values for quake, damping, etc. The resistance values from CAPWAP are not used in the analysis. WEAP analyses are performed, adjusting parameters to get a match with the SLT results and then develop the family of curves that are correlated to the SLT.
  - The developed curves are used for accepting piles in the control zone and for the specific hammer and pile size for which they were developed. If the hammer is changed, a new set of curves must be developed.
  - Additional HSDT may be performed on indicator piles in a control zone to check stresses during hard driving, or other issues, but not for acceptance.
  - In some instances, the data can be used to re-evaluate the static model(s) to possibly shorten pile lengths.

Agency:	Florida DOT
Participants:	Larry Jones, P.E. – State Geotechnical Engineer Rodrigo Herrera, P.E. – Geotechnical Engineer
Interview Date:	August 20, 2010; September 23, 2010

Current practices:

- Pre-stressed concrete pile is the predominate pile type used by FDOT.
- Driving criteria established in a test pile (TP) program based on dynamic testing.
    - TP lengths estimated by static analysis – production pile estimated length plus 15ft.
    - Hammer and driving system performance evaluated in the field through PDA/EDC
    - Dynamic load testing performed on all TPs. Results used to perform wave equation analysis to develop driving criteria.
    - TPs are always in a production pile location, but almost always done in advance of approval to starting production piles
    - Recently developed a procedure to establish lengths for production and monitor first few piles rather than do TPs.
- Do occasionally utilize design phase testing programs. Dynamically tested piles may or may not be in production pile locations; static load test piles will not be in production pile locations.
- Static load tests are not utilized very often; when used they are on design/build projects where the larger resistance factor provides economy.
- 90% of projects utilize restrikes for verification. Restrikes are typically not needed in south Florida where piles bear on weak limestone.
- Relaxation is typically not a concern. Some loss of resistance (but not typical definition of relaxation) can occur for pile groups on limestone if the driving fractures/crushes thin strata of limestone.
- Presence of limestone in south Florida does not alter the approach to driving criteria development.
- Restrikes routinely used to evaluate setup.
- Will combine EOID base resistance with restrike side resistance on occasions where the setup has exceeded the capacity of the hammer to demonstrate base resistance. Much

care must be used when doing this, paying close attention to the CAPWAP analyses and how the side resistance and base resistance are distributed. Try to take the approach of verifying the required base resistance is available (after accounting for side resistance), rather than assuming the EOID base resistance is the full base resistance.

- Have a short-term trial evaluation (through September 2010 letting) of embedded sensors in all pre-stressed concrete piles. Sensors near pile tip (within 1 pile width) are providing a good measurement of tip stress and estimates of static tip resistance.
- Consultants work with districts and design piles according to district needs, then perform construction evaluations, including final driving criteria.
- Design/Build project environment is slightly different than normal practice:
    - FDOT requires the engineer that design the foundation and the engineer that performed/approved dynamic testing (if different entities), both must approve and seal the driving criteria.
    - Piles installed to the criteria.
    - Designer provides pile driving inspectors and certifies that piles were installed according to the criteria and meet all project requirements.
    - FDOT provides the equipment and inspection personnel to perform verification testing on selected piles, if considered necessary by the District Geotechnical Engineer

<u>Concerns, problems, or challenges in current practices:</u>

- Frequency of required testing utilizing AASHTO resistance factors. It seems that the resistance factors are available for two cases: a minimal amount of testing (10%), or complete testing of all foundations (100%). It would seem that there may be room for something in between.
- Verification testing – trying to ensure verification testing is used when there is genuine concern with pile resistance or pile integrity.
- FDOT is working on an internal guidance document for assessing and applying site variability to selection of resistance factors for soil conditions typical to Florida.
- Due to extensive experience with HSDT, FDOT has a high level of confidence that when done properly, the HSDT test results are not routinely over predicting the static resistance of the piles.

<u>Specific Techniques:</u>

- After completion of HSDT, signal match analysis will be performed using CAPWAP. The information on the load distribution (tip vs. side), soil variables (quake and damping), energy transfer, pile stresses, etc. will be put into the WEAP model. A WEAP analysis will be performed that reflects the resistance for the particular blow selected for the CAPWAP analysis. The results will be compared to the HSDT results to make sure they are compatible and adjusted if necessary. A WEAP analysis will then be run using the production pile length and required nominal resistance to develop the driving criteria.

