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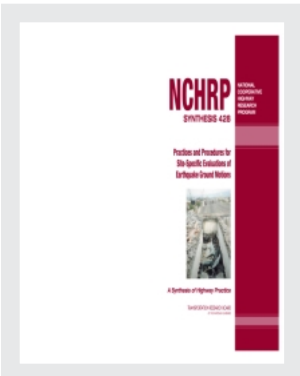

Practices and Procedures for Site-Specific Evaluations of Earthquake Ground Motions

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP SYNTHESIS 428

Practices and Procedures for Site-Specific Evaluations of Earthquake Ground Motions

A Synthesis of Highway Practice

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TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
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Cover figure: Damage to the Nimitz Freeway following the 1989 Loma Prieta earthquake (*courtesy of*: Dr. Neven Matasovic).

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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 20-5, "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 study identifies and describes current practice and available methods for evaluating the influence of local ground conditions on earthquake design ground motions on a site-specific basis. Information includes criteria used to determine when a site-specific analysis is needed, how to develop input parameters required for a site-response analysis, the nature of the site-response analysis performed (equivalent-linear, total stress nonlinear, effective-stress nonlinear), the process of model setup, and how uncertainties are dealt with in the analysis process. Information was gathered by a literature review and a survey of state departments of transportation and selected academics.

Neven Matasovic, Geosyntec Consultants, Huntington Beach, California, and Youssef Hashash, University of Illinois at Urbana-Champaign, 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.

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PRACTICES AND PROCEDURES FOR SITE-SPECIFIC EVALUATION OF EARTHQUAKE GROUND MOTIONS

SUMMARY

The current AASHTO specifications for seismic design mandate site-specific evaluation of the earthquake design ground motion (i.e., the acceleration response spectrum) for ground conditions termed Site Class F. In the AASHTO specifications, Site Class F soils include soft clay sites. These AASHTO specifications also allow discretionary site-specific analyses for other ground conditions and a reduction in mapped design ground motions of as much as 33% if justified by a site-specific ground motion analysis. Some state departments of transportation (DOTs) are taking advantage of this site response reduction provision, particularly in cases where pore pressure generation could lead to soil liquefaction.

For Site Classes C, D, and E, AASHTO's tabulated site response adjustment factors (site factors) are typically used to adjust mapped values of ground motions. However, as stipulated in AASHTO's recommendations, site-specific site response analyses have also been used in these circumstances as an alternative because the site factor approach may be inappropriate under some conditions. Of particular concern is the adequacy of the site factor approach in evaluating the response of short period structures (fundamental period of the site, $T_o < 0.5$ sec) on shallow bedrock sites (i.e., depth to bedrock less than 100 ft), and of longer period structures ($T_o > 1.0$ sec) at deep soil basin sites (e.g., depth to bedrock greater than 500 ft).

For years, the equivalent-linear total stress approach, as programmed in one-dimensional (1-D) site response analysis codes (e.g., SHAKE) has been the primary method used to evaluate the influence of local ground conditions on earthquake design ground motions on a site-specific basis. However, this type of analysis has limitations: (1) for strong shaking at some sites owing to nonlinear site response effects resulting in large shear strain response, which is not properly captured in the equivalent-linear soil models; (2) at sites where soils have the potential to develop significant seismically induced excess pore water pressures, including soil liquefaction; and (3) at soft clay sites subject to moderate intensity/long-duration motions, because the analysis cannot take the effects of cyclic degradation into consideration.

This synthesis study identifies and describes current practice and available methods for evaluating the influence of local ground conditions on earthquake design ground motions on a site-specific basis. The study focuses on evaluating the response of soil deposits to strong ground shaking, and therefore does not address representation of structural response. In accordance with current practice, the study's primary focus is on one-dimensional (1-D) site response analysis (both equivalent-linear and nonlinear). Two-dimensional (2-D) and three-dimensional (3-D) analyses are discussed, but at a more limited level. The synthesis study consists of a literature review and a survey of current practice.

The literature review revealed significant developments in the area of nonlinear site response over the past decade, including studies to define usage protocols of total stress nonlinear site response analyses. New generations of generic dynamic material property sets (e.g., modulus reduction and damping curves, and seismic pore water pressure generation model parameters) have also been developed and are now available for use in site

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response analyses. The review also showed increasing availability of commercial 2-D analysis software for site response analysis with pore water pressure generation. However, there is a lack of agreed-upon protocols for both 1-D and 2-D nonlinear site response analysis with soils that have potential for significant pore water pressure generation.

The survey identifies survey participants, survey questions, methods of processing survey responses, and relevant findings of the survey. Most of the survey participants were from state DOTs and their consultants. Selected academic researchers also participated in the survey. DOTs invited to participate in the survey included the AASHTO Highway Subcommittee on Bridges and Structures, Technical Committee T-3 states (Seismic Design) (Alaska, Arkansas, California, Illinois, Indiana, Missouri, Montana, Nevada, Oregon, South Carolina, Tennessee, Washington), plus DOTs of Georgia, Hawaii ($T\text{-}3^{+}$), Massachusetts, New York, Rhode Island, and Utah, and their consultants. The respondents represented DOTs/firms of various sizes; some described their own practices and others the practices of their DOTs or firms. The survey questions encompassed criteria used by the respondents to determine when a site response analysis (through computer software) is required; development of input parameters required for a site response analysis; nature of site response analysis (equivalent-linear, total stress nonlinear, effective-stress nonlinear) performed; and the process of model setup and development of model input parameters. The survey also asked about how uncertainties are dealt with in the analysis process and the practice for evaluating the results of site response analyses, as well as the use of site response analyses in further engineering analyses.

The survey reveals widespread use of both equivalent-linear and nonlinear site response analyses by DOTs and other participants. A significant portion of the DOTs' analyses use nonlinear site response analyses, including analyses with pore water pressure generation for liquefaction evaluation. Use of 2-D numerical models in site response evaluation, although limited, appears to be increasing. The issues associated with the use of both nonlinear effective-stress and 2-D software include development of adequate input parameters and ground motions, verification and validation of the results, evaluation of uncertainty, and vertical site response. The survey respondents provided a wide range of answers on a number of key issues in site response analysis, including input motion, material properties, analysis procedures, and use of results. The responses illustrate the lack of consensus and the need to develop guidance on these important issues.

The study concludes with a list of research topics suggested by the survey participants and identified from the literature review. The topics include benchmarking of site response models with pore water pressure generation, shear wave velocity correlation evaluation, benchmarking of 2-D and 3-D analysis codes, vertical site response, and calibration with recent (i.e., the 2011 Tohoku, Japan, earthquake) data. Research in these topics will facilitate future reliable use of advanced analysis techniques in highway engineering practice.

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CHAPTER ONE

INTRODUCTION

AASHTO specifications for seismic design, including both the 2009 Interim AASHTO Load and Resistance Factor Design (LRFD) Bridge Design Specifications and the 2009 Guide Specifications for LRFD Seismic Bridge Design, mandate site-specific evaluation of the earthquake design ground motions (i.e., the acceleration response spectrum) for ground conditions termed Site Class F. In the AASHTO specifications (AASHTO 2010a), Site Class F soils are soft clay sites. These AASHTO specifications also allow discretionary site-specific analyses for other ground conditions and a reduction in mapped ground motions by as much as 33% if justified by a site-specific ground motion analysis. Some state departments of transportation (DOTs) are taking advantage of this site response reduction provision, particularly in cases where pore pressure generation could lead to liquefaction. Furthermore, there is some evidence, part of which is based on the authors' experiences, that the AASHTO site factors, used to adjust mapped values of design ground motions for local ground conditions, may be inappropriate under some conditions. For example, they may not be appropriate for short period structures (fundamental period of the structure, $T_o < 0.5$ sec) at shallow bedrock sites (that is, depth to bedrock less than 100 ft), and for structures with a relatively long predominant period ($T_o > 1.0$ sec) at deep soil basin sites [e.g., depth to bedrock greater than 500 ft (Park and Hashash 2005a, 2005b)]. Site-specific analyses are also being used in these circumstances as an alternative to the use of AASHTO site factors.

For years, the equivalent-linear total stress approach, as programmed in one-dimensional (1-D) site response analysis codes, has been the primary method used to evaluate the influence of local ground conditions on earthquake design ground motions on a site-specific basis. However, this type of analysis has limitations: (1) for strong shaking at some sites owing to nonlinear site response effects resulting in large shear strain response; (2) at sites where there is a potential for significant seismically induced pore water pressure buildup, including soil liquefaction, because it cannot consider the effects of pore pressure generation; and (3) at soft clay sites subject to moderate intensity/long-duration motions as it cannot consider the effects of cyclic degradation.

A number of nonlinear site response analysis methods have become available over the past decade and are now being used in practice, including methods that account for deep soil basin effects and for pore water pressure generation. Significant expertise is required to conduct and interpret the results from these newer methods, often leading to questions about the validity of results. For instance, experience with the newer nonlinear analysis methods show that strains (and hence stiffness reduction) may become more localized than in an equivalent-linear total stress analysis. As a result, details of the soil profile, particularly soft layers and impedance contrasts, can have a larger effect on the results of a nonlinear analysis than they do on the results of an equivalent-linear analysis. Furthermore, all available methods of site response analysis (including equivalent-linear total stress analysis) require significant expertise and numerous discretionary decisions. For example, the analysis requires selection of an appropriate suite of time histories and a determination as to whether the small strain modulus and other soil properties should be measured in the field and/or laboratory or obtained using correlations. The analysis also requires decisions on the extent of sensitivity analyses and what modulus reduction and damping curves to use. More expertise and discretionary decision making is required with nonlinear methods than with equivalent-linear analysis and is greatest with analyses that consider pore pressure generation and dissipation. Commentary within the AASHTO specifications cautions the reader of potential issues when conducting site-specific ground motion studies, but the commentary does not provide guidance on the nature of these issues, and how or when to consider these potential issues. This lack of guidance raises concerns as to whether appropriate estimates of site-specific ground motions are being made for design, potentially resulting in either excessive project construction costs when ground motion response is overestimated or unacceptable risk to the public when ground motion response is underestimated.

This synthesis study identifies and describes current practice and available methods for site-specific analysis of earthquake ground motions. The study is primarily concerned with the response of soil deposits to strong ground shaking and, as such, does not address representation of structural response. The study's primary focus is on one-dimensional (1-D) analyses as this represents both the majority of site response analysis work to date and current state of practice. Two-dimensional (2-D) and three-dimensional (3-D) analyses are discussed, but at a limited level.

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This study starts with a discussion of current knowledge based on a review of technical literature and contacts with select publishers and software authors (researchers) for clarification. As a part of the documentation of this literature search, an attempt was made to identify and explain key concepts involved in current site response analysis practice. The study also summarizes experience gained in developing and employing these methods, including challenges in their application and perceived advantages and disadvantages of the different methods.

The literature search is followed by a survey of current practice. Most of the survey participants were from state DOTs and their consultants. Selected researchers also participated in the survey. DOT's invited to participate in the survey included T-3 states (Alaska, Arkansas, California, Illinois, Indiana, Missouri, Montana, Nevada, Oregon, South Carolina, Tennessee, Washington), plus DOTs of Georgia, Hawaii (T-3^{+}), Massachusetts, New York, Rhode Island, and Utah, and their consultants. The respondents represented DOTs/firms of various sizes; some were describing their own practices and others the practices of their DOTs or firms.

As appropriate, the synthesized survey results are related to findings from a review of current knowledge. The research and development needs identified through the work and survey responses documented here are provided at the end of this study.

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CHAPTER TWO

CURRENT STATE OF EVALUATION OF SITE EFFECTS ON GROUND MOTIONS

INTRODUCTION

Site-specific evaluation of earthquake ground motions includes a number of contributors such as soil stratigraphy, basin effects, regional geology, topographic relief, and soil-foundation-structure interaction (SFSI). The study of basin effects, regional geology, and topographic relief impacts on ground motions are primarily in the domain of engineering seismology and remains primarily in the realm of research. Code-based factors (e.g., Eurocode 8; EC8 2000) have been introduced to account for these effects, but site-specific evaluation of these effects for highway facilities is rare and will not be discussed in this study. Attempts have been made to capture some of these effects on a more limited basis through the use of 2-D and 3-D analyses and will be briefly addressed in that context only. The study of SFSI effects is an area under rapid development, mostly by structural engineers. An overview of these effects relevant to geotechnical engineers can be found in Kramer (1996) and more recently in Kramer and Stewart (2004) and is beyond the scope of this study.

This study focuses on evaluation of local soil deposit-related site effects as illustrated in Figure 1. The presentation is primarily focused on horizontally layered soil deposits, including other soil deposits and earthen structures that can be approximated as the horizontally layered soil deposits. Both total and effective stress conditions are addressed. The focus of this study is on practical applications relevant to design and analysis of highway facilities.

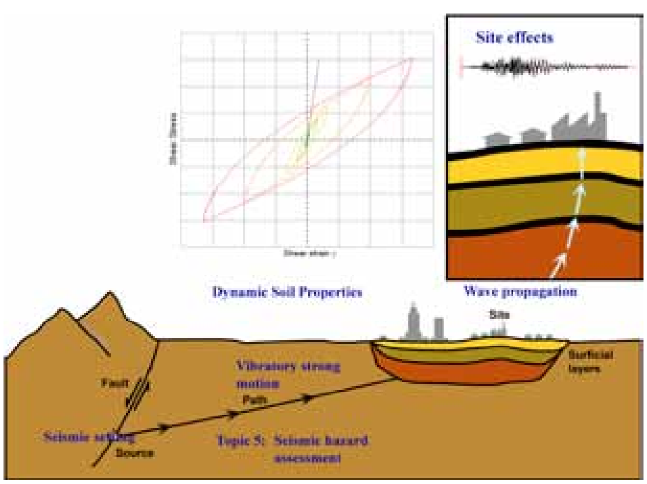

FIGURE 1 Framework of site response analysis.

SITE RESPONSE EVALUATION APPROACHES

Three general approaches can be used to evaluate soil (i.e., site) effects on ground motions: (1) the attenuation relationship approach, (2) the code-factor approach, and (3) the site response analysis approach.

The attenuation relationship approach uses attenuation relationships or ground motion prediction equations (GMPE) that consider local site effects, including soil conditions. While older attenuation equations distinguish only between soil and rock, recently published Next Generation Attenuation (NGA) relationships (e.g., Abrahamson et al. 2008) can provide ground motion prediction as a function of shear wave velocity (V_s), including velocities based on ASCE 7-type site classes that are also adopted by IBC 2006 (International Code Council 2006). In this approach, a response spectrum is developed and can be used directly in a spectral analysis. If needed, ground motions would have to be separately generated through some form of spectral matching, which will be discussed later.

The second approach for assessing soil effects on ground motions computes rock outcrop (surface rock) response spectrum using a rock attenuation equation and then modifies the rock spectrum by generic soil amplification factors such as the F_{PGA} (used in AASHTO); F_a, and F_v factors in Tables 11.4-1 and 11.4-2 of ASCE 7; or other published sources such as EPRI (Electric Power Research Institute 1993), Rodriguez-Marek et al. (2001), or Stewart et al. (2003). As in the first approach, a response spectrum is developed and can be used directly in a spectral analysis. If needed, ground motions can be generated separately through some form of spectral matching, which will be discussed later.

The third approach calls for evaluation of local site effects by conducting a detailed site response analysis using computer software. The site response analysis approach for evaluation of site effects on ground motions is widely used (see also the survey synthesis section, chapter four). This approach is favored by Geotechnical Earthquake Engineers as it takes into account the unique geotechnical characteristic (i.e., "seismic signature") of a site. The approach uses back analysis of numerous case histories and works well when the profile has significant impedance contrast and

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when material (model) parameters are established through a reasonable site characterization effort (e.g., Kwok et al. 2006, 2008).

A site response analysis is commonly performed under many conditions: (1) when soil conditions cannot be reasonably categorized into one of the standard site conditions; (2) when empirical site factors for the site are not available (e.g., such as site class F); (3) when special ground conditions govern the design (e.g., soil liquefaction, seismic settlement, lateral spreading, and slope stability); (4) for any case where the objective is to obtain ground motions considered to be more representative of the local geologic and seismic site conditions than motions obtained from the first two approaches; or (5) where (nonlinear) SFSI analysis is undertaken.

The attenuation relationship approach outlined above is addressed in greater detail elsewhere (e.g., Kramer 1996; Kramer and Stewart 2004; Abrahamson et al. 2008). The code-factor approach is also addressed in these references and in relevant codes (e.g., AASHTO 2010a; IBC 2006). The third approach for evaluation of soil effects on ground motions, commonly referred to as site response analysis, is discussed in detail in this study.

The report presumes that the reader has basic familiarity with earthquake engineering, geotechnical earthquake engineering, and soil behavior. The reader is referred to a book such as *Geotechnical Earthquake Engineering* by Kramer (1996) and *Dynamics of Structures* by Chopra (2006) for this background information.

SITE RESPONSE ANALYSIS METHODS

Site response analysis methods can be classified by the domain in which calculations are performed (frequency domain or time domain), the sophistication of the constitutive model employed (linear, equivalent-linear, and/or nonlinear), whether effects of pore water pressure generation are neglected or not (total-stress and effective-stress analyses, respectively), and the dimensionality of the space in which analysis is performed (1-D, quasi 2-D, 2-D, and 3-D). Other considerations in classifying site response analysis methods include modeling of cyclic reduction and degradation in a total-stress mode.

The following section describes the input required for site response analysis, followed by a discussion of the various methods available for site response analysis with increasing complexity: (1) frequency domain equivalent-linear analysis; (2) nonlinear time domain total stress analysis; and (3) nonlinear time domain effective-stress analysis.

INFORMATION REQUIRED FOR SITE RESPONSE ANALYSIS

A number of numerical techniques are available for site response analysis, including 1-, 2-, and 3-D equivalent-linear (frequency domain) and nonlinear (time domain) analysis approaches. All these techniques require a common set of information and input.

The input to site response analysis requires (1) input ground motion time histories; (2) identification of subsurface conditions, including geometry, stratification, and depth to bedrock and groundwater; and (3) specification of basic and advanced material properties for each layer of subsurface soil and of bedrock, such as unit weight and shear wave velocity (or low-strain shear modulus) and shear modulus and damping as a function of shear strain. More advanced analyses require additional soil properties (e.g., saturated hydraulic conductivity and wet and saturated unit weight), model (i.e., curve-fitting) parameters, and hysteretic and viscous damping model parameters (Rayleigh damping parameters for frequency dependent formulations).

Not all of the above-listed input information has the same influence on the results of the site response analysis. In most cases, input ground motions have the most influence on the results of site response analysis. The near-surface shear wave velocity profile and material nonlinearity (e.g., the modulus reduction and damping ratio curves) are, as noted by Roblee et al. (1996), the parameters that predominantly control ground motion response expressed by the acceleration response spectrum. Detailed information on the "uncertainty" related to soil property evaluation and assessment of spatial variability of ground motions can be found in Jones et al. (2002) and in Kwok et al. (2007).

Input Ground Motion Time Histories

It is generally recognized that the selection of input ground motion is one of the primary contributors, if not the primary contributor, to uncertainty in site response analysis. Various codes and design guidance documents outline procedures for selection of design ground motions. For example, ASCE (2006) (ASCE 7-05, Chapter 21, Section 21.1.1) requires that "at least five recorded or simulated rock outcrop horizontal ground motion acceleration time histories be selected from events having magnitudes and fault distances that are consistent with those that control the MCE [Maximum Considered Earthquake]." To further minimize the uncertainty related to selection of design ground motions, ASCE 7-05 also requires that the time histories be scaled such that the average acceleration response spectrum of each time history is approximately at the level of the MCE rock acceleration response spectrum over the period range of significance to

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structural response. The *AASHTO Guide Specification for Seismic Isolation Design*, 3rd Edition (AASHTO 2010b) requires the use of three sets of time histories (a single set consists of two horizontal components and a vertical component). If three time-history analyses are performed, then the maximum response is used for design. If seven or more time-history analyses are performed, then the average of the response parameter of interest may be used for design, per the same code.

In general, regardless of the source cited, the approach for the development of site-specific design ground motions (acceleration time histories and/or acceleration response spectra) considers two steps: initial selection of time histories, and modification of time histories.

The initial selection of time histories includes records that closely match the site tectonic environment, controlling earthquake magnitudes and distances, local site conditions, response spectral characteristics, and, for geotechnical evaluations, duration of strong ground shaking. Both recorded time histories from past earthquakes and carefully generated synthetic time histories may be used. Multiple time histories are considered; the number of records depends on the type of analysis and the modification method used (discussed below).

The most popular sources of this information on the Internet are the PEER Strong Motion Database (www.peer.berkeley.edu), COSMOS Virtual Data Center (http://db.cosmos-eq.org), and the KiK-net Digital Strong-Motion Seismograph Network (www.kik.bosai.go.jp). PEER provides records mostly for crustal seismic events and offers a search tool that facilitates the selection of records based on a number of site and seismogenic parameters. For subduction events, the COSMOS website provides records from a number of subduction zones around the world. Records for Japan are available from the KiK-net network. For areas in the Central and Eastern United States that lack an adequate number of recorded events, synthetic accelerograms are generated from the hazard deaggregation at the site, performed through the U.S. Geological Survey national seismic hazard mapping project website (http://eqint.cr.usgs.gov/deaggint/2002/index.php).

Modification of time histories is required because the initially selected time histories often differ from the design motions in terms of shaking peak amplitude and response spectral ordinates; they would need to be modified for use in analysis. Two modification methods are commonly used in practice: simple scaling approach and spectrum matching approach.

In the simple scaling approach, the entire time history is scaled up or down so that its spectrum approximately matches that selected for design (*target spectrum*) over the period of interest. Bommer and Acevedo (2004) present a series of recommendations applicable to the selection of real records for engineering analysis. Kottke and Rathje (2007) developed a semi-automatic procedure that facilitates the selection of a suite of motions from a user-provided library of records, and the scaling of the selected motions so that their average fits a target response spectrum. Baker et al. (2011) (http://stanford.edu/~bakerjw/gmselection.html) developed a similar procedure, with time histories scaled up or down to match the target spectrum at a predominant period of the facility of concern.

For the spectrum matching approach, a carefully selected time history (seed motion) is adjusted either in the frequency domain by varying the amplitudes of the Fourier amplitude spectrum, or in the time domain by adding wavelets in iterations until a satisfactory match to the target spectrum is obtained. Spectral matching is considered to be an “art” (Abrahamson 2008) as it requires certain skills to produce a single time history that typically replaces three to four natural records. At a minimum, magnitude, distance, spectral content, and rupture directivity need to be considered when selecting a seed motion. An example of time history successfully matched to design (target) spectrum is shown in Figure 2.

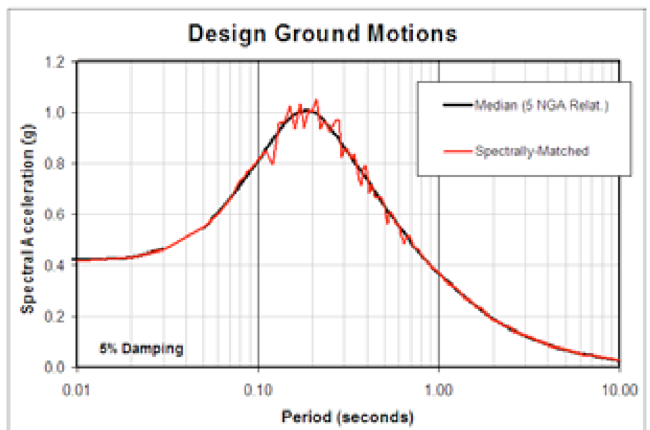

FIGURE 2 Spectrum matching approach for selection of design time histories.

The spectrum matching approach is gaining acceptance as the structural design is steadily moving away from a code-based response spectrum approach to a response spectrum developed as a part of site response analysis. This approach is especially convenient for engineers because it calls for analysis based on matching of suites of ground motions to a single spectrum, hence no “enveloping” of shear forces and moments generated by multiple time histories is required. It is also adopted for geotechnical applications (e.g., Greater Vancouver Liquefaction Task Force 2007). “User friendly” software for modifying the seed record in the time domain is available, either in stand-alone form (e.g., the original RspMatch by Abrahamson 1992; RspMatch 2005 by Hancock et

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al. 2006; RspMatch 2010 by Al Atik and Abrahamson 2010) or as part of software suites (SHAKE2000/D-MOD2000, Ordonez 2000; Matasovic and Ordonez 2007).

For sites near faults, the ground motion time history needs to include additional characteristics beyond spectral matching. These include directivity, velocity pulses, and fling effects (e.g., Somerville 1998; Munfagh et al. 1999; Bray et al. 2009). Significant specialized expertise is required to properly represent these effects in ground motion time histories; discussion of these issues is beyond the scope of this report.

Typically, the input time histories for site response analysis are specified as rock outcrop acceleration time histories that are then modified within the program to represent time histories in bedrock underlying the site. For nonlinear analysis, an "outcropping" motion is used in a simulation by introducing a layer representing an elastic half space (transmitting boundary) at the base of the soil column. Similarly, an "in-hole" (i.e., "within") motion, commonly obtained from a downhole array, is used in a simulation by using a rigid half-space. Some site response analysis programs, such as PLAXIS, OpenSees, and ABAQUS, allow the input motion to be entered as acceleration, velocity, or displacement time history. On the other hand, FLAC allows the input motion to be entered only as a velocity time history.

In areas where "competent rock" is too deep (e.g., Mississippi embayment where competent rock is at depths of 1 km or more south of Memphis), significant debate remains as to what depth could be used in site response analysis, what material/shear wave velocity needs should represent "competent rock," and what type of design motion can be used at such depth (e.g., simulated motion, bedrock outcrop motion, or deconvoluted motion).

Recent research at the Pacific Earthquake Engineering Research Center (PEER) by Haselton (2009) and Baker et al. (2011) provides a detailed review on the topic of ground motions selection and scaling with a focus on structural applications. Baker et al. (2011) introduce a new ground motions selection procedure whose response spectra match a target mean and variance. The procedure avoids the use of spectral matching approaches by taking advantage of availability of the large PEER ground motion data base. The literature review and experience clearly indicate that ground motion selection, scaling, and matching for site response analysis remain unsettled issues and more studies are needed in this area to provide better guidance to practicing engineers.

Definition of Subsurface Stratigraphy

A site response analysis requires detailed information on subsurface stratigraphy. A thorough field investigation is required to understand the geologic history of the soil deposits and define the soil and rock units and water level at a site. The shear wave velocity profile and its variability across the site is another key parameter. Direct measurement of the shear wave velocity is now commonplace using techniques such as the seismic cone penetration test (sCPT), downhole logging, suspension logging, Refraction Microtremor (ReMi), and spectral analysis of surface waves (SASW) techniques. The details of field investigations to characterize the soil profile is beyond the scope of this report and can be found in other sources (e.g., Kavazanjian et al. 1997a,b; Sabatini et al. 2002).

Development of Soil Properties

Site response analysis also requires index properties such as density, Atterberg limits, and relative density of the various layers. Strength properties such as friction angle and undrained shear strength are important input properties, especially for soft soils and areas with high levels of shaking. In addition to these properties, dynamic soil properties of the soil layers need to be defined. Laboratory tests using cyclic triaxial, cyclic direct simple shear (DSS), and resonant column devices are by far the most common devices for defining the dynamic behavior of soils at a given site. These tests hinge on the availability of high-quality undisturbed samples, which might be available for cohesive soils, but are difficult to obtain for cohesionless soils.

Cyclic laboratory tests are therefore not as commonly available, and engineers often rely on standardized dynamic soil response curves in the form of normalized modulus reduction and damping curves as a function of shear strain that approximate the nonlinear hysteretic soil behavior. Figure 3 shows the hysteretic stress strain behavior of soils under symmetrical cyclic loading by (1) an equivalent shear modulus (G) that corresponds to the secant modulus through the endpoints of a hysteresis loop; and (2) equivalent viscous damping ratio (β), which is proportional to the energy loss from a single cycle of shear deformation. Both G and β are functions of shear strain amplitude (γ), as can be inferred from Figure 3a. Plots of shear modulus normalized by the maximum shear modulus and damping as a function of shear strain are then developed, as shown in Figure 3b.

Over the years, a number of standardized families of curves have been developed and used in the practice. These include Seed and Idriss (1970), Vucetic and Dobry (1991), EPRI (1993), and more recently, Darendeli (2001) and Menq (2003). These curves are used in both equivalent-linear and nonlinear site response analysis.

EQUIVALENT-LINEAR SITE RESPONSE ANALYSIS

The equivalent-linear analysis approach was first introduced by Seed and Idriss (1970) and has remained substantially the same since. The wave propagation through the soil deposit is

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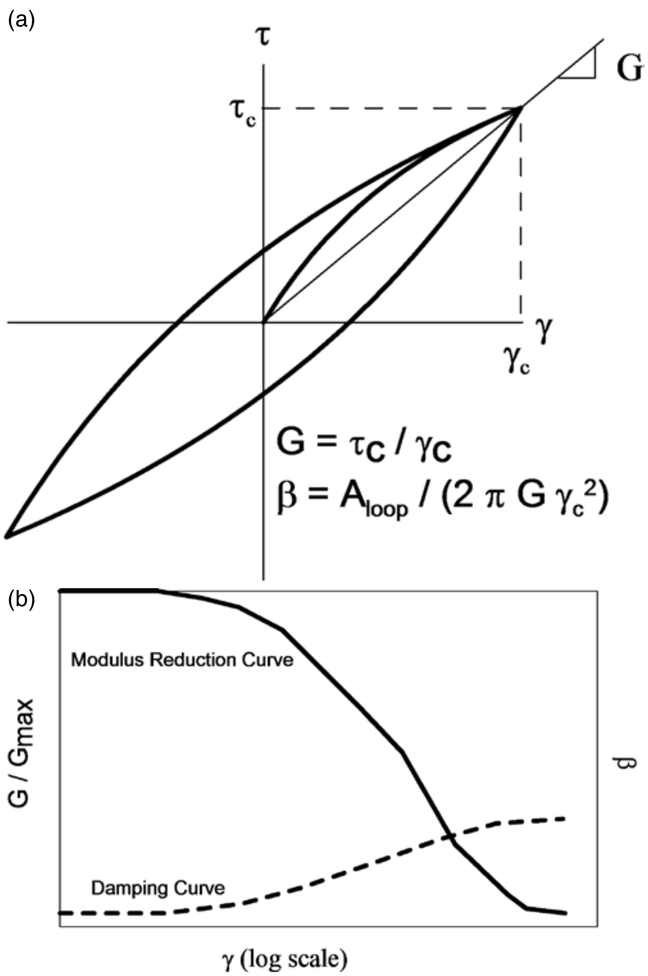

FIGURE 3 Approximation of soil nonlinear behavior (a) Hysteresis loop of soil element loaded by a single cycle of shear strain; (b) Variation of normalized modulus (G/G_{max}) and ρ with shear strain (γ) (modulus reduction and damping curves).

solved in the frequency domain, and any given soil layer is assumed to have a constant modulus and damping throughout shaking. Equivalent-linear site response analysis uses an iterative procedure in which initial estimates of G and β are provided for each soil layer. Using those linear, time-independent properties, linear-elastic analyses are performed and the response of the soil deposit is evaluated. Shear strain histories are obtained from the results, and peak shear strains are evaluated for each layer. Effective shear strains are calculated as a fraction of the peak shear strains. The effective shear strain is then used to evaluate an appropriate G and β using shear strain–dependent normalized modulus reduction and damping curves described earlier. The process is repeated until the strain-compatible properties are consistent with the properties used to perform the dynamic response analyses and the analysis converges.