- Inspectors are given a table of blows per foot for different stroke heights or energy transfer levels. Since Florida drives mostly precast concrete piles, additional instructions are also provided. These instructions are determined from the stresses monitored in the test pile and include:
    - Begin driving at lowest fuel setting until reaching a specified blow count value.
    - Reduce fuel setting during driving if blow count falls below a specified value.
    - Maximum cumulative blow count limit for the pile cushion.

- Typically have a set of criteria for each pier location based on the test pile at that location. Several pier locations can be grouped together if they are consistent enough. Small bridges may have a single criteria set for all piers.

- All inspectors must complete a qualification course to be approved for pile inspections.

- SLT and RLT are used to check the reasonableness of the pile resistance and load transfer distributions that are estimated with the CAPWAP analysis. The CAPWAP resistance values are not scaled by the SLT or RLT results. The SLT or RLT may be used to fine tune the signal matching analysis, particularly the load transfer characteristics. Production pile order lengths are rarely changed due to SLT or RLT results.

- Piles are typically driven to plan lengths, though a pile can be accepted if it has achieved minimum penetration, the blow counts are generally increasing, and it has met the minimum blow count criteria for 24 consecutive inches. Piles may also be stopped for practical refusal (20 blows per inch, no more than ¼" pile rebound, for at least 2 consecutive inches.

- If pile does not meet specified resistance criteria at end of drive, the pile will be allowed to set for up to 2 hours and then a set check performed, either with or without dynamic testing. If the pile does not meet the criteria after setup, the District Geotechnical Engineer will determine whether to perform additional set checks or to splice. When a splice will be required, the contractor may pull the pile and drive a longer pile.

- When pile achieves resistance at an elevation below minimum tip, but above the planned elevation, piles are usually cut off and not allowed to be driven to grade due to potential for damaging the pile. The contractor is sometimes allowed to drive to grade at the risk of the contractor if the pile is damaged or capacity is lost.

Agency:	Louisiana DOTD
Participants:	Chris Nickel, P.E. – Geotechnical Engineer Manager
Interview Date:	October 5, 2010

Current practices:

- Pre-stressed concrete pile is the predominate pile type used by LADOTD.
- Computer program DRIVEN used for axial analysis with model based on soil borings. Pile tip elevation set by using LRFD resistance factors.
- Test piles for LADOTD are piles installed with HSDT and SLT.
- Feasibility of using test piles is determined using a cost benefit analysis comparing the cost savings of using a higher resistance factor with a load test to the cost of the piles using the lower resistance factor without testing. The decision is not purely which costs less. Sometimes, even if the shorter piles plus the cost of the load test is slightly higher than the longer piles without a test, test piles will be included in a project to obtain data. The slight extra cost is deemed worth the data obtained.
- For small bridges with no SLT piles or no dynamic tests/monitoring, pile tip elevations are set using $\Phi = 0.5$. Piles are typically driven to grade with resistance checked with Gates formula using $\Phi = 0.4$:

$$Gates\ Formula\ R \geq \frac{Factored\ Load}{\Phi}$$

- When test piles are used, they are typically sacrificial non-production piles. Contractor equipment submittal is evaluated using wave equation analysis (WEAP).
- Revised WEAP analysis from the HSDT and CAPWAP used to establish driving criteria, tip elevation based on SLT.
- Tables of BC and stroke are provided to inspectors to verify end of drive conditions, along with additional instructions for changing stroke (fuel setting) for start of driving, other easy driving conditions, or at hard driving conditions.
- If conditions indicate that refusal conditions could be encountered, criteria will have an allowance for stopping driving within 5 to 10 feet of planned tip and cut off the pile.
- In some locations, the contractor is allowed the option of predrilling to start the piles. It is not always known if the contractor will predrill or not. WEAP analysis is performed for both cases and the inspectors charts are prepared for both with or without predrilling.

- Production piles typically driven to tip elevation. If blow count criteria not met at end of drive, restrikes may be performed. If a restrike is performed, it could be a one day set check to check blow count, or it could include longer wait times and using HSDT during the restrike.
- When setup is investigated, test piles will have restrikes over a range of times up to 14 days after initial drive. HSDT with CAPWAP would be performed for each restrike. The results of the CAPWAP analysis are used to develop a setup curve.
- During production pile installation, typically 1 to 2 piles per bridge (more on larger project) will be monitor piles with HSDT and CAPWAP analysis. Data will be used during initial drive to check pile stresses and integrity; restrikes are used to check setup.

Concerns, problems, or challenges in current practices:

- Defining refusal in a consistent manner with respect to hammer energy.
- There is an area of the state in the central part of the state where there is high toe quake at refusal blow counts. When a set check is performed the following day, the piles drive down. Possibly developing high negative pore pressures in the more sandy/silty soils in this area.
- Selecting appropriate design resistance factor.
- Pile cushions may appear to have compressed very little at the E.O.D. resulting in the request for their reuse. The reuse of these seemingly good pile cushions at the B.O.D. in soft soils may induce excess tensile stress in the pile. The thickness and life of a pile cushion is a constant issue.

Specific Techniques:

- Test pile tip elevations are estimated using $\Phi = 0.7$, then installed with HSDT and signal match analysis (CAPWAP). Piles are driven to the estimated tip elevation and load tested.
- Results of the CAPWAP analysis (quake, damping, energy, etc.) are used to refine the WEAP analysis using the resistance from the SLT and not the CAPWAP resistance.
- Revised WEAP analysis from the HSDT and CAPWAP used to establish driving criteria, tip elevation based on SLT.
- Tables of BC and stroke are provided to inspectors to verify end of drive conditions, along with additional instructions for changing stroke (fuel setting) for start of driving, other easy driving conditions, or at hard driving conditions.
- If a production pile does not achieve the required resistance, restrikes (both set checks and HSDT) can be performed, or an SLT is performed to verify resistance.

- What constitutes “a site” is determined using engineering judgment to assess the subsurface conditions and the pile static analysis. Some attempts were made to do statistical-based evaluations, but the judgment based evaluations were deemed more effective.

Agency:	Minnesota DOT
Participants:	Paul Rowekamp, P.E. – Bridge Standards Engineer Paul Kivisto, P.E. – Metro Region Bridge Engineer
Interview Date:	August 24, 2010; October 14, 2010

Current practices:

- Cast-in-place shell (closed-end pipe pile filled with concrete) displacement piles most predominate pile type. These piles tend to work better in the glacial deposits and plastic clay soils when not driving to bear on rock.
- H-piles are used when driving to bear on rock.
- Contractor is required to submit wave equation analysis for proposed the hammer to demonstrate the hammer will drive the piles to the required resistance without damage.
- Dynamic formula is used as acceptance criteria on most piles.
- 1 to 2 test piles are driven per substructure. Test piles are production piles. If test piles drive to required resistance as demonstrated by the driving formula, authorization is given to drive production piles.
- HSDT with PDA is used on larger projects and larger diameter piles with very low or high resistance values outside of the range of the driving formula. HSDT is also used for projects where a restrike is necessary to demonstrate pile resistance (when significant setup is expected), particularly when the piles is expected to "break free" within a few blows of the start of restrike.
- As LRFD transition continues, HSDT sometimes used more frequently to help "calibrate" driving formula.
- Currently have an ongoing research project with Dr. Sam Paikowsky (UMass Lowell) to evaluate selection of appropriate resistance factors during design that are compatible with the Mn/DOT pile acceptance process.
- Static load tests (SLT) are not typically done, though some recent large bridge projects with large diameter piles have included a static load test due to the high loads and lack of experience with such large piles.
- Another research project has begun to conduct 12 load tests over the next two to three years to provide data for HSDT and driving formula correlation.
- Mn/DOT has used Statnamic rapid load test (RLT) method on limited number of projects.

- When a restrike occurs where the pile is not moved, Mn/DOT does not typically evaluate adding EOID base resistance with restrike side resistance as measured by the PDA. Evaluations based more on judgment.

Concerns, problems, or challenges in current practices:

- Recent limited experiences with large diameter open-end pipe piles bearing in soil (above bedrock) indicate that the PDA is not typically providing a reliable measurement of the pile resistance. These piles typically have a required resistance well above the range of resistance evaluated by the driving formula. In many cases, the pile does not move sufficiently to provide reliable measurements with a PDA. Other than SLT or RLT, Mn/DOT is considering how to evaluate and approve piles in such situations.
- With a large part of the state being extremely rural covering a wide geographic area, performing evaluations with PDA or other devices is not economical. This is mostly due to the limited availability of qualified consultants in the rural areas and the resulting schedule impact, as well as the limited gain in design efficiency for the small projects typical of the rural areas of the state. Using a pile driving formula continues to be the most economical method of approving piles in these areas.