Equivalent-linear modeling of site response is based on a total-stress representation of soil behavior. The soil properties needed for equivalent-linear site response analysis are shear wave velocity V_s, used to compute $G_{max} = \rho V_s^2$, mass density of soil ρ, and strain-dependent normalized modulus reduction and damping curves.

As indicated in the survey responses, the equivalent-linear site response analysis method is, by far, the most widely used method for evaluation of site-specific ground motions. Advantages of the equivalent-linear method include its requirement for few, well-understood, input parameters, broad experience with its application, a large publicly available database of input parameters, and minimal computational effort.

The most commonly used equivalent-linear computer code is SHAKE (Schnabel et al. 1972). Modified versions of this program include SHAKE91 (Idriss and Sun 1992) and SHAKE2000 (Ordonez 2000). DEEPSOIL (Hashash and Park, 2001, 2002; Hashash et al. 2011), ProShake (EduPro Civil Systems 1999), CyberQuake (Modaressi and Foerster 2000). These programs use the same computational procedure as that applied in SHAKE, but they were developed independently. The equivalent-linear model has also been incorporated in 2-D site response programs such as QUAD-4 (Idriss et al. 1973), derivatives of QUAD-4 (e.g., QUAD4M, Hudson et al. 1994), and in advanced 2-D and 3-D site response models such as FLAC (Itasca 2005; latest iteration is Version 6.0).

Modified frequency-domain methods have also been developed (e.g., Assimaki and Kausel 2002; Kausel and Assimaki 2002) in which soil properties in individual layers are adjusted on a frequency-to-frequency basis to account for the strong variation of shear strain amplitude with frequency. This approach is used as a proxy for representation of nonlinear site response analysis in time domain. Another, although rarely used, improvement includes the introduction of a vertical component of ground shaking into the analysis (Idriss et al. 1973). Vertical site response analysis remains a research topic.

Another, less used method for equivalent-linear site response analysis is the random vibration theory (RVT, e.g., Rathje and Ozbey 2006), based on the equivalent-linear method. The advantage of this approach is that the user does not need to develop input ground motion time histories, and the analysis will directly provide a surface spectrum. Recent work (E.M. Rathje, personal communication, 2011) shows that the use of RVT with a single set of soil profile properties results in amplifications of the peaks of the transfer function that is not observed in conventional equivalent-linear analysis approaches. These peaks can be reduced if the soil profile properties are randomized (e.g., Monte Carlo simulation of material properties).

The equivalent-linear analysis approach has been in use since the advent of SHAKE in 1972. Hence, it is supported by a number of verification studies, including back-analy-

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ses and comparison with other analysis models (e.g., Seed et al. 1988; Idriss 1990; Dickenson et al. 1991; Idriss and Hudson 1993; Kavazanjian and Matasovic 1995; Darragh and Idriss 1997; Rathje and Bray 2001; Baturay and Stewart 2003). Based on the findings of these studies and authors' experience, the following critique applies to the equivalent-linear analysis:

- Equivalent-linear analysis is a total-stress analysis; hence, it does not account for pore pressure generation and its effect on material properties during shaking;
- This method is not recommended when the levels of shaking-induced shear strains are "high." There is no consensus on the limiting ("high") shear strain level. Studies by the authors have shown that results of equivalent-linear and nonlinear analyses start to diverge at strains as a low as 0.1%–0.2%. At strains greater than 0.5%–1% at any depth (layer) within the soil profile, the equivalent-linear analysis results are not necessarily reliable. Recently, Assimaki et al. (2008) proposed the use of a frequency index that measures the frequency content of incident ground motion relative to the resonant frequencies of the soil profile. This index is then used in conjunction with the rock-outcrop peak ground acceleration (PGA) to identify conditions where incremental nonlinear analyses, including the equivalent-linear approach, should be used instead of approximate methodologies.

Despite its apparent shortcomings, the total-stress equivalent-linear analysis is likely to remain a tool of choice for many practicing engineers and may have a slightly different and expanded role. In particular, this approach is now used not only as the "first approximation" of site response, but also for calibration of more advanced models, including nonlinear and effective-stress analyses.

Many of the modulus reduction and damping curves were based on small strain data (testing shear strain typically reaching 0.5% to 1.0%). These curves are then extrapolated at strain levels exceeding 0.5%–1%. However, the results of site response analyses increasingly show calculated strains increasing to 1.0%, especially in soft soils. CalTrans (Jackura 1992) recognized that the implied strength associated with the extended curves might either underestimate or overestimate the actual strength of soils, so the agency developed an-in house simplified procedure for "extension" of modulus reduction and damping curves. Recently, Chiu et al. (2008) and Hashash et al. (2010) proposed advanced procedures to remedy this arbitrary extrapolation of subject curves in both equivalent-linear and nonlinear analysis. Most recently, Stokoe (K.H. Stokoe, personal communication 2011) pointed out this problem and urged that a remedy approach be developed.

NONLINEAR TOTAL STRESS SITE RESPONSE ANALYSIS

In nonlinear site response analysis, the nonlinear behavior of the soil during cyclic loading can be represented, which makes it possible to move away from the inherent linear approximation of the equivalent-linear analysis approach. Cyclic hysteretic soil behavior during unloading and reloading is also represented in the nonlinear site response analysis. Furthermore, nonlinear analysis makes it possible to explicitly include soil strength and the effects of seismic pore water pressure generation on soil strength and stiffness. These options have significant effects on site response in areas of very high seismicity (e.g., PGA ≥ 0.4 g) and/or when soft and/or potentially liquefiable soils are present in local soil deposits.

In total stress site response analysis, the explicit interaction of pore fluid with the soil matrix is neglected. This is an acceptable simplification under many conditions and is numerically efficient. Kwok et al. (2007) conducted a detailed study of the total stress nonlinear site response analysis software. The study provides an excellent review of the various issues associated with this type of analysis. Kwok et al. (2007) noted the following nonlinear software that were evaluated as a part of the PEER 2G02 Project (2005–2007; J. Stewart Project Director): DEEPSOIL (Hashash and Park, 2001, 2002; Hashash et al. 2011); D-MOD_2 (Matasovic 2006; later upgraded to D-MOD2000); OpenSees (Ragheb 1994, Parra 1996, Yang 2000); SUMDES (Wang 1990, Li et al. 1992); and TESS (Pyke 2000). The study was able to identify key controlling parameters that are common to all software. The study found that when input is properly controlled, most of the software provided similar results. Hashash et al. (2010) provide a description of recent developments in nonlinear site response analysis and highlight key steps and issues required for conducting such analyses.

In nonlinear site response analysis the dynamic equation of motion is solved in the time domain. The equation is commonly written as:

$$[M]\,\{\ddot{u}\} + [C]\,\{\dot{u}\} + [K]\,\{u\} = -\,[M]\,\{\ddot{u}_g\} \quad (1)$$

where $[M]$, $[C]$, and $[K]$ are the mass matrix, viscous damping matrix, and nonlinear stiffness matrix, respectively; $\{u\}$, $\{\dot{u}\}$, and $\{\ddot{u}\}$ are, respectively, the displacements, velocities, and accelerations of the mass $[M]$ relative to the base, and $\{\ddot{u}_g\}$ is the acceleration of the base.

The stiffness matrix $[K]$ is derived from the nonlinear soil constitutive model selected to represent cyclic soil response. In principle, all damping in the soil can be captured through the hysteretic loops in the soil constitutive model. However,

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as a practical matter, most available soil constitutive models cannot properly represent measured soil damping at low strains and significantly underestimate damping at these low strains. Therefore, it is necessary to add damping through the use of velocity proportional viscous damping [C].

The dynamic equation of motion can be solved by numerical integration. The numerical integration calls for temporal discretization (i.e., system of coupled equations is discretized temporally) and solution by one of the available time-stepping schemes. Examples of time-stepping schemes include Wilson's θ algorithm (Clough and Penzien 1993) and numerous variations of Newmark's β algorithms (Newmark 1959).

To solve the equation of motion, it is necessary to discretize the domain of interest, which in this case is the soil column. Two different approaches for discretization of the soil domain are available: (1) lumped mass discretization and (2) finite element discretization.

Figure 4 shows a lumped mass model that depicts a horizontally layered soil deposit (i.e., a soil deposit that can be represented by a 1-D model). Soil mass is lumped at the layer interfaces, and soil stiffness is represented by (nonlinear) springs. The figure shows the hysteretic damping inherent with nonlinear springs and viscous damping, which is also part of the model. This model is used in nonlinear analysis software such as DESRA-2/DESRA-2C, DESRAMOD, DESRAMUSC, SUMDES, TESS, D MOD_2/D-MOD2000, and DEEPSOIL, and in many Japanese programs that are not reviewed here.

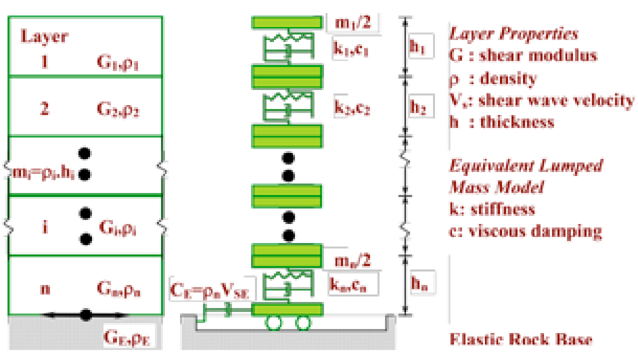

FIGURE 4 Lumped mass discretization for 1-D Nonlinear Hysteretic Site Response Model (Matasovic 1993).

A number of other programs discretize the soil domain by means of finite elements; the details of this approach are not discussed here. For dynamic problems, the equations of motions are solved using an explicit time marching integration algorithm. For example, TESS (Pyke 2000) and FLAC (Itasca 2005) use an explicit finite difference to solve the wave propagation problem. Programs such as OpenSees (Ragheb 1994; Parra 1996; Yang 2000), ABAQUS, and PLAXIS use a finite element method with explicit time integration to solve the same dynamic equation. Program PSNL, currently under development (S.L. Kramer personal communication, 2011; see description in Anderson et al. 2011) models soil profile as a continuum and can simulate dilation.

Most nonlinear codes are formulated to calculate site response in one horizontal direction of shaking, although some such as SUMDES (Wang 1990) and OpenSees (Ragheb 1994; Parra 1996; Yang 2000) allow for multidirectional shaking.

A sample 2-D finite element model (OpenSees) is shown in Figure 5. Such a model allows for simultaneous application of excitation in both horizontal and vertical directions.

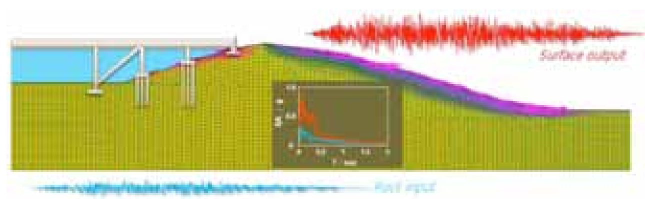

FIGURE 5 Mesh representation of 2-D Nonlinear Site Response Analysis of Embankment (Nikolaou 2011).

Regardless of the discretization method used in nonlinear site response analysis, the thickness of sublayers in a model has important consequences. The layer thickness determines the maximum frequency that can be propagated through a soil column. If the layer is too thick, the discretized domain may filter important components of the ground motion and thus underestimate the ground response. If layer thickness is too small, the computational cost can be too high. Therefore, as a practical matter, 1-D nonlinear site response models will usually have greater (i.e., finer) discretization than their 2-D and 3-D model counterparts, and thus will propagate higher frequencies and filter less of the input ground motion. The survey results in this study indicate that users of 2-D and 3-D software are not always aware of this important limitation. The graphical user interfaces can help alert the user to the maximum frequency that can be propagated. Several 1-D software (e.g., DEEPSOIL and D MOD2000) have such alerts incorporated in graphical users interfaces.

Nonlinear Constitutive Models with Hysteretic Damping

Nonlinear total stress site response analysis is generally done with relatively simplified soil constitutive models. These models evolved from the early stress-strain relationships of Ramberg and Osgood (1943) and Kondner and Zelasko (1963). The hyperbolic model introduced by Duncan and Chang (1970) for axial soil behavior, which was based on the above-cited shear stress and strain behavior models, was accompanied by sets of generic material properties and hence allowed for an elegant and simple way to capture soil nonlinearity at small axial strains. All three models provided the basis for constitutive models

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that are presently in use. These models (Pyke 1979: Matasovic 1993; Matasovic and Vucetic 1993; Darendeli 2001) provide for better simulation of nonlinear stress-strain behavior and also allow for simulation of cyclic loading and reloading in accordance with certain rules. The stress-strain relationship in these models is generally established by: an initial loading curve; a series of rules that describe the backbone curve (see Figure 6 for definition of backbone curve); and unloading-reloading behavior rules required to establish cyclic loops. The most widely used rules are the Masing rules (Masing 1926) and extended Masing rules (Pyke 1979; Wang et al. 1980; Vucetic 1990). The extended Masing rules, including unloading-reloading rules, are used in several 1-D site response analysis software (DESRA 2C, TESS, D-MOD_2, DESRAMOD, D MOD2000, and DEEPSOIL).

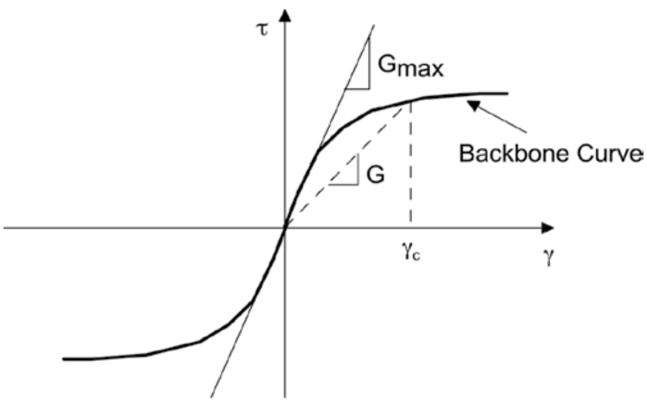

FIGURE 6 Backbone curve as stress-shear strain relationship for monotonic loading.

It has been long noted that the use of Masing rules, and to some extent extended Masing rules, leads to an overestimation of soil damping at large strains. This, in turn, may result in an underestimation of calculated ground motion intensity. To compensate for this phenomenon, Darendeli (2001) proposed the introduction of reduction factors in the development of his family of standard curves. Phillips and Hashash (2009) used a similar approach to introduce a modification to the Masing rules (MRDF) and employed that in the MRDF model used in DEEPSOIL. Figure 7 from Hashash et al. (2010) illustrates the limitations of the Masing rules (MR) and extended Masing rules (MRD) in terms of overestimation of damping at large strain levels (MR at strains > ≈0.1%; MRD at strains > ≈1%) and improvement in matching of both damping and modulus reduction curves with MRD and MRDF. Matasovic (1993) showed that using MR rather than MRD may result in a higher computed surface acceleration response and/or a shift in the response spectrum when relatively high shear strains are induced in the profile. Philips and Hashash (2009) further showed that MRD, as compared with MRDF, may result in a higher computed surface acceleration response and/or a shift in the response spectrum at strain levels exceeding approximately 1%.

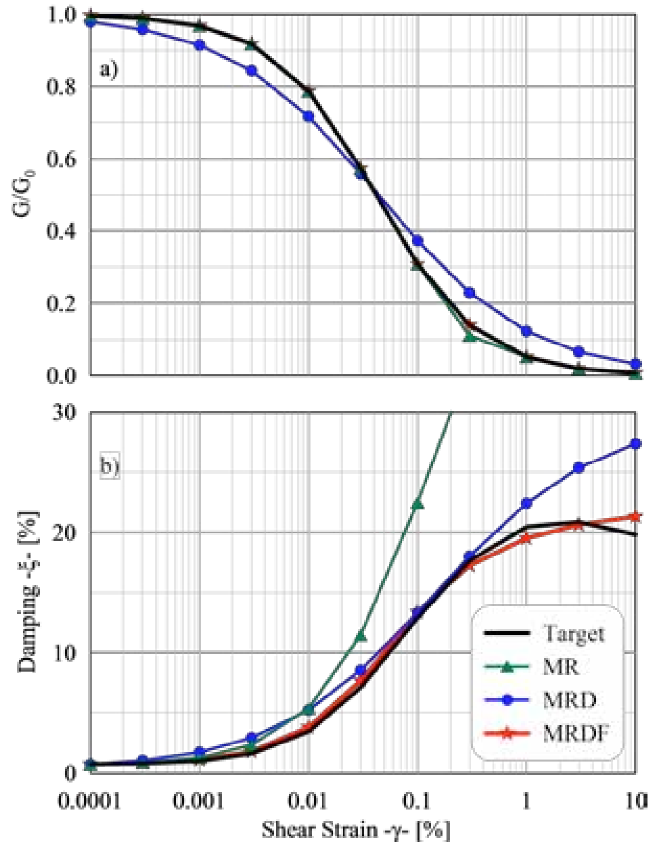

FIGURE 7 Evaluation of proposed damping reduction factor (a) modulus reduction and (b) damping curve using Darendeli's curves for cohesionless soils as target.
Note: MR = modulus re-matching only with extended Masing rules, MRD = approximate match of both modulus and damping with extended Masing rules, MRDF = modulus reduction and damping matching with non-Masing rules (after Hashash et al. 2010).

Assimaki and co-workers (e.g., Assimaki et al. 2009) have also made important contributions to a number of the above-cited issues related to site response. Their work includes the incorporation of uncertainty in site response analysis and addresses the issues related to unloading-reloading rules and damping at larger strains.

Borja et al. (1999, 2002) developed a software called SPECTRA, a 1-D nonlinear total stress site response analysis program that uses a bounding surface plasticity model to simulate stress-strain behavior. SIREN (Oasys 2006) and LS Dyna (LSTC 1988) can be used to perform total stress site response analysis.

Viscous Damping Models

Most available constitutive models show very small hysteretic damping at small strains, which is inconsistent with measured soil behavior. Viscous damping is introduced to compensate for this deficiency. The amount of viscous damping is typically selected such that the sum of hysteretic and viscous

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damping is equal to the total damping measured for the given soil type. Historically, the important role of viscous damping in site response analysis was not well understood; it was thought that this was mostly needed for numerical stability. This assumption led to significant confusion in the way it was employed and, in some cases, led to unrealistic results in nonlinear site response analysis resulting from either over or under damping. Viscous damping represents soil damping at a very small strain, so its value is generally small, typically in the range of 0.5% to 5%. It can be directly obtained from the intercept of the damping curve with the vertical axis in the damping versus shear strain curve.

The most commonly used formulation for evaluation of viscous damping is Rayleigh damping. The Rayleigh damping is frequency dependent and can be evaluated as:

$$c = \alpha_R \mathbf{m} + \beta_R \mathbf{k} \tag{2}$$

where α_R and β_R are the Rayleigh damping coefficients (Rayleigh and Lindsay 1945) and **m** and **k** are elements of the mass and stiffness matrices, respectively.

Figure 8 illustrates how Rayleigh damping, expressed through c, changes with frequency. The viscous damping ratio can be brought closer to a constant value of the target damping ratio (ξ_{tar}) by specifying c at only one frequency (e.g., at f_2 in Figure 8), which is termed the *simplified* Rayleigh damping formulation; at two frequencies (at f_1 and f_2), which is termed the *full* Rayleigh damping formulation (Hudson 1994); and at four frequencies (at f_1 through f_4), which is termed the *extended* Rayleigh damping formulation (Clough and Penzein 1993; Park and Hashash 2004). Park and Hashash (2004) have shown that the use of simplified Rayleigh damping results in significant errors and the extended Rayleigh is computationally expensive; hence, they suggest the use of full Rayleigh damping formulation. Kwok et al. (2007) recommended use of the full Rayleigh damping formulation in nonlinear (total stress) site response analysis whereby the first frequency is equal to the fundamental frequency of the soil column, and the second frequency is equal to 5 times the fundamental frequency. Full Rayleigh damping is available in a number of software, including ABAQUS, CyberQuake (Modaressi and Foerster 2000), D-MOD2000, DEEPSOIL, FLAC, OpenSees, SIREN (Oasys 2006), LS-DYNA (LSTC 1988).

Philips and Hashash (2009) introduced a new viscous damping formulation that is independent for frequencies, which is more consistent with the current understanding of soil response within the seismic frequency range of interest (Park and Hashash 2008). This formulation, used in DEEPSOIL, does not require the user to select frequencies. Many users of site response analysis are not fully aware of the implications associated with the selection of Rayleigh damping frequencies, so this frequency-independent approach eliminates a potentially confusing step in input development.

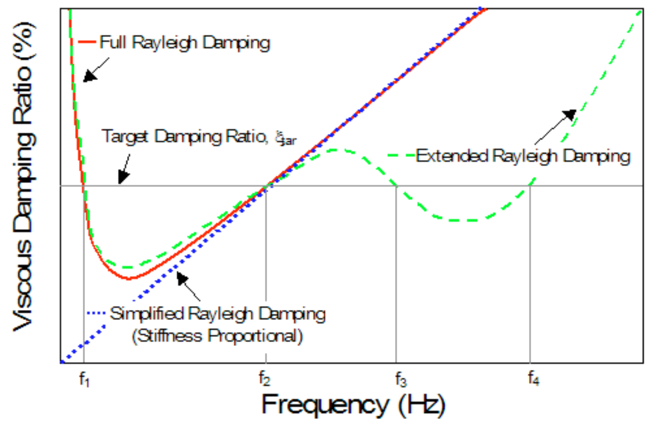

FIGURE 8 Schematic illustration of viscous damping change with frequency (after Park and Hashash 2004).

NONLINEAR SITE RESPONSE ANALYSIS WITH PORE WATER PRESSURE CHANGE

The cyclic loading of saturated soils is accompanied by pore water pressure (pwp) generation and dissipation. If the generated pore water pressures are sufficiently large, the soil stiffness and strength are significantly reduced and ultimately, in some soils, liquefaction can occur. In nonlinear site response analysis with pwp generation, the response of the soil to cyclic loading accounts for the generation of excess pwp during cyclic shearing of the soil as well as dissipation of these excess pore water pressures during and after the cyclic loading. The representation of dissipation/redistribution of pwp influences soil stiffness (modulus) and strength (shear stress) during shaking, which results in a more realistic simulation of site response. The pwp dissipation/redistribution is discussed in a later section. This section discusses pwp generation.

The influence of pwp changes during cyclic loading is incorporated in soil constitutive modeling in two ways: (1) semi-empirical pwp generation models used in combination with total stress soil models; and (2) effective-stress models whereby the pwp change is computed as the change between total stresses (or loads) and effective stresses, computed through the soil constitutive model.

Semi-Empirical Pore Water Pressure Generation Models

In this class of models, pwp generation is calculated using semi-empirical models. At the beginning of shaking (i.e., at time $t = 0$), stress-strain relationships of the soil are identical to that of the total stress models because pwp is zero. As shaking progresses, pwp is generated and cyclic degradation (of clay microstructure) starts. Subsequently, the effects of

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pwp generation and, in some models, of cyclic degradation are included by degradation of soil strength and stiffness. Some models use different factors for degradation of soil strength and stiffness. For example, Matasovic (1993) and Matasovic and Vucetic (1995b) proposed degradation index functions that degrade strength and stiffness of sands at different rates, whereas the concept of the degradation index (Idriss et al. 1978) is used to degrade strength and stiffness of soft clays.

A number of pwp generation models have been developed, starting with Martin and Seed (1978) and Martin et al. (1975). The Martin and Seed (1978) model was implemented in early iterations of FLAC by Dr. Wolfgang Roth (Roth and Inel 1993; W. Roth, personal communication, 2011). The Martin et al. (1975) pwp generation model was used in DESRA-2 (Lee and Finn 1978). A more recent example of the semi-empirical pwp model for saturated sand is the Dobry et al. (1985) model. This model was based on strain–controlled cyclic direct simple shear and cyclic triaxial testing. The model was later modified by Vucetic (1986) to allow for quasi-2-D shaking and further by Matasovic (1993) to more accurately model pwp-induced degradation of shear modulus and shear stress. The Vucetic (1986) modification of this pwp model has been successfully incorporated in DESRAMOD (Vucetic 1986), and the Matasovic (1993) modification has been incorporated in D-MOD (Matasovic 1993; Matasovic and Vucetic 1995b), D MOD_2 (Matasovic 2006) and D-MOD2000 (Matasovic and Ordonez 2007), and DEEPSOIL (Hashash et al. 2011). The pwp generation models described require the use of an equivalent number of cycles to represent earthquake shaking. Polito et al. (2008) introduced an energy-based model (GMP model) for the generation of pwp based on a large number of laboratory tests, which does not require the development of an equivalent number of cycles. This model has been implemented in DEEPSOIL (Hashash et al. 2011) combined with the degradation index framework introduced by Matasovic (1993). With the exception of the modified Dobry et al. (1985) model, as implemented in D-MOD2000, there is limited information to guide the user in selecting the appropriate pwp model parameters.

The effect of cyclic degradation on soil stiffness and strength is illustrated in Figure 9 for the MKZ constitutive model (Matasovic 1993; Matasovic and Vucetic 1995b). The initial hysteretic loop shown in the figure refers to the first cycle of cyclic loading (i.e., at time $t = 0$). The subsequent degraded hysteretic loop refers to any subsequent cycle (i.e., at time t) for which enough pwp has built up to degrade both initial shear modulus G_{mo} and initial shear stress τ_{co} at corresponding shear strain γ_{co}.

An example of a pwp model for clay is the Matasovic and Vucetic (1995a) model. This model was based on the results of cyclic simple shear testing. It can be noted that pwp in clay is of much lower intensity than in sand; and that in overconsolidated clay, both positive and negative (suction) pwp may develop (e.g., Matasovic and Vucetic 1992). Generic sets of material parameters for this model are provided in the D-MOD2000 package.

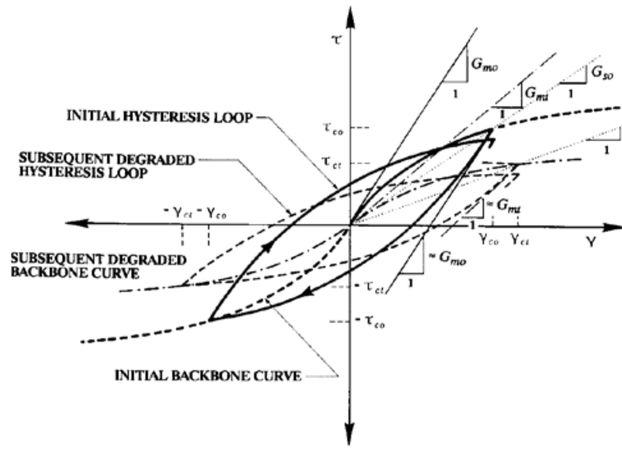

FIGURE 9 Stress-strain behavior modeling illustrating stiffness degradation with the MKZ Constitutive Model (Matasovic 1993; Matasovic and Vucetic 1993).

Advanced Effective-Stress-Based Models

Another class of soil constitutive models used in site response analysis is effective-stress models. In these models, the formulation of the constitutive law is developed in effective-stress space, and pwp is computed as the difference between effective-stresses and total stresses in the domain of interest. Examples of plasticity-based constitutive laws include Roscoe and Schofield (1963), Mroz (1967), Roscoe and Burland (1968), Prevost (1977), Dafalias and Popov (1979), Pestana (1994), Whittle and Kavvadas (1994), Byrne et al. (1995), Manzari and Nour (1997), Beaty and Byrne (1998), and Elgamal et al. (2001). These advanced constitutive models are capable of simulating complex soil behavior under a variety of loading conditions. Key elements of these models include yield surfaces, flow rules, and hardening (or softening) laws. A review of advanced constitutive models with application in site response analysis is provided in Potts and Zdravković (1999).

Generic material parameters for advanced constitutive models are often not available. Evaluation of material parameters for these models requires significant expertise and detailed site-specific soil properties. Examples of site response programs that incorporate advanced constitutive models are DYNA1D (Prevost 1989), SUMDES (Li et al. 1992), SPECTRA (Borja and Wu 1994), AMPLE (Pestana and Nadim 2000), CYCLIC 1-D (Elgamal et al. 2004), CyberQuake (Modaressi and Foerster 2000; Foerster and Modaressi 2007; Lopez-Caballero et al. 2007) and the ground response module in the OpenSees simulation plat-

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form (Ragheb 1994; Parra 1996; Yang 2000; McKenna and Fenves 2001). Other programs that have been used include ABAQUS, ADINA, PLAXIS, and FLAC. The UBC sand model (Byrne et al. 1995; Beaty and Byrne 1998) has gained acceptance in the geotechnical earthquake engineering community and is available in FLAC and more recently in PLAXIS.

Pore Water Pressure Dissipation and Redistribution Models

The layers in a soil column have finite, saturated hydraulic conductivities. Even though loading is relatively rapid during ground shaking, pore water redistribution may occur at that time as a result of differences in hydraulic gradients and hydraulic conductivities between layers, following the principles of Terzaghi's theory of consolidation.

Martin and Seed (1978) introduced an early model for pwp dissipation and redistribution. Input parameters include constrained rebound modulus and (saturated) hydraulic conductivity. The incorporation of such a model in nonlinear codes, such as CyberQuake, DESRA-2C, D-MOD_2, D MOD2000, DEEPSOIL, ABAQUS, PLAXIS, FLAC, and OpenSees, allows for calculation of simultaneous generation, dissipation, and redistribution of pwp during and after shaking. A pwp dissipation model for composite soil deposits (alternating sand and clay layers), developed by Matasovic and Vucetic (1995a), is incorporated in D-MOD_2 and D-MOD2000.