Specific Techniques:

- When HSDT with a PDA is performed, it is used to determine the pile resistance at the end of initial drive or restrike. This resistance is used to evaluate pile acceptance in lieu of the results of the dynamic formula. Once the resistance is verified by the HSDT, production piles are driven to the same tip elevation and hammer energy/blow count. The pile driving formula is not used for acceptance.
- Data from the signal matching analysis with CAPWAP is not used to modify wave equation analyses or the dynamic formula to adjust the driving criteria.

Agency:	New York State DOT
Participants:	Steve Borg, P.E. – Civil Engineer II (Geotechnical Engineer)
Interview Dates:	August 31, 2010; September 21, 2010

Current practices:

- The predominate pile types used by NYSDOT are cast-in-place piles (closed-end pipe pile filled with concrete) and H-piles. Monotube piles are used when tapered cast-in-place piles are needed. Pre-cast pre-stressed concrete cylinder piles are used in coastal and tidal deposits such as in Long Island and are sometimes used upstate.
- Cast-in-place piles are typically 12in to 14in in diameter, with the largest diameter used being 24in. These piles can be designed as either combined base resistance and side resistance, or side resistance only. H-piles are usually driven to refusal on rock. Single acting diesel hammers are becoming the most common hammer used by contractors.
- Wave equation analysis is typically used to evaluate the contractor's hammer system submittal and set the driving criteria. The inspectors are provided an acceptance blow count and minimum hammer energy or stroke criteria. Restrike blows are only used if piles do not achieve the desired resistance at the estimated drive length
- For soils conditions or large projects where High Strain Dynamic Test (HSDT) are more suitable, the HSDT are used to set the driving criteria. One test pile (a production pile) per substructure is tested at initial drive and with a 24-hour restrike. The inspector is provided the acceptance blow count and hammer performance criteria based on the HSDT results.
- With pre-cast pre-stressed cylinder piles, pre –production HSDT is performed to set pile lengths and determine the driving criteria. Evaluation of tensile and compressive stresses in the piles during driving is also a major part of dynamic testing of these piles.
- Signal matching analysis is performed on all HSDT. NYSDOT experience seems to indicate that the signal matching analysis does not necessarily always correlate to the wave equation analysis.
- NYSDOT will use the base resistance form the end of initial drive with the side resistance from restrike blows to estimate the static pile resistance. IN very long piles, the side resistance from several blows is superimposed to estimate the side shear resistance for the pile.
- Static load tests are rarely performed.
- Piles are rarely driven to a length as specified by static analysis only without verification of a blow count. Wave equation or HSDT is used on all projects.

Concerns, problems, or challenges in current practices:

- The biggest challenge for NYSDOT is developing good estimates of set up in the clays soils found in certain parts of the state. Experience indicates that setup times can range from 24 hours to one month. The project schedule is typically set such that there is not time to allow a test program to fully investigate pile set up. Piles tend to be over driven (driven to higher resistance than necessary if setup was better defined) in order to meet the schedule.

Specific Techniques:

- When using wave equation analysis for developing criteria (steel piles):
  - The wave equation analysis is performed for all hammers to be used on the project, utilizing standard values for quake and damping. A blow count, stroke, and blow rate (diesel hammers) or blow count (air hammers) are determined and given to the Structures group in a memo. This information is then transmitted to the field offices and provided to the inspectors.
  - If the criteria are not achieved at the estimated pile length, the field inspectors call the Structures group for further guidance. Typically the guidance is to wait 24 hours and perform a restrike after allowing setup, or to splice the pile and drive deeper. Geotechnical personnel are not consulted unless there is an unusual condition.
- When using high strain dynamic testing:
  - HSDT will always be used for concrete piles and may be used with steel piles. Concrete piles will typically be precast cylinder piles. A restrike test will always be performed. Signal matching analyses (CAPWAP) will always be performed and will be done while on site.
  - A wave equation analysis will be performed to check the suitability of the proposed hammer(s). Driving criteria will not be provided. HSDT will be performed on test piles by NYSDOT personnel at end of initial drive and a restrike.
  - For steel piles, the initial drive will be to the estimated pile length. If the required resistance is achieved at initial drive or restrike, the driving criteria of minimum blow count and hammer energy correlated from the HSDT and CAPWAP will be provided immediately to the field engineer and inspectors. If the required resistance is not achieved at restrike, the Structures group will be contacted to evaluate splicing and driving pile deeper followed by re-testing.
  - For concrete piles, the piles are either ordered to the length designated on the plans and HSDT used to establish acceptance criteria for the order lengths, or a test pile program is performed with test piles ordered to an estimated length

and installed at specific locations. The results of the test piles are used to establish order lengths for the remaining piles.

- Criteria for use during "easy driving" are also provided for concrete piles to prevent tensile stresses from developing in the pile during "easy driving", causing pile damage. These criteria are followed until normal driving conditions are encountered when the normal criteria established for the piles can be used for acceptance.

Agency:	North Carolina DOT
Participants:	Chris Chen, Ph.D., P.E. – Technical Support Supervisor
Interview Date:	August 20, 2010; October 12, 2010

Current practices:

- H-piles are commonly used throughout the state; pre-stressed concrete piles are used primarily in the coastal plain. Composite piles (pre-stressed concrete with H-pile "stinger" on the end), open-ended or close-ended pipe piles are used occasionally in the central or coastal regions.
- H-piles driven to refusal on rock or in residual soils. H-piles are often used as friction piles in the coastal plain.
- Wave equation analysis is done for all hammer submittals from contractor. The NCDOT will provide the required blow count (blows per foot) and equivalent set for 10 blows for the required driving resistance.
- Typical criteria will include a minimum tip elevation (for interior bents as stated in the contract plans) and a blow count at minimum stroke/energy based on the wave equation analysis. Piles are to be driven to the resistance as indicated by the blow count or to be driven to refusal for piles on rock.
- Refusal is defined as 240 blows per foot or any equivalent set.
- Minimum tips elevations set for lateral stability for interior pile bents.
- If bearing were not achieved at the estimated elevation, restrikes can be performed (from 4 hours to 1 day). Increasing pile length is also an option.
- PDA is not routinely used for monitoring piles or developing criteria. PDA is mostly used if there is a concern that the pile did not achieve bearing, or concern with pile stresses or damage (constructability).
- PDA tests performed on production piles. Piles typically specified with extra length for either mounting PDA gauges or driving piles deeper to achieve bearing.
- PDA is often used on pre-stressed concrete piles to check potential overstress damage; and used to check bearing if jetting is performed.
- PDA frequency:
  - Follow AASHTO LRFD frequency (higher PDA frequency) if AASHTO resistance factors were used in design.

  - Specify frequency (lower PDA frequency) and location within NCDOT policy for lower resistance factors.

- PDA is often used for pipe piles to verify bearing.
- Restrikes are used generally 35-40% of the time for friction piles (H or open-ended pipe piles) in the coastal plain; typically to check piles that do not achieve resistance at end of drive. Restrikes, in general, are not used for displacement piles (pre-stressed concrete piles or closed-ended pipe piles). Also, restrikes are not used in the piedmont residual soils.

<u>Concerns, problems, or challenges in current practices:</u>

- Due to variability across the state, wave equation analysis is done for every project. Would like to develop some guidelines or approval charts to attempt to allow some projects to not have wave equation analysis for hammer approval.

<u>Specific Techniques:</u>

- If there is a concern with pile bearing or constructability issues (such as overstressing the piles) during the design phase, the PDA testing will be specified. Tests will be performed on the first production pile. Non-production test piles, in general, are not used.
- If piles do not meet initial driving criteria during installation, the PDA may be used to verify that the bearing has been achieved, or to adjust the driving criteria. Depending upon PDA test results, Engineer may decide to lower the required bearing (lower driving resistance in LRFD or lower factor of safety in ASD) or to drive pile deeper (pile splicing may be required and will be more expensive). As a precautious strategy, Engineer will specify PDA tests in contract plan in case PDA tests are needed.
- On larger projects on the east coast of the state where concrete piles are used, a design phase testing program may be performed to assist in establishing pile order lengths, as well as the driving criteria.
- When the PDA tests are performed, signal matching with CAPWAP is also performed.
- The pile resistance and soil parameters from the CAPWAP analysis are used to perform adjusted wave equation analyses to provide the driving criteria (blow count and minimum stroke/energy at the minimum tip elevation).
- If setup is anticipated for clay soils, restrikes with the PDA may be used to verify bearing and provide a restrike blow count for acceptance when production piles do not meet target resistance and are checked after setup has occurred.