CALIBRATION AND BENCHMARKING STUDIES

A number of individuals and groups have conducted evaluations of site response analysis procedures versus measured response from earthquake recordings and downhole vertical arrays.

Researchers have used a range of inverse analysis techniques to calibrate soil constitutive models in site response analysis procedures to discover soil behavior. These include ad hoc, system identification (e.g., Zeghal and Elgamal 1993; Glaser and Baise 2000; Assimaki and Steidl 2007), and evolutionary soil models (e.g., Tsai and Hashash 2007).

Kramer and Paulsen (2004) conducted an informal survey on the practical use of site response analysis models. They found that 1-D equivalent-linear site response analysis is by far the most commonly used approach and that there is a lack of guidance on use of nonlinear site response analysis, so it is not used often.

A number of benchmarking exercises have also been conducted to evaluate site response analysis tools. A key recent exercise is the PEER benchmarking exercise for total stress site response analyses (Kwok et al. 2007; Stewart et al. 2008). Another interesting benchmarking exercise, the evaluation of site response at Turkey Flat (Real et al. 2006; Kramer 2009), highlighted the challenges in computing the response at a well-constrained relatively stiff soil site. Hashash et al. (2010) provide a recent review of many of the issues associated with 1-D nonlinear site response analysis.

GUIDANCE DOCUMENTS FOR SITE RESPONSE ANALYSIS

The FHWA guidance document for seismic design of highway facilities (FHWA-NHI-11-032: LRFD Seismic Analysis and Design of Transportation Geotechnical Features and Structural Foundations, 2011) is posted at http://www.fhwa.dot.gov/engineering/engineering/geotech/pubs/nhi11032/nhi11032.pdf. In the meantime, an older document (Kavazanjian et al. 1997a, b) that focuses on geotechnical analysis and design of highway facilities, including dynamic site characterization for site response analysis, is still available for download. Several other guidance documents are used in transportation engineering and other seismic design practices. These documents and their websites are listed in Table 1. Many of these documents were referred to by survey respondents (see chapter four).

Most of the DOTs documents follow, in some way, the general guidelines for conducting a site response analysis outlined in AASHTO documents. Some documents discuss the use of equivalent-linear analysis while others discuss the use of nonlinear site response analyses with and without pwp generation. However, with the exception of *NRC RG 1.208: A Performance–Based Approach to Define the Site-Specific Earthquake Ground Motion*, these documents do not provide sufficient guidance on the mechanics and steps required for developing design ground motions, characterizing the site, or performing appropriate site response analysis.

SOFTWARE USED IN PRACTICE

Table 2 lists and classifies currently available site response analysis software. However, any listing of such programs is likely to be incomplete and subject to interpretation.

Table 2 shows that geotechnical engineers have a variety of equivalent-linear and nonlinear software to choose from for 1-D and multidimensional site response analyses. Some of the software is widely used, for example SHAKE and its numerous DOS- and Windows-based derivatives. Some of the Windows-based equivalent-linear software operates as pre-processors and post-processors for SHAKE91 (e.g., ProShake and SHAKE2000), whereas others were written from scratch (e.g., EERA and equivalent-linear mode of DEEPSOIL). The Windows-based software generally offers convenient plotting of input data (soil profile and ground motions) and resulting output. More important, they guide

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TABLE 1
GUIDANCE DOCUMENTS FOR SEISMIC DESIGN

	Document	Website (if available)
1	Caltrans Seismic Design Criteria	http://www.dot.ca.gov/hq/esc/earthquake_engineering/SDC_site/
2	Washington State Department of Transportation, *Geotechnical Design Manual (2011)*	http://www.wsdot.wa.gov/Publications/Manuals/M46-03.htm
3	Illinois Department of Transportation	http://www.dot.il.gov/bridges/brmanuals.html
4	*AASHTO Guide Specifications for LRFD Seismic Bridge Design* (1st Edition) (2010a) Revision to *AASHTO Guide Specifications for LRFD Seismic Bridge Design*	https://bookstore.transportation.org
5	*NCHRP Report 611*	http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_611.pdf
6	ASCE 7-05, ASCE 7-10 (pending) ASCE 4, ASCE 43-05	
7	NRC RG 1.208: *A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion*	http://www.nrc.gov/reading-rm/doc-collections/reg-guides/power-reactors/rg/01-208/01-208.pdf
8	U.S. Army Corps of Engineers EM110-2-6050: *Response Spectra and Seismic Analysis for Concrete Hydraulic Structures*	http://140.194.76.129/publications/eng-manuals/em1110-2-6050/toc.htm
9	Oregon Department of Transportation, *Geotechnical Design Manual*	ftp://ftp.odot.state.or.us/techserv/Geo-Environmental/Geotech/GeoManual/FinalGDM12-1009/Volume1GeotechDesignManualFinal_Dec2009.pdf
10	South Carolina Department of Transportation, Seismic Design Specifications for Highway Bridges	http://www.scdot.org/doing/bridge/bridgeseismic.shtml
11	South Carolina Department of Transportation, *Geotechnical Manual*	http://www.scdot.org/doing/bridge/geodesignmanual.shtml
12	Georgia Department of Transportation, *Bridge and Structures Policy Manual*	http://www.dot.state.ga.us/doingbusiness/PoliciesManuals/roads/BridgeandStructure/GDOT_Bridge_and_Structures_Policy_Manual.pdf
13	Rhode Island LRFD *Bridge Design Manual*	http://www.dot.ri.gov/documents/engineering/br/RILRFDBridgeManual.pdf

TABLE 2
SITE RESPONSE SOFTWARE USED IN ENGINEERING PRACTICE

Dimensions	OI	Equivalent-Linear	Nonlinear
1-D	DOS	SHAKE/SHAKE91	AMPLE, DESRA-2C, DESRAMOD, D-MOD_2, DESRAMUSC, LS-Dyna, SUMDES, TESS, SIREN,
	Graphical User Interface	ShakeEdit, ProShake, SHAKE2000, EERA, DEEPSOIL, WinMOC	CyberQuake, D-MOD2000, DEEPSOIL, FLAC, NERA, VERSAT 1-D
2-D / 3-D	DOS	FLUSH, SASSI, QUAD4/QUAD4M, FLUSH	DYNAFLOW, DYSAC2, TARA-2, TARA-3
	Graphical User Interface	QUAKE/W, SUPER SASSI, SASSI2000	FLAC, PLAXIS, PLAXIS 3D, ABAQUS, OpenSees, VERSAT 2-D

Notes:

1. Only the latest versions of a particular software are listed in Table 2. Full software reference is provided in Appendix C.
2. Several of the listed software have options to use more than one constitutive model, including equivalent-linear, bi-linear, and nonlinear models (e.g., FLAC, PLAXIS, ABAQUS, and D-MOD2000).
3. Several of the listed software have a pore water pressure generation option (e.g., D-MOD2000, DEEPSOIL, CyberQuake, DESRA-2C, DESRAMUSC, OpenSees, PLAXIS, TESS, SUMDES, DYSAC2, and FLAC).

the user through the key elements of the input and reduce the number of errors. The importance of a user interface to enhancing the quality of analysis cannot be overemphasized. FLUSH, SASSI, and QUAD4M are well established and widely used 2-D, DOS-based, equivalent-linear programs. (Windows-based graphical user interfaces are available for QUAD4M and SASSI, but they are proprietary to the United States Army Corps of Engineers and Stevenson & Associates Inc., respectively). QUAKE/W is similar to QUAD4M, but it does not calculate the average acceleration of sliding mass as QUAD4M does and it has a Windows GUI. Nonlinear software for 1-D analyses with GUI are gaining popularity (e.g., as D-MOD2000 and DEEPSOIL in the United States practice; Cyberquake in European practice). Nonlinear 2-D site response software with GUI, such as FLAC and PLAXIS, is also gaining acceptance.

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CHAPTER THREE

APPROACH TO SURVEY OF CURRENT PRACTICE

BACKGROUND

To obtain a better understanding of which practices, procedures, and site response models are used in engineering practice, a formal survey was developed and posted on a website specializing in this type of application. The draft version of the survey was pretested by a select group of DOT representatives. The formal invitations to participate were sent through TRB to a number of individuals that practice in the areas of geotechnical earthquake engineering and structural engineering (structural dynamics). In particular, the invitations were sent to the DOT representatives and consultants identified by DOTs. In the second solicitation for participation in the survey, invitations were sent to consultants identified in the first round by survey participants and the principal investigators (PIs), and also to select domestic and international researchers and software developers identified by PIs.

It should be noted that the list of participants was not developed with any explicit consideration of strict statistical concepts. The results of the survey, therefore, may be biased and unrepresentative of the distributions of site response models and practices that are in use. Nevertheless, the survey fulfilled its original goal of identifying practices, procedures, and site response models used in practice and provided additional insights into the manner in which engineers use those models.

OVERVIEW OF THE SURVEY

The survey covered eight main topics (see Table 3). The topics and their sequence were designed to reflect the steps that a practicing engineering would take in addressing the topic of site-specific evaluation of earthquake ground motions. A number of the questions and topics are similar to those in the survey of Kramer and Paulsen (2004), but the current survey goes into greater detail. The survey starts by asking the respondents questions about their general practice and about the guidelines and manuals they use for site-specific evaluations. The survey then asks respondents about the criteria they use to determine when a site response analysis using computer software is required. The next questions are about the development of input required for a site response analysis, including (1) ground motions and seismic hazard and (2) characterization of properties of the soil column. The survey then presents a series of questions about the nature of site response analysis (equivalent-linear, total stress nonlinear analysis, effective-stress nonlinear analysis) and the process of model setup and development of model input parameters. Respondents are asked about their approach to dealing with uncertainties in the analysis process. Finally, the survey asks respondents about how they evaluate the results of site response analyses and how they use the output from site response analyses in further engineering analyses.

TABLE 3
MAIN SURVEY TOPICS

Topic No.	Topic Description
1	General Practice
2	Criteria and Programs Used in Site Response Analysis
3	Dimensions, Analysis, and Model Type
4	Seismic Hazard Motion Input Required for Site Response Analysis
5	Soil Profile Input Required for Site Response Analysis
6	Site Response Analysis (Procedures, Models, Programs, etc.)
7	Consideration of Uncertainties in Site Response Analysis
8	Evaluation and Use of Results

Although most of the survey's 37 questions were multiple choice, many required that respondents assign percentages to various choices and others requested that users indicate multiple selections where appropriate. Several questions asked respondents to provide additional information within the multiple choices. The respondents were also asked to provide other information if the listed choices were not representative of their practice. Finally, the respondents were encouraged to comment on the general subject matter and on issues that they believed were important to advancing the practice of seismic site response analysis. (See Appendix A for a copy of the survey.)

SURVEY RESPONDENTS

Thirty-seven of the 70 people who were invited to participate in the survey responded. An additional two respondents provided incomplete yet useful responses that were included

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in the analysis, increasing the statistical database to 39. The abbreviated responses provided by e-mail, received from four state DOTs, were not included in statistical processing but were considered as well where appropriate.

We received responses from 16 states, including all T-3 states and 5 of the 6 T-3$^+$ states. The balance of respondents who completed the study were consultants identified by DOTs of T-3$^+$ states, including states that do not perform site response analyses in-house and researchers that were contacted primarily to obtain relevant information about the programs and/or models they developed. This study does not further identify the respondents to preserve the promised anonymity.

The respondents represented DOTs/firms with a wide variety of sizes; some were describing their own practices and others the practices of their DOTs or firms. Some indicated that their responses represented their own views and practices, and others indicated that their responses represented the practice of DOTs and/or firms with many engineers. Figure 10, generated by the survey program, shows the geographic distribution of the survey respondents.

FIGURE 10 Geographic distribution of survey respondents as generated by the survey program.

SURVEY RESPONSES

The full details of the survey responses appear in Appendix B. The authors have examined the responses for regional differences or differences between DOTs of T-3 states and their consultants. The survey responses did not show trends that warrant the separation of the survey into subcategories by respondent type. The following chapter presents a synthesis of the survey findings and are used to evaluate the current state of practice.

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CHAPTER FOUR

SURVEY RESPONSES AND RELEVANT LITERATURE

GENERAL PRACTICE

The first set of questions asked the respondents about the nature of their practice, the number of projects they are involved with, and the design guidance documents they use in site response analysis. Most of the respondents provided responses based on their agency or firm practice, with size varying from a single person practice to large firms with up to 500 engineers. Many of the respondents participated in more than seven projects a year involving site response analysis while a significant number of respondents were involved with only one to two projects a year.

A number of respondents use guidelines for their seismic practice. Information from these documents are shown in Appendix B, Table B4. The most commonly used document is the AASHTO guideline itself or state DOT adaptations of the guideline. However, these guidelines do not provide detailed procedures for conducting a site response analysis.

CRITERIA AND PROGRAMS USED IN SITE RESPONSE ANALYSIS

A number of approaches are available to engineers for conducting a site-specific evaluation of ground motions. These include (1) empirically derived site factors and (2) computer software for site response analysis.

The survey respondents were asked what factors triggered the use of site response analysis versus the use of standard code-based factors. The respondents were also asked to identify conditions in which the use of code-based factors was acceptable (Tables B5 and B6). All respondents indicated that they use code-based factors, especially in preliminary design. Code-based factors are used for class sites other than F, including sites suspected to have high soil liquefaction potential.

The respondents were asked to provide detailed descriptions of conditions whereby the use of site response analysis is required. The respondents provided detailed input on the various options provided in the survey, and this feedback in provided in Table B7 through Table B12. A total of 10 of 32 respondents indicated that they perform site response all the time, which is a significant number indicating that site response analysis is relied upon extensively in engineering practice. Most respondents said that they use site response analysis when they anticipate F and E site classes, soft ground conditions, and liquefaction. Site response analyses are required where a hazard level is high, with varying definitions of what is considered high. Analyses were also required when important or critical structures were being considered, again with a range of definitions as to how a structure is classified.

DIMENSIONS, ANALYSIS, AND MODEL TYPE

The responses showed that 1-D equivalent-linear analyses are by far the most commonly used method in contemporary geotechnical earthquake engineering practice. When T-3^{+} respondents and consulting firms were asked to estimate the percentages of different types of analyses (relative to the total number of site response analyses performed), both said that they used 1-D equivalent-linear analyses much more frequently than other types of analyses (Table B13).

Some respondents pointed out that site response efforts are usually controlled by budget and time constraints. Others expressed concern that equivalent-linear analyses were often used for soft clay and liquefiable sites and for very strong levels of shaking where their inherent assumptions about material behavior are least valid. What is revealing in the responses is that half of respondents perform nonlinear site response analyses, indicating the significant rise in popularity of this type of analyses. This is a marked difference from the findings of Kramer and Paulsen (2004), where few used nonlinear site response analyses.

The computer software used to perform these analyses are listed in Table B14. For equivalent-linear analyses, the most commonly used program is one of the many available flavors of the program SHAKE. A few respondents indicated they used the program DEEPSOIL. For nonlinear analyses, D-MOD (i.e., D-MOD2000) was the most commonly used software followed by DEEPSOIL and then FLAC. Several respondents also listed multipurpose analysis software such as ABAQUS, PLAXIS, and DYNAFLOW. It is worth noting that this reflects U.S. practice. CyberQuake (Modaressi and Foerster 2000) is widely used in a number of European countries.

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The survey also asked the respondents about the software verification and validation procedures (see Table B15). Their answers ranged from none to extensive evaluation to comparisons between software. A number of users conducted equivalent-linear analyses and compared them with nonlinear analyses. Others performed analyses using multiple programs and looked for consistency. Verification and validation are complex and challenging tasks. Although extensive studies are available for 1-D, there is a dearth of 2-D and 3-D verification studies.

SEISMIC HAZARD AND MOTION INPUT REQUIRED FOR SITE RESPONSE ANALYSIS

The seismic ground motion at a site is commonly defined as a target response spectrum corresponding to a given desired hazard level. Such a spectrum can be derived using deterministic or probabilistic seismic hazard analysis. More recently, conditional mean spectrum (CMS) has also been used (Baker and Cornell 2006; Baker 2011). The target response spectrum is developed at an equivalent rock outcrop and then site factors are used to include the effect of local conditions on the ground motions. More recently, with the use of NGA attenuation relationships, the site factors are embedded in the equations through the use of V_{s30} (average shear wave velocity of top 30 meters) as an input parameter (Abrahamson and Silva 2008; Boore and Atkinson 2008; Campbell and Bozorgnia 2008; Chiou and Youngs 2008; Idriss 2008; and USGS 2008). However, the user needs to be familiar with important limitations when using these equations.

A series of questions were posed related to the seismic hazard input used by respondents in the site response analysis. Many respondents rely on U.S. Geologic Survey maps and web tools or their adaptations in various code provisions (AASHTO, ASCE7-05, IBC). However, a significant number of respondents use computer software (EZ-Frisk, RISK-Engineering 2009, Haz-38) or spreadsheets to program ground motion prediction equations (GMPE).

Selection of spectrally compatible ground motion time histories is the next important step in developing input for site response analysis. Many of the respondents selected natural time histories; significantly fewer used synthetic ground motions. Many of the respondents used rigorous spectral matching procedures. RspMatch is by far the most widely used program for development of these motions.

Although a number of respondents indicated that they used up to three ground motions in the spectral matching process, many said that they use seven pairs (two horizontal directions) for site response analyses. A few indicated that they use more. For some projects, respondents said that they needed to use a greater number of motions (say, 15 to 20) to achieve statistically significant results. Many respondents were also aware of the need for special considerations for ground motions, including directivity, and velocity pulses to capture near-fault effects.

The respondents had varying responses to the question of how they handle uncertainty in the selected ground motions, but one common theme was that the motions were allowed to vary to some degree about the target response spectrum. Some said that the degree of deviation was within 50% for the spectrum, whereas others stated that it was within 84 percentile of the ground motion. Clearly, the responses do not reflect a consensus by the respondents.

The respondents generally agreed that the topic of input ground motions needs more work and guidance is needed in this area. A few of the respondents were aware of the significance of using Conditional Mean Spectrum (CMS) in generating input ground motion. Respondents also indicated the need for guidance on generation of ground motions for deep basins where rock depth is great. A respondent indicated that the development of the PEER ground motion toolbox (http://peer.berkeley.edu/peer_ground_motion_database/) is an important step forward.

SOIL PROFILE INPUT INFORMATION REQUIRED FOR SITE RESPONSE ANALYSIS

Site response analyses require information on the soil profile, including stratigraphy, shear wave velocity, location of the water table, and dynamic soil properties.

Most of the survey respondents indicated that they directly measure shear wave velocity—an important parameter. This reflects an important positive development in the profession. Nevertheless, a substantial number of respondents reported that they obtain the shear wave velocity (V_s) profile from correlations of penetration resistance. Significant uncertainty is associated with these correlations, and studies are needed on their validity and alternatives for direct measurement of shear wave velocity.

A number of respondents said that they performed laboratory tests on soil samples to develop dynamic soil properties; however, more respondents indicated that they used modulus reduction and damping curves available in the literature. In addition to the Darendeli, Vucetic-Dobry, and Seed-Idriss curves, the respondents also used EPRI curves. A number of respondents use specialized custom-developed curves.

The respondents were very much aware of the need to account for uncertainty in soil properties, but there was no consensus on the best approach. Several use upper, lower bound soil profile approaches, and a few use systematic randomization approaches (Toro and Silva 2001; Romero

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and Rix 2005). Cost was often cited as a reason for not conducting parametric studies, but a number of the survey respondents indicated that they subcontract this work to specialists/experts.

SITE RESPONSE ANALYSIS

Equivalent-Linear Models

The survey responses reflect a broad range of opinions as to when an equivalent-linear (EL) site response analysis is needed. Most respondents concurred that a site response analysis is needed when dealing with softer soil sites (classes E and F); some indicated that they use them for C and D classes as well. There were no clear criteria on the input PGA that would trigger a site response analysis. Some respondents said that they used it for low levels of seismic hazard, while others reported that they used it when the hazard is high. Most recognized that a nonlinear (NL) site response analysis is warranted for more important structures (e.g., base isolated or long structures).

Equivalent-linear analysis is a robust approach that has been used in the profession for the past 40 years. The literature (e.g., Hashash et al. 2010) indicates that 1-D EL site response analysis can always be performed regardless of whether the higher dimension or nonlinear site response analyses are included. One-dimensional EL site response analyses provide the key characteristics of a site and the propagated ground motion. They can be used to flush out errors that might inadvertently be introduced in more advanced site response analyses.

Equivalent-linear analyses require characterization of dynamic soil properties by modulus reduction and damping curves. A number of relationships for such curves are available in the literature. In the 1970s, separate curves were presented for sands and clays before the effects of soil plasticity and effective confining pressure on soil behavior were well understood. The responses showed, however, that the original sand and clay curves are still widely used in contemporary practice. Other widely used curves include Vucetic and Dobry (1991), EPRI (1993), and Darendeli (2001).

The available literature does not provide a systematic evaluation of the various modulus reduction and damping curves and their applicability. Indeed, the rigorously documented curves of Darendeli (2001) and Menq (2003) have not been yet published in the refereed literature. All these curves are generic in nature and can be selected based on soil index properties and stress history. Only one respondent indicated that they directly measure soil dynamic properties in the laboratory.

The survey indicates that 1-D, equivalent-linear analyses are by far the most commonly used by DOTs surveyed, but this is not the case among their consultants and researchers. The most commonly used program for equivalent-linear analysis is SHAKE2000, followed by DEEPSOIL.

Nonlinear Total Stress Analysis

The survey responses reflect a broad range of opinions as to when a nonlinear (NL) site response analysis is needed. Most respondents concur that a site response analysis is needed when dealing with softer soil sites (i.e., with classes E and F), though, as with equivalent-linear analyses, others reported that they use them for site classes C and D classes as well. There were no clear criteria regarding what PGA input would trigger a site response analysis. Some respondents indicated that they use it only for high PGA levels (PGA > 1.0 g) whereas others indicated a lower PGA threshold (0.4–0.5g). Most respondents recognized that for more important structures (e.g., base isolated and long structures), an NL site response analysis is warranted. There was a consensus amongst respondents that an NL site response analysis could be used when computed shear strains exceed 1%. A number of respondents said that NL analyses are used to reduce demand on a structure.

The responses reflect the occasional confusion about the use and role of site response analysis and the need for greater understanding and guidelines. The use of strain-based criteria for switching to nonlinear analysis is reasonable as this reflects when nonlinear soil behavior becomes important. However, a 1% shear strain threshold is likely too high, as many soils would be at or near failure at this level. Studies by the authors have shown that nonlinearity in soil behavior can affect site response at strains as small as 0.1% or lower. A PGA or ground intensity measure on its own probably will not be sufficient because strain levels in soft soils can be quite high even for what appears to be a low level of shaking. Better guidance is clearly needed on when a nonlinear site response analysis is necessary.

Nonlinear site response analyses use constitutive models that represent nonlinear soil behavior. Models are parameterized in different ways, so comparison is much more difficult than for equivalent-linear site response analyses. The survey responses indicate that the choice of nonlinear soil model was closely tied to the choice of nonlinear site response software, because some nonlinear software does not offer multiple soil models. Modified hyperbolic models with Masing rules were the most widely reported nonlinear soil models. The respondents indicated that they tried to calibrate their models to match both modulus reduction and damping curves.

Nonlinear Effective-Stress Analysis

The survey responses reflect a broad range of opinions as to when an NL effective-stress site response analysis is needed.

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Most respondents concurred that a site response analysis is needed for softer soil sites (classes E and F). There were no clear criteria regarding the input PGA; however, most of the respondents used a lower PGA threshold for NL effective-stress analysis than the threshold used in the NL total stress analysis. For more important structures, an NL site effective-stress response is warranted. There was no consensus among respondents on the pwp ratio threshold for which NL effective-stress analysis results might be considered.

The choice of nonlinear effectives stress soil model was closely tied to the choice of nonlinear site response software. For 1-D site response, Matasovic's (1993) pwp model is used (D-MOD2000, DEEPSOIL), OpenSees users apply the Elgamal model, and FLAC users employ UBC.

EVALUATION AND USE OF RESULTS

Consideration of Uncertainties in Site Response Analysis

The results of site response analyses, like those of all other analyses, are influenced by uncertainties in input parameters. The survey attempted to determine the users' perceptions of where uncertainties influenced the results of site response analyses most strongly and how these uncertainties were accounted for in the design process.

The survey listed a series of input parameters to typical site response analyses and asked which were considered most important. Respondents could (and did) indicate more than one parameter. Many of the respondents consistently indicated that uncertainties in input motions were most important. Several users expressed particular concern in eastern North America where few strong-motion records are available. Uncertainties in material properties (e.g., soil stiffness and damping at high strain levels) were also considered to be important. Few respondents were concerned with damping at small strains even though the literature review highlighted its importance in an analysis. About one-third of respondents considered geometry and bedrock properties to be among the most important uncertainties. A similar number of respondents emphasized material properties and input motions.

A number of different methods for accounting for uncertainties in design were reported. The most common method was the use of sensitivity analysis; details on how the results of sensitivity analyses were interpreted were not requested. About one-third of the total number of respondents based their analyses on best-estimate values of input parameters and then applied some degree of conservatism to the results.

Evaluation of Validity of Site Response Analysis Results

Survey participants were concerned about evaluating the validity of their results and used a number of approaches in this evaluation. They looked for reasonableness of the results and compared the results with empirical correlations such as existing code factors for similar site classes. They also used multiple software and analysis approaches.

Use of Results

Site response analyses provide a range of information that can be used for engineering analyses. Most respondents use the resulting computed surface response spectrum and computed surface time histories. The ground motion is presumably used in the dynamic analysis of the bridge structure. The respondents also said that they use profiles of PGA, shear strains, and shear stresses in their engineering analyses. One respondent reported that the type of output used depends on the type of engineering analysis (structure response versus soil liquefaction evaluation).

A number of respondents indicated that they use the shear strain profile as an input for pile analysis or for tunnel analysis. A few respondents reported that they did perform base line corrections on the output motion. However, many respondents indicated that they either did not perform site response analyses or had specialists/consultants perform these analyses for them.

For the simplified method of soil liquefaction assessment, most respondents reported that they use surface PGA from equivalent-linear analysis. Few respondents, though, indicated that they use computed surface PGA from nonlinear total stress analysis. A number of respondents said that they did not use cyclic stress ratio from site response analysis. Some respondents indicated that they performed effective-stress nonlinear site response analyses. These responses reflect significant confusion and lack of guidance as to the use of site response analysis for soil liquefaction evaluation.

Many respondents indicated that they use PGA, or a percentage of it, in a pseudo-static-type slope stability analysis and for the simplified Newmark-type sliding block analysis. One respondent indicated a preference for a 2-D site response analysis.

Most respondents said that they use pwp generation to evaluate the occurrence of liquefaction in a soil profile. One respondent indicated that the analyses may mask liquefaction potential in the top layers owing to soil softening in the lower layers. Another respondent said that it was difficult to determine pwp parameters required in an analysis. Another indicated the need for further guidance on this issue.

GENERAL COMMENTS ON THE SURVEY

Among the wide range of comments were areas requiring additional guidance. These included (1) vertical site

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response, (2) SFSI analysis, (3) 3-D effects, and (4) 2011 Tohoku, Japan Earthquake data analysis. Most of those surveyed recognize the need for significant project oversight by independent review panels composed of both highly qualified practitioners and academics. Many were also interested in receiving the results of this survey and synthesis.

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CHAPTER FIVE

CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

CONCLUSIONS

Since their introduction in the 1970s, tools and techniques for performing site response analysis have continued to evolve. Advances in both computer hardware and software have played a role in improving analyses. Software developments have resulted in wide and almost exclusive use of site response analysis in practice, as revealed by the survey performed as a part of this study. Moreover, it appears that practitioners can now afford and do perform sensitivity analyses and use larger suites of input ground motions. Nevertheless, significant confusion remains about how to select appropriate input ground motions and the number of ground motion sets needed. Automated graphics capabilities allow error-checking of input data and evaluation of the reasonableness of analytical results. Ground response animation, available in some software, can provide useful insight into site response.

Other improvements to site response analysis practice have resulted from the development of more advanced analytical models, particularly for nonlinear, effective-stress modeling of site response. Multidimensional nonlinear analysis software employing advanced, plasticity-based constitutive models are now available. The survey indicates that one-dimensional (1-D), equivalent-linear analyses are by far the most commonly used by departments of transportation DOTs surveyed, but this is not the case among their consultants and researchers. The most commonly used program for equivalent-linear analysis is SHAKE2000, followed by SHAKE and DEEPSOIL. The survey further reveals that a variety of modulus reduction and damping curves are used to represent equivalent-linear and nonlinear dynamic properties of soil.

It appears that nonlinear models for 1-D analyses are becoming more common in DOT practice, especially among their consultants. The most commonly used program for both nonlinear and nonlinear effective-stress analysis is D-MOD2000, followed by DEEPSOIL and FLAC. Multidimensional nonlinear analyses and multidimensional effective-stress analyses are not used often. Survey participants cite the engineering time required to develop multidimensional models as the main reason for their sparse use. The most commonly used program for two-dimensional (2-D) equivalent-linear site response analysis is QUAD4M, followed by FLAC. FLAC and ABAQUS are the most widely used for nonlinear (i.e., bi-linear) 2-D and three-dimensional (3-D) site response analyses.

The survey respondents recognize that analytical procedures have developed much more quickly than the practical procedures for developing the input parameters those analytical procedures require. The literature search performed as a part of this study reveals a lack of practical guidance documents for multidimensional 2-D and especially 3-D site response analysis.

Dynamic soil properties appear to be most commonly determined by field testing and empirical correlation. Respondents cited uncertainties in input motions as the greatest influence on site response analyses. Finally, sensitivity analyses appeared to be the most common tool for evaluating the effects of uncertainties on computed site response.

It appears that 1-D equivalent-linear analyses have become the *de facto* standard for site response analysis of highway facilities. It also appears that users have concerns about the applicability of equivalent-linear analyses in cases where site-specific response analyses are most useful: soft sites, liquefiable sites, and sites subjected to very strong shaking. The DOT adoption of nonlinear analyses, however, appears to be restrained by uncertainty in how to develop the input parameters required for available nonlinear models, and by the lack of well-documented validation studies for those models. Despite these limitations, more than half of the respondents use nonlinear site response analyses. Nevertheless, consistent with findings by Kwok et al. (2007), these limitations of nonlinear codes must be overcome for nonlinear site response analysis to become more widespread in geotechnical earthquake engineering practice.

SUGGESTIONS FOR FURTHER RESEARCH

The results documented here reveal a mismatch between current practice, as applied for highway facilities in T-3^{+} states, and the state-of-the-art, as implied from the literature search. This mismatch between state-of-the-practice (SOP) and state-of-the-art (SOA) is common in all engineering disciplines. This gap might be narrowed by comparing the survey results to findings of the literature search to iden-

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tify needs and opportunities. Those that appeared the most urgent and the most valuable to survey respondents are outlined below in a relative order of importance.

Benchmarking of One-Dimensional Site Response Analysis with Pore Water Pressure Generation

A landmark benchmarking project was performed in 2006/2007 by PEER (Kwok et al. 2007). The project involved benchmarking available total stress nonlinear site response analysis computer software against theoretical problems, but also included conducting back analysis of relevant case histories. The results of that study, described in a series of presentations and technical papers, speeded up practical application of nonlinear analysis to the levels identified in this survey. (The respondents used nonlinear methods to conduct approximately half of 1-D site response analyses.)

Given the importance of use on nonlinear effective-stress analysis for site class E (soft soils) and site class F (liquefiable soils and very soft clays in the profile), and its gradual increase in use, a rigorous benchmarking study of 1-D nonlinear software with pwp generation should be conducted.

Threshold for Equivalent-Linear Versus Nonlinear Site Response Analysis

Nonlinear site response analyses generally demand more resources and technical expertise than their equivalent-linear counterparts. Therefore, practicing engineers have a keen interest in the development of criteria for deciding when an equivalent-linear site response analysis is acceptable and when nonlinear site response is necessary. The available guidance is not sufficient and a systematic study is needed to develop such guidance.

Input Ground Motion Selection

The selection of input ground motion time histories for site response analysis remains a challenging task. A detailed study should develop guidelines for the selection of seed ground motions, scaling, and spectral matching specific to site response analysis. Such a study should consider issues, including the appropriateness of the input and propagated motions for a number of engineering applications, including liquefaction assessment, bridge design, slop stability, and soil-structure interaction analysis. This research can benefit from a number of recent studies on the ground motions selection for structural applications.

Implied Strength in Modulus Reduction Curves

In site response analyses that mobilize large strains, widely used modulus reduction curves need to be improved so that they can represent the soil constitutive behavior such that the implied strength is reasonable and corresponds to that of the soil profile during shaking.

Benchmarking of Multidimensional Total and Effective-Stress Site Response Software

The survey and literature review show increasing reliance on 2-D analysis software such as FLAC, OpenSees, and PLAXIS to evaluate site response and liquefaction. There is a pressing need for a rigorous benchmarking study of the software being used and usage protocols. This research topic could be considered after 1-D effective-stress site response analysis has been benchmarked.

Benchmarking of V_s Correlations and Evaluation

This survey revealed that most respondents use correlations between standard penetration test (SPT) blow counts and V_s to develop the V_s profile for site response analysis. Although this is generally poor practice, it cannot be entirely avoided given the large legacy SPT data sets available to many DOTs and their (erroneous) belief that direct V_s measurements are cost prohibitive.

Given the importance of the V_s profile in site response analyses, a systematic study of V_s – SPT and other correlations (e.g., $V_s - q_c$ and $V_s - S_u$) could be undertaken. The work would involve a comparison of shear wave velocity profiles established by correlative expressions to the results of actual measurements. It is important that the findings of such a study clearly identify which correlations may be recommended for given site conditions (e.g., should an SPT-based correlation be used when site-specific results of S_u measurements are available?) and the possible range of error. The study would also identify available V_s measurement tools and the relative merits of various V_s measurements, including downhole, sCPT, OYO suspension logging, ReMi, SASW, and MASW.

Evaluation of Liquefaction from Site Response Analysis

The survey revealed significant confusion on the part of the users with regard to the use of site response analysis for liquefaction evaluation either directly from models that generate pwp or indirectly through the use of the simplified method for liquefaction analysis. Guidance on this issue would be greatly welcomed by the profession.

Site Response in Deep Deposits

A challenging issue in site response analysis in deep soil deposits is how to select the depth of the soil column to be considered because the significant impedance contrast can be several kilometers deep. Guidance is needed on conducting site response analysis of deep deposits.

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Vertical Site Response Evaluation

In dynamic analysis of structures and soil structure interaction, 3-D motions are required as input. This survey found that the overwhelming majority of work done on site response analysis is related to horizontal motion. The literature is insufficient on how to handle local site effects on vertical ground motion propagation. Currently, PEER has an effort focused on vertical site response as part of an update of NGA-West. A detailed study on vertical site response would be timely and fill a major gap in the body of knowledge in site response.

Calibration of Nonlinear Site Response Analysis from Recent Japan Earthquake

The March 2011 earthquake in Japan has provided the research community with an extensive data set from multiple large events. This data set includes a significant number of downhole arrays (KiK-net) that have been excited by the main shock as well as by several large foreshocks and aftershocks. This data set provides a unique opportunity to validate and improve site response analysis models. A study that focuses on the use of this data set will be very useful for increasing the reliability of site response analysis procedures, especially for long duration earthquakes, and the proper representation of cyclic soil behavior under repeated cycles of loading, which has been studied only in the laboratory.

Verification and Validation of Software

As DOTs and/or their consultants adopt specific software, or new and improved software becomes available, a need emerges for software use guidance and for software verification and validation procedures. The experience from the recent PEER-sponsored 2G02 Project (Stewart et al. 2008) indicates that these procedures should be developed by a team of software developers under the guidance of independent third parties. The survey and literature review reveal the absence of such software use guidance and software verification and validation procedures, which causes significant confusion on the part of users.

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REFERENCES

(Also included are references cited in Appendix C.)

American Association of State Highway and Transportation Officials (AASHTO), *LRFD Bridge Design Manual*, 4th ed., AASHTO, Washington, D.C., 2009.

American Association of State Highway and Transportation Officials (AASHTO), *Load and Resistance Factor Design (LRFD) Bridge Design Specifications*, 5th ed., AASHTO, Washington. D.C., 2010a.

American Association of State Highway and Transportation Officials (AASHTO), *Guide Specification for Seismic Isolation Design*, 3rd ed., AASHTO, Washington. D.C., 2010b.

ABAQUS, "ABAQUS/Standard, A General Purpose Finite Element Code," ABAQUS, Inc., formerly Hibbitt, Karlsson & Sorensen, Inc., Pawtucket, R.I., 2005.

Abrahamson, N.A., "Non-stationary Spectral Matching," *Seismological Research Letters*, Vol. 63, No. 1, 1992, 30 pp.

Abrahamson, N.A., "Spectral Matching Using RSP-MATCH," *Geotechnical Earthquake Engineering and Soil Dynamics IV*, Geotechnical Special Publication No. 181, ASCE-Geo-Institute, Sacramento, Calif., 2008.

Abrahamson, N., et al., "Comparisons of the NGA Ground-Motion Relations," *Earthquake Spectra*, Vol. 24, No. 1, 2008, pp. 45–66.

Abrahamson, N. and W. Silva, "Summary of the Abrahamson & Silva NGA Ground-motion Relations," *Earthquake Spectra*, Vol. 24, No. 1, 2008, pp. 67–97.

Al Atik, L. and N. Abrahamson, "Nonlinear Site Response Effects on the Standard Deviations of Predicted Ground Motions," *Bulletin of the Seismological Society of America*, Vol. 100, No. 3, 2010, pp. 1288–1292.

Anderson, D.G., S. Shin, and S.L. Kramer, "Observation from Nonlinear, Effective-Stress Ground Motion Response Analyses Following the AASHTO Guide Specific for LRFD Seismic Bridge Design," *Proceedings, TRB 2011 Annual Meeting*, Jan. 23–26, 2011, 19 pp.

American Society of Civil Engineers (ASCE), *Minimum Design Loads for Buildings and Other Structures*, ASCE Standard ASCE/SEI 7-05, ASCE, Reston, Va., 2006

Assimaki, D. and E. Kausel, "An Equivalent-Linear Algorithm with Frequency- and Pressure-Dependent Moduli and Damping for the Seismic Analysis of Deep Sites," *Soil Dynamics and Earthquake Engineering*, Vol. 22, No. 3, 2002, pp. 959–965.

Assimaki, D., E. Kausel, and A.J. Whittle, "Model for Dynamic Shear Modulus and Damping for Granular Soils," *Journal of Geotechnical & Geoenvironmental Engineering*, Vol. 126, No. 10, 2002, pp. 859–869.

Assimaki, D., W. Li, J.H. Steidl, and K. Tsuda, "Site Amplification and Attenuation via Downhole Array Seismogram Inversion: A Comparative Study of the 2003 Miyagi-Oki Aftershock Sequence," *Bulletin of the Seismological Society of America*, Vol. 98, No. 1, 2008, pp. 301–330.

Assimaki, D., W. Li, J. Steidel, and J. Schmedes, "Quantifying Nonlinearity Susceptibility via Site-Response Modeling Uncertainty at Three Sites in the Los Angeles Basin," *Bulletin of the Seismological Society of America*, Vol. 98, No. 5, 2009, pp. 2364–2390.

Assimaki, D. and J. Steidl, "Inverse Analysis of Weak and Strong Motion Downhole Array Data from the Mw 7.0 Sanriku–Minami Earthquake," *Soil Dynamics and Earthquake Engineering*, Vol. 27, 2007, pp. 73–92.

Baker, J.W., "The Conditional Mean Spectrum: Tool for Ground Motion Selection," *Journal of Structural Engineering*, Vol. 137, No. 3, 2011, pp. 322–331.

Baker, J.W. and C.A. Cornell, "Spectral Shape, Epsilon and Record Selection," *Earthquake Engineering and Structural Dynamics*, Vol. 35, No. 9, 2006, pp. 1077–1095.

Baker, J.W., T. Lin, S.K. Shahi, and N. Jayaram, *New Ground Motion Selection Procedures and Selected Motions for the PEER Transportation Research Program*, PEER 2011/03 report, 2011.

Baturay, M.B. and J.P. Stewart, "Uncertainty and Bias in Ground-Motion Estimates from Ground Response Analyses," *Bulletin of the Seismological Society of America*, Vol. 93, No. 5, pp. 2025–2042, Oct. 2003.

Bardet, J.P., K. Ichii, and C.H. Lin, *EERA—A Computer Program for Equivalent-linear Earthquake Site Response Analyses of Layered Soil Deposits*, Department of Civil Engineering, University of Southern California, Los Angeles, 2000.

Bardet, J.P. and T. Tobita, *NERA—A Computer Program for Nonlinear Earthquake Site Response Analyses of Layered Soil Deposits*, Research Report, Department of Civil Engineering, University of Southern California, Los Angeles, 2001.

Beaty, M. and P.M. Byrne, "An Effective-stress Model for Predicting Liquefaction Behavior of Sand," in *Geotechnical Earthquake Engineering and Soil Dynamics III*, P. Dakoulas, M. Yegian, and R. Holtz, Eds., ASCE, *Geotechnical Special Publication 75*, Vol. 1, 1998, pp. 766–777.

Copyright National Academy of Sciences. All rights reserved.

Bommer, J.J. and A.B. Acevedo, "The Use of Real Earthquake Accelerograms as Input to Dynamic Analysis," *Journal of Earthquake Engineering*, Vol. 8 (Special Issue 1), 2004, pp. 43–91.

Boore, D.M. and G.M. Atkinson, "Ground-motion Prediction Equations for the Average Horizontal Component of PGA, PGV, and 5%-damped PSA at Spectral Periods Between 0.01 s and 10.0 s," *Earthquake Spectra*, Vol. 24, No. 1, 2008, pp. 99–138.

Borja, R.I. and W.H. Wu, "Vibration of Foundations on Incompressible Soils with no Elastic Region," *Journal of Geotechnical Engineering*, Vol. 120, 1994, pp. 1570–1592.

Borja, R.I., H.Y. Chao, F. Montáns, and C.H. Lin, "Nonlinear Ground Response at Lotung LSST Site," *Journal of Geotechnical & Geoenvironmental Engineering*, Vol. 125, No. 3, 1999, pp. 187–197.

Borja R.I., B.G. Duvernay, and C.H. Lin, "Ground Response in Lotung: Total Stress Analyses and Parametric Studies," *Journal of Geotechnical & Geoenvironmental Engineering*, Vol. 128, No. 1, 2002, pp. 54–63.

Bray, J.D., A. Rodriguez-Marek, and J.L. Gillie, "Design Ground Motions Near Active Faults," *Bulletin of the New Zealand Society for Earthquake Engineering*, Vol. 42, No. 1, 2009, 8 pp.

Byrne, P.M., D. Roy, R.G. Campanella, and J. Hughes, "Predicting Liquefaction Response of Granular Soils from Pressuremeter Tests," ASCE National Convention, San Diego, *ASCE Geotechnical Special Publication* 56, 1995, pp. 122–135.

Campbell, K.W. and Y. Bozorgnia, "NGA Ground Motion Model for the Geometric Mean Horizontal Component of PGA, PGV, PGD and 5% Damped Linear Elastic Response Spectra for Periods Ranging from 0.01 to 10 s," *Earthquake Spectra*, Vol. 24, No. 1, 2008, pp. 139–171.

Chiou, B.S.J. and R.R. Youngs, "An NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra," *Earthquake Spectra*, Vol. 24, No. 1, 2008, pp., 173–215.

Chiu, P., D.E. Pradel, A.O.-L. Kwok, and J.P. Stewart, "Seismic Response Analyses for the Silicon Valley Rapid Transit Project," *Geotechnical Earthquake Engineering and Soil Dynamics IV* (GSP 181), Sacramento, Calif., 2008.

Chopra, A.K., *Dynamics of Structures*, 3rd ed., Prentice-Hall, Inc., Englewood Cliffs, N.J., 2006.

Clough, R.W. and J. Penzien, *Dynamics of Structures*, 2nd ed., McGraw Hill, London, U.K., 1993.

Dafalias, Y.F. and E.P. Popov, "A Model for Nonlinearly Hardening Materials for Complex Loading," *Acta Mechanica*, Vol. 21, No. 3, 1979, pp. 173–192.

Darendeli, M.B., "Development of a New Family of Normalized Modulus Reduction and Material Damping Curves," Ph.D. dissertation, University of Texas at Austin, 2001.

Darragh, R.B. and I.M. Idriss, *A Tale of Two Sites: Gilroy #2 and Treasure Island—Site Response Using an Equivalent-linear Technique*, NEHRP Professional Fellowship Report, EERI, Oakland, Calif., 1997.

Dickenson, S.E., R.B. Seed, J. Lysmer, and C.M. Mok, "Response of Soft Soils during the 1989 Loma Prieta Earthquake and Implications for Seismic Design Criteria," *Proceedings*, Pacific Conference on Earthquake Engineering, Auckland, New Zealand, 1991.

Dobry, R., W.G. Pierce, R. Dyvik, G.E. Thomas, and R.S. Ladd, "Pore Pressure Model for Cyclic Straining of Sand," *Research Report*, Civil Engineering Department, Rensselaer Polytechnic Institute, Troy, N.Y., 1985, 56 pp.

Duncan, J.M. and C.-Y. Chang, "Nonlinear Analysis of Stress and Strain in Soils," *Journal of the Soil Mechanics and Foundations Division*, Vol. 96, No. SM5, 1970, pp. 1629–1653.

EduPro, "ProShake: Ground Response Analysis Program," *User's Manual*, EduPro Civil Systems, Inc., Redmond, Wash., 1999 [Online]. Available: http://www.proshake.com.

Electric Power Research Institute (EPRI), "Guidelines for Determining Design Basis Ground Motions," Report EPRI TR-102293, EPRI, Palo Alto, Calif., 1993.

Elgamal, A., T. Lai, Z. Yang, and L. He, "Dynamic Soil Properties, Seismic Downhole Arrays and Applications in Practice," 4th International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, San Diego, Calif., 2001.

Elgamal, A.-W., Z. Yang, and J. Lu, "A Web-based Platform for Computer Simulation of Seismic Ground Response," *Advances in Engineering Software*, Vol. 35, No. 5, 2004, pp. 249–259.

EUROCODE, "Design Provisions for Earthquake Resistance of Structures, Part 1-1: General rules-Seismic Actions and General Requirements for Structures," EC 8, 2000.

Federal Highway Administration (FHWA), *LRFD Seismic Analysis and Design of Transportation Geotechnical Features and Structural Foundations*, NHI-11-032, FHWA, Washington, D.C., Mar. 2011.

Finn, W.D.L. and M. Yogendrakumar, "Seismic Soil-Structure Interaction," Proceedings of the Pacific Conference on Earthquake Engineering, Wairakei, New Zealand, 1987, pp. 73–81.

Foerster, E. and H. Modaressi, "Nonlinear Numerical Method for Earthquake Site Response Analysis II—Case

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Studies," *Bulletin of Earthquake Engineering*, Vol. 5, 2007, pp. 325–345.

Glaser, S.D. and L.G. Baise, "System Identification Estimation of Soil Properties at the Lotung Site," *Soil Dynamics and Earthquake Engineering*, Vol. 19, 2000, pp. 521–531.

Greater Vancouver Liquefaction Task Force, "Task Force Report, Geotechnical Design Guidelines for Buildings on Liquefiable Sites in Accordance with NBC 2005," 2007 [Online]. Available: http://www.civil.ubc.ca/liquefaction/.

Geo-Slope International Ltd. (GSI), "QUAKE/W for Finite Element Dynamic Earthquake Analysis," *User's Guide*, GSI, Calgary, AB, Canada, 2006, 624 pp.

Hancock, J., J. Watson-Lamprey, N.A. Abrahamson, J.J. Bommer, A. Markatis, E. McCoy, and R. Mendis, "An Improved Method of Matching Response Spectra of Recorded Earthquake Ground Motion Using Wavelets," *Journal of Earthquake Engineering*, Vol. 10, Special Issue 1, 2006, pp. 67–89.

Hart, J.D., and E.L. Wilson, *Simplified Earthquake Analysis of Buildings Including Site Effects*, Report No. UCB/SEMM-89/23, Department of Civil Engineering, University of California, Berkeley, 1989.

Haselton, C.B., Ed., "Evaluation of Ground Motion Selection and Modification Methods: Predicting Median Interstory Drift Response of Buildings," PEER Ground Motion Selection and Modification Working Group PEER 2009/01—Report, 2009.

Hashash, Y.M.A. and D. Park, "Nonlinear One-dimensional Seismic Ground Motion Propagation in the Mississippi Embayment," *Engineering Geology* (*Amsterdam*), Vol. 62, Nos. 1–3, 2001, pp. 185–206.

Hashash, Y.M.A. and D. Park, "Viscous Damping Formulation and High Frequency Motion Propagation in Nonlinear Site Response Analysis," *Soil Dynamics and Earthquake Engineering*, Vol. 22, No. 7, 2002, pp. 611–624.

Hashash, Y.M.A., C. Phillips, and D. Groholski, "Recent Advances in Non-Linear Site Response Analysis," Proceedings of the 5th International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, San Diego, Calif., 2010.

Hashash, Y.M.A., D.R. Groholski, C.A. Phillips, D. Park, and M. Musgrove, *DEEPSOIL 4.0, User Manual and Tutorial*, 2011, 98 pp.

Hudson, M., I.M. Idriss, and M. Beikae, "QUAD4M—A Computer Program to Evaluate the Seismic Response of Soil Structures using Finite Element Procedures and Incorporating a Compliant Base," *User's Manual*, Center for Geotechnical Modeling, Department of Civil and Environmental Engineering, University of California, Davis, 1994, 27 pp. (plus appendices).

Idriss, I.M., "Response of Soft Soil Sites during Earthquakes," *Proceedings, H. Bolton Seed Memorial Symposium*, J.M. Duncan, Ed., Vol. 2, 1990, pp. 273–290.

Idriss, I.M., "An NGA Empirical Model for Estimating the Horizontal Spectral Values Generated by Shallow Crustal Earthquakes," *Earthquake Spectra*, Vol. 24, No. 1, 2008, pp. 217–242.

Idriss, I.M., R. Dobry, and R.D. Singh, (1978), "Nonlinear behavior of soft clays during cyclic loading," *Journal of Geotechnical Engineering*, ASCE, Vol. 104, No. 12, pp. 1427-1447.

Idriss, I.M., R. Dobry, and R.D. Singh, "Nonlinear Behavior of Soft Clays During Cyclic Loading," *Journal of the Geotechnical Engineering Division*, Vol. 104, No. 12, 1978, pp. 1427–1447.

Idriss, I.M. and J.I. Sun, "User's Manual for SHAKE91, A Computer Program for Conducting Equivalent Linear Seismic Response Analyses of Horizontally Layered Soil Deposits," Center for Geotechnical Modeling, Department of Civil & Environmental Engineering, University of California, Davis, 1992.

Idriss I.M. and M. Hudson, *Response of the San Justo Dam to the Loma Prieta Earthquake of October 17, 1989*, Report No. CGM/93-01, Department of Civil and Environmental Engineering, University of California, Davis, Jan. 1993.

Idriss, I.M., J. Lysmer, R. Hwang, and H.B. Seed, "QUAD-4—A Computer Program for Evaluating the Seismic Response of Soil Structures by Variable Damping Finite Element Procedures," EERC Report 73-16, University of California, Berkeley, 1973, 67 pp.

International Code Council, "2006 International Building Code," Falls Church, Va., 2006.

Itasca Consulting Group, Inc., "FLAC (Fast Lagrangian Analysis of Continua) Version 5.0," Itasca Consulting Group, Inc., Minneapolis, Minn., 2005 [Online]. Available: http://www.itascacg.com.

Jackura, K.A., "Caltrans Procedures for Development of Site Specific Acceleration Response Spectra," Caltrans Internal Memorandum, California Department of Transportation, Sacramento (also presented in the *Proceedings of Seismic Design and Retrofit of Bridges*, Berkeley, Calif., June 8–9, 1992).

Jones, A.L., S.L. Kramer, and P. Arduino, "Estimation of Uncertainty in Geotechnical Properties for Performance-Based Earthquake Engineering," PEER Report 2002/16, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, 2002, 100 pp.

Kausel, E. and D. Assimaki, "Seismic Simulation of Inelastic Soils via Frequency-Dependent Moduli and Damp-

Copyright National Academy of Sciences. All rights reserved.

ing," *Journal of Engineering Mechanics*, Vol. 128, No. 1, 2002, pp. 34–47.

Kavazanjian, E. and N. Matasovic, "Seismic Analysis of Solid Waste Landfills," In *Geoenvironment 2000*, ASCE Geotechnical Specialty Publication No. 46, New York, N.Y., 1995, pp. 1066–1080.

Kavazanjian, E., Jr., N. Matasovic, T. Hadj-Hamou, and P.J. Sabatini, "Geotechnical Earthquake Engineering for Highways—Volume I: Design Principles," *Geotechnical Engineering Circular* No. 3, FHWA-SA-97-076, Federal Highway Administration, Washington, D.C., 1997a, 186 pp.

Kavazanjian, E., Jr., N. Matasovic, T. Hadj-Hamou, and P.J. Sabatini, "Geotechnical Earthquake Engineering for Highways—Volume II: Design Examples," *Geotechnical Engineering Circular No. 3*, FHWA-SA-97-077, Federal Highway Administration, Washington, D.C., 1997b, 163 pp.

Kondner, R.L. and J.S. Zelasko, "A Hyperbolic Stress-strain Formulation of Sands," *Proceedings of the 2nd Pan American Conference on Soil Mechanics and Foundation Engineering*, Sao Paulo, Brazil, 1963, pp. 289–324.

Kottke, A. and E.M. Rathje, "Semi-Automated Selection and Scaling of Earthquake Ground Motions," *Proceedings of the 4th International Conference on Earthquake Geotechnical Engineering*, Paper 1248, CD-ROM, Thessaloniki, Greece, June 2007.

Kramer, S.L., "Geotechnical Earthquake Engineering," Prentice Hall, Upper Saddle River, N.J., 1996, 653 pp.

Kramer, S.L., "Analysis of Turkey Flat Ground Motion Prediction Experiment—Lessons Learned and Implications for Practice," SMIP09 Seminar on Utilization of Strong-Motion Data, 2009, pp. 1–22.

Kramer, S.L. and S.B. Paulsen, "Practical Use of Geotechnical Site Response Models," *Proceedings of the International Workshop on Uncertainties in Nonlinear Soil Properties and their Impact on Modeling Dynamic Soil Response*, University of California, Berkeley, 2004, 10 pp.

Kramer, S.L. and J.P. Stewart, "Geotechnical Aspects of Seismic Hazards," in *Earthquake Engineering—From Engineering Seismology to Performance-Based Engineering*, Y. Bozorgnia and V.V. Bertero, Eds., CRC Press, Boca Raton, Fla., 2004.

Kwok, O.-L.A., J.P. Stewart, Y.M.A. Hashash, N. Matasovic, R. Pyke, Z. Wang, and Z. Yang, "Utilizing Nonlinear Seismic Ground Response Analysis for Turkey Flat Blind Predictions," Third International Symposium on the Effects of Surface Geology on Seismic Motion, Grenoble, France, 2006.

Kwok, O.-L.A., J.P. Stewart, Y.M.A. Hashash, N. Matasovic, R. Pyke, Z. Wang, and Z. Yang, "Use of Exact Solutions of Wave Propagation Problems to Guide Implementation of Nonlinear Ground Response Analysis Procedures," *Journal of Geotechnical & Geoenvironmental Engineering*, Vol. 133, No. 11, 2007, pp. 1385–1398.

Kwok, O.-A.L., J.P. Stewart, and Y.M.A. Hashash, "Nonlinear Ground-Response Analysis of Turkey Flat Shallow Stiff-Soil Site to Strong Ground Motion," *Bulletin of Seismological Society of America*, Vol. 98, No. 1, 2008, pp. 331–343.

Lee, M.K.W. and W.D.L. Finn, "DESRA-2, Dynamic Effective Stress Response Analysis of Soil Deposits with Energy Transmitting Boundary Including Assessment of Liquefaction Potential," *Soil Mechanics Series No. 36*, Department of Civil Engineering, University of British Columbia, Vancouver, Canada, 1978, 60 pp.

Li, X.S., Z.L. Wang, and C.K. Shen, "SUMDES: A Nonlinear Procedure for Response Analysis of Horizontally Layered Sites Subjected to Multi-Directional Earthquake Loading," Department of Civil Engineering, University of California, Davis, 1992.

Liou, C.P., V.L. Streeter, and F.E. Richart, "Numerical Model for Liquefaction," *Journal of the Geotechnical Engineering Division*, Vol. 103, No. GT6, 1977, pp. 589–597.

Lopez-Caballero, F., A. Arezou Modaressi, F. Razavi, and H. Modaressi, "Nonlinear Numerical Method for Earthquake Site Response Analysis—Elastoplastic Cyclic Model and Parameter Identification Strategy," *Bulletin of Earthquake Engineering*, Vol. 5, 2007, pp. 303–323.

LSTC, "LS-Dyna, A General Purpose Transient Dynamic Finite Element Program Capable of Simulating Complex Real World Problems," 1988.

Lysmer, J., T. Udaka, C.-F. Tsai, and H.B. Seed, *FLUSH—A Computer Program for Approximate 3-D Analysis of Soil-Structure Interaction Problems*, Report EERC 75-30, Earthquake Engineering Research Center, University of California, Berkeley, 1975, revised Mar. 1979, 83 pp. (plus appendices).

Manzari, M.T. and M.A. Nour, "On Implicit Integration of Bounding Surface Plasticity Models," *Computers and Structures*, Vol. 63, 1997, pp. 385–395.

Martin, G.R., W.D.L. Finn, and H.B. Seed, "Fundamentals of Liquefaction under Cyclic Loading," *Journal of the Geotechnical Engineering Division*, Vol. 101, 1975, No. GT5, 423–438.

Martin, P.P. and H.B. Seed, "APOLLO, A Computer Program for the Analysis of Pore Pressure Generation and Dissipation in Horizontal Sand Layers During Cyclic Earthquake Loading," Report No. EERC 78-21, Earthquake Engineering Research Center, University of California, Berkeley, 1978.

Masing, G., "Eigenspannungen und Verfestigung beim Messing," *Proceedings of the 2nd International Con-*

Copyright National Academy of Sciences. All rights reserved.

gress on Applied Mechanics, Zürich, Switzerland, 1926, pp. 332–335.

Matasovic, N., "Seismic Response of Composite Horizontally Layered Soil Deposits," Ph.D. dissertation, Civil and Environmental Engineering Department, University of California, Los Angeles, 1993, 452 pp.

Matasovic, N., "D-MOD_2—A Computer Program for Seismic Response Analysis of Horizontally Layered Soil Deposits, Earthfill Dams, and Solid Waste Landfills," *User's Manual*, GeoMotions, LLC, Lacey, Wash., 2006, 20 pp. (plus appendices).

Matasovic, N. and M. Vucetic, "A Pore Pressure Model for Cyclic Straining of Clay," *Soils and Foundations, Journal of the JSSMFE*, Vol. 32, No. 3, 1992, pp. 156–173.

Matasovic, N. and M. Vucetic, "Cyclic Characterization of Liquefiable Sands," *Journal of Geotechnical Engineering*, Vol. 119, No. 11, 1993, pp. 1805–1822.

Matasovic, N. and M. Vucetic, "Generalized Cyclic Degradation-Pore Pressure Generation Model for Clays," *Journal of Geotechnical Engineering*, Vol. 121, No. 1, 1995a, pp. 33–42.

Matasovic, N. and M. Vucetic, "Seismic Response of Soil Deposits Composed of Fully Saturated Clay and Sand Layers," *Proceedings of IS-Tokyo'95, The First International Conference on Earthquake Geotechnical Engineering*, K. Ishihara, Ed., A.A. Balkema, Netherlands, 1995b.

Matasovic, N. and G.A. Ordonez, "D-MOD2000—A Computer Program Package for Seismic Response Analysis of Horizontally Layered Soil Deposits, Earthfill Dams, and Solid Waste Landfills," *User's Manual*, GeoMotions, LLC, Lacey, Wash., 2007, 182 pp. [Online]. Available: http://www.geomotions.com.

McKenna, F. and G.L. Fenves, *The OpenSees Command Language Manual, Version 1.2*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, 2001 [Online]. Available: http://opensees.berkeley.edu.

Menq, F., "Dynamic Properties of Sandy and Gravelly Soils," Ph.D. dissertation, University of Texas at Austin, 2003.

Modaressi, H. and E. Foerster, *CyberQuake. User's Manual*, BRGM, France, 2000.

Mroz, Z., "On the Description of Anisotropic Work Hardening," *Journal of Mechanics and Physics of Solids*, Vol. 15, 1967, pp. 163–175.

Munfagh, G., E. Kavazanjian, Jr., N. Matasovic, T. Hadj-Hamou, and J. Wang, "Ground Motion Characterization," Chapter 4, in *Geotechnical Earthquake Engineering Reference Manual*, FHWA-HI-99-012, Federal Highway Administration, Washington, D.C., 1999.

Muraleetharan, K.K., K.D. Mish, C. Yogachandran, and K. Arulanandan, *User's Manual for DYSAC 2: Dynamic Soil Analysis Code for 2 Dimensional Problems*, Report, Department of Civil Engineering, University of California, Davis, 1991.

Newmark, N.M., "A Method of Computation for Structural Dynamics," *Journal of Engineering Mechanics Division*, Vol. 85, 1959, pp. 67–94.

Nikolaou, S., "Performance-Based Design—Concepts in Geotechnical Earthquake Engineering," *Geo-Strata*, 2011, pp. 42–47.

Oasys, "SIREN" (A new program that provides the functionality for prediction of site response to a seismic event), 2006.

Ordonez, G.A., "SHAKE2000: A Computer Program for the 1-D Analysis of Geotechnical Earthquake Engineering Problems," *User's Manual*, GeoMotions, LLC, Lacey, Wash., 2000, 264 pp. [Online]. Available: http://www.geomotions.com.

Park, D. and Y.M.A. Hashash, "Soil Damping Formulation in Nonlinear Time Domain Site Response Analysis," *Journal of Earthquake Engineering*, Vol. 8, No. 2, 2004, pp. 249–274.

Park, D. and Y.M.A. Hashash, "Estimation of Seismic Factors in the Mississippi Embayment: I. Estimation of Dynamic Properties," *Soil Dynamics and Earthquake Engineering*, Vol. 25, 2005a, pp. 133–144.

Park, D. and Y.M.A. Hashash, "Estimation of Seismic Factors in the Mississippi Embayment: II. Probabilistic Seismic Hazard with Nonlinear Site Effects," *Soil Dynamics and Earthquake Engineering*, Vol. 25, 2005b, pp. 145–156.

Park, D. and Y.M.A. Hashash, "Rate-Dependent Soil Behavior in Seismic Site Response Analysis," *Canadian Geotechnical Journal*, Vol. 45, No. 4, 2008, pp. 454–446.

Parra, E., "Numerical Modeling of Liquefaction and Lateral Ground Deformation Including Cyclic Mobility and Dilation Response in Soil Systems," Ph.D. dissertation, Department of Civil Engineering, Rensselaer Polytechnic Institute, Troy, N.Y., 1996.

Pestana, J.M., "A Unified Constitutive Model for Clays and Sands," Sc.D. Thesis, MIT, Cambridge, Mass., 1994.

Pestana, J.M. and F. Nadim, "Nonlinear Site Response Analysis of Submerged Slopes," Report No. UCB/GT/2000-04, Department of Civil and Environmental Engineering, University of California. Berkeley, 2000.

Phillips, C. and Y.M.A. Hashash, "Damping Formulation for Nonlinear 1D Site Response Analyses," *Soil Dynamics and Earthquake Engineering*, Vol. 29, No. 7, 2009, pp. 1143–1158.

Copyright National Academy of Sciences. All rights reserved.

PLAXIS-B.V, "PLAXIS: Finite Element Package for Analysis of Geotechnical Structures," Delft, Netherlands, 2002.

Polito, C.P., R.A. Green, and J.H. Lee, "Pore Pressure Generation Models for Sands and Silty Soils Subjected to Cyclic Loading," *Journal of Geotechnical & Geoenvironmental Engineering*, Vol. 134, No. 10, 2008, pp. 1490–1500.

Potts, D.M. and L. Zdravković, *Finite Element Analysis in Geotechnical Engineering: Theory*, Thomas Telford Ltd., London, U.K., 1999.

Prevost, J.H., "Mathematical Modeling of Monotonic and Cyclic Undrained Clay Behavior," *International Journal of Numerical and Analytical Methods in Geomechanics*, Vol. 1, No. 2, 1977, pp. 195–216.

Prevost, J.H., "DYNA1D—A Computer Program for Nonlinear Seismic Site Response Analysis: Technical Documentation," Report No. NCEER-89-0025, National Center for Earthquake Engineering Research, Buffalo, N.Y., 1989.

Pyke, R.M., "Nonlinear Soil Models for Irregular Cyclic Loadings," *Journal of Geotechnical Engineering Division*, Vol. 105, No. GT6, 1979, pp. 715–726.

Pyke, R.M., "TESS: A Computer Program for Nonlinear Ground Response Analyses," TAGA Engineering Systems & Software, Lafayette, Calif., 2000 [Online]. Available: http://www.tagasoft.com.

Qiu, P., "Earthquake Induced Nonlinear Ground Deformation Analyses," Ph.D. dissertation, University of Southern California, Los Angeles, 1997.

Ragheb, A.M., "Numerical Analysis of Seismically Induced Deformations in Saturated Granular Soil Strata," Ph.D. dissertation, Department of Civil Engineering, Rensselaer Polytechnic Institute, Troy, N.Y., 1994.

Ramberg, W. and W.R. Osgood, "Description of Stress-Strain Curves by Three Parameters," *Technical Note 902*, National Advisory Committee for Aeronautics, Washington, D.C., 1943.

Rathje, E.M. and J.D. Bray, "One- and Two-dimensional Seismic Analysis of Solid-Waste Landfills," *Canadian Geotechnical Journal*, Vol. 38, 2001, pp. 850–862.

Rathje, E.M. and M.C. Ozbey, "Site Specific Validation of Random Vibration Theory-Based Seismic Site Response Analysis," *Journal of Geotechnical & Geoenvironmental Engineering*, Vol. 132, No. 7, 2006, pp. 911–922.

Ray, R.P., "Recent Improvements in MOC for Earthquake Response," *Proceedings of the Geotechnical Earthquake Engineering and Soil Dynamics*, GSP 181, Sacramento, Calif., 2008, 10 pp.

Rayleigh, J.W.S. and R.B. Lindsay, *The Theory of Sound*, Dover Publications, New York, N.Y., 1945.

Real, C.R., A.F. Shakal, and B.E. Tucker, "Overview of the Turkey Flat Ground Motion Prediction Experiment," SMIP06 Seminar on Utilization of Strong-Motion Data, 2006, pp. 117–136.

RISK-Engineering, "EZ-FRISK" (Software for earthquake ground motion estimation, maintained and distributed by FUGRO), 2009.

Roblee, C.J., W.J. Silva, G.R. Toro, and N. Abrahamson, "Variability in Site-Specific Seismic Ground-Motion Design Predictions," Proceedings of Uncertainty '96 held in Madison, Wisc., July 31–Aug. 3, 1996, C.D. Shackelford, P.P. Nelson, and M.J. S. Roth, Eds., ASCE Geotechnical Special Publication No. 58, 1,460 pp.

Rodriguez-Marek, A., J.D. Bray, and N.A. Abrahamson, "An Empirical Geotechnical Seismic Site Response Procedure," *Earthquake Spectra*, Vol. 17, No. 1, 2001, pp. 65–87.

Romero, S.M. and G. Rix, "Ground Motion Amplification of Soils in the Upper Mississippi Embayment," GIT-CEE/GEO-01-1, Georgia Institute of Technology, Atlanta, 2005.

Roscoe, K.H. and J.B. Burland, "On the Generalized Stress-strain Behavior of 'Wet' Clay," J. Heyman and F.A. Leckie, Eds., *Engineering Plasticity*, University Press, Cambridge, Mass., 1968, pp. 535–609.

Roscoe, K.H. and A.N. Schofield, "Mechanical Behavior of an Idealized 'Wet' Clay," *Proceedings of 2nd European Conference on Soil Mechanics*, Wiesbaden, Germany, Vol. 1, 1963, pp. 47–54.

Roth, W.H. and S. Inel, "An Engineering Approach to the Analysis of VELACS Centrifuge Tests," *Proceedings, Verification of Numerical Procedures for the Analysis of Soil Liquefaction Problems*, Arulanandan and Scott, Eds., Davis, Calif., 1993, p. 1209–1229.

Sabatini, P.J., R.C. Bachus, P.W. Mayne, J.A. Schneider, and T.E. Zettler, *Geotechnical Engineering Circular No. 5, FHWA—Evaluation of Soil and Rock Properties*, Report FHWA-IF-02-034, FHWA, Washington, D.C., 2002.

Schnabel, P.B., J. Lysmer, and H.B. Seed, "SHAKE: A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites," Report No. EERC 72-12, Earthquake Engineering Research Center, University of California, Berkeley, 1972.

Seed, H.B. and I.M. Idriss, "Soil Moduli and Damping Factors for Dynamic Response Analyses," Report No. EERC 70–10, Earthquake Engineering Research Center, University of California, Berkeley, 1970, 40 pp.

Copyright National Academy of Sciences. All rights reserved.

Seed, H.B., M.P. Romo, J.I. Sun, A. Jaime, and J. Lysmer, "The Mexico Earthquake of September 19, 1985—Relationships Between Soil Conditions and Earthquake Ground Motions," *Earthquake Spectra*, Vol. 4, No. 4, 1988, pp. 687–729.

Somerville, P., "Emerging Art: Earthquake Ground Motion," *Proceedings ASCE Specialty Conference, Geotechnical Earthquake Engineering and Soil Dynamics III*, Seattle, Wash. Vol. 1, 1998, pp. 1–38.

Stevenson & Associates Inc. (SAI), "SUPER SASSI/PC Program: Complete Dynamic Soil-Structure Interaction Analysis System on Personal Computers," SAI, 1995, Original code: SASSI, Lysmer et al., University of California, Berkeley, 1988.

Stewart, J.P., A.H. Liu, and Y. Choi, "Amplification Factors for Spectral Acceleration in Tectonically Active Regions," *Bulletin of the Seismological Society of America*, Vol. 93, 2003, pp. 332–352.

Stewart, J.P., A.O. Kwok, Y.M.A. Hashash, N. Matasovic, R. Pyke, Z. Wang, and Z. Yang, "Benchmarking of Nonlinear Geotechnical Ground Response Analysis Procedures," Report PEER 2008/04, Pacific Earthquake Engineering Research Center, University of California, Berkeley, 2008.

Toro, G.R. and W.J. Silva, "Scenario Earthquakes for Saint Louis, MO, and Memphis, TN, and Seismic Hazard Maps for the Central United States Region Including the Effect of Site Conditions," USGS 1434-HQ-97-GR-02981, 2001.

Tsai, C.-C. and Y.M.A. Hashash, "A Novel Framework Integrating Downhole Array Data and Site Response Analysis to Extract Dynamic Soil Behavior," *Soil Dynamics and Earthquake Engineering*, Vol. 28, No. 3, 2007, pp. 181–197.

U.S. Geological Survey (USGS), "Documentation for the 2008 Update of the United States National Seismic Hazard Maps," U.S. Geological Survey Open-file report 2008–1128, USGS, Washington, D.C., 2008.

Vucetic, M., "Pore Pressure Buildup and Liquefaction of Level Sandy Sites During Earthquakes," Ph.D. dissertation, Rensselaer Polytechnic Institute, Troy, N.Y., 1986, 616 pp.

Vucetic, M., "Normalized Behavior of Clay under Irregular Cyclic Loading," *Canadian Geotechnical Journal*, Vol. 27, 1990, pp. 29–46.

Vucetic, M. and R. Dobry, "Effect of Soil Plasticity on Cyclic Response," *Journal of Geotechnical Engineering*, Vol. 117, No. 1, 1991, pp. 89–107.

Wang, Z.L., Q.Y. Han, and G.S. Zhou, "Wave Propagation Method of Site Seismic Response by Visco-Elastoplastic Model," *Proceedings, Seventh World Conference on Earthquake Engineering*, Vol. 2, Istanbul, Turkey, 1980, pp. 379–386.

Wang, Z.L., "Bounding Surface Hypoplasticity Model for Granular Soils and Its Applications," Ph.D. dissertation, University of California at Davis, 1990.

Whittle, A.J. and M.J. Kavvadas, "Formulation of MIT-E3 Constitutive Model for Overconsolidation Clays," *Journal of Geotechnical Engineering*, Vol. 120, No. 1, 1994, pp. 173–198.

Wu, G., "VERSAT-2D," Wutec Geotechnical International, Vancouver, B.C., Canada, 2010.

Yang, Z., "Numerical Modeling of Earthquake Site Response Including Dilation and Liquefaction," Ph.D. dissertation, Department of Civil Engineering and Engineering Mechanics, Columbia University, New York, N.Y., 2000.

Zeghal, M., and A.W. Elgamal, "Lotung Sites: Downhole Seismic Data Analysis," Electric Power Research Institute, Palo Alto, Calif., 1993.

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BIBLIOGRAPHY

American Association of State Highway and Transportation Officials (AASHTO), *Standard Specifications for Highway Bridges*, AASHTO, Washington, D. C., 1992.

American Association of State Highway and Transportation Officials (AASHTO), *AASHTO Guide Specifications for LRFD Seismic Bridge Design*, 1st ed., AASHTO, Washington, D.C., 2009.

Arslan, H. and B. Siyahi, "A Comparative Study on Linear and Nonlinear Site Response Analysis," *Environmental Geology*, Vol. 50, No. 8, 2006, pp. 1193–1200.

Beresnev, I.A., A.M. Nightengale, and W.J. Silva, "Properties of Vertical Ground Motions," *Bulletin of the Seismological Society of America*, Vol. 92, No. 8, 2002, pp. 3152–3164.

Bernardie, S., E. Foerster, and H. Modaressi, "Non-Linear Site Response Simulations in Chang-Hwa Region During the 1999 Chi-Chi Earthquake, Taiwan," *Soil Dynamics and Earthquake Engineering*, Vol. 26, No. 11, 2006, pp. 1038–1048.

Berrill, J.B. and R.O. Davis, "Energy Dissipation and Seismic Liquefaction of Sands: Revised Model," *Soils and Foundations*, No. 25, 1985, pp. 106–118.

Beyen, K. and M. Erdik, "Two-Dimensional Nonlinear Site Response Analysis of Adapazarî Plain and Predictions Inferred from Aftershocks of the Kocaeli Earthquake of 17 August 1999," *Soil Dynamics and Earthquake Engineering*, Vol. 24, No. 3, 2004, pp. 261–279.

Boaga, J., G. Vignoli, and G. Cassiani, "Shear Wave Profiles from Surface Wave Inversion: The Impact of Uncertainty on Seismic Site Response Analysis," J*ournal of Geophysics and Engineering*, Vol. 8, No. 2, 2011, pp. 162–174.

Bonilla, L.F., R.J. Archuleta, and D. Lavallée, "Hysteretic and Dilatant Behavior of Cohesionless Soils and Their Effects on Nonlinear Site Response: Field Data Observations and Modeling," *Bulletin of the Seismological Society of America*, Vol. 95, 2005, pp. 2373–2395.

Booker, J.R., M.S. Rahman, and H.B. Seed, "GADFLFA-A Computer Program for the Analysis of Pore Pressure Generation and Dissipation During Cycle or Earthquake Loading," Report No. UCB/EERC-76/24, University of California, Berkley, 1976.

Borja, R.I. and A.P. Amies, "Multiaxial Cyclic Plasticity Model for Clays," *Journal of Geotechnical & Geoenvironmental Engineering*, Vol. 120, No. 6, 1994, pp. 1051–1070.

Borja, R.L., J.E. Andrade, and R.J. Armstrong, "Combined Deterministic-Stochastic Analysis of Local Site Response," *Proceedings, 13th World Conference on Earthquake Engineering*, Paper No. 2533, Vancouver, B.C., Canada, Aug. 1–6, 2004.

Bozorgnia, Y. and K.W. Campbell, "The Vertical-to-Horizontal Response Spectral Ratio and Tentative Procedures for Developing Simplified V/H and Vertical Design Spectra," *Journal of Earthquake Engineering*, Vol. 8, No. 2, 2004, pp. 175–207.

Cramer, C.H., "Quantifying the Uncertainty in Site Amplification Modeling and Its Effects on Site-specific Seismic-hazard Estimation in the Upper Mississippi Embayment and Adjacent," *Bulletin of the Seismological Society of America*, 2006.

Davidenkov, N.N., "Energy Dissipation in Vibrations," *Journal of Technical Physics*, Vol. 8, No. 6, 1938.

Dobry, R., R.S. Ladd, F.Y. Yokel, R.M. Chung, and D. Powell, "Prediction of Pore Water Pressure Buildup and Liquefaction of Sands During Earthquakes by the Cyclic Strain Method," Building Science Series 183, National Bureau of Standards, U.S. Department of Commerce, U.S. Government Printing Office, Washington, D.C., 1982, 150 pp.

Elgamal, A.W. and H. Liangcai, "Vertical Earthquake Motions Records: An Overview," *Journal of Earthquake Engineering*, Vol. 8, No. 5, 2004, pp. 663–697.

Elgamal, A.W., Z. Yang, and J. Lu, "A Web-based Platform for Computer Simulation of Seismic Ground Response," *Advances in Engineering Software*, Vol. 35, No. 5, 2004, pp. 249–259.

Finn, W.D.L., K.W. Lee, and G.R. Martin, "An Effective Stress Model for Liquefaction," *Journal of the Geotechnical Engineering Division*, Vol. 103, No. GT6, 1977, pp. 517–533.

Frankel, A.D., D.L. Carver, and R.A. Williams, "Nonlinear and Linear Site Response and Basin Effects in Seattle for the M 6.8 Nisqually, Washington, Earthquake," *Bulletin of the Seismological Society of America*, 2002.

GeoMotions, "D-MOD2000: A Nonlinear Computer Program for Seismic Response Analysis of Horizontally Layered Soil Deposits, Earthfill Dams, and Solid Waste Landfills," GeoMotions, Lacey, Wash., 2000 [Online]. Available: www.GeoMotions.com.

Gerolymos, N. and G. Gazetas, "Constitutive Model for 1-D Cyclic Soil Behaviour Applied to Seismic Analysis of Layered Deposits," *Soils and Foundation*, Vol. 45, No. 3, 2005, pp. 147–159.

Ghaboussi, J. and S.U. Dikmen, "Effective Stress Analysis of Seismic Response and Liquefaction: Case Studies,"

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Journal of Geotechnical Engineering, Vol. 110, No. 5, 1984, pp. 645–658.

Ghaboussi, J., D.A. Pecknold, M. Zhang, and R. Haj-Ali, "Autoprogressive Training of Neural Network Constitutive Models," *International Journal for Numerical Methods in Engineering*, Vol. 42, No. 1, 1998, pp. 105–126.

Green, R.A., J.K. Mitchell, and C.P. Polito, "An Energy-Based Pore Pressure Generation Model for Cohesionless Soils," John Booker Memorial Symposium—Developments in Theoretical Geomechanics, Rotterdam, Netherlands, 2000, pp. 383–390.

Haciefendioğlu, K. and K. Soyluk, "Nonlinear Response of Earthfill Dams to Spatially Varying Ground Motion Including Site Response Effect," *Advances in Structural Engineering*, Vol. 14, No. 2, 2011, pp. 223–234.

Hardin, B.O. and V.P. Drnevich, "Shear Modulus and Damping in Soils: Measurement and Parameter Effects," *Journal of Soil Mechanics and Foundation Engineering Division*, Vol. 98, No. SM6, 1972, pp. 603–624.

Hardin, B.O. and V.P. Drnevich, "Shear Modulus and Damping in Soils: Design Equations and Curves," *Journal of the Soil Mechanics and Foundations Division*, Vol. 98, No. SM7, 1972, pp. 667–692.

Harichance, Z., H. Afra, and S.M. Elachachi, "An Identification Procedure of Soil Profile Characteristics from Two Free Field Acclerometer Records," *Soil Dynamics and Earthquake Engineering*, Vol. 25, 2005, pp. 431–438.

Hashash, Y.M.A., "Viscous Damping Formulation and High Frequency Motion Propagation in Non-Linear Site Response Analysis," *Soil Dynamics and Earthquake Engineering*, Vol. 22, No. 7, 2002, pp. 611–624.

Hashash, Y.M.A. and D. Groholski, "Extraction of Dynamic Pore Water Pressure Generation Behavior via Inverse Analysis in Seismic Site Response Modeling," 1st International Symposium on Computational Geomechanics (ComGeo I), Juan-les-Pins, Cote d'Azur, France, 2009.

Hudson, M., I.M. Idriss, and M. Beikae, "QUAD4M: A Computer Program to Evaluate the Seismic Response of Soil Structures Using Finite Element Procedures and Incorporating a Compliant Base," rev. 2003, Center for Geotechnical Modeling, Department of Civil and Environmental Engineering University of California, Davis, 2003.

Idriss, I.M., "QUAD-4: A Computer Program for Evaluating the Seismic Response of Soil Structures by Variable Damping Finite Element Procedures," July 1973.

Idriss, I.M. and H.B. Seed, "An Analysis of Ground Motions During the 1957 San Francisco Earthquake," *Bulletin of the Seismological Society of America*, Vol. 58, 1968, pp. 2013–2032.

Ishibashi, I. and X. Zhang, "Unified Dynamic Shear Moduli and Damping Ratios of Sand and Clay," *Soils and Foundations*, Vol. 33, No. 1, 1993, pp. 182–191.

Ishihara, K., "Evaluation of Soil Properties for Use in Earthquake Response Analysis," in *Geomechanical Modelling in Engineering Practice*, R. Dungar and J.A. Studer, Eds., A.A. Balkema, Rotterdam, Netherlands, 1986, pp. 241–275.

Ishihara, K., J. Lysmer, S. Yasuda, and H. Hirao, "Prediction of Liquefaction in Sand Deposits During Earthquakes," *Soils and Foundations*, Vol. 16, No. 1, 1976, pp. 1–16.

Iwasaki, T., F. Tatsuoka, and Y. Takagi, "Shear Moduli of Sands Under Cyclic Torsional Shear Loading," *Soils and Foundations*, Vol. 18, No. 1, 1978, pp. 32–56.

Jacobsen, L.S., "Steady Forced Vibrations as Influenced by Damping," *Transactions*, ASME, Vol. 52, No. 15, 1930, pp. 169–181.

Jin, X., G. Kong, and H. Ding, "Nonlinear Seismic Response Analysis of Horizontal Layered Site," *Journal of Earthquake Engineering and Engineering Vibration*, Vol. 24, No. 3, 2004, pp. 38–43.

Kawano, M., K. Asano, H. Dohi, and S. Matsuda, "Verification of Predicted Non-Linear Site Response During the 1995 Hyogo-Ken Nanbu Earthquake," *Soil Dynamics and Earthquake Engineering*, Vol. 20, Nos. 5–8, 2000, pp. 493–507.

Kim, D.S., K.H. Stokoe, and W.R. Hudson, "Deformational Characteristics of Soils at Small to Intermediate Strains from Cyclic Tests," 1177-3, Center of Transportation Research, Bureau of Engineering Research, Austin, Tex., 1991.

Kokusho, T., "Cyclic Triaxial Test of Dynamic Soil Properties for Wide Strain Range," *Soils and Foundations*, Vol. 20, No. 2, 1980, pp. 45–60.

Lai, C.G. and G.J. Rix, "Simultaneous Inversion of Rayleigh Phase Velocity and Attenuation for Near-Surface Site Characterization," Georgia Institute of Technology, Atlanta, 1998.

Laird, J.P. and K.H. Stokoe, "Dynamic Properties of Remolded and Undisturbed Soil Samples Test at High Confining Pressure," GR93-6, Electric Power Research Institute, Washington, D.C., 1993.

Lee, C.P., Y.B. Tsai, and K.L. Wen, "Analysis of Nonlinear Site Response Using the LSST Downhole Accelerometer Array Data," *Soil Dynamics and Earthquake Engineering*, Vol. 26, No. 5, 2006, pp. 435–460.

Lee, K.L. and A.S. Albaisa, "Earthquake Induced Settlements in Saturated Sands," *Journal of Geotechnical Engineering*, Vol. 100, No. GT4, 1974, pp. 387–406.

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Lee, M.K.W. and W.D.L. Finn, "DESRA-1, Program for the Dynamic Effective Stress Response Analysis of Soil Deposits Including Liquefaction Evaluation," *Soil Mechanics Series No. 36*, Department of Civil Engineering, University of British Columbia, Vancouver, B.C., Canada, 1975.

Li, W., D. Assimaki, and M. Fragiadakis, "Site Response Modeling Variability in 'Rupture-to-Rafters' Ground Motion Simulations," Proceedings, 14th World Conference on Earthquake Engineering, Oct. 12–17, 2008, Beijing, China.

Li, W. and D. Assimaki, "Site- and Motion-Dependent Parametric Uncertainty of Site-Response Analyses in Earthquake Simulations," *Bulletin of the Seismological Society of America*, Vol. 100, No. 3, 2010, pp. 954–968.

Liu, M. and D.G. Gorman, "Formulation of Rayleigh Damping and Its Extensions," *Computers and Structures*, Vol. 57, No. 2, 1995, pp. 277–285.

Lysmer, J., T. Udaka, C.F. Tsai, and H.B. Seed, *FLUSH—A Computer Program for Approximate 3-D Analysis of Soil-Structure Interaction Problems*, Report No. EERC 75-30, Earthquake Engineering Research Center, University of California, Berkeley, 1975, 83 pp.

Martin, P.P., "Non-Linear Methods for Dynamic Analysis of Ground Response," Ph.D. dissertation, University of California, Berkeley, 1975.

Martin, P.P. and H.B. Seed, "MASH, A Computer Program for the Non-Linear Analysis of Vertically Propagating Shear Waves in Horizontally Layered Deposits," Report No. EERC 78-23, Earthquake Engineering Research Center, University of California, Berkeley, 1978.

Martin, F.D., H. Kawase, and A.M. Razavi, "Nonlinear Soil Response of a Borehole Station Based on One-Dimensional Inversion during the 2005 Fukuoka Prefecture Western Offshore Earthquake," *Bulletin of the Seismological Society of America*, Vol. 100, No. 1, Feb. 1, 2010, pp. 151–171.

Matesic, L. and M. Vucetic, "Strain-rate Effect on Soil Secant Shear Modulus at Small Cyclic Strains," *Journal of Geotechnology and Geoenvironmental Engineering*, Vol. 129, No. 6, 2002, pp. 536–539.

Mok, C.M., C.Y. Chang, and D.E. Legaspi, "Site Response Analyses of Vertical Excitation," Geotechnical Earthquake Engineering and Soil Dynamics III, Seattle, Wash., 1998, pp. 739–753.

Moreno-Torres, O., Y.M.A. Hashash, and S.M. Olson, "A Simplified Coupled Soil-Pore Water Pressure Generation for Use in Site Response Analysis," *GeoFlorida Advances in Analysis, Modeling & Design*, West Palm Beach, Fla., 2010.

Muravski, G., "On Description of Hysteretic Behavior of Materials," *International Journal of Solids and Structures*, Vol. 42, 2005, pp. 2625–2644.

Muravski, G. and S. Frydman, "Site Response Analysis Using a Nonlinear Hysteretic Model," S*oil Dynamics and Earthquake Engineering*, Vol. 17, 1998, pp. 227–238.

Nishi, K., J. Tohma, and M. Kanatani, "Effective Stress Analysis for Level Sand Deposits with Cyclic Mobility," 5th International Conference on Numerical Methods in Geomechanics, Nagoya, Japan, 2004.

Ordaz, M. and E. Faccioli, "Site Response Analysis in the Valley of Mexico: Selection of Input Motion and Extent of Non-linear Soil Behaviour," *Earthquake Engineering & Structural Dynamics*, Vol. 23, No. 8, 1994, pp. 895–908.

Papazoglou, A.J. and A.S. Elnashai, "Analytical and Field Evidence of the Damaging Effect of Vertical Earthquake Ground Motion," *Journal of Earthquake Engineering and Structural Dynamics*, Vol. 25, No. 10, 1996, pp. 1109–1137.

Park, D. and Y.M.A. Hashash, "Rate-dependent Soil Behavior in Seismic Site Response Analysis," *Canadian Geotechnical Journal*, Vol. 45, No. 4, 2008, pp. 454–446.

Phillips, C. and Y.M.A. Hashash, "A Simplified Constitutive Model to Simultaneously Match Modulus Reduction and Damping Soil Curves for Nonlinear Site Response Analysis," *Geotechnical Special Publication*, Sacramento, Calif., 2008.

Press, W.H., S.A. Teukolsky, W.T. Vetterling, and B.P. Flannery, *Numerical Recipes in FORTRAN 77 The Art of Scientific Computing*, Cambridge University Press, Cambridge, U.K., 1992.

Prevost, J.H., "Mathematical Modeling of Monotonic and Cyclic Undrained Clay Behavior," *International Journal of Numerical and Analytical Methods in Geomechanics*, Vol. 1, No. 2, 1977, pp. 195–216.

Prevost, J.H., *DYNAFLOW*: *A Nonlinear Transient Finite Element Analysis Program*, Department of Civil Engineering and Operational Research, Princeton University, 1981 (last update Jan. 1994).

Prevost, J.H., *DYNA1D: A Computer Program for Nonlinear Site Response Analysis, Technical Documentation*, National Center of Earthquake Engineering Research, SUNY at Buffalo, N.Y., 1989.

Prevost, J.H. and C.M. Keane, "Multimechanism Elasto-Plastic Model for Soils," *Journal of Engineering Mechanics*, Vol. 116, No. 9, 1990, pp. 1924–1945.

Puzrin, A.M. and J.B. Burland, "A Logarithmic Stress–Strain Function for Rocks and Soils," *Geotechnique*, Vol. 46, No. 1, 1996, pp. 157–164.

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Pyke, R.M., H.B. Seed, and C.K. Chan, "Settlement of Sands under Multidirectional Shaking," *Journal of Geotechnical Engineering Division*, Vol. 101, No. GT4, 1975, pp. 379–398.

Rathje, E.M., N.A. Abrahamson, and J.D. Bray, "Simplified Frequency Content Estimates of Earthquake Ground Motions," *Journal of Geotechnical & Geoenvironmental Engineering*, Vol. 124, No. 2, 1998, pp. 150–159.

Rathje, E.M., A.R. Kottke, and W.L. Trent, "Influence of Input Motion and Site Property Variabilities on Seismic Site Response Analysis," *Journal of Geotechnical & Geoenvironmental Engineering*, Vol. 136, No. 4, 2010, pp. 607–619.

Rayhani, M.H.T., M.H. El Naggar, and S.H. Tabatabaei, "Nonlinear Analysis of Local Site Effects on Seismic Ground Response in the Bam Earthquake," *Geotechnical and Geological Engineering*, Vol. 26, No. 1, 2008, pp. 91–100.

Roten, D., D. Fäh, L.F. Bonilla, S. Alvarez-Rubio, T.M. Weber, and J. Laue, "Estimation of Non-linear Site Response in a Deep Alpine Valley," *Geophysical Journal International*, Vol. 178, No. 3, 2009, pp. 1597–1613.

Seed, H.B. and I.M. Idriss, "Influence of Soil Conditions on Ground Motions during Earthquakes," *Journal of Soil Mechanics and Foundation Division*, Vol. 95, 1969, pp. 99–137.

Seed, H.B., I.M. Idriss, F. Makdisi, and N. Bannerjee, "Representation of Irregular Stress Time Histories by Equivalent Uniform Stress Series in Liquefaction Analyses," Report No. UCB/EERC/75-29, Earthquake Engineering Research Center, University of California, Berkeley, Calif.

Seed, H.B., R.M. Pyke, and G.R. Martin, "Effect of Multi-Directional Shaking on Pore-Pressure Development in Sands," *Journal of the Geotechnical Engineering Division*, Vol. 104, No. GT1, 1978, pp. 27–44.

Sheahan, T.C., C.C. Ladd, and J.T. Germaine, "Rate Dependent Undrained Shear Behavior of Saturated Clay," *Journal of Geotechnical & Geoenvironmental Engineering*, Vol. 122, No. 2, 1996, pp. 99–108.

Sidarta, D. and J. Ghaboussi, "Modelling Constitutive Behavior of Materials from Non-uniform Material Tests," *Computers and Geotechnics*, Vol. 22, No. 1, 1998, pp. 53–71.

Silver, M.L. and H.B. Seed, "Volume Changes in Sands during Cyclic Loading," *Journal of Soil Mechanics and Foundation Division*, Vol. 97, No. SM9, 1971, pp. 1174–1178.

Steidl, J.H., "Site Response in Southern California for Probabilistic Seismic Hazard Analysis," *Bulletin of the Seismological Society of America*, Vol. 90, 6 Suppl., 2000, pp. S149–S169.

Stewart, J. and A.O.L. Kwok, "Nonlinear Seismic Ground Response Analysis: Code Usage Protocols and Verification Against Vertical Array Data," Geotechnical Earthquake Engineering and Soil Dynamics IV Congress 2008—Geotechnical Earthquake Engineering and Soil Dynamics, GSP 181.

Streeter, V.L., E.B. Wylie, and F.E. Richart, "Soil Motion Computations by Characteristics Methods," *Proceedings, ASCE National Structural Engineering Conference*, San Francisco, Calif., 1973.

Streeter, V.L., E.B. Wylie, and F.E. Richart, "Soil Motion Computation by Characteristic Method," *Journal of the Geotechnical Engineering Division*, Vol. 100, No. GT3, 1974, pp. 247–263.

Sugito, M., H. Goda, and T. Masuda, "Frequency Dependent Equi-Linearized Technique for Seismic Response Analysis of Multi-Layered Ground," *Doboku Gakkai Rombun-Hokokushu/Proceedings of the Japan Society of Civil Engineers*, Vol. 493, No. 3–2, 1994, pp. 49–58.

Tan, K. and M. Vucetic, "Behavior of Medium and Low Plasticity Clays Under Cyclic Shear Conditions," *Proceedings 4th International Conference on Soil Dynamics and Earthquake Engineering*, Mexico City, Mexico, 1989, pp. 131–142.

Tsai, C.-C. and Y.M.A. Hashash, "Learning of Dynamic Soil Behavior from Downhole Arrays," *Journal of Geotechnical & Geoenvironmental Engineering*, Vol. 135, No. 6, 2009, pp. 745–757.

Tsang, H.H., A.M. Chandler, and N.T.K. Lam, "Estimating Non-Linear Site Response by Single Period Approximation," *Earthquake Engineering and Structural Dynamics*, Vol. 35, No. 9, 2006, pp. 1053–1076.

Tsuda, M., J. Steidl, R. Archuleta, and D. Assimaki, "Site-Response Estimation for the 2003 Miyagi-Oki Earthquake Sequence Considering Nonlinear Site Response," *Bulletin of the Seismological Society of America*, Vol. 96, No. 4A, 2006, pp. 1474–1482.

Vucetic, M. and R. Dobry, "Cyclic Triaxial Strain-controlled Testing of Liquefiable Sands," Advanced Triaxial Testing of Soil and Rock, ASTM STP 977, American Society for Testing and Materials, Philadelphia, Pa., 1988, pp. 475–485.

Vucetic, M., "Cyclic Threshold Shear Strains in Soils," *Journal of Geotechnical Engineering*, Vol. 120, 1994, pp. 2208–2228.

Vucetic, M. and R. Dobry, "Pore Pressure Buildup and Liquefaction of Level Sandy Sites During Earthquakes," Research Report, Rensselaer Polytechnic Institute, Troy, N.Y., 1986, 616 pp.

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Wang, Z.L., C.Y. Chang, and C.C. Chin, "Hysteretic Damping Correction and Its Effect on Non-Linear Site Response Analyses," *Geotechnical Special Publication*, Sacramento, Calif., 2008.

Watabe, M., M. Tohido, O. Chiba, and R. Fukuzawa, "Peak Accelerations and Response Spectra of Vertical Strong Motions from Near-Field Records in USA," Eighth Japan Earthquake Engineering Symposium, Tokyo, Japan, 1984, pp. 301–306.

Wilson, E., *Dynamic Analysis by Numerical Integration*, Computers and Structures Inc., San Francisco, Calif., 2005.

Youd, T.L., "Compaction of Sands by Repeated Shear Straining," *Journal of Soil Mechanics and Foundation Division*, Vol. 98, 1972, pp. 709–725.

Zhai, E., W. Roth, E. Dawson, and C. Davis, "Seismic Deformation Analysis of an Earth Dam—A Comparison Study Between Equivalent-Linear and Nonlinear Effective Stress Approaches," Paper No. 3298, 13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada, 2004.

Zheng, W. and R. Luna, "Nonlinear Site Response and Liquefaction Analysis in the New Madrid Seismic Zone," *Geotechnical and Geological Engineering*, Vol. 29, No. 4, 2011, pp. 1–13.

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GLOSSARY

A_{loop}: Area of hysteresis loop

[C]: velocity proportional damping matrix

f_1 and f_2, f_3, f_4: Frequencies for Rayleigh viscous damping

G: Shear modulus

G_{max}: Maximum shear modulus (usually obtained from shear wave velocity)

h, h_i: thickness of layer

$[K]$: stiffness matrix

k, k_i: element of stiffness matrix

$[M]$: Mass matrix

m: element of mass matrix

q_c: uncorrected tip resistance from CPT sounding

S_u: undrained shear strength of soil

T_o: Fundamental period of a soil column or structure

$\{u\}$: displacement vector

V_s: Shear wave velocity

V_{s30}: (average) shear wave velocity of the top 30 meters

α_R: Rayleigh damping coefficient

β: damping or coefficient in Newmark-type numerical integration of equation of motion

β_R: Rayleigh damping coefficient

γ: shear strain

γ_c: cyclic shear strain

τ_c: cyclic shear stress

ξ_{tar}: Target damping ratio

Θ: Wilson time stepping coefficient

ρ: mass density of soil

1-D: One dimensional

2-D: Two dimensional

3-D: Three dimensional

CMS: Conditional Mean Spectrum

COSMOS: The Consortium of Organizations for Strong-Motion Observation Systems

CPT: Cone Penetration Test

CSR: Cyclic Stress Ratio

DOT: Department of transportation

DSHA: Deterministic Seismic Hazard Analysis

DSS: (cyclic) Direct Simple Shear (test)

EL: Equivalent-Linear

EPRI: Electric Power Research Institute

GMPE: Ground Motion Prediction Equation

IBC: International Building Code

LRFD: Load and Resistance Factor Design

MCE: Maximum Considered Earthquake

MR: Modulus Re-matching only with extended Masing rule

MRD: approximate match of both modulus and damping with extended Masing rule

MRDF: Modulus reduction and damping matching with non-Masing rule

NGA: Next Generation Attenuation (relationship)

NL: Nonlinear

PEER: Pacific Earthquake Engineering Research Center

PI: Principal Investigator

PSHA: Probabilistic Seismic Hazard Analysis

pwp: pore water pressure

ReMI: Refraction Microtremor

RVT: Random Vibration Theory

SASW: Spectral Analysis of Surface Waves

sCPT: seismic Cone Penetration Test

SFSI: Soil-Foundation-Structure Interaction (the same as SSI: Soil-Structure-Interaction)

SPT: Standard Penetration Test

SSI: Soil-Structure Interaction

UHRS: Uniform Hazard Response Spectrum

USAEC: United States Corps of Engineers

USGS: United States Geologic Survey

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APPENDIX A

Survey Questionnaire

Page One—General questions

1.)

Dear Colleague:

The Transportation Research Board (TRB) is preparing a synthesis on *Practice and Procedures for Site-Specific Evaluation of Earthquake Ground Motions, NCHRP Synthesis 20-05/Topic 42-03, State DOT's Survey*. This is being done for NCHRP, under the sponsorship of the American Association of State Highway and Transportation Officials, in cooperation with the Federal Highway Administration.

The synthesis study intends to identify and describe current practice and available methods for site specific analysis of earthquake ground motions. The study will include a summary of experience gained in developing and employing these methods, including challenges in their application and perceived advantages and disadvantages of the different methods. This study will help establish and improve the state of practice, providing a summary of best design practices, as well as identifying research and development needs on this important topic. This questionnaire will help us understand the current practice in site specific analysis of ground motions at selected state departments of transportation and will help us identify some of the challenges encountered when conducting the analyses. We appreciate you taking the time to complete this survey. Please do not hesitate to contact us should you have any questions. As a token of our appreciation we will provide you electronically with a copy of the completed study.

The results of this study will be reported only in aggregate form (no individual names will be reported).

This survey is being sent to state departments of transportation and their consultants. Your cooperation in completing the questionnaire will ensure the success of this effort. If you are not the appropriate person at your agency to complete this survey, please forward it to the correct person.

Please compete and submit this survey by COB Friday, February 25, 2011. We estimate that it should take no more than 60 minutes to complete. If you have any questions, please contact our principal investigator Dr. Neven Matasovic (NMatasovic@Geosyntec.com, 714-465-1244) or Prof. Youssef Hashash (hashash@illinois.edu, 217-333-6986). Any supporting materials can be sent directly to by e-mail or at the postal address shown at the end of the survey.

QUESTIONNAIRE INSTRUCTIONS

1. **To view and print the entire questionnaire, Click on the following link and print using "control p".**

2. **To save your partial answers, or to forward a partially completed questionnaire to another party, click on the "Save and Continue Later" link in the upper center of your screen on page 2 and onwards. A link to the partial survey will be e-mailed to you or a colleague.**

3. **To view and print your answers before submitting the survey, click forward to page 8. Print using "control p".**

4. **To submit the survey, click on "Submit" on the last page.**

Name of Respondent: ______________________________

Title of Respondent: ______________________________

Name of State Agency and office: ______________________________

Address: ______________________________

E-mail: ______________________________

Telephone number: ______________________________

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2.) Do your following responses apply to (check all that applies)?

[ ] Your own individual practice

[ ] The practice of your office/number of engineers

[ ] The practice of your agency/number of engineers

3.) Approximately how many of your projects involve site response analyses in a given year?

( ) 1–2

( ) 3–6

( ) 7–12

( ) 13–25

( ) 26–50

( ) >50

4.) Guidelines and manuals for seismic site response

[ ] Your agency has a manual for seismic design; please provide title and web link

[ ] Your manual has provisions for seismic site response analysis/provide title and web link

Page Two—Criteria and programs used

5.) When is the use of code-based site factors acceptable for characterizing site effects?

[ ] Preliminary design

[ ] Small structures

[ ] Seismic hazard is low

[ ] Always

[ ] Never

[ ] Other—please provide a brief narrative

6.) When is the use of computer analysis required for site response analysis?

[ ] Site class dependent—please list site class

[ ] Seismic hazard level—please specify

[ ] Ground conditions (e.g., liquefiable soils, or organic soils, or very soft soils subjected to strong shaking, please specify)

[ ] Structure type—please specify

[ ] Other—please describe

7.) Of the total number of site response analyses you perform, indicate the approximate percentages that fall within each of the following categories:

One-dimensional equivalent-linear: ________________________________

One-dimensional nonlinear total stress (no pore water pressure): __________

One-dimensional nonlinear effective-stress (with pore water pressure): ___

Two- or three-dimensional equivalent-linear: _________________________

Two- or three-dimensional nonlinear Total Stress Analysis: _____________

Two- or three-dimensional nonlinear Effective-Stress Analysis: __________

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8.) What computer program(s) do you use for each of the following types of analyses (list more than one if appropriate; leave blank if you do not perform one of these types of analyses)?

One-dimensional equivalent-linear: ______________________________________

One-dimensional nonlinear—Total stress (no pore water pressure): ________________

One-dimensional nonlinear—Effective-stress (with pore water pressure): ___________

Two- or three-dimensional equivalent-linear: _______________________________

Two- or three-dimensional nonlinear: ____________________________________

9.) Please describe validation/verification requirements you have for computer code usage.

Page Three—Seismic hazard motion input required for site response analysis

Note for the following questions: Input ground motions are required for performing site response analysis based on specific hazard levels. The questions below will help us understand how you develop these ground motions.

10.) How do you define the seismic hazard at your site and the target rock response spectra?

[ ] USGS Maps

[ ] Code Provision—List code

[ ] Site specific deterministic—describe program

[ ] Site specific probabilistic—describe program

[ ] Other, please specify:

11.) How do you develop hazard compatible ground motion time histories at rock?

[ ] Simple scaling of motions from widely available libraries

[ ] rigorous spectral matching (specify method if known)

[ ] Synthetic ground motions

[ ] Other, please specify:

12.) How many motion time histories do you generate or require for a given hazard level

( ) 1 motion

( ) 3 motions

( ) 7 motions

( ) Other, please specify:

13.) For sites where near faults effects are significant, what special requirements do you impose on the suite of input ground motions?

[ ] None

[ ] incorporate directivity

[ ] include velocity pulse

[ ] use two component motions (e.g., Fault normal/parallel)

[ ] check cross-correlation of the input ground motion time histories

[ ] Other, please specify:

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14.) How do you handle uncertainty in the input ground motion?

15.) Please include other comments you may have related to the topic of input motions.

Page Four—Soil profile input information required for site response analysis

16.) What special geotechnical field and laboratory investigations do you require/perform to obtain information suitable for site response analysis?

[ ] None

[ ] Direct measurement of shear wave velocity

[ ] Cyclic triaxial, direct simple shear or resonant column tests

[ ] Other, please specify:

17.) How do you obtain the shear wave velocity profile for the soil column?

[ ] SPT correlations

[ ] CPT correlations

[ ] Seismic cone

[ ] downhole

[ ] crosshole

[ ] suspension logger

[ ] surface wave/SASW/MASW

[ ] Other, please specify:

18.) How do you define the dynamic soil properties (modulus reduction and damping curves) for site response analysis? (lab testing, published correlations based soil index properties such as Darandelli, Vucetic and Dobry, Seed and Idriss...)

[ ] laboratory testing

[ ] Darendeli

[ ] Vucetic-Dobry

[ ] Seed-Idriss

[ ] Other, please specify:

19.) Do you account for uncertainty in the soil profile properties? If yes, how? If not, why not?

20.) Please include other comments you may have related to the topic of soil profile input

Page Five—Site response analysis

21.) When is an equivalent-linear analysis (e.g., SHAKE or similar program) used or required?

[ ] Site class dependent—please list site class

[ ] Seismic hazard level—please specify

[ ] Structure type—please specify

[ ] Other, please describe:

22.) What soil models do you usually use for equivalent-linear site response analyses (mark all that applies)?

[ ] EPRI

[ ] Ishibashi-Zhang

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[ ] Iwasaki

[ ] Seed-Idriss Sand

[ ] Seed-Idriss Clay

[ ] Vucetic-Dobry

[ ] Darendeli

[ ] Other:

23.) When is a nonlinear total stress (no pore water pressure generation) analysis used or required?

[ ] Site class dependent—please list site class

[ ] Seismic hazard level—please specify

[ ] Structure type—please specify

[ ] Strain amplitude—please specify

[ ] Other, please describe:

24.) What soil models do you usually use for nonlinear total stress site response analyses (mark all that applies)?

[ ] Hyperbolic with Masing criteria

[ ] Modified Hyperbolic with Masing criteria (e.g., M-K-Z)

[ ] Modified Hyperbolic with non Masing criteria (e.g., MRDF to match both modulus reduction and damping curves)

[ ] Cundall-Pyke model

[ ] Mohr-Coulomb

[ ] Other—whatever model is included in my software—please specify:

[ ] It is important for the model to match both modulus reduction and damping curves

[ ] It is only important that the model matches modulus reduction regardless of the damping curve.

25.) When is a nonlinear effective-stress (with pore water pressure generation) analysis used or required?

[ ] Site class dependent—please list site class

[ ] Seismic hazard level—please specify

[ ] Structure type—please specify

[ ] When porewater pressure ratio exceeds a given value—please specify

[ ] Other, please describe:

26.) What soil models and porewater pressure generation models do you use in nonlinear effective-stress site response analyses (mark all that applies)?

[ ] Dobry

[ ] Elgamal

[ ] GMP (Green)

[ ] Martin-Finn-Seed

[ ] Matasovic (Modified Dobry et al. porewater pressure model)

[ ] UBC Sand

[ ] Other

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Page Six—Evaluation and use of results

27.) What do you consider to be the top three uncertainties in the input to a typical seismic site response analysis?

[ ] Low-strain stiffness (represented by G_{max} or V_s)

[ ] Higher strain stiffness (represented by modulus reduction or backbone curve)

[ ] Small strain damping behavior represented by viscous damping

[ ] Large strain damping behavior (represented by damping curve or unloading-reloading model)

[ ] Soil layer thickness

[ ] Depth to bedrock

[ ] Character of bedrock (V_s, modulus reduction and damping behavior)

[ ] Input motions

[ ] Other:

28.) How do you typically account for such uncertainties in design?

[ ] Select reasonably conservative values of input parameters

[ ] Use "best estimate" input parameters, then apply conservatism to results

[ ] Perform sensitivity analyses

[ ] Perform probabilistic analyses (e.g. FOSM, Monte Carlo)

[ ] We don't address uncertainties explicitly

[ ] Other, please specify:

29.) How do you evaluate the validity of the overall site response model at your site?

[ ] Compare with empirical correlations

[ ] Perform sanity checks

[ ] Other, please specify:

30.) What output do you use from site response analysis?

[ ] Surface response spectra

[ ] Surface velocities

[ ] Surface displacements

[ ] Surface time histories

[ ] Profiles of PGA

[ ] Profiles of strains

[ ] Profiles of displacements

[ ] Profiles of shear stress

[ ] Other, please specify:

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31.) Do you use output of profiles of strains and lateral deformations in a structural analysis? (e.g., pile lateral loading…), please explain, do you perform any baseline correction of the output motions?

32.) Do you use profile of peak ground acceleration for liquefaction analysis? Please explain. When you evaluate cyclic stress ratio (CSR) for liquefaction analyses, how often do you do so by means of site response analyses (as opposed to using the simplified method)? What criteria do you use for deciding when to do so?

33.) Do you use profile of peak ground acceleration for slope stability analysis? Please explain.

34.) For analyses where pore water pressure generation is evaluated, how do you use the analysis output?

35.) Please include other comments you may have related to the topic on evaluation and use.

Page 7—Helpful contacts

36.) As part of this synthesis study we will also survey private consulting firms and engineers who conduct site specific response analysis. Can you please provide us with contact information of key firms and engineers that provide site response analysis services to your DOT?

	Firm Name	Contact Person	Contact information
Contact 1	___	___	___
Contact 2	___	___	___
Contact 3	___	___	___
Contact 4	___	___	___
Contact 5	___	___	___
Contact 6	___	___	___
Contact 7	___	___	___
Contact 8	___	___	___
Contact 9	___	___	___
Contact 10	___	___	___

37.) Please feel free to include any thoughts or comments you would like to share with us.

Thank You!

Thank you for taking our survey. Your response is very important to us.

Postal address:

Dr. Neven Matasovic

Geosyntec

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APPENDIX B

Compiled Survey Responses

2.) Do your following responses apply to (check all that applies)?

[ ] Your own individual practice

[ ] The practice of your office/number of engineers

[ ] The practice of your agency/number of engineers

TABLE B1
APPLICABILITY OF RESPONSE TO ENGINEERING PRACTICE

	Respondents Count	# of Engineers Ave/Total	Range of # of Engineers
Your own individual practice	10		
The practice of your office	17	93/1298	3–500
The practice of your agency	14	49/246	1–100

3.) Approximately how many of your projects involve site response analyses in a given year?

( ) 1–2

( ) 3–6

( ) 7–12

( ) 13–25

( ) 26–50

( ) >50

TABLE B2
NUMBER OF PROJECTS INVOLVING SITE RESPONSE ANALYSES IN A GIVEN YEAR

No. of Projects	Count
1–2	12
3–6	3
7–12	8
13–25	3
26–50	1

4.) Guidelines and manuals for seismic site response

[ ] Your agency has a manual for seismic design; please provide title and web link

[ ] Your manual has provisions for site response analysis/provide title and web link

TABLE B3
RESPONDENTS WHO USE GUIDELINES AND MANUALS FOR SEISMIC SITE RESPONSE

	Count
Your agency has a manual for seismic design	12
Your manual has provisions for seismic site response analysis	10

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TABLE B4
GUIDELINES AND MANUALS FOR SEISMIC SITE RESPONSE

1	Caltrans Seismic Design Criteria http://www.dot.ca.gov/hq/esc/earthquake_engineering/SDC_site/
2	http://www.wsdot.wa.gov/Publications/Manuals/M46-03.htm
3	Internal draft guidelines that are not for public release.
4	http://www.dot.il.gov/bridges/brmanuals.html
5	2009 LRFD Seismic Design Provisions; *NCHRP Report 611*
6	2009 LRFD Seismic Design Provisions; *NCHRP Report 611*
7	ASCE 7, ASCE 4, ASCE43-05, NRC RG 1.208; U.S. Army Corps of Engineers EM110-2-6050
8	AASHTO LRFD Specifications
9	http://www.dot.ca.gov/hq/esc/earthquake_engineering/SDC_site/
10	Geomotions
11	ODOT Geotechnical Design Manual ftp://ftp.odot.state.or.us/techserv/Geo-Environmental/Geotech/GeoManual/FinalGDM12-10-09/Volume1GeotechDesignManualFinal_Dec2009.pdf
12	http://www.wsdot.wa.gov/Publications/Manuals/M46-03.htm
13	http://www.scdot.org/doing/bridge/bridgeseismic.shtml, http://www.scdot.org/doing/bridge/geodesignmanual.shtml
14	GA DOT website
15	http://www.dot.ri.gov/documents/engineering/br/RILRFDBridgeManual.pdf

Page Two—Criteria and programs used

5.) When is the use of code-based site factors acceptable for characterizing site effects?

[ ] Preliminary design

[ ] Small structures

[ ] Seismic hazard is low

[ ] Always

[ ] Never

[ ] Other, please provide a brief narrative:

TABLE B5
CIRCUMSTANCES WHEN THE USE OF CODE-BASED SITE FACTORS IS ACCEPTABLE FOR CHARACTERIZING SITE EFFECTS

	Count
Preliminary design	16
Small structures	12
Seismic hazard is low	14
Always	11
Never	0
Other – See next table	17

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TABLE B6

ADDITIONAL CIRCUMSTANCE WHEN THE USE OF CODE-BASED SITE FACTORS IS ACCEPTABLE FOR CHARACTERIZING SITE EFFECTS

1	Site Classes A through E
2	All cases except for Site Class "F" locations, which are typically susceptible to liquefaction.
3	Exceptions: Non-ordinary structures as defined in SDC, Soil type F
4	For buildings it is acceptable for sites other than Site Class F, for bridges it is acceptable for site class other than F and when the bridge is not critical, for other structures it depends on the code standards and the criticality of the project.
5	More conservative site is assumed.
6	As per AASHTO recommendations, site class F and also as per ODOT GDM Section 6.5.1.4
7	Most structures except when the conditions stated in Q6 below apply.
8	We will generally use the code-based site factors either at the start of a project or to compare/check results from site response analyses
9	Although it is important to understand the general site response behavior in your environment (i.e., if you work in Boston—you should have done at least one site response computation with a typical profile—to understand the local issues.
10	Always, except very large expensive/critical structures
11	For soils other than soft/liquefiable soils
12	We only use for small to mid-size CBC projects. Almost everything else uses some form of NGA.
13	structures of low importance
14	For most of the bridges in New York State being in low seismic zone.
15	When the site is not site class F
16	Code-based site factors are used where seismic hazard is simple (no long duration, directivity, basis) and site conditions are not anticipated to result in a code exceedance, and where the cost impact of conservative design is not significant
17	A. Typically SCDOT uses the site factors for the vast majority of our bridges; however, depending on the bridge a Site-Specific Response Analysis may be required. The SCDOT 2008 Seismic Design Specifications for Highway Bridges and the 2010 Geotechnical Design Manual delineate when a Site-Specific Response Analysis is required. In addition, SCDOT may require a Site-Specific Response Analysis for bridges that are considered major. Currently SCDOT has a research project reviewing and developing new site factors for South Carolina.

6.) When is the use of computer analysis required for site response analysis?

[ ] Site class dependent—please list site class

[ ] Seismic hazard level—please specify

[ ] Ground conditions (e.g., liquefiable soils, or organic soils, or very soft soils subjected to strong shaking, please specify)

[ ] Structure type—please specify

[ ] Other, please describe:

TABLE B7

CIRCUMSTANCES WHEN SITE RESPONSE ANALYSIS IS REQUIRED

	Count
Site class dependent	27
Seismic hazard	14
Ground conditions (e.g., liquefiable soils, or organic soils, or very soft soils subjected to strong shaking)	28
Structure Type	19
Always	12

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TABLE B8

SITE CLASS REQUIRED FOR SITE RESPONSE ANALYSIS (NUMBER IN PARENTHESIS IS RESPONDENTS COUNT)

F(20), F (for all bridges, $T > 0.5$ sec), E(10) E (deep sites, high motion, critical bridges), D(3), C(2). When required by code, when unique soil conditions exist, when there appears to be advantage to the client, or when the client requires. Often we will look to the site analysis for higher PGA values and for deeper soil profiles. B. A Site-Specific Response Analysis is required for Site Class F as defined in the 2010 Geotechnical Design Manual. Certain bridge types (i.e., spans greater than 300 feet, etc.) or as determined by SCDOT personnel. See p. 12-22, GDM (2010)

TABLE B9

SEISMIC HAZARD LEVEL REQUIRED FOR SITE RESPONSE ANALYSIS

1	We do site specific analysis to determine input parameters for simplified liquefaction analysis.
2	hazard level not covered by codes
3	PBA > 0.2 g
4	PGA > 0.6 g and the site is near major fault(s) capable of generating large earthquakes
5	PGA values that could result in soil nonlinearity or liquefaction
6	High
7	high ground motions
8	PGA > 0.15g
9	For certain conditions specified by CBC 2010
10	When the design is required for higher hazard level than the 2500 year return earthquake
11	high hazard

TABLE B10

GROUND CONDITIONS WHEN SITE RESPONSE ANALYSIS IS REQUIRED

1	Liquefaction
2	Liquefiable soils, or organic soils
3	Site class F sites
4	F sites, deep E sites
5	Liquefiable site
6	Section 6.5.1.4 in ODOT GDM
7	Sites with soft soils that display significant degradation of strength and stiffness under strong ground shaking. Sites with surficial soil layers that have drastically different strength and stiffness (e.g., soft clay over rock).
8	Deep soils, liquefiable soils, very soft soils
9	Liquefiable soils, deep soft clay profiles, or when the soil profile makes the simplified site factors suspect
10	Any unusual soil conditions—very deep, liquefiable, organic soils—or other soils with unusual behavior, sharp impedance contrasts...
11	liquefiable soils
12	liquefiable soils
13	soft soils such as Bay Mud and liquefiable soils in strong shaking areas
14	large impedance contrast
14	brittle quarry slopes subject to strong shaking
16	Most codes require site response for liquefiable sites
17	liquefiable soils or significant amounts of soft soils
18	liquefiable soils, expected significant site effect, soft soils
19	all conditions that will classify the site as site class F
20	Liquefiable soils
21	liquefiable soils, soft soils
22	same as site class F
23	liquefiable or soft soils, high impedance contrasts

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TABLE B11
STRUCTURE TYPE WHERE SITE RESPONSE ANALYSIS IS REQUIRED

1	lifeline, "mega-bridge" structures such as the Knik Arm Crossing
2	Non-ordinary structures as defined in SDC (life line bridges, large toll bridges, etc.)
3	Occ IV, critical facilities
4	high-rise tower >>50 story
5	Base isolation
6	High rises/highly irregular structures that requires dynamic time history analysis to be completed for design, and essential buildings/structures/bridges.
7	Essential Bridges
8	Critical or essential bridges—or where there is a significant cost associated with use of simplified site factors
9	high risk
10	Critical structures
11	Critical structure or base-isolated structure
12	high importance
13	Nuclear Structure in Safety Category I and II
14	critical structures
15	irregular, special structures
16	For larger projects; e.g., bridges and dams will be required regardless of site class
17	Significant or complicated structure requiring more in-depth analysis for economical design

TABLE B12
OTHER CONDITIONS WHERE SITE RESPONSE ANALYSIS IS REQUIRED

1	offshore structures
2	For projects where earthquake time histories at depths are needed for design analysis of the structures.
3	performance-based structural analysis
4	http://www.dot.il.gov/bridges/AGMU%20091.pdf
5	We rely on site class definition based on Method B (N values) and use USGS maps to calculate the 5% damped design response spectrum
6	client request
7	To be considered in the future
8	Liquefiable Soils
9	Sometimes done when SE is doing sophisticated time history analyses, so more sophisticated ground motion development is warranted.
10	Research
11	We do a computer analysis for bridges in Seismic Performance Category B zones. Georgia does not have and SPC C or D bridges

7.) Of the total number of site response analyses you perform, indicate the approximate percentages that fall within each of the following categories:

One-dimensional equivalent-linear: ______________________________

One-dimensional nonlinear—Total stress (no pore water pressure): ______________

One-dimensional nonlinear—Effective-stress (with pore water pressure): __________

Two- or three-dimensional equivalent-linear: ______________________

Two- or three-dimensional non-linear—Total Stress Analysis: ______________

Two- or three-dimensional non-linear—Effective-Stress Analysis: ______________

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TABLE B13

APPROXIMATE PERCENTAGES OF SITE RESPONSE ANALYSES THAT FALL WITHIN EACH OF THE FOLLOWING CATEGORIES, NUMBER IN PARENTHESES IS NUMBER OF RESPONDENTS

One-dimensional equivalent-linear [28, respondents]	0% (2), 30% (2), 35% (1) 40% (1), 50% (2), 60% (1), 65% (1), 70% (2), 75% (2), 80% (2), 90% (1), 100% (13)
One-dimensional nonlinear—Total stress (no pore water pressure) [17]	0% (3), 3% (1), 5% (1), 10% (3), 100% (1), 15% (1), 20% (3), 25% (1), 30% (1), 50% (2), 70% (1), 85% (1)
One-dimensional nonlinear—Effective-stress (with pore water pressure) [18]	0% (2), 3% (1) 10% (3), 15% (2), 20% (2), 25% (2), 30% (2), 40% (2), 100% (1), always in parallel with equivalent linear
Two- or three-dimensional equivalent-linear [7]	0% (4), 10% (1), 15% (2)
Two- or three-dimensional non-linear—Total Stress Analysis [8]	0% (4), 5% (1), 10% (1), 15% (1), 100% (1). usually we run FLAC analysis and use one dimensional analysis to get the input motion at the base of the model
Two- or three-dimensional non-linear—Effective-Stress Analysis [10]	0% (1), 5% (4), 15% (1), 20% (1), 25% (1), 40% (1)

8.) What computer program(s) do you use for each of the following types of analyses (list more than one if appropriate; leave blank if you do not perform one of these types of analyses)?

One-dimensional equivalent-linear: ______________________________

One-dimensional nonlinear—Total stress (no pore water pressure): ______________

One-dimensional nonlinear—Effective-stress (with pore water pressure): __________

Two- or three-dimensional equivalent-linear: _______________________

Two- or three-dimensional nonlinear: ___________________________

TABLE B14

SOFTWARE PROGRAMS USED FOR SITE RESPONSE ANALYSIS, NUMBER IN PARENTHESES IS NUMBER OF RESPONDENTS

One-dimensional equivalent-linear	SHAKE2000 (12), SHAKE (10), DEEPSOIL (4), SHAKE 91 (4), PROSHAKE (3), Shake-Edit (1), SCDOT SHAKE, in-house, No limits in the past - any program, Assimaki and Kausel.
One-dimensional nonlinear—Total stress (no pore water pressure)	D-MOD2000 (12), DEEPSOIL (7), FLAC (3), OpenSees (1), SIREN (1), Finite difference code developed @ GATech (1)
One-dimensional nonlinear—Effective-stress (with pore water pressure)	D-MOD2000 (13), DEEPSOIL (3), FLAC (4), OpenSees (1), DYNAFLOW (1), various
Two- or three-dimensional equivalent-linear	QUAD4M (6), FLAC (3), SIGMA/W (1), Quake/W (2), SUMDES (1), SASSI (1), ABAQUS (1), Seisab (1)
Two- or three-dimensional non-linear	FLAC (8), ABAQUS (2), PLAXIS (2), Dynaflow (1),

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9.) Please describe validation/verification requirements you have for computer code usage.

TABLE B15
VALIDATION/VERIFICATION REQUIREMENTS FOR COMPUTER CODE USAGE

Count	Response
1	Compare with code spectra
1	Comparison between different codes; comparison to known solutions
1	Comparison between different computer codes.
1	Downhole array data, centrifuge experimental studies
1	None used
1	Peer review
1	SHAKE—verified according to nuclear standards Deepsoil—used verification from literature
1	Site Response Analysis has been done by the Consultants.
1	We have been using FLAC and SHAKE for a long time and have developed a feel for it.
1	Described in Kwok et al. paper in JGGE
1	in-house procedure
1	None
1	Verify total stress between DMOD and SHAKE under small PBA where nonlinearity is minimal.
1	Peer review of non-linear Comparison of equivalent-linear, non-linear, and predicted ground motions of code and attenuation models.
1	Compare with previous studies—Check strain levels to see if 1-D equiv. lin. is applicable—Check stress levels to see if 1-D equiv. lin. is applicable—Check 2-D equiv. lin. results with 1-D equiv. lin.—Check 1-D total stress and effective-stress results with 1-D equiv. lin.—Do parametric runs to check model sensitivity (input motions, G-gamma curves, depth to bedrock, V_s).
1	All of the site response work I do is for research purposes. We use vertical array data to validate the code and make recommendations on site response methodology.
1	Typically, validation requirements involve an alternate calculation showing similar/identical results. However, critical and nuclear projects have required NQA-1 software V&V standards, which are much more stringent.
1	Prior to completing a 1-D nonlinear total stress analysis, a equivalent-linear must be completed. Prior to completing a 1-D nonlinear effective-stress analysis, the soil liquefaction analysis using the simplified method and the 1-D nonlinear total stress analysis must be completed. Prior to completing a 2-D analysis, a compatible 1-D analysis must be completed along with simplified analysis that will help calibrate the soil models used. I would not consider a 3-D analysis for design unless the earthquake loading can be modeled in 3-D and that research has shown the soil models available are adequate for 3-D analysis. 3-D modeling may be used to augment the 2-D modeling for design.
1	Varies highly by project. Some projects have no requirements. Some DOTs require only software from "pre-approved lists" be used. NRC and DOE require highest levels of V&V.
1	We are now using CSI Bridge (SAP) and we are in the process of working out our differences with our geotechnical engineers regarding liquefaction.
1	Check output (shear stress, strain levels, etc.) to see how they compare with reasonable ranges for the modeled soils, compare spectra to results from other previous analysis of sites with similar conditions.
1	Compare several programs of similar capabilities and against case studies with documented field data of performance. Some centrifuge tests as well.
1	During our extensive seismic retrofit program (1990 to 2000) we validated SHAKE with recordings from downhole arrays.
1	First let me explain that if we are using an effective-stress analyses, we are always conducting total stress analyses with the same program. So I made the numbers for these methods the same. We rarely would conduct a nonlinear total stress analysis by itself, because we don't find many sites that would warrant only this type of analysis. This is a little different for PLAXIS and FLAC where we have conducted seismic slope stability analyses for clay slopes. Now regarding calibration, we try to validate use of the code when we receive it by comparing to problems in the user's manual. If a person is running the code for the first time, we make sure he/she can validate the code against the user's manual. For equivalent-linear SHAKE analyses, we validate by checking input/output during our QA/QC process. We will also run suites of EQ records to define a range of motions, and we will vary the soil model to evaluate typical response. We will also compare against code-based site class factors (though usually these differ). We follow much the same process for the nonlinear codes. We will also compare total stress from SHAKE versus DMOD. We will also calibrate the soil model against lab and field data. For FLAC and PLAXIS we would calibrate a column versus SHAKE for the free field.
1	Validation checked by running results in Bridge Pier Program and looking at changes in footings and column sizes.
1	C. According to Chapter 26 of the GDM (2010) commercially available software packages are typically produced by either a university or software development firm and sold for profit. Software developed in this manner normally goes through extensive QA/QC prior to being sold. Therefore, the only documentation SCDOT requires for these software packages is the contact information for the developer. Software obtained from the FHWA website requires no additional information.
1	For NQA1 projects, we do have a V&V process. For all other projects, we rely on the V&V done by the vendor of the commercial software.

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Page Three—Seismic hazard motion input required for site response analysis

Note for the following questions: Input ground motions are required for performing site response analysis based on specific hazard levels. The questions below will help us understand how you develop these ground motions.

10.) How do you define the seismic hazard at your site and the target rock response spectra?

[ ] USGS maps

[ ] Code Provision—List code

[ ] Site specific deterministic—describe program

[ ] Site specific probabilistic—describe program

[ ] Other, please specify:

TABLE B16
METHODS TO DEFINE THE SEISMIC HAZARD AND THE TARGET ROCK RESPONSE SPECTRA—SEE DETAILED RESPONSES UNDER EACH ITEM ON THE NEXT TWO PAGES

Value	Count
USGS Maps	22
Code Provision—List code	19
Site specific deterministic—describe program	13
Site specific probabilistic—describe program	21
Other, please specify:	9

Code Provision
AASHTO LRFD (USGS 1000 year hazard maps)
AASHTO LRFD Bridge Design
Ibc
ASCE 7
ASCE 7-05 and AASHTO
AASHTO
AASHTO CD for DOT projects
IBC
AASHTO LRFD
International/California Building Code
AASHTO, USEPA guidance
CBC, IBC
NEHRP
NYCDOT Seismic Guidelines
IBC, NEHRP, AASHTO
NBCC (national building code of Canada)
USGS deagg
AASHTO 17th Edition
AASHTO

Site specific deterministic
New Generation Attenuation Equations (NGA)
EZ-FRISK
gis-hazard
SISMIC, Open SHA
GMPE available in SHAKE-2000 for Subduction Zone Earthquake and the NGA GMPE spreadsheets available from PEER web site
MathCAD with NGA models for crustal motions. Our California offices use Tom Blake's programs
EZ-FRISK/PEER NGA spreadsheet
Spreadsheets (NGA-based)
NGA
EZ-FRISK or deterministic attenuation model spreadsheet
EZ-Frisk, Spreadsheet Template
in-house

Site specific probabilistic
PSHA
Deaggregated data from USGS website
An internal tool (ARS online) based on USGS 1,000 yr RP

Other, please specify:
Deaggregate PSHA maps for fault data to use with liquefaction analysis
Most of the time we are using the USGS Maps
Seismologist

Table continued on p.55

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Table continued from p.54

Site specific probabilistic
EZ-FRISK
gis-hazard, EZ-FRISK
HAZ38 & USGS software
SISMIC, Open SHA
Site specific PSHA completed by others that uses the computer program HAZ-38 or later
We subcontract this to a specialist
Rarely do these analyses, but we have our own PSHA model and we have leased the PSHA code from Risk Engineering. We have also used Tom Blakes program in the past for locations in California.
EZ-FRISK
openSHA
EZ-FRISK
EZ-FRISK
EZ-FRISK or HAZ42 compared with USGS maps
Developed by Geophysical Institute of Israel
EZ-Frisk
in-house
in house

Other, please specify:
USGS deaggregation
USGS Interactive Deaggregation website
USGS NSHMP Java program
Source-specific attentuation for predominant sources, CMS utilized for target
D. SCDOT uses software exclusively developed for SCDOT called SCENARIO_PC to determine ground motions for both geologically realistic and hard rock. The software was developed by a partnership of USC (University of South Carolina) and Virginia Tech. The program accounts for the extremely thick (in excess of 2,900 feet) soil thickness adjacent to Coastal South Carolina.

11.) How do you develop hazard compatible ground motion time histories at rock?

[ ] Simple scaling of motions from widely available libraries

[ ] rigorous spectral matching (specify method if known)

[ ] Synthetic ground motions

[ ] Other, please specify:

TABLE B17

METHODS TO DEVELOP HAZARD COMPATIBLE GROUND MOTION TIME HISTORIES AT ROCK (FIRST ONE IS SIMPLE SCALING)—SEE DETAILED COMMENTS ON THE NEXT PAGE

Value	Count
Simple scaling of motions from widely available libraries	18
Rigorous spectral matching (specify method if known)	19
Synthetic ground motions	12
Other, please specify	8

Rigorous spectral matching methods
RASCAL
RSPMATCH
Inhouse
RspMatch (rarely used)
RSPMatch 2005
RSPMatch
We typically subcontract this
We use RSMatch in SHAKE2000. We also have a version of the Abrahamson code that we have used on projects.

Table continued on p.56

Other, please specify:
Synthetic and Scaled Real
we don’t do this
No
Risk Engineering Time Histories for NYCDOT
It usually comes from owner’s engineers—the majority are based on spectral matching—some agencies prefer linear scaling for a specific period of interest
SigmaSpec used for predominant periods of interest
Don’t use.

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Table continued from p.55

Rigorous spectral matching methods
RSPMatch
Rspmatch
done by others
Typically we use RSPMatch. Have also used Tinker.
RSPMatch software
RspMatch
Jack Baker
Abrahamson
RSPMATCH
Shahbazian, A. and S. Pezeshk. (2010). "Improved Velocity and Displacement Time Histories in Frequency-Domain Spectral-Matching Procedures." Bulletin of the Seismological Society of America, 100(6), pp. 3213–3223, Dec. 2010, doi: 10.1785/0120090163
RSPmatch

12.) How many motion time histories do you generate or require for a given hazard level

( ) 1 motion

( ) 3 motions

( ) 7 motions

( ) Other, please specify:

TABLE B18
NUMBER OF MOTIONS TIME HISTORIES GENERATED OR REQUIRED FOR A GIVEN HAZARD LEVEL

Value	Count
3 motions	4
7 motions	10
Other, please specify	20

Other, please specify:
3 real + 1 synthetic
This is so seldom done, that we have no standard or requirements. We generally look at perhaps 3.
1 for Resp. Spect. Analyses and 3 for Time Histories
Use 3 if matched to design bedrock spectra, use 7 if simple scaling is used
7 pairs or 14 time histories
We will use 3 to 7, depending on the project. Most of the time we would like to have at least 3 motions representing the 3 seismic sources in the PNW (crustal, subduction interface and subduction intraface). For geotechnical modeling, we will usually use a minimum of 7. We will use three if we are doing spectra matching for structural purposes.
we don't use
0
NA
5 or 7
varies by project, usually selected by SE
multimodal not considered

Table continued on p.57

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Table continued from p.56

Other, please specify:
3 to 7. But we typically try to use at least 7.
If using spectral matching, typically only 3 motions. If using scaling, 7 or more.
Monte Carlo convergence
Nuclear 1, hydro facility 3, other facility 7
We generate thousands to develop a probabilistic approach
For the recent large projects the trend has been 6 motions per level of earthquake (say 6 for 475 yr EQ)- some agencies (for school retrofit) require 10 motions
Typically 3 if matched, 7 or more if not, depending on the problem
Not used.

13.) For sites where near faults effects are significant, what special requirements do you impose on the suite of input ground motions?

[ ] None

[ ] incorporate directivity

[ ] include velocity pulse

[ ] use two component motions (e.g., Fault normal/parallel)

[ ] check cross-correlation of the input ground motion time histories

[ ] Other, please specify:

TABLE B19

SPECIAL REQUIREMENTS IMPOSED ON THE SUITE OF INPUT GROUND MOTIONS FOR SITES WHERE NEAR FAULTS EFFECTS ARE SIGNIFICANT

Value	Count
None	7
Incorporate directivity	15
Include velocity pulse	14
Use two component motions (e.g., Fault normal/parallel)	16
Check cross-correlation of the input ground motion time histories?	6
Other, please specify:	10

Other, please specify:
never encountered
Work in progress; near faults reviewed for significance, depending on importance of bridge detailed analysis may be performed considering directivity and pulse effects.
We use the Caltrans approach for adjusting the spectra.
not applicable
Presently considering different approaches
Select the existing motions near the faults that have velocity pulse
No experience or any structures near faults
This is beyond my expertise.
No faults are visible in South Carolina due to the thickness of the Coastal Plain deposits.

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14.) How do you handle uncertainty in the input ground motion?

TABLE B20
HANDLING OF UNCERTAINTY IN THE INPUT GROUND MOTION

By including phase spectra from real intraplate earthquakes in the analysis
Depending on the EQ, we sometimes use plus one sigma motions.
I am mostly using input/output pairs—so the input motion is not uncertain.
Input of a number of records from different earthquakes and different sites
Monte Carlo simulations on amplitude, duration & frequency content
NA
Not handled
Nothing specific other than number of time histories
Rock motion input motions are selected considering different fault rupture propagation scenarios
Should consider more time histories
Use more time histories if within 40 km of causative fault
When synthetics are generated a Monte Carlo simulation can be developed.
by selecting a representative suite
follow AASHTO, we are not seismic experts
mainly be running a minimum number of motions (say 6 to 10)
probabilistic evaluation parametric sensitivity studies
Select no more than two motions from any event use 7 ground motions.
We will evaluate a range of ground motions representing different possible earthquakes. When selecting the input motions, we try to select records that are characteristic of the likely sources, relative to distance, magnitude, and style of faulting. Our rock is usually very deep, and so we often look at the effects of varying input level. Once we have results, we will make a judgment based on the spectral amplification factor to determine whether we use the mean or envelope the SAF.
Typically handled by incorporating sigma from the attenuation relationships into the PSHA. For DSHA, I sometimes use the 84th-percentile ground motions for critical structures.
Compare the computed spectrum using random vibration theory approach where time histories are not required and target rock spectrum is the only input.
Perform the spectra matching to make sure the spectra ordinates not less than 90% of the target. Check strong motion duration. Check power spectra density.
Conservatism in analysis; e.g., using envelope spectra, when peak motions occur at different times, and at different directions/orientations.
If the objective of the site response analysis is to develop a mean response spectrum for design, then I will use 7 pairs of time histories that are scaled within ±50% of the target spectrum and computed site specific soil amplification factors. If the objective is to evaluate the site response for a given force level specified by the target spectrum, then a suite of 7 spectrally matched time histories that has the seismic characteristics (e.g., near-fault, duration) of the various sources will be used in the analysis.
I'm not sure if I understand what this question is getting at. Do you mean uncertainty that the spectrally matched ground motion is representative of the design ground motion? If so, this is mitigated through use of multiple input motions.
The uncertainty is handled using 7 motions that either match the target spectrum on average or are spectrally matched. We try to pick the motions from different earthquakes, similar earthquake magnitudes, significant durations, similar tectonic regimes and soil/rock conditions.
How much historical data do we have? Even are developed models are a composite of other EQ. So we have a great deal of uncertainty.
Use PSHA maps Use multiple time-histories for each source for input Perform sensitivity analysis of soil properties Use mean + 1SD for design response spectrum.
Through the use of 7 appropriate (mechanism, distance, magnitude, near-fault etc.) time histories; results are averaged, however, decreasing variability.
A parametric study is required, which involves changing soil properties and moving the B-C boundary vertically in the soil column. Use of multiple motions.
Typically handled through enveloping of results from analysis. Also assisted through use of ground motions with some consistency in the periods of interest. Spectral matching used in cases of time-series input to structural analysis.
In generating artificial earthquake, there are uncertainties in all seismological parameters such as stress drop, kappa, geometric attenuation, etc. We consider uncertainties in all these parameters and develop a set of logic trees to handle them.

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15.) Please include other comments you may have related to the topic of input motions.

TABLE B21
GENERAL COMMENTS ON THE TOPIC OF INPUT MOTIONS

Georgia is a low seismic risk state. Most of this is not required.
I generally shy away from synthetic motions and spectral averaging (too black boxy).
I support use of CMS
No consensus on proper use so we don't play expert at this time.
We typically subcontract development of site specific input motions to a specialist.
I have done some work on looking at the variability of input motions for Boston Massachusetts—where we choose input motions that fall within a bounded spectral range.
Ground motion scaling and selection is a topic of research. We are working on several aspect of this problem.
Many site characteristic factors, such as magnitude, type of earthquake, epicenter distance, impact the input motion selection. It is lack of specific guideline for how to select the input motions in most of code or provision.
It is important to understand the objectives of the site response analysis and the predominant periods of the structures to be constructed at the site. Also, the analysis should be completed using a suite of time histories that are representative of the seismic hazard at the site.
In Utah where bedrock can be very deep, there appears to be a disproportionate number of professionals that de-convolve ground motions to bedrock. I was always taught that such practices can be risky, especially when little is known about the true depth of bedrock and the overlying soils are soft and subject to large strains. I have always developed target response spectra and ground motions for Site Class C soils and applied them in my model as input at depths where I know Site Class C soils exist. This is a topic that has come under heavy debate here in Utah, and some guidance would be welcomed.
Need consensus among researches how to develop motions that meet the target spectrum either UHS or CMS.
Using the CSI Bridge and the USGS maps for our higher level analysis using the guide spec appears to be our best option.
Note that new PEER ground motion selection website is a very promising tool. http://peer.berkeley.edu/peer_ground_motion_database/
More guidance is needed in this area—particularly for spectral matching versus scaling. We usually scale if we are interested in pore pressure response, but we will spectrally match if there is no liquefaction and the results will be used by the bridge engineer.
We typically like to spectrally match the time histories instead of scaling. However, selection of appropriate time histories is an art and should be done carefully.

Page Four—Soil profile input information required for site response analysis

16.) What special geotechnical field and laboratory investigations do you require/perform to obtain information suitable for site response analysis?

[ ] None

[ ] Direct measurement of shear wave velocity

[ ] Cyclic triaxial, direct simple shear or resonant column tests

[ ] Other, please specify:

TABLE B22
SPECIAL GEOTECHNICAL FIELD AND LABORATORY INVESTIGATIONS DO YOU REQUIRE/PERFORM TO OBTAIN INFORMATION SUITABLE FOR SITE RESPONSE ANALYSIS

Value	Count
None	4
Direct measurement of shear wave velocity	30
Cyclic triaxial, direct simple shear or resonant column tests	12
Other, please specify:	6

Table continued on p.60

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Table continued from p.59

Other—please specify:
As a minimum, we would like V_s measurements in the field, but this does not always happen. On some projects we are able to justify cyclic testing—particularly if stability issues are a problem. Most of the testing is on silts for pore pressure response and post-cyclic behavior (residual strength and volumetric strain).
dependent on location/structure
sampling to detail stratigraphy
Most projects use correlations for G/G_{max} and damping curves. However, we do use in-house RCTS testing when needed.
Cyclic hollow-cylinder tests
Usually shear wave velocity along with G/G_{max} and damping curves out of literature.

17.) How do you obtain the shear wave velocity profile for the soil column?

[ ] SPT correlations

[ ] CPT correleations

[ ] Seismic cone

[ ] downhole

[ ] crosshole

[ ] suspension logger

[ ] surface wave/SASW/MASW

[ ] Other, please specify:

TABLE B23
METHODS TO OBTAIN THE SHEAR WAVE VELOCITY PROFILE FOR THE SOIL COLUMN

	Count
SPT correlations	21
CPT correlations	16
Seismic cone	23
Downhole	19
Crosshole	12
Suspension logger	19
Surface wave/SASW/MASW	19
Other, please specify:	9

Other—please specify: How do you obtain the shear wave velocity profile for the soil column>
Re-Mi
Occasionally we will have resonant column/torsional shear tests conducted.
We use SPT blow counts, not shear wave velocity.
Refraction Microtremor (ReMi)
downhole array seismogram inversion
ReMi
On occasions when cost does not allow measurements, we use SPT to correlate to Vs based on this article: “Empirical Relationships To Estimate Shear-Wave Velocity Profiles From SPT Information in the New Madrid Seismic Zone,” M.S. Thesis, 2009, Andy Kizzee
Mainly SCPT sometimes other geophysical tests (downhole crosshole.).

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18.) How do you define the dynamic soil properties (modulus reduction and damping curves) for site response analysis? (lab testing, published correlations based soil index properties such as Darandelli, Vucetic and Dobry, Seed and Idriss...)

[ ] laboratory testing

[ ] Darendeli

[ ] Vucetic-Dobry

[ ] Seed-Idriss

[ ] Other, please specify

TABLE B24

DEFINITION OF DYNAMIC SOIL PROPERTIES (MODULUS REDUCTION AND DAMPING CURVES) FOR SITE RESPONSE ANALYSIS

	Count
Laboratory testing	11
Darendeli	15
Vucetic-Dobry	20
Seed-Idriss	18
Other, please specify	20

Other, please specify:
Honestly not sure
EPRI
For Peat we may use no G-gamma reduction or Rollins et al.
In-house for east coast soils
EPRI (1993)
EPRI
We will also use lab tests, as above
USGS Seismic Design Parameters (Version 2.10)
Menq from UT in sands
Hardin and Drnevich
Not considered at this time
EPRI (1993), Matasovic and Kavazanjian (1998), Rollins (1998), Schnabel (1973)
Roblee and Chiou Geoindex curves
Constitutive modeling “experiments,” analytical expressions using constitutive models (e.g., Assimaki et al. 2000).
EPRI, Stoke
published data
mainly above
EPRI
G.SCDOT uses the correlations developed by Andrus. These correlations were developed specifically for soils in South Carolina.
correlated from SPT information

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19.) Do you account for uncertainty in the soil profile properties? If yes, how? If not, why not?

TABLE B25
UNCERTAINTY IN THE SOIL PROFILE PROPERTIES

	Response
1	Multiple profiles—upper bound and lower-bound analyses
1	Consider a range of properties
1	Depends on size/area of project... Use parametric variation feature of SHAKE2000 in some cases
2	No
1	Not at this time.
1	Sometimes use ±20% or so for soil properties, depending upon the application.
1	Vary the V_s profile by plus/minus 15 to 20% of the measured V_s
1	We have only had this done by outside consultants (university work)
1	We typically subcontract this to a specialist
1	We use ±20% of the measured shear wave velocities.
1	Yes, but only develop a range of properties and then use engineering judgment.
1	Consider Upper Bound and Lower Bound ground models
1	No consensus on how to account for “uncertainty”
1	Use a range of properties and try different modulus and damping curves
1	Yes, parametric sensitivity studies
1	Some of my research looks at the effect of spatial variability of soils on site response. In this case—we use three dimensional varying soil properties. We specify the spatial variability with geostatistical methods. We have also looked at the effects of small changes in 1-D profiles on ground motions.
1	When SASW and ReMi are used, there is uncertainty and non-uniqueness that has to be dealt with. For example, we use multi-mode considerations for inversion process and we use a hybrid dispersion curve using both MASW and ReMi to reduce uncertainties.
1	Uncertainty in soil column is primarily considered for V_s. This is typically varied by 10 to 15% about measured or target values.
1	Use site data on V_s if available. If not available, Toro et al. (1997) model. Use sigma terms on MRD from Darendeli/Menq.
1	Sensitivity analyses for V_s estimates, depth to half space (very hard rock) and V_s contrast at soil–rock interface (impedance effects).
1	Sometimes use various damping and modulus relationships, conduct limited sensitivity analysis on G_{max}; this depends on the amount and quality of exploration and soils data and confidence in the input soil parameters.
1	Yes, by RVT and/or ranging the N-SPT across site and determine the V_s based on V_s-N correlation.
1	Yes. The site response analysis will be completed with three V_s profiles: the lower, upper, and best estimate profile based on the soil data and test results obtained at the site. Using the best estimate profile, the different material curves will be used to complete the analysis using one or two earthquake histories.
1	Generally not. The complexity of the many permutations of possible soil property combinations would render the analyses cost prohibitive.
1	Depending on the nature of the project, we may include the lower and upper bounds of the soil properties in our analyses. However, often we only use the best estimate values. For DOE/NRc projects we also do the randomization of the properties and layers.
1	Yes. Monte Carlo realizations using non-Gaussian stochastic fields. Low and large strain properties, depth dependent standard deviation.
1	We will evaluate the upper bound, lower bound and mean in the Vs profile. The variation on Vs is at least ±10% or more if data seem to require. We may also vary the modulus reduction and damping strain relationships.
1	Rarely....only if the budget will allow. If I do, I typically will consider the soil profile as epistemic uncertainty and use a logic tree approach.
1	Yes. Consider the uncertainty by using three soil profiles at best estimate, lower, and upper bounds.

20.) Please include other comments you may have related to the topic of soil profile input

TABLE B26
OTHER COMMENTS RELATED TO THE TOPIC OF SOIL PROFILE INPUT

	Response
1	Georgia is a low risk seismic state and most of this is not required.
1	We typically subcontract this to a specialist.

Table B26 continued on p. 63

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Table B26 continued from p. 62

TABLE B26
OTHER COMMENTS RELATED TO THE TOPIC OF SOIL PROFILE INPUT

	Response
1	When site response studies are done for nuclear projects, multiple realizations (30 or more) are used to evaluate the uncertainty in Vs, layer location, modulus reduction, and damping curves. We have not done this ourselves. For this work we used Bob Youngs at Geomatrix because of his long involvement in this area. As I note later, you may want to contact Bob and Walt Silva to obtain their views on your questions. An interesting aspect of nuclear projects is that they use equivalent- linear codes, and sometimes they set up soil models that are several thousand feet in thickness. For these analyses they give a lot of attention to proper definition of damping (kappa) to avoid overdamping the response. This approach has been troublesome to me. We have been reluctant to use models greater than 300 to 400 ft in thickness in our analyses because of uncertainties in damping characteristics.
1	It is important to consider the uncertainties associated to the soil input parameters used in the site response analysis.
1	We rarely have structures that require the level of investigation needed to develop finely tuned soil models. Conservative approximations are satisfactory in most cases.
1	In addition to Vs profile, depth to bedrock, impedance contrast between rock-soil are critical and hard to measure accurately esp. for deep soil such as Jakarta.
1	Use inversion of ground/downhole records to refine layering at field test beds when description available is coarse.
1	It is important to perform either non-invasive or invasive procedures to obtain shear wave velocity of soils. I prefer downhole as you get a better estimate of shear wave velocity as well as SPT. By doing downhole, you can get soil samples and also do laboratory testing of the soil.
1	We have found that small differences in a 1-D soil profile do not have a significant impact—but that 3-D variability can have a significant impact.
1	To the best of my knowledge, the only result taken from the soil profile is the risk of liquefaction.

Page Five—Site response analysis

21.) When is an equivalent-linear analysis (e.g., SHAKE or similar program) used or required?

[ ] Site class dependent—please list site class

[ ] Seismic hazard level—please specify

[ ] Structure type—please specify

[ ] Other, please describe:

TABLE B27
CONDITIONS WHERE EQUIVALENT-LINEAR ANALYSIS (E.G., SHAKE OR SIMILAR PROGRAM) IS USED OR REQUIRED—DETAILED DESCRIPTION IS PROVIDED NEXT

	Count
Site class	22
Seismic Hazard	13
Structure Type	19
Other	16

Site class dependent—please list site class:
Site F
Site Class F, or sometimes even for E to lower the seismic design category
deep E, F, shallow sites
Sd or Se or Sf
Site Class F
C, D, E, & F. Used together with the nonlinear analysis for E and F with ground shaking larger than 0.6 g.
Site Class E and sometimes D when soil conditions seem to warrant
F
Site Class E consisting of soft soils

Table continued on p. 64

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Table continued from p. 63

Site class dependent—please list site class:
E or F
Typically E, F
Site Class F and sometimes Site Class E for soft and critical structures
F
C-D or better
> class C
E, liquefiable
F

Seismic hazard level—please specify:
500 and 2,500 years
All hazard levels. Used together with the nonlinear analysis when PGA > 0.6 at soft soil sites
When PGA is between 0.1 and 0.5, and depending on project requirements
PGA greater than 0.4g
PGA > 0.15G
See CBC 2010
<0.5 g
low hazard
<0.4g
Seismic Performance Category B

Structure type—please specify:
"Non-ordinary" structures based on Caltrans SDC guidelines
critical facilities
high-rise structure (>30 story)
All, used together with the nonlinear analysis for structures supported on piles penetrating through soil layers with drastically different strength and stiffness.
non-essential bridges
Critical or essential bridges or when the cost of mitigation is high
Major
tall structures over soft soils
Critical structures-hospitals, lifeline highway bridges, power plants, waste containment facilities
Often used when structural analysis requires time histories
Critical or base-isolated structures
medium to high importance
important structures
important structures
important structures

Other—please describe:
That is all we have used so far.
We rarely use SHAKE, but if the soils are very susceptible to liquefaction, we have been known to do the analysis, but this is not always the case.
liquefiable soils on Jetty

Table continued on p. 65

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Table continued from p. 64

Other—please describe:
See ODOT GDM Section 6.5.1.4
Return period of shaking or required performance
NA
Used when nonlinear or effective-stress not required
Rarely
NA
Structures with fundamental period > 0.5 second over liquefiable soils.
ok when strains modest
client driven
When no water table in profile
validation exercises
Site Class F (see above); structures that meet the criteria of 2008 Seismic Design Specifications for Highway Bridges; and as required by SCDOT personnel.

22.) What soil models do you usually use for equivalent-linear site response analyses (mark all that applies)?

[ ] EPRI

[ ] Ishibashi-Zhang

[ ] Iwasaki

[ ] Seed-Idriss Sand

[ ] Seed-Idriss Clay

[ ] Vucetic-Dobry

[ ] Darendeli

[ ] Other:

TABLE B28
DISTRIBUTION OF EQUIVALENT-LINEAR DYNAMIC SOIL MODEL PROPERTIES USED IN PRACTICE

Value	Count
EPRI	17
Ishibashi-Zhang	6
Iwasaki	3
Seed-Idriss Sand	18
Seed-Idriss Clay	9
Vucetic-Dobry	21
Darendeli	15
Other	10

Other soil models
Not sure
Others may be considered depending on soil types, or based on lab testing
up to the design consultant
NA
Menq
Hardin and Drnevich

Table continued on p. 66

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Table continued from p. 65

Other soil models
measured, usually with RCTS
locally developed
correlated from SPT information

23.) When is a nonlinear total stress (no pore water pressure generation) analysis used or required?

[ ] Site class dependent—please list site class

[ ] Seismic hazard level—please specify

[ ] Structure type—please specify

[ ] Strain amplitude—please specify

[ ] Other, please describe:

TABLE B29
CRITERIA WHERE NONLINEAR TOTAL STRESS (NO PORE WATER PRESSURE GENERATION) ANALYSIS IS USED OR REQUIRED – SEE NEXT PAGES FOR DETAILS

	Count
Site Class	15
Seismic Hazard	11
Structure type	10
Strain amplitude—please specify	14
Other	18

Site class dependent—please list site class:
Site Class F, or sometimes even for E to lower the seismic design category
Sd or Se
E & F
Site Class E deep clay sites or when unusual soil profiles occur—maybe when shallow rock occurs.
F
E, F
F
D, E
> D
E or liquefiable

Seismic hazard level—please specify:
PGA > 0.6 g at soft sites, PGA > 1 g for stiff sites
PGA > 0.5 to 0.7
See CBC 2010
> 0.5 g
high hazard
> 0.4g
>0.5g

Structure type—please specify:
critical facilities
Very tall structure w period > 5 s (> 40–50 story)
Essential bridges in liquefiable soils
Essential or critical bridges—or where lateral spreading could be an issue
often used when structural analysis requires time histories
important structures
important

Strain amplitude—please specify:
greater than 1 percent
Strain > 1% and used for design of the deep foundation or below grade structures
>1 to 2%
strain >1%
Preferred where shear strain is greater than about 1%
>1 percent
High > 1%
large anticipated strain
>1%

Table continued on p.67

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Table continued from p.66

Other—please describe:
Haven't used it yet
Nonlinear analyses were used by some of our consultants
Deep basins
typically not performed
When we believe that it will reduce the design spectra
NA
up to the design consultant
Rarely
NA
when large strains occur
not typically used
None
Never is nonlinear analysis required, and rarely is it used. Only for very critical projects have I ever been able to justify its use.
Sometimes the motivation is to reduce the seismic demand
Do not use non-linear analysis.
Not used.

24.) What soil models do you usually use for nonlinear total stress site response analyses (mark all that applies)?

[ ] Hyperbolic with Masing criteria

[ ] Modified Hyperbolic with Masing criteria (e.g., M-K-Z)

[ ] Modified Hyperbolic with non Masing criteria (e.g., MRDF to match both modulus reduction and damping curves)

[ ] Cundall-Pyke model

[ ] Mohr-Coulomb

[ ] Other—whatever model is included in my software—please specify

[ ] It is important for the model to match both modulus reduction and damping curves

[ ] It is only important that the model matches modulus reduction regardless of the damping curve.

TABLE B30

SOIL MODELS FOR NONLINEAR TOTAL STRESS SITE RESPONSE ANALYSES

	Count
Hyperbolic with Masing criteria	4
Modified Hyperbolic with Masing criteria (e.g., M-K-Z)	12
Modified Hyperbolic with non Masing criteria (e.g., MRDF to match both modulus reduction and damping curves)	4
Cundall-Pyke model	2
Mohr-Coulomb	2
Other—whatever model is included in my software—please specify	9
It is important for the model to match both modulus reduction and damping curves	13
It is only important that the model matches modulus reduction regardless of the damping curve.	0

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Table continued from p.67

Other—
Don't know
We work with the models in DMOD, FLAC, and PLAXIS—trying out different options to see the effects of these changes.
up to the design consultant
insufficient experience
None
Strongly prefer to match both modulus and damping curves, but not all software/models do this currently.
multiyield plasticity pressure independent
We usually use UBCHYST a nonliner total stress model developed at the U of British Columbia- it is important to consider shear failure.
Not used.

25.) When is a nonlinear effective-stress (with pore water pressure generation) analysis used or required?

[ ] Site class dependent—please list site class

[ ] Seismic hazard level—please specify

[ ] Structure type—please specify

[ ] When porewater pressure ratio exceeds a given value—please specify

[ ] Other, please describe:

TABLE B31
CONDITIONS FOR NONLINEAT EFFECTIVE-STRESS (WITH POREWATER PRESSURE GENERATION) ANALYSIS – SEE NEXT PAGES FOR DETAILS

	Count
Site class	12
Seismic hazard level	6
Structure type	10
When porewater pressure ratio exceeds a given value—please specify	10
Other	16

Site class dependent—please list site class:
Site Class F, or sometimes even for E to lower the seismic design category
F
Sf
F
Site Class F for IBC projects and when liquefaction is predicted for DOT projects
F, T > 0.5 sec
F
E,F
F
F, Liquefiable

Table continued on p.69

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Table continued from p.68

Seismic hazard level—please specify:
high
Whenever porewater pressure buildup is expect—might be as low as 0.15 to 0.2 g
PGA > 0.3 g
>0.4 g

Structure type—please specify:
Critical facilities
critical, essential
Near-shore structures
essential bridges in liquefiable soils
Critical and essential bridges and where lateral spreading is expected.
High importance, sensitive
important

When porewater pressure ratio exceeds a given value—please specify:
close to 90 eff. overburden
0.8
0.5
around 0.9 or so
0.2
(limited experience on this)
Ru > 0.3

Other—please describe:
Haven't used it yet
Nonlinear analyses were used by some of our consultants
When liquefaction is an issue or very soft deposits, or deep basins
Used when soil strain levels of equivalent—linear methods exceed limits, for pore pressure generation and liquefaction analysis, to develop response spectra considering liquefied soil effects
when interested in pore pressure generation
for liquefiable site
up to the design consultant
rarely
NA
insufficient experience to say
none
Typically only when potentially liquefiable soils are present.
Never. I have encountered few professionals that would dare use such analysis on a design project.
For larger project we do FLAC analysis with coupled effective-stress analysis and may use the results for near surface response spectrum.
Do not use nonlinear analysis.
Not required.

26.) What soil models and porewater pressure generation models do you use in nonlinear effective-stress site response analyses (mark all that applies)?

[ ] Dobry

[ ] Elgamal

[ ] GMP (Green)

[ ] Martin-Finn-Seed

[ ] Matasovic (Modified Dobry et al. porewater pressure model)

[ ] UBC Sand

[ ] Other

TABLE B32
SOIL MODELS AND POREWATER PRESSURE GENERATION MODELS IN NONLINEAR EFFECTIVE-STRESS SITE RESPONSE ANALYSES

Value	Count
Dobry	3
Elgamal	3
Martin-Finn-Seed	5
Matasovic (modified Dobry et al. porewater pressure model)	16
UBC Sand	8
Other	7

Table continued on p.70

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Table continued from p.69

Other:
Haven't done it yet
up to the design consultant
insufficient experience to say
None
Locally developed
Multi-yield plasticity pressure dependent, Dafalias-Manzari
Not required.

Page Six—Evaluation and use of results

27.) What do you consider to be the top three uncertainties in the input to a typical seismic site response analysis?

[ ] Low-strain stiffness (represented by G_{max} or V_s)

[ ] Higher strain stiffness (represented by modulus reduction or backbone curve)

[ ] Small strain damping behavior represented by viscous damping

[ ] Large strain damping behavior (represented by damping curve or unloading–reloading model)

[ ] Soil layer thickness

[ ] Depth to bedrock

[ ] Character of bedrock (V_s, modulus reduction and damping behavior)

[ ] Input motions

[ ] Other

TABLE B33
THE TOP THREE UNCERTAINTIES IN THE INPUT TO A TYPICAL SEISMIC SITE RESPONSE ANALYSIS

Value	Count
Low-strain stiffness (represented by G_{max} or V_s)	11
Higher strain stiffness (represented by modulus reduction or backbone curve)	15
Small strain damping behavior represented by viscous damping	5
Large strain damping behavior (represented by damping curve or unloading-reloading model)	17
Soil layer thickness	1
Depth to bedrock	13
Character of bedrock (V_s, modulus reduction and damping behavior)	6
Input motions	19
Other	7
Other:	
uncertainty in pore pressure models	
This assumes that V_s profiles are either available or can be estimated with confidence. If the V_s Information is not available, then V_s would move to the top of the list.	
All	
liquefaction resistance properties, permeability	
all of them	
depth to B-C boundary	

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28.) How do you typically account for such uncertainties in design?

[ ] Select reasonably conservative values of input parameters

[ ] Use “best estimate” input parameters, then apply conservatism to results

[ ] Perform sensitivity analyses

[ ] Perform probabilistic analyses (e.g., FOSM, Monte Carlo)

[ ] We don’t address uncertainties explicitly

[ ] Other, please specify:

TABLE B34
ACCOUNTING FOR UNCERTAINTIES IN DESIGN

Value	Count
Select reasonably conservative values of input parameters	5
Use “best estimate” input parameters, then apply conservatism to results	11
Perform sensitivity analyses	19
Perform probabilistic analyses (e.g., FOSM, Monte Carlo)	6
We don't address uncertainties explicitly	6
Other—please specify	6
Other—please specify: How do you typically account for such uncertainties in design?	
See answers to 14 and 19	
We subcontract this to specialists	
NA	
Follow ASSHTO and avoid site class f classification	
We usually come up with a range for results (a practical upper and lower range and a best estimate)	

29.) How do you evaluate the validity of the overall site response model at your site?

[ ] Compare with empirical correlations

[ ] Perform sanity checks

[ ] Other, please specify:

TABLE B35
EVALUATION OF THE VALIDITY OF THE OVERALL SITE RESPONSE MODEL AT A SITE

	Count
Compare with empirical correlations	21
Perform sanity checks	18
Other—please specify	13
Other—please specify:	
Not sure.	
Comparison with recorded motions at similar sites	
compare with IBC spectra	
check soil response output to lab test results	
We will compare to site class factors, published data, or alternate methods. For example, we check DMOD total stress versus SHAKE analyses.	
with vertical arrays	
Compare with code-based spectra and nearby recorded motions	

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Table B35 continued from p. 71

TABLE B35
EVALUATION OF THE VALIDITY OF THE OVERALL SITE RESPONSE MODEL AT A SITE

	Count
We do not	
Use judgment informed by previous analyses and recorded ground motions for similar sites.	
field recordings at similar sites	
Compare with response spectra from building codes	
Compare results of two programs if applicable	
Compare the results of the Site-Specific Response Analysis to the results of the 3-point method.	

30.) What output do you use from site response analysis?

[ ] Surface response spectra

[ ] Surface velocities

[ ] Surface Displacements

[ ] Surface time histories

[ ] Profiles of PGA

[ ] Profiles of strains

[ ] Profiles of displacements

[ ] Profiles of shear stress

[ ] Other, please specify:

TABLE B36
OUTPUT USED FROM SITE RESPONSE ANALYSIS

	Count
Surface response spectra	29
Surface velocities	7
Surface Displacements	8
Surface time histories	21
Profiles of PGA	17
Profiles of strains	17
Profiles of displacements	10
Profiles of shear stress	14
Other—please specify	6
Other—please specify: What output do you use from site response analysis?	
amplification factor at surface	
The output that will be used really depends upon the purpose of the analysis; i.e., ground motions for building response analysis versus CSR for a liquefaction triggering analysis.	
profiles of PPR, peak acceleration	
pore pressures	
Deeper response spectra are also used (Depth-to-Motion concept).	
seismic reactions	

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31.) Do you use output of profiles of strains and lateral deformations in a structural analysis? (e.g., pile lateral loading...), please explain, do you perform any baseline correction of the output motions?

TABLE B37

USE OF OUTPUT OF PROFILES OF STRAINS AND LATERAL DEFORMATIONS IN A STRUCTURAL ANALYSIS (E.G., PILE LATERAL LOADING, AND BASEELINE CORRECTION OF THE OUTPUT MOTIONS)

Count	Response
1	No
5	No
1	No
1	No. No.
1	No. Yes.
1	No.
1	Rarely
1	Yes, sometimes we can use this as input to the response of the structural elements.
1	Yes, we use soil profile curvature to estimate kinematic bending moments
1	Yes. Yes.
1	No
1	no and no
1	None
1	not explicitly
1	Pile lateral loading, base line correction if necessary usually using long period filter
1	Yes, in some cases
1	We perform baseline corrections of displacement time histories at different soil layers to drive p-y soil springs attached to piles (soil-structure interaction).
1	I haven't personally, but my colleagues have to estimate kinematic loading on piles. Baseline correction is typically performed prior to using any of the ground motions.
1	The relative strain within the structure (e.g., piles or tunnel) is provided for use in the structural analysis. The force based method will also be used to check if the strain method is reasonable. I typically do not use the output ground motions for the design analysis.
1	Yes, we have used peak displacement profiles from site response analysis to as input to Winkler beam on nonlinear foundation analysis of kinematic pile bending.
1	Bridge Designer Response: typically AKDOT does not use the lateral deformation profile from the Site-Specific analysis.
1	We usually use baseline corrected input motions. But anyways what is important for us are the relative movements (movement at each point minus movement of the excited base).
1	A sub-consultant is currently running DESRA for us and using the displacements in a lateral pile response program to estimate condensed stiffness matrix for the pile group and kinematic motions. This is a fairly specialized area, and so we prefer to have a specialist do this type of analysis.
1	Sometimes the output strains are used in the structural analysis of piles and also of racking of underground structures. Input motions are baseline corrected and then output motions are checked for baseline corrections

32.) Do you use profile of peak ground acceleration for liquefaction analysis? Please explain. When you evaluate cyclic stress ratio (CSR) for liquefaction analyses, how often do you do so by means of site response analyses (as opposed to using the simplified method)? What criteria do you use for deciding when to do so?

TABLE B38

USE OF PROFILE OF PEAK GROUND ACCELERATION FOR LIQUEFACTION ANALYSIS

Count	Response
1	No
1	No, we don't have liquefaction. We don't evaluate CSR.
1	Not typical
1	Not very often unless the simplified method gives marginal safety factors for liquefaction.

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Table B38 continued from p. 73

TABLE B38
USE OF PROFILE OF PEAK GROUND ACCELERATION FOR LIQUEFACTION ANALYSIS

Count	Response
1	We always use the simplified method.
1	When the project and importance of the structure demands the site response, both are performed.
1	Yes, use the PGA for the site. Rarely done.
1	Yes, importance of structure.
1	http://www.dot.il.gov/bridges/AGMU%20101.pdf
1	No
1	No, perform effective-stress analyses when liquefaction is to be predicted.
1	Yes, when a site response analysis is performed. They are compared. No criteria are used.
1	We don't do this very often. Perhaps only for critical projects where 2-D effects are important.
1	Two approaches used in parallel: 1. PGA from SHAKE used as input for simplified analysis 2. Effective-stress analysis using D-MOD.
1	Almost never. For liquefaction analysis of level grounds, we almost always use the simplified method and don't rely on CSR from the site response. For cases with static shear stresses, we need to get CSR from numerical modeling such as QUAD4M-U.
1	I have not used the profile of PGA for a liquefaction analysis. I have used CSR computed from site response in a liquefaction evaluation before, but only when strain levels were reasonable (i.e., less than 1%) and when I was performing the site response analysis for another reason. I have never performed site response solely for obtaining estimates of the CSR.
1	No. Rarely. I typically use the simplified liquefaction method based on PGA from site response or code-based procedure at ground surface.
1	We sometimes use site-specific CSR, but we first check it with the Cetin et al. (2004) CSR to see if it makes sense to use it with the simplified method.
1	I prefer to use CSR from site response for liquefaction analysis, as long at the triggering method isn't based on biased CSR estimates.
1	Yes. For most projects, use a simplified method. For critical structures, use the site response output directly.
1	Use CSR from analysis for determining liquefaction potential when FOS (liquefaction) is close to 1.0 by using the simplified methods (and expensive mitigation may be required). Also to evaluate liquefaction effects below depths for about 50 feet.
1	We will use the CSR from the site response analyses for liquefaction analyses. This probably represents less than 10% of our liquefaction analyses. Most of the time, we use the simplified liquefaction method.
1	Yes, PGA is used for liquefaction analysis. I don't understand the second part of this question. By simplified method you mean the code procedure. If I perform site specific analysis, I use site response analysis results for liquefaction analysis.
1	In some cases CSR from site response is chosen on the basis of reflecting better the "rd" reduction.
1	Yes, use peak ground acceleration for liquefaction analysis. Usually do not use site response analysis in CSR evaluation. If an active fault is within 10 km of the bridge site, then we use site response analysis.
1	Yes, to check the induced stress using simplified method; then compare to direct CSR from site response analyses.
1	The liquefaction will be completed using the simplified method with the PGA computed from equivalent-linear or total stress site response analysis. The PGA profile calculated by the site response analysis will also be compared to the simplified method. The site response analysis method is used for sites with soil deeper than 70 feet that are suspected to be liquefiable.
1	For screening purpose of for very small projects we may use simplified method. For final design and for larger projects, we may use CSR directly out of site response analysis. I know Idriss does not like this and recommends using PGA from site response analysis in conjunction with rd from simplified method which in way does not make a lot of sense. Needs to be clarified. For larger projects displacements are important and not liquefaction assessment. We generally calibrate UBCSAND to liquefaction charts and lab test results and then estimate the displacements. There is a great need for lab test results with shear stress bias.
1	Whenever we run SHAKE for ground motions we use shear stress profiles to estimate CSR for liquefaction analyses.

33.) Do you use profile of peak ground acceleration for slope stability analysis? Please explain.

TABLE B39
USE OF PROFILE OF PEAK GROUND ACCELERATION FOR SLOPE STABILITY ANALYSIS

Count	Response
1	Hardly working on this subject.
1	No
1	No, but I could see doing that sometime.
1	No.

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Table B39 continued from p. 74

TABLE B39
USE OF PROFILE OF PEAK GROUND ACCELERATION FOR SLOPE STABILITY ANALYSIS

Count	Response
1	No.
1	No. Sometimes PGA at slope base obtained from 1-D analysis for rock input at depth.
1	Not sure.
1	Not very often, only on dams and embankment slope stability.
1	We use half of the PGA by seismic coefficient.
1	Will use percentage of PGA for pseudostatic slope stability analysis.
1	Yes—as input for Newmark analyses.
1	Yes, to evaluate horizontal equivalent accelerations within slide mass.
1	Yes.
1	I have not been using it.
1	No
1	No, developing new method based on shear stress distribution.
1	We use 500 yr. PGA for most slopes.
1	Yes; peak at ground surface and distribution with depth to evaluate effective value for design.
1	The PGA at various depths are used to compute the equivalent maximum horizontal acceleration for the critical failure surface identified, which will then be used in the Newmark analysis to estimate deformation.
1	We have, but not very often. If you are going to all the trouble of developing time histories and dynamic properties for response analysis of a slope, you might as well go ahead and do a 2-D analysis instead of 1-D plus Newmark.
1	Typically no... In a limit equilibrium method, we will consider the most critical failure surface and use the shear stress profile from site response analyses to calculate the acceleration for the mass above the critical surface.
1	SCDOT slope stability begins at PGA to determine if the slope is stable. If a slope instability is encountered then a displacement analysis (Newmark) is performed after determining the yield acceleration.
1	Use 50% of PGA for slope stability analysis. For determination of permanent displacement we use yield acceleration/peak acceleration.

34.) For analyses where pore water pressure generation is evaluated, how do you use the analysis output?

TABLE B40
USE OF COMPUTED PORE WATER PRESSURE

1	Check r_u vs. time for the various layers.
1	Consider effect of decreased effective-stress on soil/foundation behavior.
1	Develop a profile where r_u generated is > 0.7
1	Don’t use.
1	Evaluate surface spectrum and displacement profile.
1	Examine r_u vs. time
1	I compare it to the equivalent-linear output and nonlinear output.
1	I have never performed such an analysis in engineering practice.
1	Just to verify if liquefaction does occur due to increase in pore pressure.
1	Not sure
1	Not used
1	Considered for total stress only.
1	Do not consider
1	Examine level of pore pressures
1	input for effective-stress SSI problems
1	insufficient experience with this
1	To check whether liquefaction expected. Don't trust results post-liquefaction

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Table B40 continued from p. 75

TABLE B40
USE OF COMPUTED PORE WATER PRESSURE

1	To evaluate potential for liquefaction
1	To understand soil behavior
1	For important project we usually use effective-stress FLAC analysis in which the above is automatically considered.
1	For layers which have high excess pore water pressure, we reduce the strength of that layer for stability analysis.
1	We used the porewater pressure to determine whether liquefaction is occurring. We will use the porewater pressure information to decide whether to modify P-y curves and to select residual strength values.
1	To determine liquefaction potential in soil column, however, these programs may mask the actual pore pressure generation and liquefaction potential in the upper layers in some conditions due to soil softening in lower layers. FE analysis methods may be required.
1	Evaluate liquefaction potential using the excess pore pressure ratio, checked with the results of simplified methods for the top 40 to 70 feet and cyclic lab test results if available.

35.) Please include other comments you may have related to the topic on evaluation and use.

TABLE B41
OTHER COMMENTS RELATED TO THE TOPIC ON EVALUATION AND USE

Count	Response
1	Georgia is a low risk seismic state and most of this doesn't apply.
1	We rarely perform these analyses internally as they are needed infrequently.
1	None
1	Based on CPT or SPT, the site will liquefy. But site response indicated the pore pressure did not increase to induce liquefaction. Pore pressure parameter in effective-stress site response is difficult to determine, such the computed pore pressure is less reliable.
1	I have lots of not sure answers, I know. Perhaps this is a reflection on the need to involve Geotechnical and Structural simultaneously when this type of work is done.
1	I have learned that the interpretation of results from effective-stress analyses is very complex. Issues such as shielding of upper layers, dilation, model calibration become critical. Further guidance is needed in these areas.

37.) Please feel free to include any thoughts or comments you would like to share with us.

TABLE B42
GENERAL COMMENTS ON THE OVERALL SURVEY

Count	Response
1	Not using site specific analysis in the state of Indiana.
1	Thanks for including me on this. Please send me the results when they are available.
1	Use Japan 2011 data for validation exercises of existing site response methodologies.
1	I think you have the names for others in Kleinfelder already. Thanks for doing this study. I look forward to seeing the results.
1	My responses come from the perspective of a researcher who is interested in site response—and does research in the evaluation and validation of different methods. I primarily use vertical array data where both the down hole and surface ground motions are known. We use this to investigate the effect of soil variability on site response—and are currently doing a project that tries to identify sites where 3-D nonlinear (effective-stress) is required versus 1-D equivalent-linear.
1	This survey is overly addressed for a state that has low seismic risk. Our peak accelerations in Georgia are around 0.1 g. Most of the state is even less.
1	In real world, we must correct the 1-D site response with various correction factors i.e. basin, basin edge effect, directivity, sloping bedrock. I hope few empirical factors can be developed to include to account for those factors. Software and study on SSI must be enhanced, to allow complete modeling of structure. Need to research on combined kinematic and inertial lateral load acting on pile.
1	This is a good survey. I am looking forward to the report. Current practice for the site response analyses mainly focus on the horizontal motions, and seldom on the vertical motions. More and more important facilities need the time history analysis for either design or safety evaluation. It would be greatly helpful if some guideline can be provided for generating the site specific vertical motion.
1	I wish I could have been more help. But the fact is, we rarely do site specific analysis, other than USGS Deaggregation then attenuation relationships plus site factors to get motions for the simplified liquefaction analysis.
1	I suggest contacting Wall Silva and Bob Youngs to get their perspective. Their applications have been mainly for nuclear projects. Though they are using equivalent-linear analyses, they are also conventionally looking at the sensitivity to material property variations and they use pretty deep soil columns. Their experience might prove to be interesting. Carl Costantino is another person working in the same area, who is very knowledgeable in site response analyses using equivalent-linear and nonlinear methods. I suggest Ernie Naesgaard because of his work with Peter Byrne at UBC and his use of the program FLAC and the UBC sand model. If you do not have or cannot find contact information for these people, let me know. I can provide e-mails and telephone numbers.

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APPENDIX C

Site Response Analysis Software—Software URLs, References, and Use in Highway Engineering Practice as Identified by Survey Respondents

SITE RESPONSE ANALYSIS SOFTWARE (SOFTWARE USED BY SURVEY RESPONDENTS IS IDENTIFIED WITH "BOLD" TYPEFACE)

Software		Web/ftp Site	Reference
1.	SHAKE2000	http://www.geomotions.com	Ordonez (2000)
2.	PROSHAKE	http://www.proshake.com	EduPro Civil Systems (1999)
3.	D-MOD2000	http://www.geomotions.com	Matasovic (2006) (D-MOD_2); Matasovic and Ordonez (2008)
4.	DEEPSOIL	http://deepsoil.cee.illinois.edu	Hashash and Park (2001; 2002), Hashash et al. (2011)
5.	CyberQuake	http://www.brgm.fr	Modaressi and Foerster (2000)
6.	OpenSees	http://opensees.berkeley.edu	Ragheb (1994); Parra (1996); Yang (2000)
7.	SIREN	http://www.oasys-software.com/products/seismic/siren/	Oasys (2006); Heidebrecht et al. (1990, 1991)
8.	FLAC	www.itascacg.com	Itasca (2005)
9.	PLAXIS	http://www.plaxis.nl	PLAXIS-B.V. (2002)
10.	ABAQUS	http://www.abaqus.com	ABAQUS (2005)
11.	TNO Diana	http://www.midas-diana.com/gts/	MIDAS (2008)
12.	VERSAT 1-D	http://www.wutecgeo.com/v-2d.htm	Wu (2010)
13.	VERSAT 2-D	http://www.wutecgeo.com/v-2d.htm	Wu (2010)
14.	QUAKE/W	www.geo-slope.com	GSI (2006)
15.	EERA	http://gees.usc.edu/GEES/Software/EERA2000/Default.htm	Bardet et al. (2000)
16.	NERA	http://gees.usc.edu/GEES/Software/NERA/2001/Default.htm	Bardet and Tobita (2001)
17.	QUAD4M	http://nisee.berkeley.edu/elibrary/getpkg?id=QUAD4	Idriss et al. (1973); Hudson et al. (1994)
18.	Cyclic 1-D	http://cyclic.ucsd.edu/	Elgamal et al. (2004)
19.	DESRAMUSC		Qiu (1997)
20.	SHAKE91		Idriss and Sun (1992)
21.	LS Dyna		LSTC (1988)
22.	Dyna 1-D		Prevost (1989)
23.	DESRAMOD		Vucetic (1986)
24.	TESS		Pyke (2000)
25.	D-MOD		Matasovic (1993)
26.	PSNL		Kramer (2010)
27.	SPECTRA		Borja and Wu (1994)
28.	AMPLE		Pestana and Nadim (2000)
29.	SUMDES		Li et al. (1992)
30.	DYSAC 2		Muraleetharan et al. (1991)
31.	FLUSH		Lysmer et al. (1975)
32.	MASH		Martin and Seed (1978a)
33.	SUPER SASSI		SAI (1995)
34.	SASSI2000	http://nisee.berkeley.edu/elibrary/Text/200703021	NISEE—Univ. of California, Berkeley
35.	PLAXIS 3D	http://www.plaxis.nl	PLAXIS-B.V. (2002)
36.	TARA-2		Finn and Yogendrakumar (1987)
37.	WinMOC		Ray (2008)
38.	MARDESRA		Martin (1990), Personal Communication
39.	WAVES		Hart and Wilson (1989)

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Table continued from p.77

SITE RESPONSE ANALYSIS SOFTWARE (SOFTWARE USED BY SURVEY RESPONDENTS IS IDENTIFIED WITH “BOLD” TYPEFACE)

Software	Web/ftp Site	Reference
40. CHARSOIL		Liou et al. (1977)
41. UFSHAKE		Urzua (1995), Personal Communication
42. SAF-DYNA		Urzua (1995), Personal Communication
43. DYNAFLOW		Prevost (1998), Personal Communication
44. LIQCA		No Information
45. Dyneq		No Information
46. FLIP		No Information
47. ShearBeam		No Information

Software cited in this appendix does not imply an endorsement of any product or supplier. Trade names and web addresses appear herein solely because they are considered essential to the object of this report.

Notes:

1. Only the latest and/or currently available version of the program is listed.
2. Only key references related to the programs are listed. These references are included in the “References.”
3. Many of the programs are available from multiple sources and in multiple versions.
4. Only year of the initial “Personal Communication” is listed.

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Abbreviations used without definition 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
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
SAE	Society of Automotive Engineers
SAFETY-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

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