Agency:	Ohio DOT
Participants:	Jawdat Siddiqi, P.E. – Assistant Administrator /Foundation Engineer
Interview Date:	October 22, 2010

Current practices:

- ODOT typically uses either H-piles driven to refusal on rock, or cast in place piles (closed-end pipe piles filled with concrete) used as friction piles.
- H-piles
  - Designed for bearing on rock.
  - The specified resistance is based on the limiting structural resistance of the pile.
  - H-piles rarely used as friction piles. Only such use is in boulder fields.
  - For piles bearing on competent hard rock, the pile tip elevation is specified. For piles bearing in weathered rock, the pile tip elevation is not specified. The refusal criterion is specified.
  - Refusal criterion is 20 blows per inch.
- Cast-in-place pipe piles
  - The closed-end pipes are typically 12, 12, or 16 inch diameter with wall thickness ranging from ¼ to ½ inch.
  - Designed for friction resistance using a resistance factor of $\Phi = 0.7$ based on high strain dynamic testing (HSDT).
  - The resistance of cast-in-place pipe piles is a specified effective geotechnical resistance for a given pile diameter and wall thickness. The effective geotechnical resistance values are based on an evaluation of the hammers typically used by the contractors in Ohio.
- HSDT (PDA testing) with signal matching analysis (CAPWAP) is required for all friction piles. A minimum of two HSDT per pile size and resistance are required at each bridge structure. For example, if a bridge has 120 ton and 150 ton 12 inch cast-in-place piles, there will be 4 HSDT performed.
- Friction piles are typically driven to a resistance, not a specified length. Piles can have varied lengths on a structure or within a substructure unit.
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- The criteria are established for the end of initial drive (EOID) conditions. Setup is not typically considered.
- Criteria consist of a blow count at a minimum hammer energy/stroke for each pile size and resistance.
- When setup is considered, piles will be driven to a specified tip elevation. Setup will be confirmed through restrike tests.
- Static load tests are only used if the quantity of pile (each size and resistance combination) exceeds 10,000 linear feet for a project. SLT data are only used for confirmation of resistance.
- Site variability is addressed by requiring a soil boring at each substructure and requiring the piles at the substructure to be designed according to that boring. Site variability is also addressed during installation by having the pile criteria based on driving to the required resistance as determined by HSDT, rather than driving to a specified length.
- Have had one recent project with large diameter open-ended pipe piles. An interior ring was installed in the piles to encourage plugging to allow for reliance on end bearing. All piles were subjected to HSDT with restrikes to evaluate setup. The required resistance was not achieved at EOID.

Concerns, problems, or challenges in current practices:

- Working through issues of making sure consultants evaluate the constructability of pile designs. Currently the piles can be designed by a consultant, but the WEAP analysis is done by the contractor to select the hammer. Design consultants are not always considering drivability in their designs.

Specific Techniques:

- Bearing pile are H-piles driven to refusal, with resistance limited by the limiting structural resistance.
- Friction piles are closed-end pipe piles driven to required resistance based on HSDT.
- CAPWAP analysis or other HSDT data is not used to adjust wave equation analyses. It is only used to determine resistance and hammer performance for the driving criteria.
- Static load tests are only used if pile quantity exceeds 10,000 linear feet for any pile size and resistance combination.
- Static load tests are not incorporated into the driving criteria.

Agency:	Utah DOT
Participants:	Jon Bischoff, P.E. - Geotechnical Engineer Darin Sjoblom, P.E. – Geotechnical Engineer
Interview Date:	August 19, 2010

Current practices:

- Mostly use 12in diameter closed-end concrete-filled pipe piles in alluvial soils (layered sands, gravels, and clays). Lake bottom clays are the predominate soil.
- Often relying on setup to achieve required resistance.
- Typical criteria is drive to an estimated length (with minimum length) with blow count for stroke (diesel) or hammer energy (hydraulic) at the tip after verification by PDA. Minimum hammer energy is always specified.
- Minimum embedment usually based on settlement (serviceability), or trying to get to a specific dense layer for bearing.
- Typically trying to tip in a denser layer for some base resistance, but sometimes have piles with side resistance only.
- Typically do a HSDT test w/PDA on first pile with a restrike w/PDA to verify setup.
- Struggle with setup exceeding hammer capabilities to demonstrate resistance. Many of the local contractors do not have hammers large enough verify resistance if design is for large resistance. Try to avoid such problems with verifying resistance by not specifying high capacity piles – limit to 600kips – to avoid problems with verification of resistance.
- Will combine EOID base resistance with restrike side resistance (CAPWAP for both) when hammer can't demonstrate required resistance at restrike due to the hammer being too small.
- Relaxation is rare.
- Test pile is almost always a production pile. Pre-production test piles are rare.
- Internal "rule of thumb" for test quantities is 1 HSDT per substructure unit. If it is phased construction, then each phase has one HDSDT per substructure unit.
- Static load tests are very rare. Conditions are so variable that there is concern with extrapolating the results to a broad area. What is acceptable when the variability is great? Doing a static test at each bridge is not economical when PDA, CAPWAP have good experience, results.

Concerns, problems, or challenges in current practices:

- Continue to have issues with consultants understanding the design process. There are misunderstandings or differences of opinion as to some of the methods/processes in the AASHTO design code. The most significant is the issue of downdrag. UDOT does not agree with the AASHTO code process, believing it leads consultants to overestimate (doubling) downdrag effects. UDOT uses the neutral plane method (Fellenius, 1989) for settlement calculations.
- Most consultants are good with wave equation analysis, but some designs still not consistent with the WEA or misunderstand WEA. Design is not constructable.
- UDOT likes using the PDA and CAPWAP. Their opinion was that 2007 AASHTO required too many HSDTs to get the resistance factor, but that 2010 AASHTO is more reasonable.

General approach to static design:

- Consultants mostly use programs (FHWA DRIVEN or other commercial products).
- UDOT uses Unified Pile Design method – Beta Method (Fellenius, 1989). The Beta method (effective stress method) is used for both sands and clays.
- Still struggle with settlement – how large to make the footing at the neutral plane for analysis. Typically use FHWA methods to determine size of footing at the neutral plane with some adjustments based on judgment.
- SPT is most common field data. CPT is also significant, especially when liquefaction concerns/analysis. CPT is not usually used on in-house designed projects due to difficulty of contracting the service. Consultant-designed projects and design/build projects commonly use CPT.
- Beta is correlated to the site investigation with SPT, CU triaxial, and direct shear (granular) test data. The effective parameters (drained) from Cu tests are used for analysis.

Conclusion/Wrap Up:

- UDOT relies heavily on setup demonstrated by restrikes for pile resistance.
- Piles are usually drive to bearing in a dense layer while achieving a minimum blow count at a specific stroke/energy. Occasionally drive to tip elevation only – no dense bearing layer.
- Using the PDA during initial drive and on restrikes of the first pile (or one of the first) in each substructure unit is a significant part of verification of driving criteria.
- Occasionally will do additional restrikes (both with and without PDA) after setup if there are concerns that it does not have required resistance.

References:

Fellenius, B.H. 1989. “Unified Design of Piles and Pile Groups”, Transportation Research Record 1169, pp75-82. Transportation Research Board, Washington, D.C.

Agency:	Washington DOT
Participants:	Tony Allen, P.E. – State Geotechnical Engineer
Interview Date:	September 11, 2010

Current practices:

- Most common pile type is cast-in-place shell (closed end pipe), 24in diameter (range can be 18in to 36in). The marine division typically uses 30in to 36in diameter open-ended pipe piles, and for trestles and docks, 18in precast piles.

- Most of the state has silt and sand sediments, with piles driven to dense glacially overridden deposits. In the southern portion of the state near the Columbia River, the medium dense to dense sands are relatively deep, so piles are typically designed to rely heavily on side friction resistance. At the north end of the state is an area called the Bellingham Drift that has clay soils with significant setup. These clayey materials are also very deep, requiring that piles be designed to depend heavily on side friction resistance.

- The WSDOT driving formula is used to determine pile resistance during driving for most piles. The formula is correlated to wave equation predictions and field test data as documented in "Development of the WSDOT Pile Driving Formula and Its Calibration for Load and Resistance Factor Design (LRFD)" WA-RD 610.1, March 2005, and Allen, T.M., 2007, "Development of a New Pile Driving Formula and Its Calibration for Load and Resistance Factor Design," *Transportation Research Record 2004*, Washington, DC, pp. 20-27.

- HSDT with CAPWAP is used in the marine division where there are significant uplift requirements and often difficult driving conditions. HSDT also used for piles larger than 30in diameter, as well as on very large projects. HSDT with CAPWAP is more likely to be used for friction piles, particularly if significant setup expected.

- When HSDT is used, typically on the first production pile in a pier, and then periodically to monitor hammer performance. For bridge piers, 1 to 2 piles per pier are tested. Marine terminals have all piles subject to uplift tested.

- Wave equation analysis is used to evaluate hammers if the required nominal pile resistance is over 300 tons.

- SLT is not common at this time. Projects with large diameter piles will typically have one SLT. It may also be used for very large projects, unusual pile types/sizes, or unusual conditions.

- In the Bellingham Drift where significant setup is anticipated, restrike data is used to determine acceptance. WSDOT has past load test data demonstrating the approximate relationship of setup with time. For current projects where such deposits are present, restrikes with PDA and CAPWAP are used at each pier to adjust acceptance.

- When driving, if required resistance is met after meeting minimum tip elevation requirements, driving is stopped. Piles are not usually driven to grade once the required resistance is achieved.

- If the required resistance is not met at the estimated design tip, a restrike may be used after allowing the pile to set, or the pile will be spliced and driven deeper. Contractual issues are taken into consideration when using pile splices.

Concerns, problems, or challenges in current practices:

- Selecting the appropriate static resistance calculation methods for large diameter piles

- Developing design and driving criteria for large diameter piles.

- Predicting and evaluating the development of a soil plug in open-ended pipe piles.

- Predicting the amount of setup that is likely to occur.

Specific Techniques:

- If WSDOT formula is the acceptance criteria, the inspector just uses the formula. Required blow counts are developed as a function of hammer stroke. If wave equation and/or HSDT are used for acceptance criteria, the inspectors will have a series of curves for blow count as a function of stroke to achieve the required resistance. If the wave equation is used, it is typically used in combination with HSDT (PDA) and CAPWAP.

- When wave equation and HSDT plus CAPWAP are used for acceptance, the wave equation analysis is used to estimate the blow count required, using the HSDT and CAPWAP to refine the wave equation input parameters to develop driving criteria. Then the pile is driven to that to that blow count. The resistance as given by the PDA is not relied upon to determine acceptance, but HSDT plus CAPWAP resistance may be relied upon for acceptance or to correlate with the Wave Equation output to match, as much as possible, the resistance predicted by the CAPWAP analysis and the transferred energy measured by the PDA. Production piles are driven to the blow count criteria predicted by the correlated wave equation analysis.

- Typically, when significant setup is anticipated, the end of Initial Drive (EOID) CAPWAP resistance is used to establish the end bearing resistance of the pile, and the Beginning of Redrive (BOR) CAPWAP resistance is used to establish the skin friction resistance for correlating to the wave equation for the development of driving criteria.

- When Static Load Tests are used:
  - SLT data can be used to back correlate soil parameters and then adjust the static pile analysis. Piles are then driven to a design tip elevation based on the revised static analysis. The blow count is ignored for pile acceptance in that case. This approach would only be used where piles are driven into deposits that are likely to have a lot of setup that takes a long time to develop.
  - If HSDT data is available with SLT data, the wave equation analysis is adjusted using the CAPWAP results (soil resistance distribution, quake, damping, etc.) to correlate to the SLT resistance. A blow count and stroke relationship can then be provided to the inspector.
  - If more than one SLT is done, then the data may or may not be averaged, depending on the consistency of subsurface conditions at the site. If multiple SLT's are done, it is more likely that the results of each test would be applied to a given portion of the site that has a stratigraphy that is consistent with the stratigraphy at the SLT site.
  - If the SLT resistance is significantly greater than the resistance determined by CAPWAP from HSDT data, the dynamic results will usually be scaled up to correlate to the SLT results. If the dynamic results are significantly higher than the SLT, the results may or may not be scaled.

Abbreviations used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation