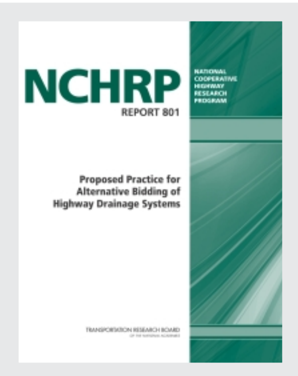

Proposed Practice for Alternative Bidding of Highway Drainage Systems

DETAILS

138 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-30859-5 | DOI 10.17226/22157

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 801

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Subscriber Categories
Construction • Hydraulics and Hydrology • Materials

Research sponsored by the American Association of State Highway and Transportation Officials
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WASHINGTON, D.C.
2015
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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

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

NCHRP REPORT 801

Project 10-86
ISSN 0077-5614
ISBN 978-0-309-30859-5
Library of Congress Control Number 2015936491

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The members of the technical panel selected to monitor this project and to review this report were chosen for their special competencies and with regard for appropriate balance. The report was reviewed by the technical panel and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the Governing Board of the National Research Council.

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

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CRP STAFF FOR NCHRP REPORT 801

NCHRP PROJECT 10-86 PANEL
Field of Materials and Construction—Area of Specifications, Procedures, and Practices

AUTHOR ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 10-86 by Golder Associates Inc. (Golder), in conjunction with Bergmann Associates Inc. (Bergmann), and Dr. Ian Moore with Queen's University.

Dr. Michael Maher, PhD, PEng, Principal and Global Transportation Sector Leader for Golder was the Principal Investigator. The other principal authors for this report were Dr. Gregory Hebeler, PhD, PE, Associate and Senior Geotechnical Engineer for Golder; Colby Caywood, PE, CPESC, Senior Engineer for Golder; Andrew Fuggle, PhD, Geotechnical Engineer for Golder; and Joseph VanKerkhove, PE, Project Manager for Bergmann. Dr. Ian D. Moore, PhD, PEng, Professor at Queen's University provided technical direction and support for this project. Other acknowledgments include Kenneth Avery, PE, CFM, Water Resources Business Segment Leader for Bergmann; and Edward Morales, PE, Senior Structural Engineer for Bergmann.

Invaluable cooperation and support were provided by Pennsylvania Department of Transportation (PennDOT) and Missouri Department of Transportation (MoDOT) for participation in the full pilot project phase of this research. Participation in the baseline pilot project studies was also provided by California Department of Transportation (Caltrans), Florida Department of Transportation (FDOT), Michigan Department of Transportation (MDOT), Ministry of Transportation Ontario (MTO), Nebraska Department of Roads (NDOR), New York State Department of Transportation (NYSDOT), and Virginia Department of Transportation (VDOT).

The authors would like to thank the NCHRP Project 10-86 panel for its direction, advice, and support.

FOREWORD

By Edward T. Harrigan
Staff Officer
Transportation Research Board

This report presents a proposed practice for alternative bidding of highway drainage systems. Thus, the report will be of immediate interest to engineers in state highway agencies and the construction industry with responsibility for the design, construction, and maintenance of these systems.

Traditionally, transportation agencies have used a "means and methods" approach for selection and specification of products such as drainage pipe systems. In this approach, the owner-agencies specify a particular drainage pipe system during the design process, and the cost of the specified system is included in the contractors' bids for the project.

This research investigated an alternative approach, the use of a performance-based process for selection of drainage pipe systems. Such a selection process is based on satisfying performance criteria for the drainage system while considering the full range of suitable pipe materials. This approach has the potential to foster competition among various pipe types judged to be of satisfactory quality and equally acceptable on the basis of engineering and cost analyses. Giving contractors the ability to choose from among alternative drainage pipe systems during the bidding process on the basis of performance and cost can help agencies promote competition that will lower agency costs while achieving satisfactory performance.

The objective of NCHRP Project 10-86 was to develop a proposed practice suitable for adoption by AASHTO to guide owner-agencies and industry in implementing a performance-based process for contractor selection and delivery of drainage pipe systems on highway construction projects. The research was performed by Golder Associates Inc., Atlanta, Georgia, in conjunction with Bergmann Associates Inc., Rochester, New York, and Dr. Ian Moore of Queen's University, Kingston, Ontario, Canada.

The key product of the research is the proposed practice presented in Appendix A of the report. The practice applies rational, performance-based criteria to the selection, installation and post-construction acceptance of highway drainage pipe systems. It specifically addresses the selection of pipe solutions by evaluating the hydraulic capacity, structural capacity, and durability of pipe systems in distinct stages. Since durability is predicted in terms of estimated service life, the practice emphasizes proper characterization of the site conditions and comprehensive post-installation inspection to confirm construction quality. The practice was tested and refined through comparisons in nine states to standard agency procedures for pipe specification and was shown to satisfactorily consider the wide variety of factors required to successfully bid alternative pipe systems.

This report fully documents the research and includes the following two appendixes: Appendix A: AASHTO Recommended Practice for Alternative Bidding of Highway Drainage System and Appendix C: Summary of Durability Evaluation Methods and Software Applications. In addition, Appendix B: Worked Example of the Recommend Practice is available to download from the NCHRP Project 10-86 web page at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2964.

CONTENTS

Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

CHAPTER 1

Background

1.1 Research Problem Statement

The United States invests billions of dollars in road infrastructure each year, with a significant portion of these costs going to drainage components. Given the scale of investment, as well as tightening budgets, it is more critical than ever to optimize value across all areas of transportation projects. The last few decades have seen huge improvements in drainage pipe materials and products. However, these innovations have yet to be fully embraced by agencies and individual design firms, because it is difficult to keep up with the vast array of new pipe options and individual pipe systems.

Designing, specifying, and bidding drainage pipe systems for highway projects are generally routine activities that occur on virtually every highway construction project. Because most pipe systems by their nature are routine, and separately are relatively low cost items, there is little incentive on individual projects to go beyond the basic task of identifying a system that works. Thus, the extensive database that exists on this topic addresses all the basic design issues, but generally fails to define a logical design practice that is (a) thorough, (b) comprehensive, and (c) does not stop when the first viable design option is found, but instead, finds every viable option that will meet an owner-agency requirement in terms of function and performance. While in most instances the traditional "means and methods" specification approach to tender delivers a serviceable drainage system, it severely limits competition among the manufacturers and suppliers of pipe products. The process can be further impaired by a lack of understanding of drainage pipe alternatives or by misconceptions about the suitability or relative performance of different pipe systems.

If transportation projects took full advantage of available drainage-system technology, value could be significantly increased. Giving contractors the ability to choose, at the bidding stage, from among alternative solutions that are of satisfactory quality and equally acceptable on the basis of engineering design criteria has been shown to promote competition and lower costs.

1.2 Objective of NCHRP Project 10-86

The general objective of NCHRP Project 10-86 is to develop a procedure suitable for adoption by American Association of State Highway Transportation Officials (AASHTO) to guide owner-agencies and industry in the implementation of performance-based procurement for drainage systems on highway construction contracts.

A solution lies in an approach that allows all pipe products on the market to be objectively categorized by assessing their quality, performance, and serviceability; by making this information readily available to agencies and their designers; and by creating a streamlined (and preferably automated) design and selection process that allows a rapid and reliable selection of suitable pipe systems for a particular application. This approach will allow all acceptable pipe systems to be included in a roadwork's tender on an equal footing.

The NCHRP Project 10-86 research team was assigned to devise a system that is technically sound, that is versatile (i.e., can be adapted for any jurisdiction in any geographic location), and that can deliver better performing highway drainage systems on a much more cost-effective basis than the traditional approaches to drainage system design and procurement.

Specific objectives of NCHRP Project 10-86 were to perform the following:

- Review and consider the state of the practice regarding drainage systems.
- Develop a Recommended Practice for pipe system evaluation that encompasses key factors controlling pipe materials and performance (site characteristics, strength, hydraulics, durability, constructability, construction and post-construction costs, maintenance, and rehabilitation).
- Evaluate the Recommended Practice through trial applications representing a variety of geographical and use conditions in cooperation with a number of state DOTs.

- Present the Recommended Practice in AASHTO format suitable for balloting and subsequent implementation by owner agencies.

The Recommended Practice for establishing and implementing successful alternative bidding of highway drainage systems is in the form of a framework that ensures technical soundness, completeness, and transparency in design, while maintaining the ability of agencies to use their local experience and risk tolerance in the alternative pipe system selection process. The level of risk associated with the use of new products or construction practices is mitigated through a robust assessment of the structural, hydraulic, and durability performance of each installation using local environmental parameters, experience, and state-of-the-art assessment methodologies. The Recommended Practice has been developed with the specific intent to allow for future refinement and development of a standardized design and bidding tool, if further standardization is achieved across certain aspects of drainage pipe design.

The Recommended Practice will have the following functions:

- Provide a systematic, rational, comprehensive, and technically sound process for the evaluation of pipe systems (incorporating pipe and backfill materials and their interaction).
- Aid designers and bidders in selecting appropriate and cost-effective pipe systems for specific applications and site locations.
- Be used by agency engineers or consulting engineers retained on behalf of agencies for conventionally procured contracts or by designers as part of design build consortia on alternative financing and procurement contracts.
- Incorporate a comprehensive evaluation of site characteristics (environmental, geotechnical, hydrogeological).
- Evaluate hydraulics, structural performance, and durability in a streamlined and technically sound manner.
- Integrate use of best available practices.
- Use a novel matrix approach that facilitates clarity and transparency.
- Allow confidence in, and tracking of, post-construction performance.
- Be mindful of constructability, operational, and maintenance requirements.
- Have an expandable framework enabling modifications as new methods and materials are developed.
- Have an underlying framework that is flexible, enabling customization to address individual agency needs.
- Handle major design issues in an efficient manner and provides options for special design cases.

1.3 Purpose and Structure of the Report

This report summarizes information from the research completed as part of NCHRP Project 10-86 as an accompaniment to the Recommended Practice for Alternative Bidding of Highway Drainage Systems (Appendix A). While a great deal of information is presented in this report, it does not cover all aspects or interim decisions related to the project.

The developed Recommended Practice for Alternative Bidding of Highway Drainage Systems in AASHTO format is provided as Appendix A. An accompanying user's manual including worked examples (Appendix B) is available on the NCHRP Project 10-86 web page at www.trb.org.

CHAPTER 2

Research Approach

The approach used to develop the Recommended Practice and meet the objectives of NCHRP Project 10-86 was to be completed in four phases of work, as directed by the NCHRP Project 10-86 panel. These phases are described as follows:

- Phase 1—Develop the Recommended Practice outline using a literature review, DOT Survey, and identification of gaps in knowledge in current practice.
- Phase 2—Develop the Recommended Practice and prepare a working draft of the procedure.
- Phase 3—Evaluate and revise the Recommended Practice through a pilot project phase, testing the procedure on actual DOT drainage system projects.
- Phase 4—Develop final deliverables including the Recommended Practice.

This research approach was originally outlined in the work plan provided to the NCHRP Project 10-86 panel at the initiation of this project. However, as development of the Recommended Practice progressed, the details of the methodologies and approaches used in each phase of work were modified based on findings from the current state of practice and other lessons learned. Additional details of each of these phases, including findings and results, are described in this report.

2.1 Phase 1—Develop the Recommended Practice Outline

The first phase of the project involved the development of an outline of the Recommended Practice, including the key features that were necessary based on the current state of practice. That outline and the current state of practice were developed based on three critical tasks: a literature review, a survey of state DOTs, and the identification of gaps in knowledge.

2.1.1 Literature Review

A literature review was performed to research and document current practices and was used to develop a working outline and a basic framework for the Recommended Practice, as well as to identify gaps in knowledge that may affect the Recommended Practice. The results of the literature review and the gaps in knowledge identified were used extensively to develop the draft Recommended Practice that was prepared in Phase 2 of this project. The literature review focused on the following topics:

- Existing bid practices
- Design and construction considerations (focusing on hydraulic and structural design)
- Long term performance and service life of pipe (durability)
- Post-installation inspection and acceptance criteria

A reference database was developed to track each document reviewed, the reference type, and technical topics covered. A unique code was provided for each reference to track and organize the files. References from AASHTO, state DOTs, trade associations, regulatory and guidance agencies, federal agencies, and journals were included in the review.

2.1.2 Survey of State DOTs

To complement the literature review, a survey of state DOTs was implemented to gather additional information on design, specification, bidding, installation oversight, inspection, and maintenance of drainage pipe systems to identify the current state of practice.

The DOT survey was developed during the early stages of the project and after review and approval by the NCHRP Project 10-86 panel; it was sent to all the state DOTs through the members of the AASHTO Subcommittee on Materials.

The DOT survey and results are described in greater detail in Chapter 3.

Based on the survey results, a long-list of potential states for participation in the pilot projects was identified.

2.1.3 Identification of Gaps in Knowledge and Practice

Gaps in existing knowledge that affected the development of the Recommended Practice were identified in this phase of work. The techniques used to identify these critical gaps included consideration of previous NCHRP studies, the results of the literature review, the results of the DOT survey, and discussion with other agencies and technical resources.

Gaps in practice were typically defined as either knowledge gaps or implementation gaps. Knowledge gaps are areas where there is a deficiency in design theory/methodologies or performance data to support rigorous and robust design and performance decisions. Implementation gaps occur where there is clear and technically valid information (design method, performance data, etc.) to support use of a design method, evaluation criteria, or pipe product, but implementation has not yet been instituted.

2.1.4 Recommended Practice Outline

Based on results from the literature review, the DOT survey, and the identification of gaps in knowledge, an outline of the Draft Recommended Practice was prepared for the Phase 1 report, submitted in December 2011. The Draft Recommended Practice was further refined using the results of internal testing. The research team applied current state protocols to the Draft Recommended Practice to identify refinements and decision points. The Draft Recommended Practice was found to be applicable to the range of state policies and provided valuable insight into some of the finer details necessary to more fully develop the Recommended Practice through the pilot project phase.

2.2 Phase 2—Develop the Recommended Practice

Testing the Recommended Practice through actual DOT pilot projects was essential to develop a final, implementable procedure. This phase of work focused on developing a work plan for the pilot project phase as well as identifying appropriate projects to be used to test the procedure and evaluate the results within the required timeframe.

After much coordination and contact with DOTs, projects were identified with Pennsylvania Department of Transportation (PennDOT) and Missouri Department of Transportation (MoDOT). Additionally, the research team met with Florida Department of Transportation (FDOT) to discuss the Recommended Practice and obtain feedback based on FDOT's experience with alternative bidding of drainage systems. However, due to constraints experienced by most agencies in making an active project available for use as a full pilot project within the timeframe of NCHRP Project 10-86, a modified supplemental approach to this phase was used, consisting of the completion of seven additional baseline pilot projects. Application of each of these pilot projects is discussed in additional detail in Section 2.3.

2.3 Phase 3—Evaluate and Revise the Recommended Practice

This phase of the research project consisted of evaluating the Recommended Practice through the pilot project phase, revising the Recommended Practice as needed, and developing an implementation plan so that the Recommended Practice could gain acceptance by AASHTO, state and local transportation agencies, and industry.

2.3.1 Pilot Project Testing

The purpose of the pilot project phase of NCHRP Project 10-86 was to assist in trialing and refining the Recommended Practice by applying a range of drainage scenarios, environmental conditions, technical evaluation criteria, and bidding policies. This phase was a key element to gaining acceptance of the recommendations and guidelines. It served to prove the feasibility of implementing the developed procedures and to engage stakeholders (DOTs) in the development and refinement phases of the work. The pilot project phase also provided the opportunity to test implementation of the Recommended Practice on a small scale (on individual projects) with a few select DOTs providing insight into the requirements that will be needed to implement a new alternative bidding protocol into a state agency.

Applying the Recommended Practice to the DOT pilot projects had two phases. Phase 1 consisted of applying the Recommended Practice per the agency's standard design methodologies. Phase 2 consisted of repeating the process using national standards, technical approaches, and protocols as recommended by the research team. The two pilot projects were performed at PennDOT and MoDOT.

The baseline pilot projects consisted of the application of each agency's current policies to a common reference "baseline" project (for which the MoDOT pilot project was selected for comparison).

The baseline projects allowed for trialing and applying the Draft Recommended Practice across a wide range of agency policies developed under varying drainage, climatological, and environmental conditions; technical evaluation criteria; and bidding practices. This approach compared the Draft Recommended Practice with existing agency practices as applied to a standard project and identified where shortcomings or complications could arise. The process allowed an evaluation of an agency's current protocols (design guidelines, regulations, restrictions, etc.) with regard to alternative bidding and technical evaluation, and was intended to allow for early identification and handling of potential barriers to the adoption of the Recommended Practice by state DOTs. The baseline pilot projects were implemented with the cooperation of the specific agency so that the team could solicit feedback upon completion.

2.3.2 Revision of Recommended Practice and Implementation Plan

This pilot project phase provided lessons learned that were used to improve the Recommended Practice. These lessons were also used to develop the implementation plan, so that the Recommended Practice could gain acceptance by AASHTO, state and local transportation agencies, and industry.

2.4 Phase 4—Develop Final Deliverables including the Recommended Practice

The final phase of the project focused on preparing the final Recommended Practice in AASHTO format and this report.

CHAPTER 3

State of the Practice Summary

To develop a national recommended practice for alternative bidding of culverts and storm sewers, it was necessary to understand the state of gravity drainage system practice for roadway projects across U.S. DOTs. As such, part of NCHRP Project 10-86 focused on reviewing the state of the practice for design, specification, and bidding of drainage pipe systems for highway projects through a DOT survey and a literature review.

The state of the practice reviews consisted of technical and policy reviews of federal standards, specifications, and guidelines; relevant research reports; academic papers; case studies; industry literature; and the existing state of the practice across U.S. DOTs. The state of the practice reviews provided information across all aspects of gravity drainage pipe system design, selection, installation, quality control, performance, rehabilitation, and modes of failure.

There is a vast amount and range of information available on drainage systems from text books, published literature, research reports, and product information generated by pipe manufacturers and their trade associations. The following national guidelines and specifications are intended to guide and control design on federally funded roadway projects:

- AASHTO Highway Drainage Guidelines (AASHTO, 2007)
- AASHTO LRFD bridge design specifications (AASHTO, current year)
- AASHTO LRFD bridge construction specifications (AASHTO, current year)
- AASHTO Standard Practice documents
- ASTM and AASHTO test and material standards
- Federal Highway Administration (FHWA) Hydraulic Design Series and Hydraulic Engineering Circulars
- FHWA Culvert Design Software, HY-8
- FHWA Storm Drain Design Software, HY-12
- United States Army Corps of Engineers (USACE), Hydrologic Engineering Center River Analysis System (HEC-RAS)

However, these national resources and guidelines are then integrated and modified into state guidelines, specifications, and practices. Based on the current review, state practices for drainage pipe system design, bidding, installation, inspection, maintenance, and other factors vary tremendously, with limited consistency across states on many issues.

The state of U.S. DOT practice greatly influenced the direction and choices made in developing the Recommended Practice, and key elements are presented in this report to provide context. The results of the DOT survey undertaken as part of this project provided detailed information on the current state of the practice for highway drainage system design. The results and summary findings of the survey, along with the results of a literature review that supplements the questionnaire responses, are presented in this chapter of the report. This report notably does not present a full summary of the range of state practices, and the reader is referred to the following resources for additional information:

- White and Hurd (2011)
- Taylor, C. and Jeff, M. (2012)
- Mitchell et al. (2005)
- Zhao, J. Q., et al. (1998)
- Gabriel and Moran (1998) (The update is *NCHRP Synthesis 474*, which will be published in spring 2015)
- Caltrans Design Information Bulletin (no. 83-02 (2011))

3.1 Survey of State DOTs

A survey of all state DOTs was undertaken by communicating with each DOT's AASHTO Subcommittee on Materials representative or alternate designee. The intent of the DOT survey was to determine the current state of practice regarding the use of bidding alternative materials for drainage systems. The research team received responses from 37 state

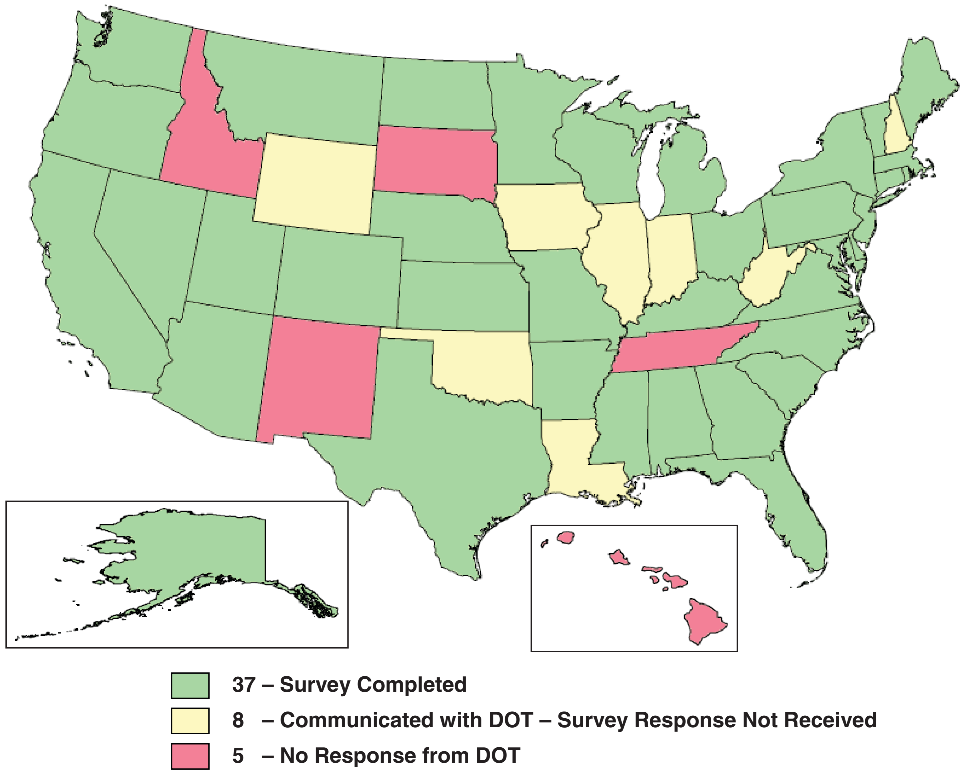


Figure 1. NCHRP Project 10-86 state DOT survey response graphic (Alaska and Hawaii not to scale).

DOTs, a 74 percent return rate, as shown in Figure 1. The DOT survey questions and responses are presented in Figures Q1 through Q14 with brief commentary. It is acknowledged that in some instances the responses to the survey represent subjective personal knowledge of the current state of practice for a given agency, as formal tracking of various survey items is not completed by all agencies.

Question 1: Does your agency have a current policy for allowing the selection of alternative pipe systems?

Of the 37 responses to Question 1, 32 DOTs (86%) indicated that they do have a current policy addressing alternative pipe system selection. Only one DOT indicated that no policy was in effect. Four others indicated that some restrictions apply in accordance with their policies.

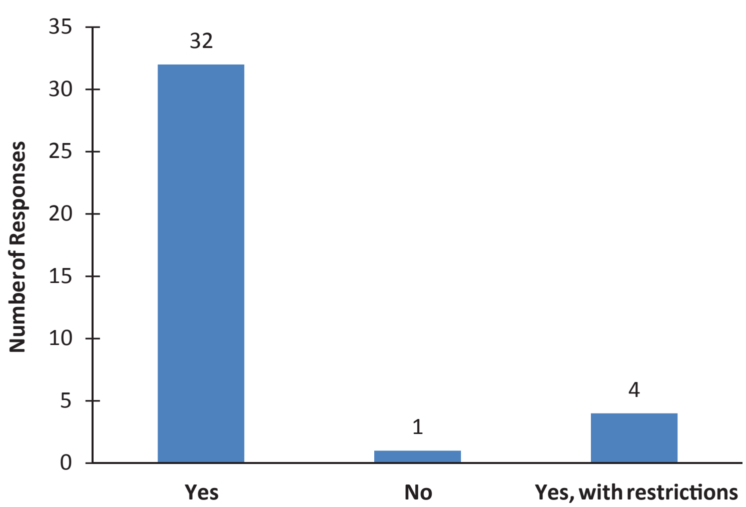


Figure Q1. Number of DOTs that use an alternative pipe system selection policy.

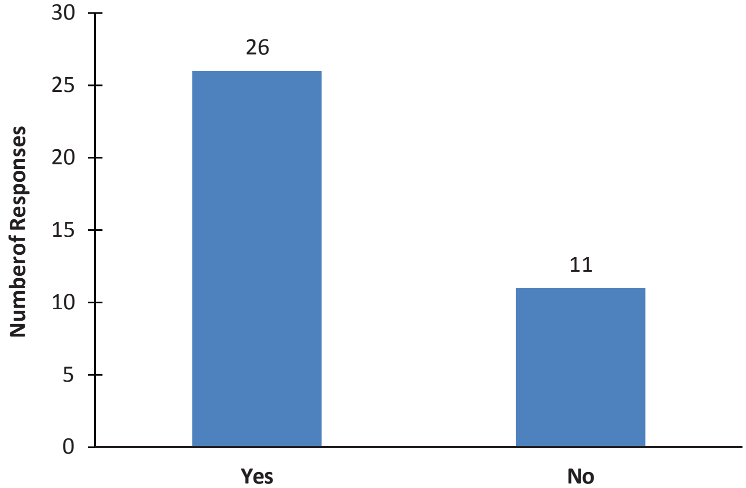


Figure Q2. Number of DOTs that have or are evaluating new pipe types.

Question 2: Has your agency approved (or is currently evaluating) any new or non-traditional pipe materials?

Approximately 70% of DOTs have approved or were evaluating new or non-traditional pipe types. Of those DOTs, the percentages considering the following pipe types were as follows:

- Polypropylene—34% of DOTs
- Steel reinforced polyethylene—32% of DOTs
- Fiberglass—12% of DOTs
- PVC—12% of DOTs
- HDPE (7% solid wall and 3% single wall)—10% of DOTs

This response confirms the active nature of the pipe supply industry and the extent to which research and new product development are ongoing. The openness of state agencies to evaluate new products is also encouraging and highlights the need to coordinate these evaluation efforts and to capture best practices across the country.

Question 3: For culvert design, does your state have any unique conditions that require a special design focus (such as hydraulic or structural) above and beyond standard practices (such as AASHTO recommendations)? Unique conditions could include very low pH, saltwater environments, heavy logging trucks, lack of stone backfill, aquatic organism passage, etc.

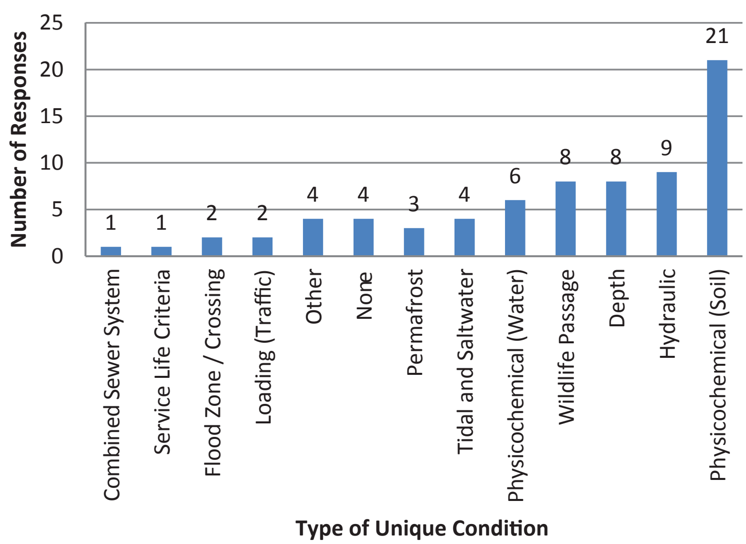


Figure Q3. Number of DOTs whose states have unique design conditions.

Many of the DOTs (57%) have soil conditions that may affect the durability of pipe systems. Therefore, it was recognized that durability analyses, particularly for corrosion and abrasion, should be a key component of an alternative pipe selection process. Some of the other conditions and criteria, such as wildlife passage requirements, are left to be independently assessed by those agencies during a pipe system selection process.

It was recognized that alternative pipe system bidding needed to be streamlined and to be able to handle routine designs efficiently. This response allowed the research team to evaluate what special design conditions could be handled within the framework and which ones would need to be addressed outside it.

Question 4: If your agency utilizes fill height tables for structural design, are those tables state/agency specific? How were the tables developed?

Most state DOTs utilize fill height tables that were developed specifically for that agency. However, the development of those fill height tables came from a variety of sources or was unknown. The responses suggested that the use of fill height tables was universally accepted as the most practical means for structural design of typical highway drainage pipe systems.

Question 5: Does your agency consider the potential impact of changes in Manning's *n* values over the service life of the pipe?

The majority of DOTs do not consider the potential impact on pipe capacity of Manning's *n* values over the service life of

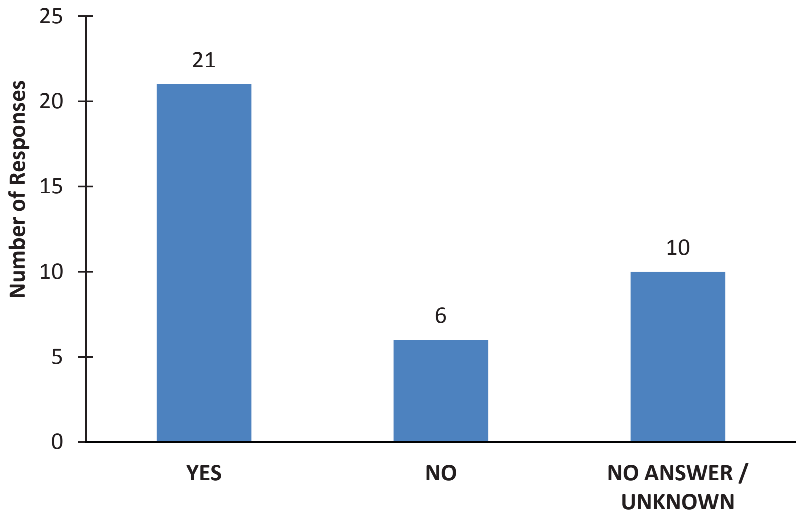


Figure Q4a. Number of DOTs whose fill height tables are agency-specific.

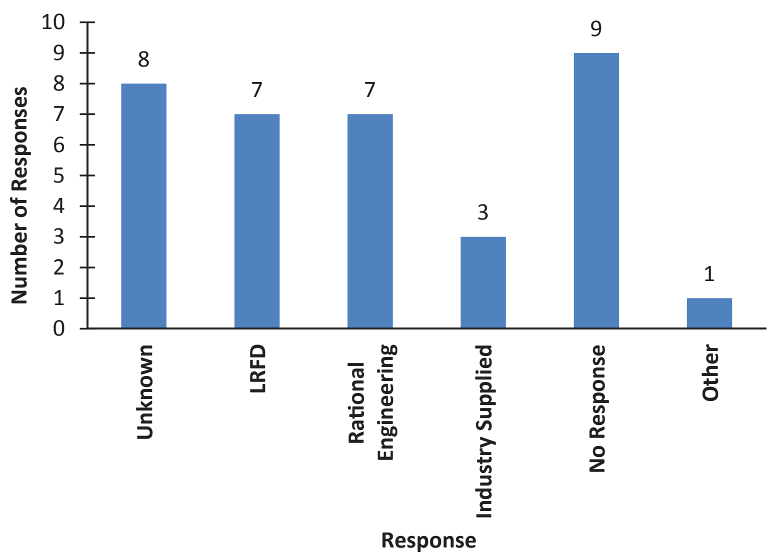


Figure Q4b. How were agency-specific fill height tables prepared?

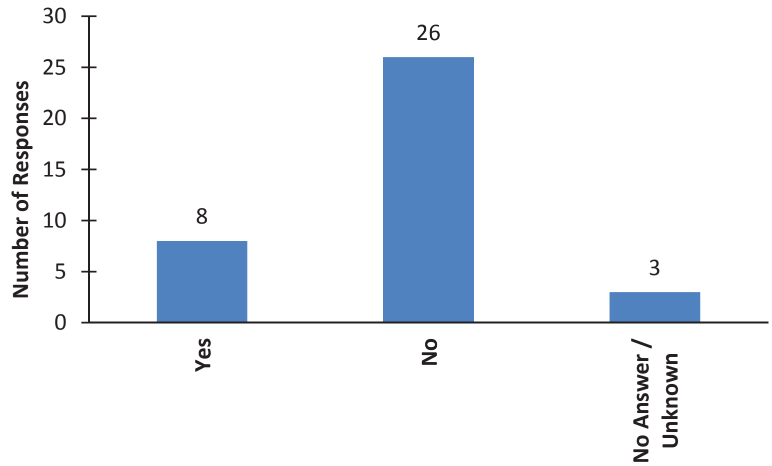


Figure Q5. Number of DOTs that consider changes in Manning's n *values over the service life of the pipe.*

the pipe. Of those DOTs that do, typically culverts with natural bottoms are those that require a more detailed evaluation of appropriate roughness values in design. Additionally, some DOTs increase the Manning's *n* value from the manufacturer as a factor of safety.

Question 6: Does your agency currently use the concept of pipe Design Service Life?

Most of the DOTs indicated they use the concept of Design Service Life (DSL) in the design of pipe systems. The DSL ranged from 25 to 100 years, primarily based on roadway classification or Average Daily Traffic (ADT) criteria.

Question 7: During the design stage, does your agency consider or plan for future remediation of the pipe system?

Of those DOTs that do plan for future remediation of the pipe system (including due to special conditions), the most cited example was oversizing culverts in very deep fills to allow for sliplining in the future for repair if needed.

Question 8: Based on past experience, how would you rate your reliance on in-situ treatments for extending the life of drainage pipes? If in-situ treatments are routinely used, which techniques are used?

Almost all the DOTs surveyed have routinely or occasionally used in-situ treatments for pipe system rehabilitation. Most agencies tend to have a program in place to consider options for trenchless pipe system rehabilitation. Several DOTs who occasionally used in-situ treatments were trying to avoid disruption to the public for a culvert replacement. The most common method of in-situ rehabilitation is sliplining followed by Cured-In-Place Pipe (CIPP) and invert paving.

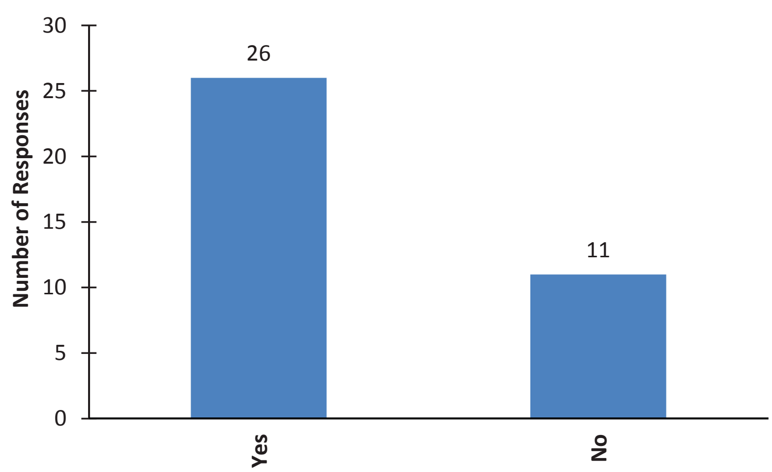


Figure Q6. Number of DOTs that use the concept of Design Service Life.

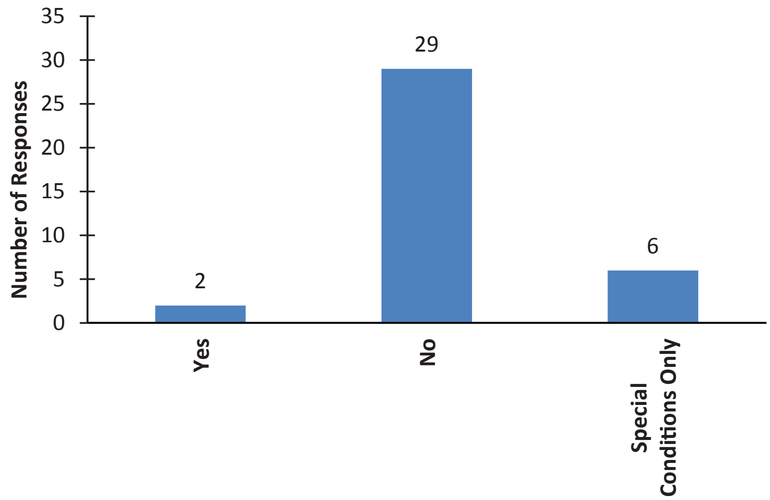


Figure Q7. Number of DOTs that plan for future remediation of the pipe system.

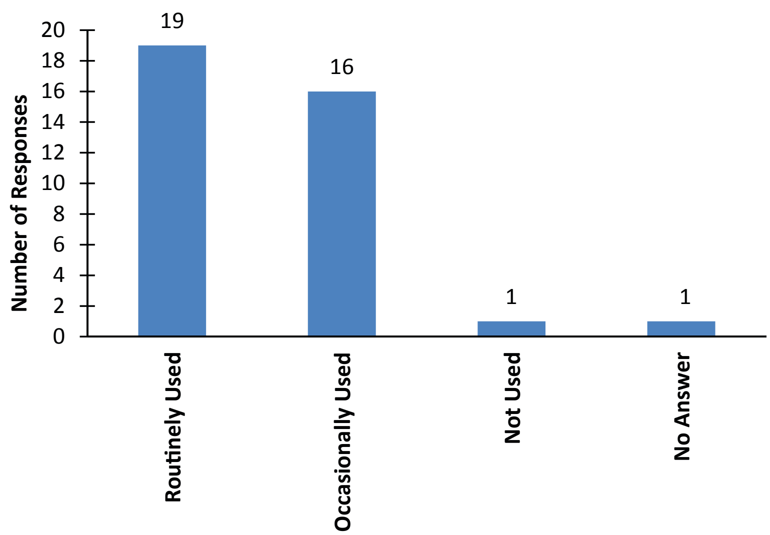


Figure Q8a. Number of DOTs that routinely use in-situ treatments for pipe systems.

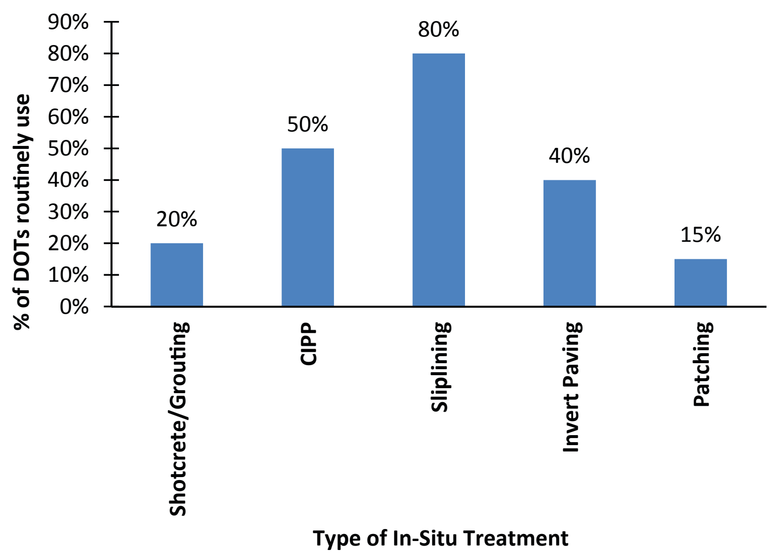


Figure Q8b. Types of in-situ treatments used by DOTs.

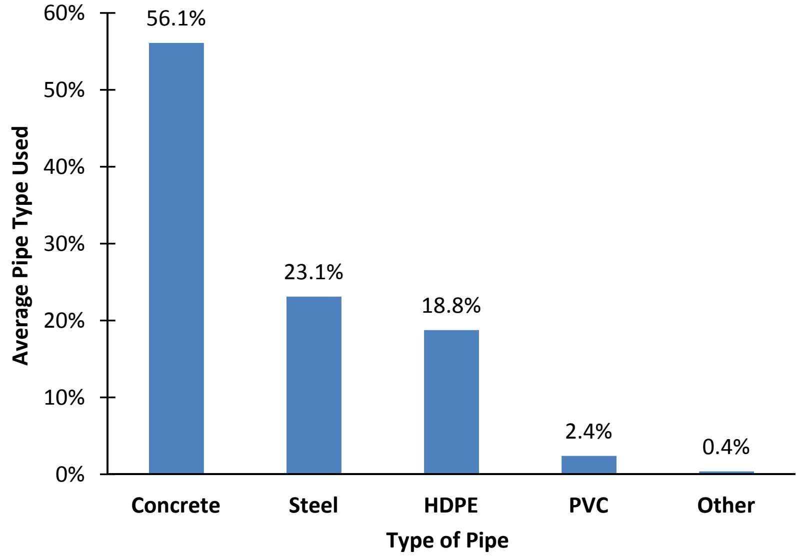


Figure Q9. Average percentage of pipe type used by DOTs.

Question 9: In the last 5 years, which of the following pipe types has your agency installed for highway drainage systems: concrete, steel, HDPE, PVC, other.

Figure Q9 shows an average across all DOTs for the pipe types used in drainage systems. However, the responses were also examined to see how pipe type use varied by DOT. For approximately 50% of DOTs, at least half of the pipe used in drainage projects was concrete. For approximately 14% of DOTs, both HDPE and steel were used in at least one-half of the projects.

Questions 10 and 11 (a–f): For rigid and flexible drainage pipe systems, what post-construction inspection methodologies does your agency use?

For both rigid and flexible pipe, visual and video inspection are the most common post-installation inspection methods for pipe drainage systems. Mandrel testing is still fairly common for flexible pipe.

Questions 10 and 11 (g): For rigid and flexible pipe systems, at which stage of the construction contract are the inspections undertaken?

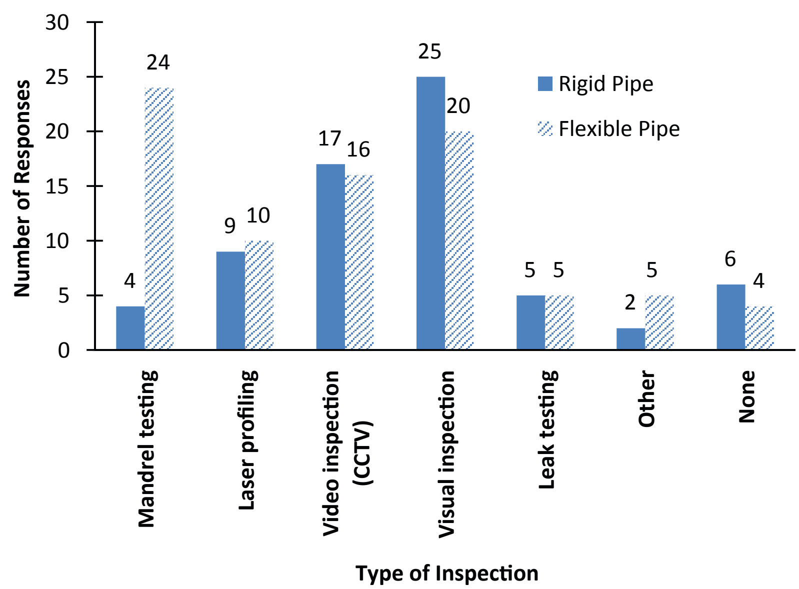


Figure Q10–11 (a–f). Post-installation inspection methods used by DOTs.

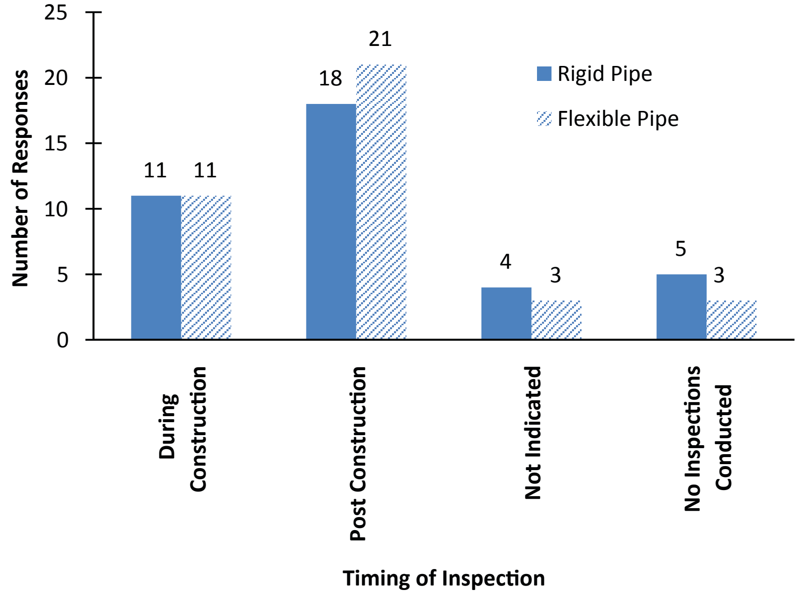


Figure Q10–11g. When does pipe system inspection occur?

Installation of pipe systems most commonly occurs after construction; however, many DOTs aim to have inspection complete by the time construction is done. While 8 responses indicated no inspections were conducted for either rigid or flexible pipes, only one responding agency indicated they do not inspect any pipes.

Question 12: Does your agency require a guarantee or warranty period on drainage pipe systems?

Only a few DOTs had a requirement for a 1-year warranty after the contract. It is noted that a greater percentage of installations may have warranties even if not required by agency policy.

Question 13: Has your agency undertaken any documented case studies on the durability, structural integrity, hydraulic performance, or corrosion resistance of drainage pipe systems?

Approximately 43% of DOTs have well-documented studies on the performance and durability of pipe. The corrosion and durability of pipe and the use of flexible pipe are the most common topics. Some of these studies were used in the development of design guidelines. Many of the more recent studies are available online.

Question 14: Does your agency have a practice of inspecting pipe systems on a periodic basis?

The DOTs that regularly inspect pipe systems are generally focused on larger structures or those associated with bridges. Some DOTs have initiated an asset-management database and may develop a pipe system inspection protocol in the future.

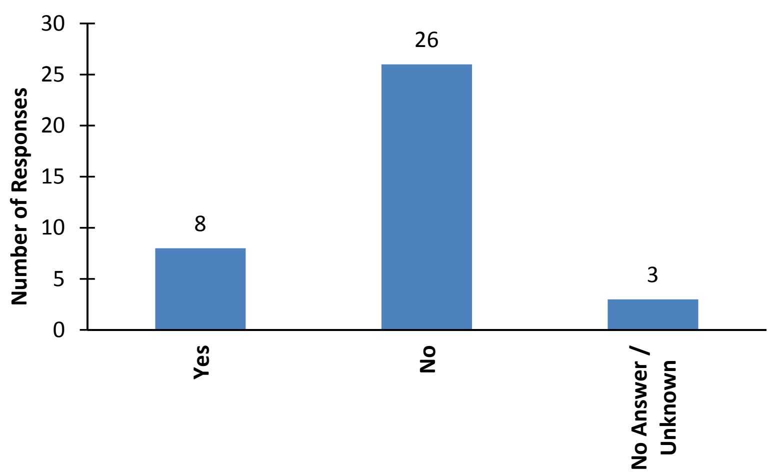


Figure Q12. Number of DOTs that require a guarantee on drainage pipe systems.

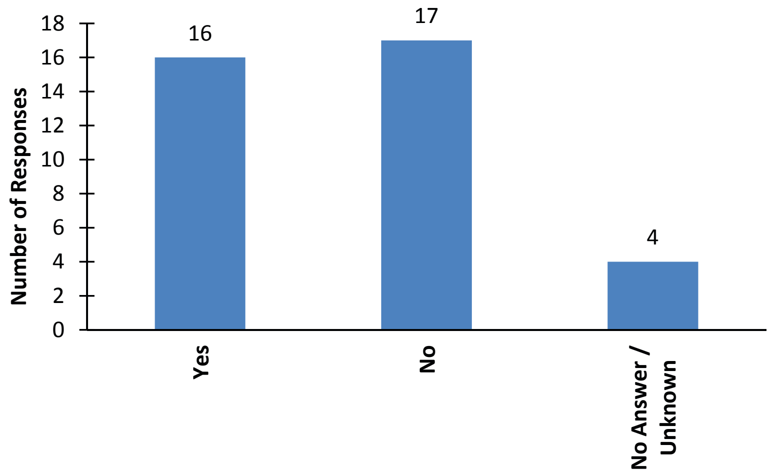


Figure Q13. Documented studies on pipe system performance/durability.

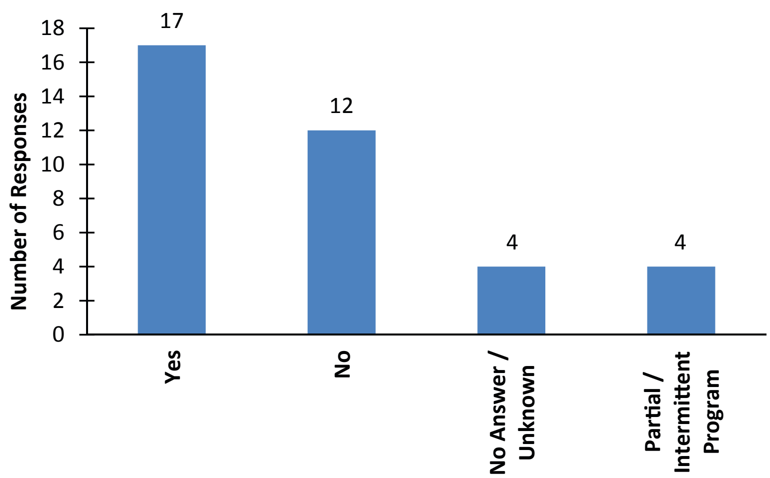


Figure Q14. Number of DOTs that inspect pipe systems on a regular basis.

3.2 Commentary on Select Portions of the State of Practice

A literature review was performed during the execution of NCHRP Project 10-86 to research and document current practices and was used to develop and guide the framework for the Recommended Practice, as well as to identify gaps in knowledge and application that had the potential to impact the Recommended Practice. While the review of the state of highway drainage practices completed during the execution of NCHRP Project 10-86 covered a significant breadth and depth of topics related to the materials, design, bidding, installation, inspection, maintenance, and other aspects of highway drainage systems, only select summary commentary on specific topics most relevant to the understanding and use of the developed Recommended Practice for Alternative Bidding of Highway Drainage Systems are summarized in this report. The literature review focused on the following topics:

- State agency bid practices
- Design and construction considerations
- Long term performance and service life of pipe (durability)
- Post-installation inspection and acceptance criteria

Summaries of each of these reviews are included in the following subsections with the resources in the bibliography providing sources of additional information on other related topics. It is acknowledged that certain aspects of the state of the practice have been updated since completion of the main literature review for this project at the end of 2011, and that aspects of the review summary presented do not capture recent updates.

3.3 Existing Alternative Pipe Bidding Systems

A review of state agency bidding practices and guidelines indicated that while the majority of states surveyed indicated that they have an alternative pipe bidding system in place, the extent to which such a system is implemented and the scope of pipe alternatives permitted are extremely variable. As reported by White and Hurd (2011), none of the current state policies provides a complete protocol for alternate pipe material selection. The bidding of alternative pipe materials is facilitated in different ways by different states as highlighted in the selected summaries below that outline some portions of the state of practice.

- In Alaska, the use of a particular bid item code indicates that a choice is available to the bidder. The choice is limited to four options and no further refinement of the options available is possible. Thus, if a choice exists, it is between all four of the allowable pipe materials. In practice, however, only HDPE and metal pipes are used.
- A system using groups of allowable pipe materials is also used by MoDOT. MoDOT utilizes a standard (across all projects) list of three groups and specifies the allowable group directly in the bid documents. Both hydraulically smooth and rough pipes are included in the same groups, but no adjustments are made for the difference in hydraulic performance. MoDOT also includes different inspection requirements for the different pipe groups, coupling pipe selection to quality control.
- Kentucky and California specify the allowable alternative pipes in the construction drawings, rather than in the bid documents (tabulation sheets).
  - Kentucky uses the fill height tables to indicate what alternatives are available, and every pipe bid item in the bid documents appears to allow the contractor to choose from all those available for that diameter. This approach closely couples the structural performance (fill height tables) to the pipe material selection. No adjustments are made for differences in pipe system hydraulic capacity or durability.
  - California specifies in the drainage quantity sheets (part of the construction drawings) which pipes may be bid using alternative materials. For each item a number of alternatives are presented, and where necessary the thickness of the metal pipe is specified.
- Pennsylvania specifies the allowable alternatives directly in the bid documents using an either/or system. The as-designed pipe is shown, along with either 2 or 3 alternatives based on the roadway classification requirements. Each item (both as-designed and alternatives) is uniquely identified by a bid item number. A master list is maintained for all items that could possibly be included in contracts.
- Michigan previously required alternative bidding but removed the requirement based on the provisions of MAP-21.
- Nebraska policy specifies that designers select the allowable pipe material options for each installation. The contractor has the option to choose the final pipe material from the list of options provided. In most cases the contractor has the option of selecting the class of pipe and type of installation in accordance with the fill height tables shown on the plans. Nebraska uses a pipe type tender code with numerical designations of 8 digits used by designers to streamline the specification of suitable pipe options.
- Florida policy is based on an optional culvert material system and states that optional culvert materials must be considered for all culverts. After the initial hydraulic design, available culvert materials shown in the FDOT Drainage Manual must be evaluated as potential options. The evaluation must consider functionally equivalent performance in durability and structural capacity. Florida offers the publicly available Culvert Service Life Estimator (CSLE) software to facilitate evaluations of expected service life (ESL) for considered culvert materials in comparison to the required DSL.
- The Ministry of Transportation Ontario (MTO) system allows for a range of pipe sizes and makes allowance for differences in hydraulic performance between rough and smooth pipes. The MTO system is based on the premise that designers specify a list of allowable pipe material types (with applicable minimum material specifications and installation and bedding requirements) and allows the contractors to use whichever of the products they prefer. The MTO bidding process uses a succinct bidding code format to identify qualifying pipe types from the master list of pipe culvert tender items maintained by the agency for use in contracts.

The differences between current agency practices can materially affect the proposed alternative pipe systems. This is a reflection of the differences in local experience, the risk tolerance of given agencies toward various design criteria, and the structure of alternative pipe selection processes. The review of agency practices and the DOT survey responses found that the absence of both a policy and a comprehensive rational mechanism to facilitate the selection of alternative pipe materials tends to restrict the specification, selection, and installation of available alternative pipe materials and in the team's view, can lead to the exclusion of a wide range of viable pipe options from consideration.

Because the range of bidding practices and procedures was seen to vary widely across the information reviewed, the Recommended Practice was designed to be flexible, customizable (to accommodate specific DOT requirements), and able to be easily integrated into existing state DOT bidding structures to allow for rapid and easy incorporation into current practice.

3.4 Literature Review—Design and Construction Considerations

Design and construction considerations were reviewed to determine current practice and guidelines for implementation into the Recommended Practice. In particular, hydraulic, structural, and durability design considerations were reviewed extensively. For culvert hydraulic considerations, flow control and Manning's *n* values were reviewed. For structural considerations, the basic structural design of buried culverts was reviewed, as well as state DOT fill height tables. The state of the practice to account for durability considerations was also reviewed, with practice found to be more variable and less theoretically based than for hydraulic and structural considerations. While design criteria necessarily vary from agency to agency, the state of the practice review aimed to capture the range of underlying design principles to ensure that the process adopted for the Recommended Practice is sufficiently rigorous to gain acceptance.

3.4.1 Hydraulic Design Considerations

Hydraulic design is an integral and fundamental component of specifying any highway drainage system. This hydraulic design literature review included a brief summary of state of the practice design methodologies and analysis into variations in design methods and hydraulic parameters used in typical DOT practice.

Hydraulic Design Series 5 (HDS 5) (FHWA 2012) provides a list of potential hydraulic considerations for highway drainage system design as follows:

- Flow Control and Measurement
- Low Head Installations
- Section Variations (e.g., Bends, Junctions, Wyes, Transitions, etc.)
- Siphons
- Aquatic Organism Passage
- Scour at Inlets/Outlets
- Sedimentation and Debris Control
- Skewed Barrels/Inlets
- Multiple Barrels
- Perforated Pipes

One or many of these considerations may apply to a given culvert and storm sewer design, and may control pipe selection from a hydraulic perspective. While many of these aspects are accounted for in the Recommended Practice through evaluation of the baseline hydraulic design, others are not directly incorporated into the decision framework and require outside consideration by the design engineer.

3.4.1.1 Hydraulic Pipe System Evaluation

The state of practice for hydraulic design of roadway drainage systems (culverts and storm sewers) often involves evaluation of the two types of flow control (inlet and outlet) to determine the controlling mechanism for each drainage element configuration. The hydraulic capacity of a culvert depends on a range of factors for each type of control, as summarized in Table 1.

Table 1. Factors influencing culvert performance (FHWA 2012).

FACTOR	INLET CONTROL	OUTLET CONTROL
Headwater Elevation	X	X
Inlet Area	X	X
Inlet Edge Configuration	X	X
Inlet Shape	X	X
Barrel Roughness		X
Barrel Area		X
Barrel Shape		X
Barrel Length		X
Barrel Slope	*	X
Tailwater Elevation		X

*Barrel slope affects inlet control performance to a small degree, but may be neglected.

The hydraulic factors in Table 1 can be broken out into the following:

- **Inlet Characteristics** (inlet area, inlet edge configuration, and inlet shape)
- **Site/Geometric Characteristics** (headwater elevation, barrel length, barrel slope, and tailwater elevation)
- **Pipe Selection Characteristics** (barrel roughness, barrel area/size, and barrel shape)
- **Hydraulic Design Constraints** (headwater elevation, tailwater elevation, outlet velocity)
- **Design Determination** (barrel roughness, barrel area/size, barrel shape, inlet area, inlet edge configuration, and inlet shape)

The inlet characteristics are the only characteristics that affect both inlet and outlet control design, and thus they can be modified to help improve the performance of a culvert system for both types of control. Site and geometric characteristics are determined primarily by the location of the pipe, and typically remain constant in the design.

Typically, pipe selection characteristics are iteratively modified and the resulting headwater elevation is compared with the headwater elevation hydraulic design constraint and outlet velocity design constraints, if any, to help determine the design of a pipe. The barrel roughness is a function of the material used to fabricate the barrel and represents the effect of friction loss within the pipe. It is usually set at a recommended value based on pipe material type to determine the minimum required barrel area/size and in special circumstances, the barrel shape (the barrel shape is typically determined based on the site/geometric conditions, e.g., low available pipe cover, wider bottom opening of pipe). The barrel roughness is represented by a hydraulic resistance coefficient, the Manning's *n* value.

The Manning's equation is an empirical relationship commonly used to calculate barrel friction losses in pipe system and design. The Manning's *n* value is based on either hydraulic test results or resistance values calculated using a theoretical equation such as the Darcy equation and converting to a Manning's *n*. The use of the Manning's equation for culvert design is the predominant means of evaluating the hydraulic adequacy of various pipe materials for a given drainage application used in practice.

3.4.1.2 Review of Recommended Manning's n *Values*

The following references were reviewed to develop a database of typical Manning's *n* values used in practice that could be analyzed to evaluate the trends within the range of practice. It is noted that there are numerous other references that provide tabulated *n* values, but the research team believes this sampling of references satisfies the intent to evaluate the range of *n* values utilized in common practice.

- Software References
  - CulvertMaster—Bentley (previously Haestad Methods) culvert design and analysis software
  - HEC-RAS—United States Army Corps of Engineers (USACE) Hydrologic Engineering Center River Analysis System software
  - HY-8—Federal Highway Administration (FHWA) culvert design and analysis software
  - Hydraflow Express—AutoCAD Civil 3D Hydraflow Express Extension hydrology and hydraulic software
- Design Manual References
  - FHWA HDS 5—May 2005 edition
  - Caltrans Highway Design Manual, October 4, 2010
  - PennDOT Drainage Manual, Publication 584, 2010 edition

Each reference provided either a recommended *n* value, a range of *n* values, or both. As noted, some non-standard pipes from the references were not considered within this review. Figures 2 through 8 provide summary plots showing the ranges of Manning's *n* values across several pipe types for these references.

The literature review into the variability and state of practice regarding Manning's *n* values suggests the following:

- Recommended Manning's *n* values are not consistent across reference guidelines.
- It appears that consideration for variations in pipe roughness over time via abrasion, corrosion, or other mechanisms may explain some of the variations observed in the recommended Manning's *n* values; however, it is often unclear if and to what magnitude such considerations are included in setting the recommended Manning's *n* values for design, for example,
  - HDS 5 states that *n* values for concrete pipe were increased from 0.009 to between 0.011 and 0.013 based on field installation and aging, and
  - The American Concrete Pipe Association indicates that a general "design factor" of 20 to 30 percent has historically been used to account for the difference between laboratory *n* values and actual installed conditions.
- Although theoretically and experimentally proven to have significantly different flow characteristics (and Manning's *n* values), many reference guidelines group different corrugation types (annular vs. helical) and profile sizes (e.g., 3×1 vs. $2\text{-}\frac{2}{3} \times \frac{1}{2}$) together.

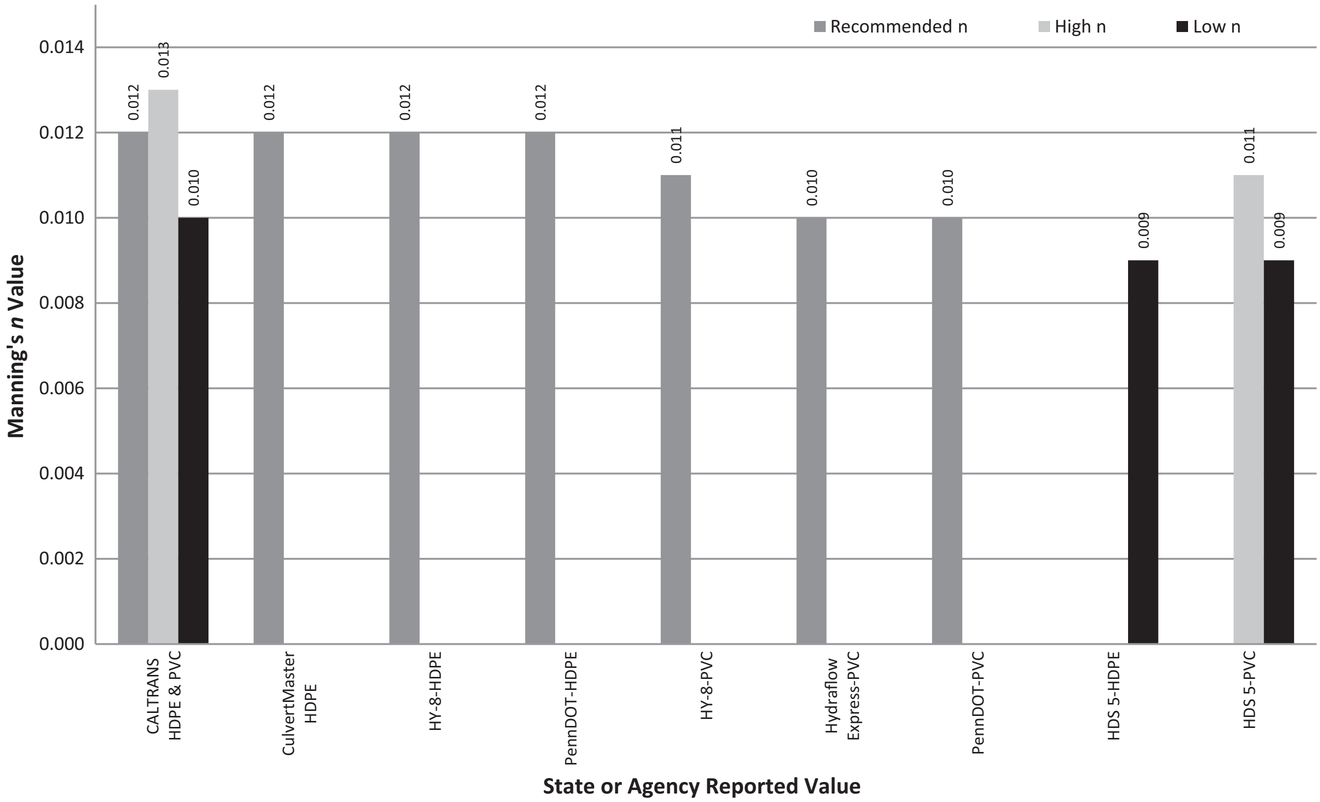


Figure 2. Distribution of Manning's n *values for smooth thermoplastic (HDPE and PVC) pipes.*

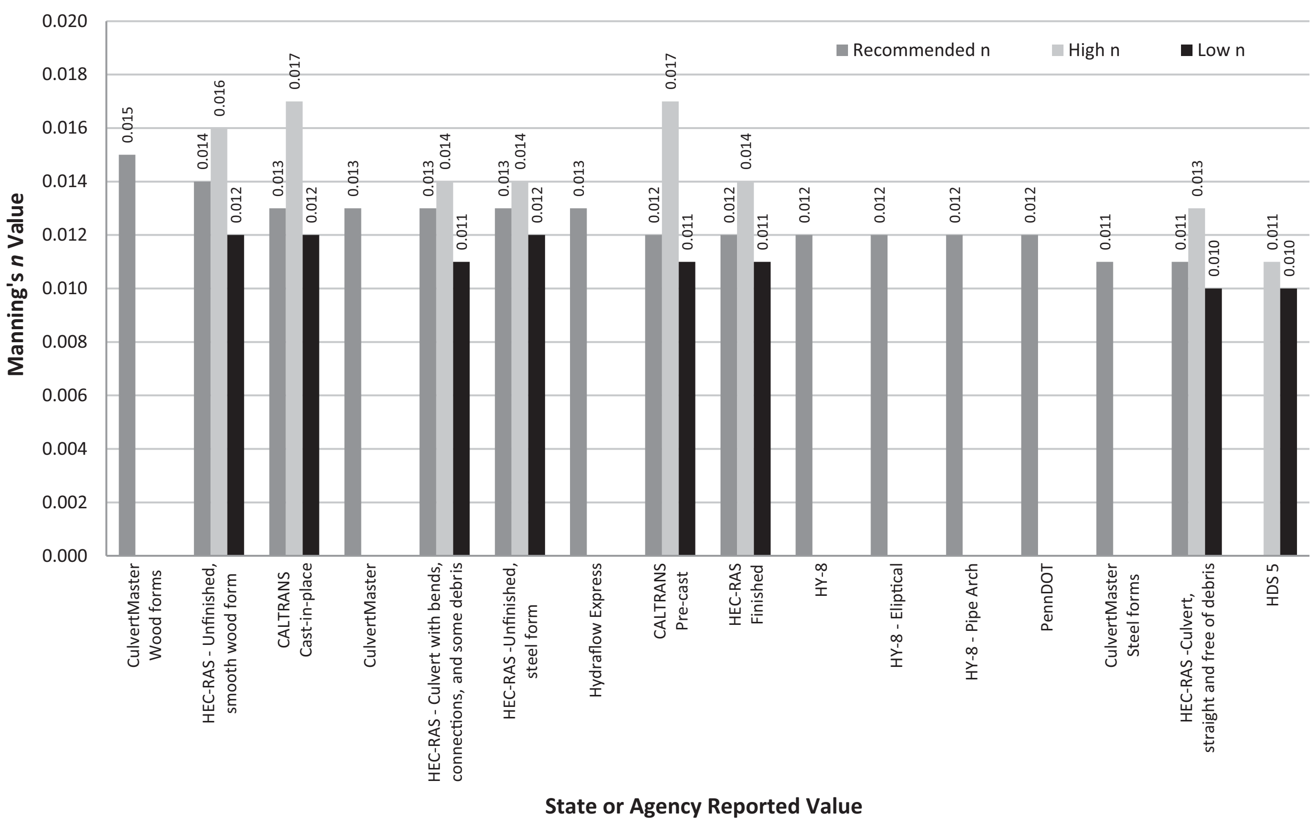


Figure 3. Distribution of Manning's n *values for concrete pipes.*

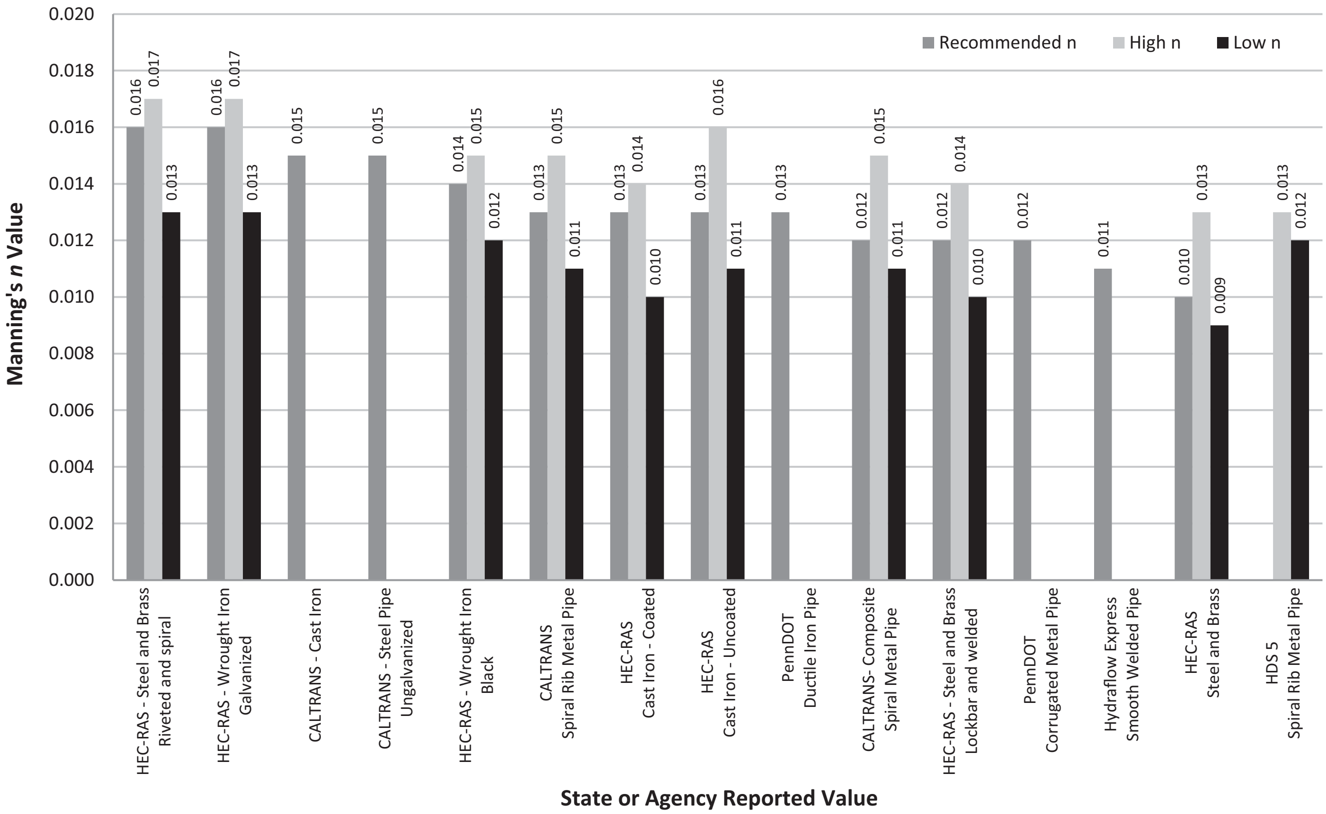


Figure 4. Distribution of Manning's n *values for smooth metal pipes (e.g., cast iron, ductile iron, spiral rib, etc.).*

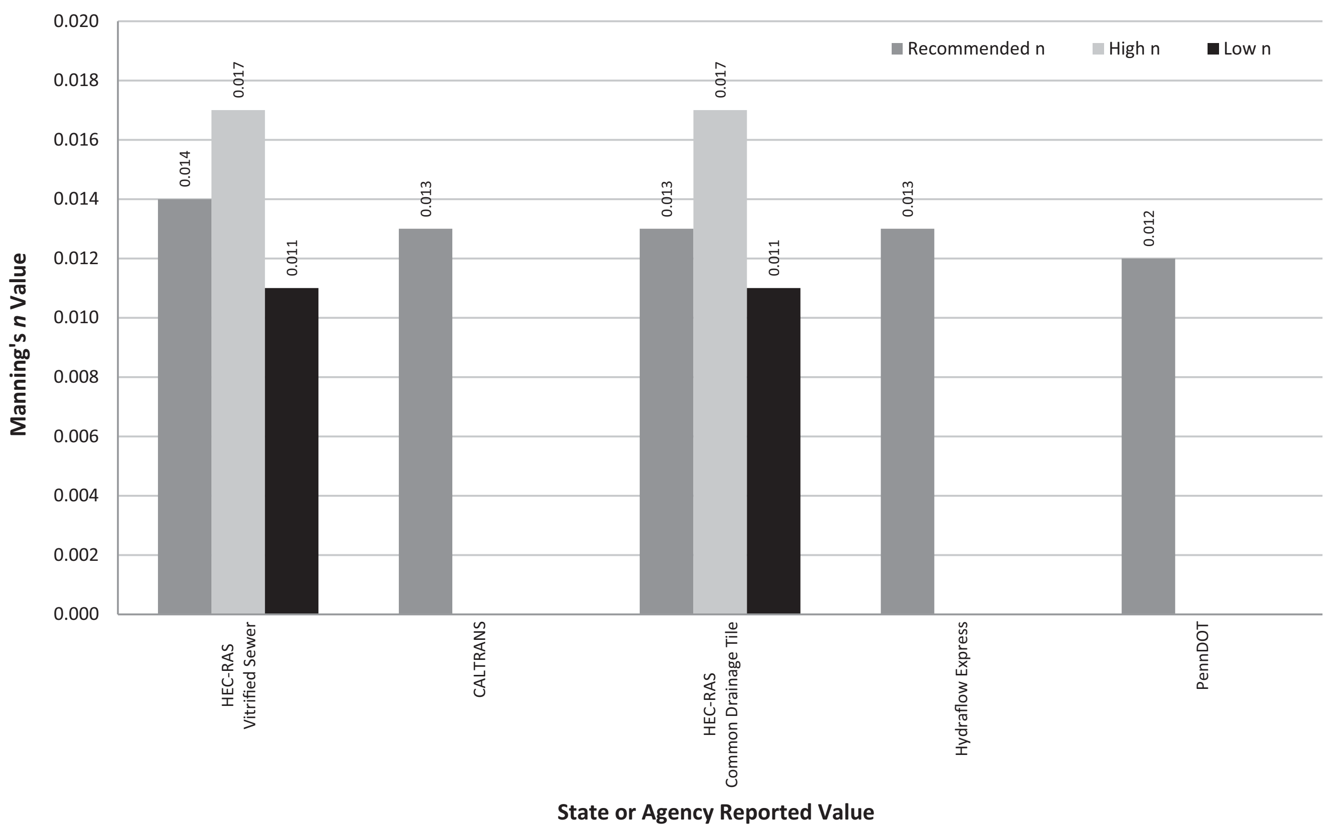


Figure 5. Distribution of Manning's n *values for clay pipes.*

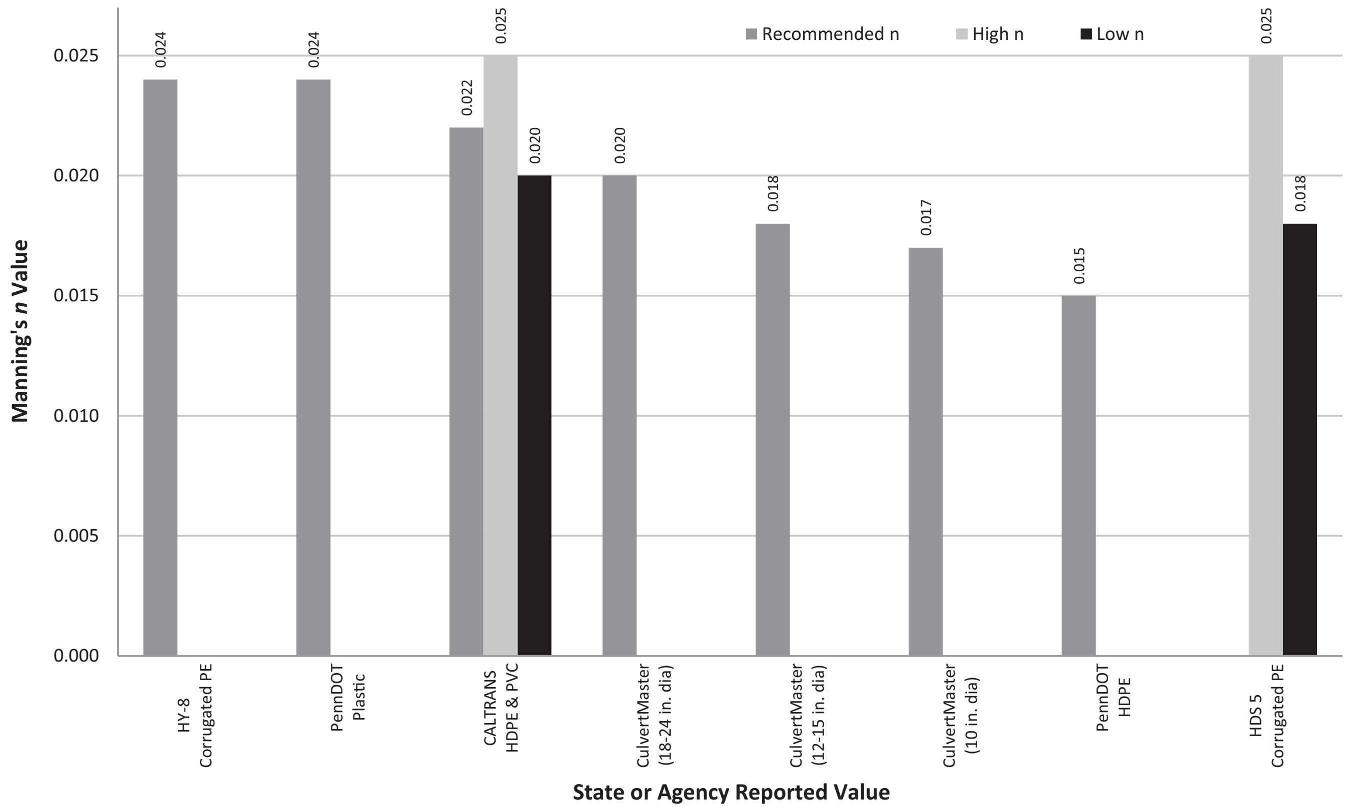


Figure 6. Distribution of Manning's n *values for corrugated thermoplastic pipes.*

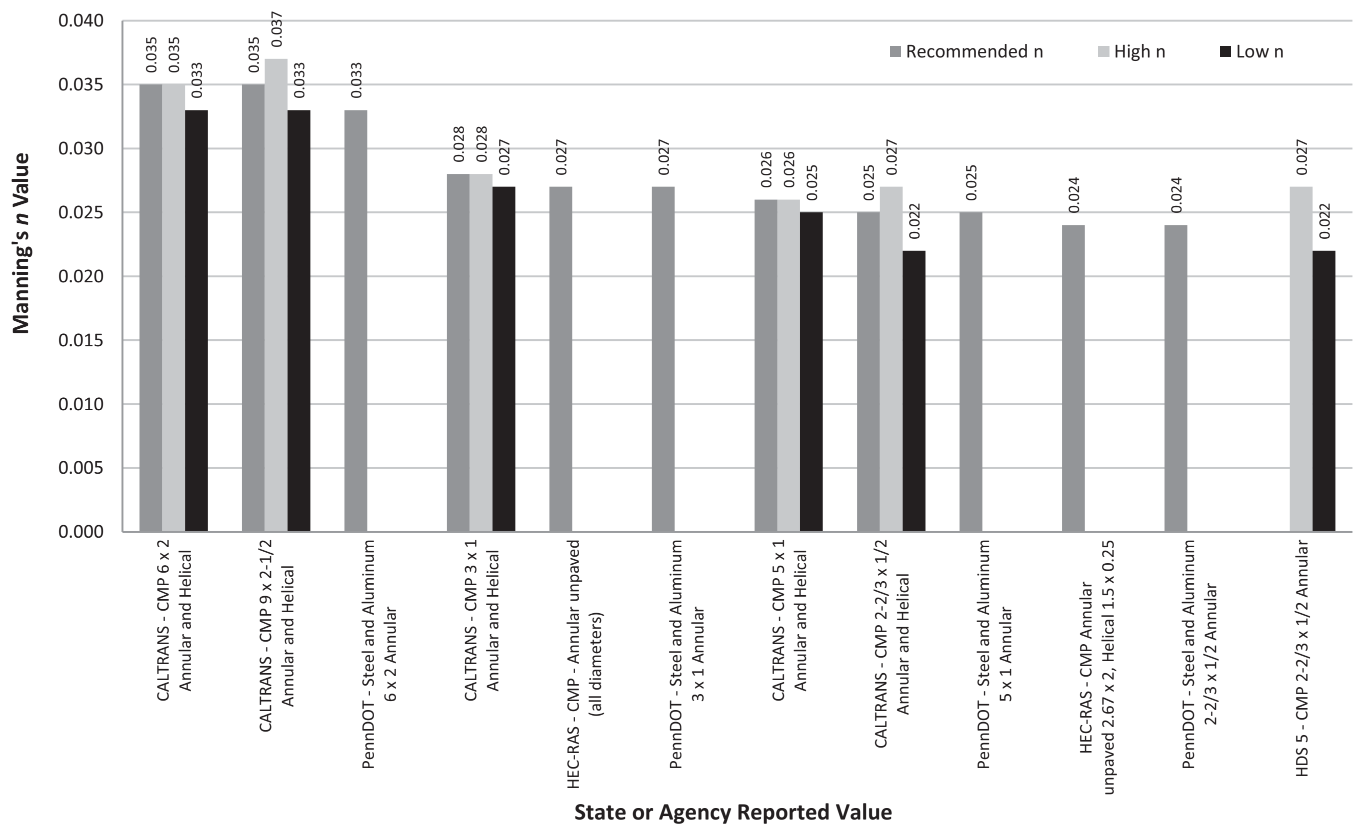


Figure 7. Distribution of Manning's n *values for corrugated steel and metal pipes—annular corrugations.*

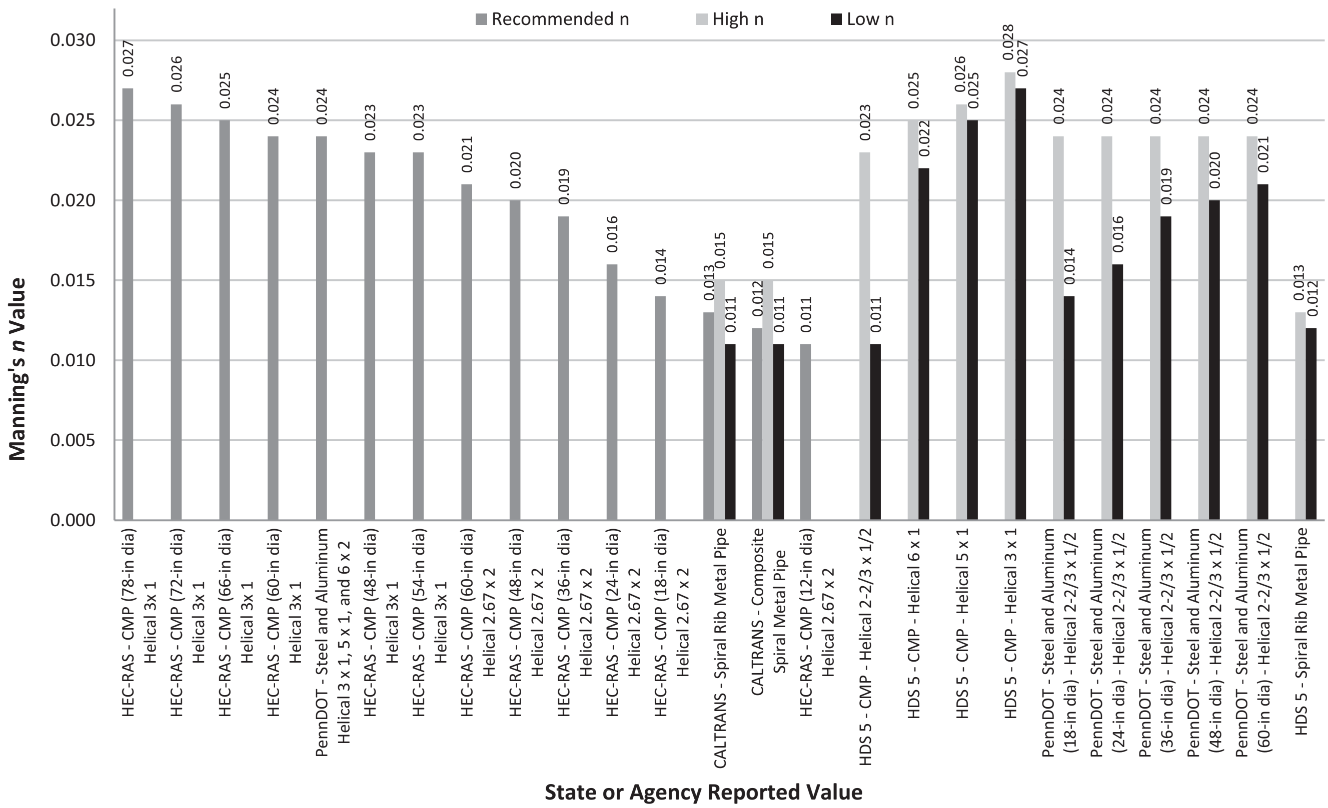


Figure 8. Distribution of Manning's n *values for corrugated steel and metal pipes—helical corrugations.*

- Manning's *n* values can vary significantly with pipe diameter for corrugated and structural plate sections, but are essentially independent of pipe size for smooth walled pipes.
- Many references lack independent consideration of helical corrugation profiles.

Based on the literature review it seems that preliminary hydraulic screening of suitable pipe materials is often completed by assuming one or more generalized Manning's *n* values. Implementation of such an approach is useful for preliminary screening in cases when an automated database or software system is not available.

3.4.2 Structural Design Considerations

Structural design of culverts is necessary to ensure the strength and serviceability of the drainage system. In the structural design of culvert pipe systems, an integral relationship exists between the pipe and the surrounding material in which it is installed. The design of the pipe products, the installation procedures, trench or embankment geometry, and the quality and compaction of bedding and backfill materials are all integral parts of the structural design of buried pipes. Designers shall thus specify in the documents, as appropriate, the bedding detail and installation method for each pipe material or class of pipe selected.

In general, the structural design of buried culverts depends on a number of factors including the following:

- Pipe
  - Material type
  - Material class
  - Diameter
  - Wall thickness
  - Wall profile
- Installation configuration
  - Depth
  - Trench width
  - Slope angle of trench
- Material properties
  - Native soil/rock properties
  - Bedding properties and compaction
  - Backfill properties and compaction
  - Foundation material

3.4.2.1 Structural Pipe System Evaluation

The primary reference available to practitioners today for buried pipe design is the AASHTO LRFD Bridge Design Specifications, Section 12 (AASHTO current version). This reference provides design guidelines for different materials, including those most commonly used for highway drainage pipes (metal, reinforced concrete, and thermoplastic). However, different state DOTs are often using different versions of the AASHTO LRFD code at any given time, with several states having not yet fully integrated LRFD-based design methodologies into practice.

Within the AASHTO LRFD Bridge Design Specifications, buried structures are designed such that they resist factored loads given by specified load combinations. Tables of load combinations and load factors are provided. The factored loads are then compared with the factored resistance to determine the suitability of the design. Tables of resistance factors for buried structures are provided, along with procedures for calculating the nominal resistance.

Performance criteria are usually established by the design engineer based on required performance and capacity of the specified products. When a product capacity is reached or exceeded, it is said that a performance limit has been reached. Performance limits are established for each product to prevent conditions that may interfere with the design function, including the ability to meet the specified service life.

AASHTO requires that both service and strength limit states be checked. For metal and thermoplastic pipes the governing service limit state is deflection. For reinforced concrete pipe the governing service limit state is crack width.

The strength limit states are as follows (AASHTO 2010):

- Metal Pipes
  - Wall area
  - Buckling
  - Seam failure
  - Flexibility limit for construction
  - Flexure of box and deep corrugated structures only
- Concrete Pipes
  - Flexure
  - Shear
  - Thrust
  - Radial tension
- Thermoplastic Pipes
  - Wall area (including local buckling)
  - Buckling
  - Flexibility limit

The specific corrugation profile geometry for corrugated pipes often controls the structural evaluation for flexible pipe systems. It is important to note that corrugation profiles for metal pipe are nationally standardized and defined in AASHTO material and industry trade association (e.g., American Iron and Steel Institute [AISI]) specifications, whereas thermoplastic pipes consist of manufacturer specific (and often patented) corrugation profile geometries. The thermoplastic pipe industry has discussed development of pipe classes based on LRFD design considerations but none are known to exist at this time, thus requiring individual evaluation and consideration of thermoplastic pipes on a manufacturer by manufacturer basis.

Loads on unpressurized gravity pipes include the following:

- Soil pressure
  - Rigid pipes
  - Flexible pipes
- Wheel loading (live loads)
- Soil subsidence
- Seismic loads
- Frost loading
- Loads due to expansive soils
- External water pressure (internal water pressure including effects such as water hammer need to be considered in pressurized applications)
- Flotation

When fill height tables are used for routine design, soil loads and wheel loads are considered. If other non-typical structural loadings are anticipated for a given application, fill height table evaluations usually need to be supplemented with more detailed designs.

In addition to the structural evaluation of the typical pipe wall section, joints, transitions, and other components of the pipe system are also evaluated for structural adequacy. Manufacturing practice for pipe systems typically strives to achieve structural capacities for joints, transition pieces, and other non-standard sections equal to or greater than the main pipe profile for a given pipe class so that structural evaluations only need to be completed on the standard pipe section. Formal methods for the structural design of joints are provided in the final report from NCHRP Project 15-38 found in *NCHRP Web-Only Document 190: Structural Design of Culvert Joints.*

While joints, transitions, and other special pipe sections may have performance issues, these issues are often related to installation deficiencies (rather than to inherent structural failure) and as such do not impact the basic structural assessment and adequacy of given piping systems. In other words, no consideration for the impacts of improper installation is considered in the screening of pipes for structural adequacy to meet a given loading condition in this work. Consideration for proper installation, including development of detailed specifications and post-installation inspection protocols are critical elements to successful pipe installations, and are assumed adopted in the standard practices of each transportation authority that uses an alternative pipe bidding system.

Current practice for confirming the structural adequacy of a particular pipe is to refer to “fill height tables” that indicate the maximum acceptable loading (expressed as a height of fill material) for each pipe product. Minimum fill heights are also specified to protect the pipe from in-service (traffic) loading and construction equipment (although protection from construction loadings are often contract requirements left to the installer and enforced via post-installation inspections and quality control protocols). Fill height tables generally consider different pipe material types, bedding classes, pipe profiles and configurations, and diameters. Some tables also consider other variables such as trench/embankment installations, service life, and foundation conditions. The designer can use these tables to quickly evaluate the structural adequacy of pipe materials (e.g., pipe wall thickness and/or corrugation profile and/or class of pipe) for most applications.

The AASHTO LRFD Bridge Design Code does not specify or provide recommendations for standardized bedding and backfill requirements for all material types (nor does any other nationally standardized guidance). While concrete pipe design is grouped into standard installation classes that are generally recognized and used nationally, flexible pipe installations are generally not standardized, and have resulted in each state agency developing agency-specific protocols and guidance for installation and subsequent structural evaluations, which has created large variations in the structural capacity evaluated for pipe systems in different jurisdictions.

3.4.2.2 Review of Fill Height Tables

The NCHRP Project 10-86 research team completed a review of state agency fill height tables circa 2011 and compiled the graphs in Figures 9 through 21, which demonstrate the wide range of structural design values in current practice.

Information on the structural design of culverts using fill height tables was reviewed from 46 state DOTs as well as from relevant trade associations, such as the American Concrete Pipe Association (ACPA). Additional information on this topic was obtained through the DOT survey questionnaire, which was returned by 37 DOTs.

Based on the review of state DOT fill height tables, it can be seen that significant variation exists across the practice for all pipe types and classes. Additionally, many pipe products do not have specific fill height tables. Because the use of fill height tables is the standard of practice and greatly simplifies structural evaluation, products that do not have fill height tables or have tables that are not accepted by a state agency are often excluded from consideration.

The inconsistency of the preparation, use, and variables for structural design and fill height tables results in an implementation gap that affects the current state of the practice, and prevents national standardization and in-service tracking of structural pipe system performance.

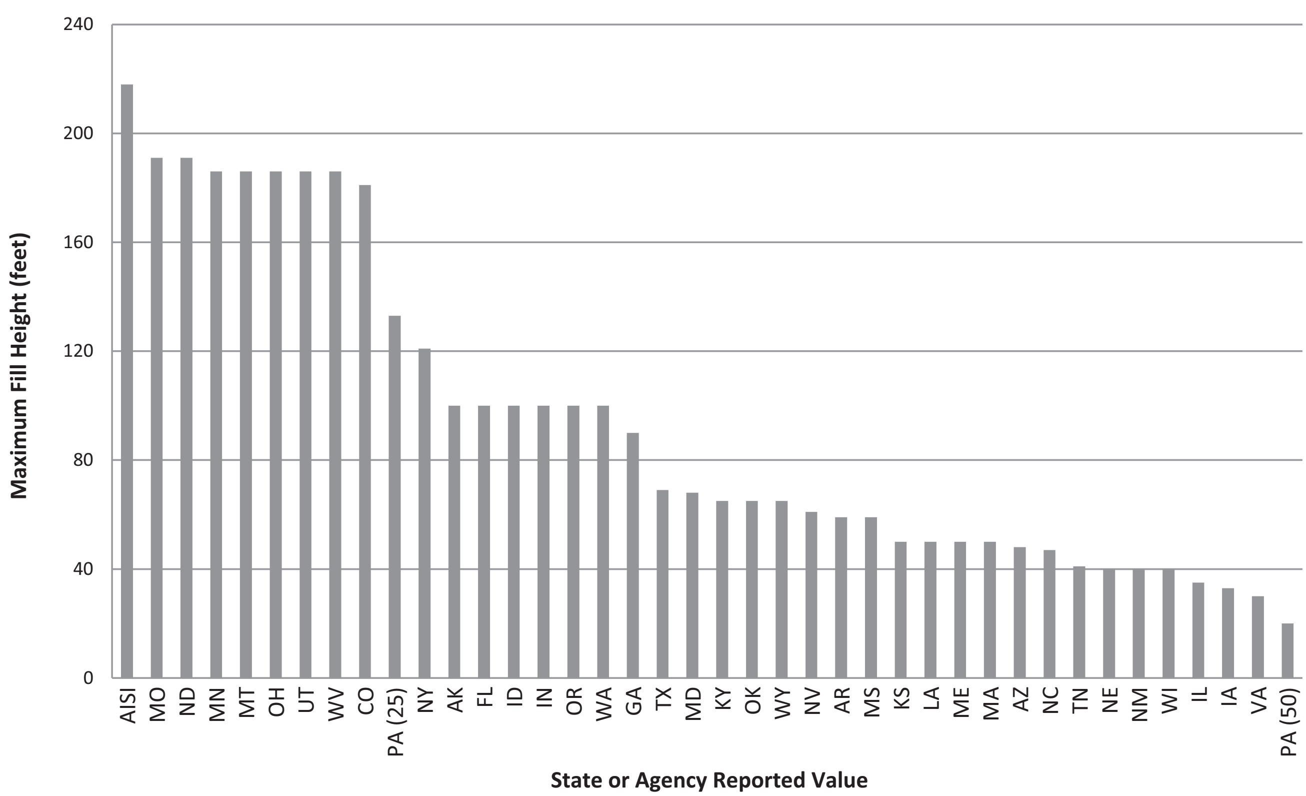


Figure 9. Distribution of maximum fill heights for 24" 12 gage galvanized steel pipe (2-2/3 × 1/2 corrugations). (Note: Values in parentheses indicate design life.)

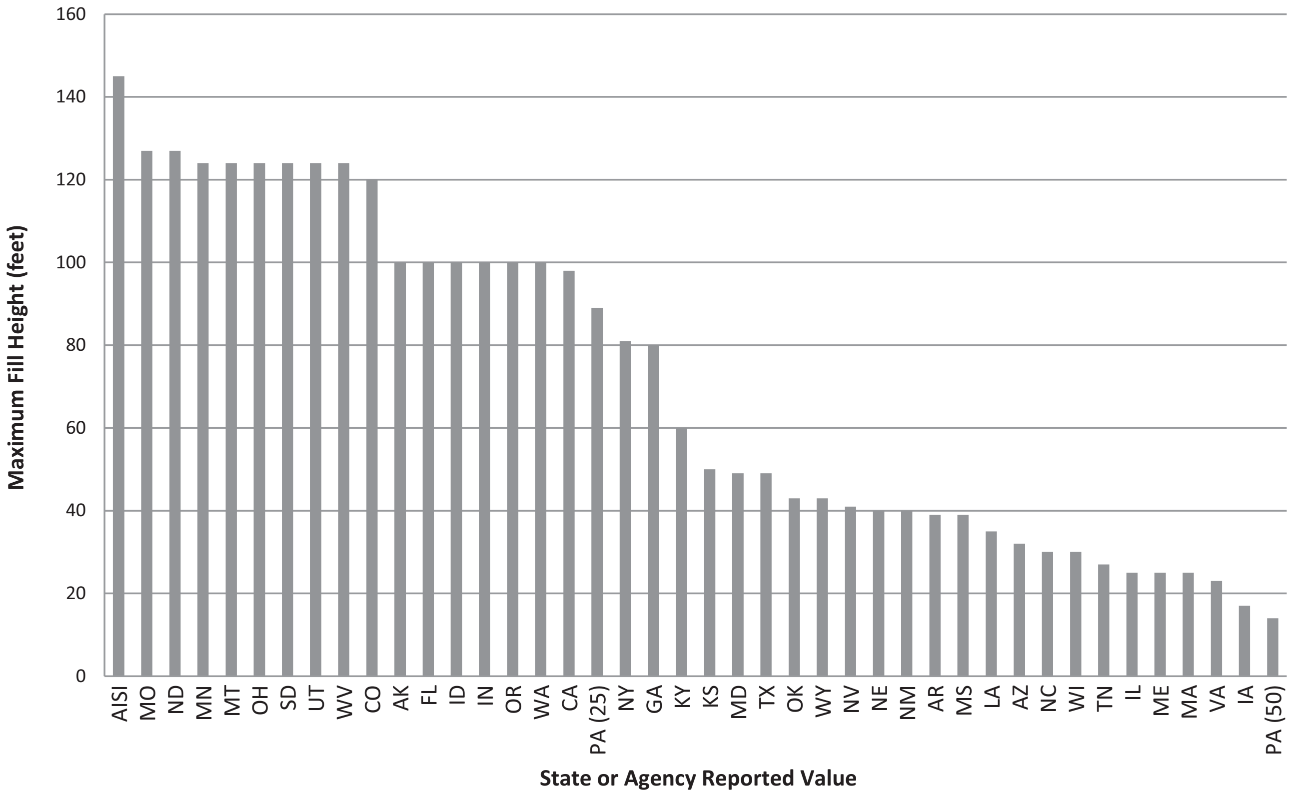


Figure 10. Distribution of maximum fill heights for 36" 12 gage galvanized steel pipe (2-⅔ × ½ corrugations). (Note: Values in parentheses indicate design life.)

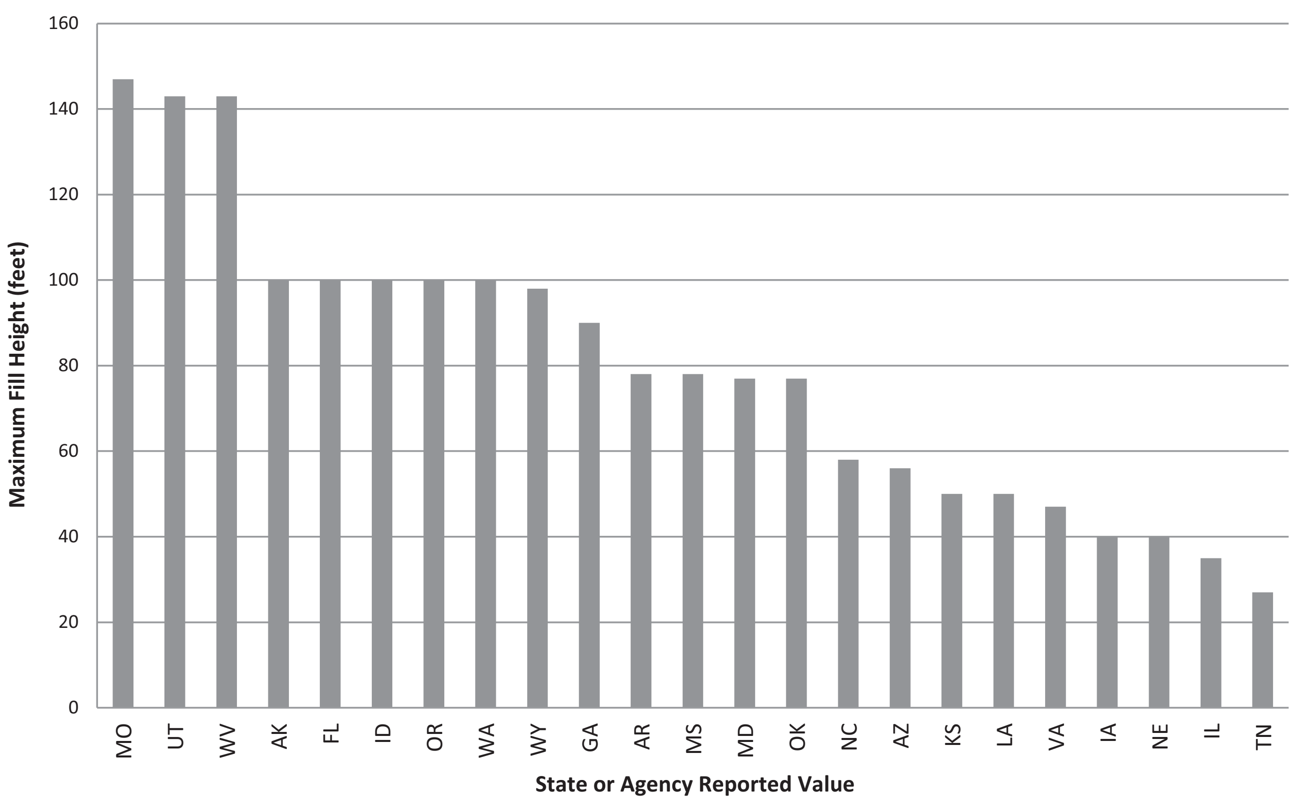


Figure 11. Distribution of maximum fill heights for 36" 12 gage galvanized steel pipe (3 × 1 corrugations).

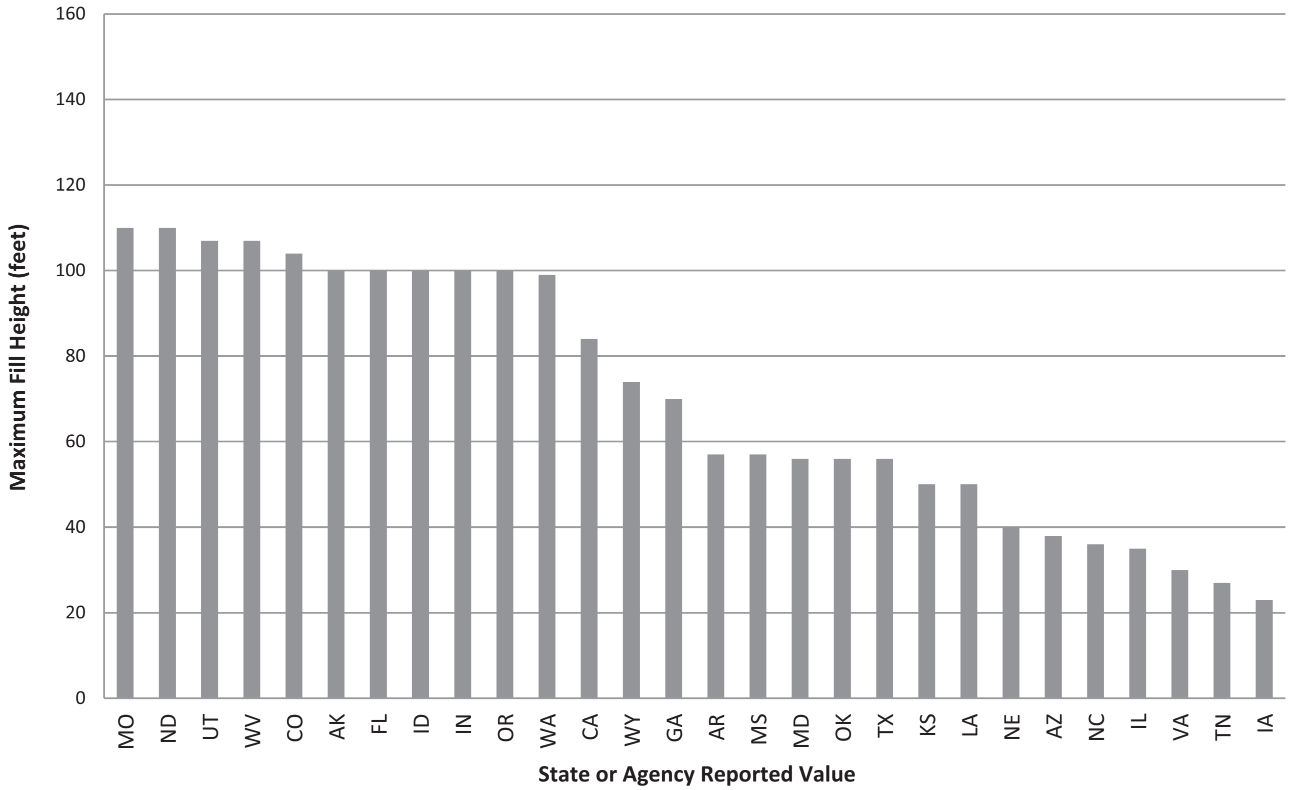


Figure 12. Distribution of maximum fill heights for 48" 12 gage galvanized steel pipe (3 × 1 corrugations).

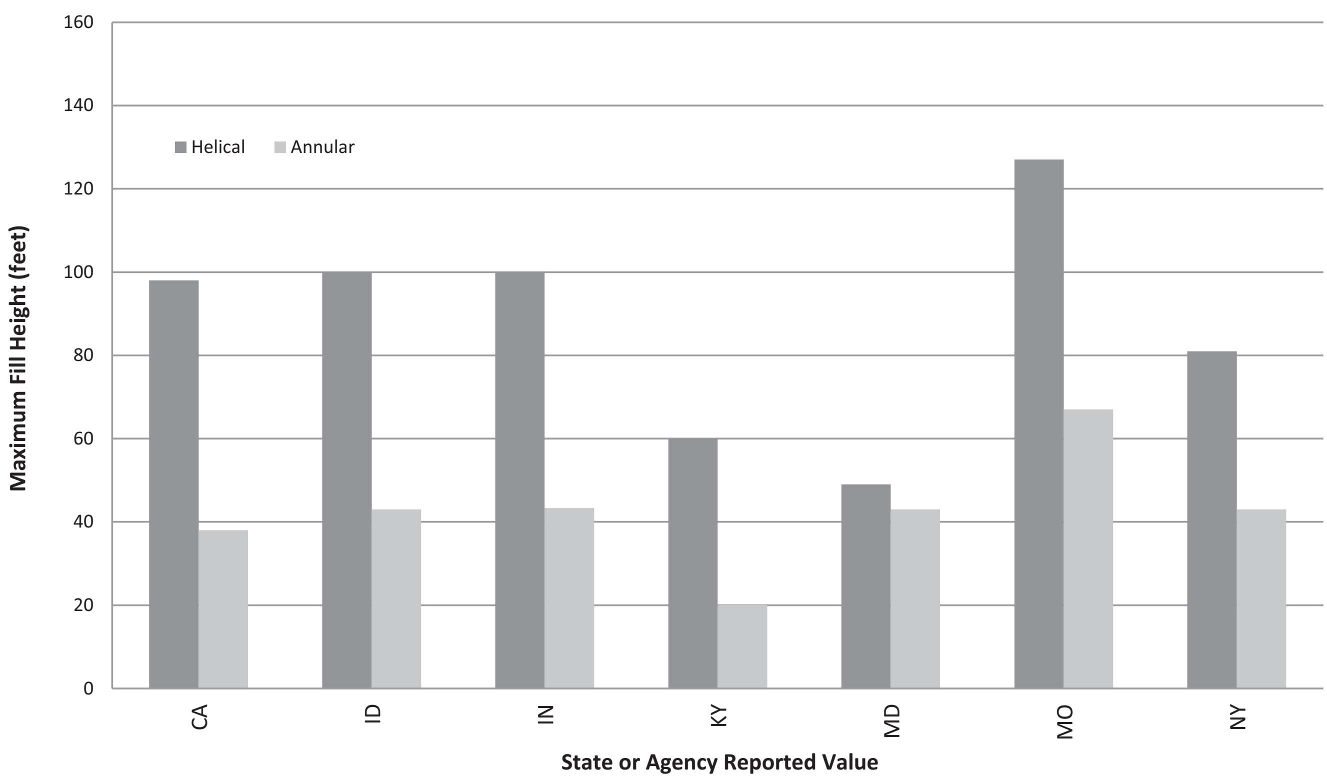


Figure 13. Comparison of maximum fill heights for helical and annular profiles (2-⅔ × ½ corrugations, 36" diameter).

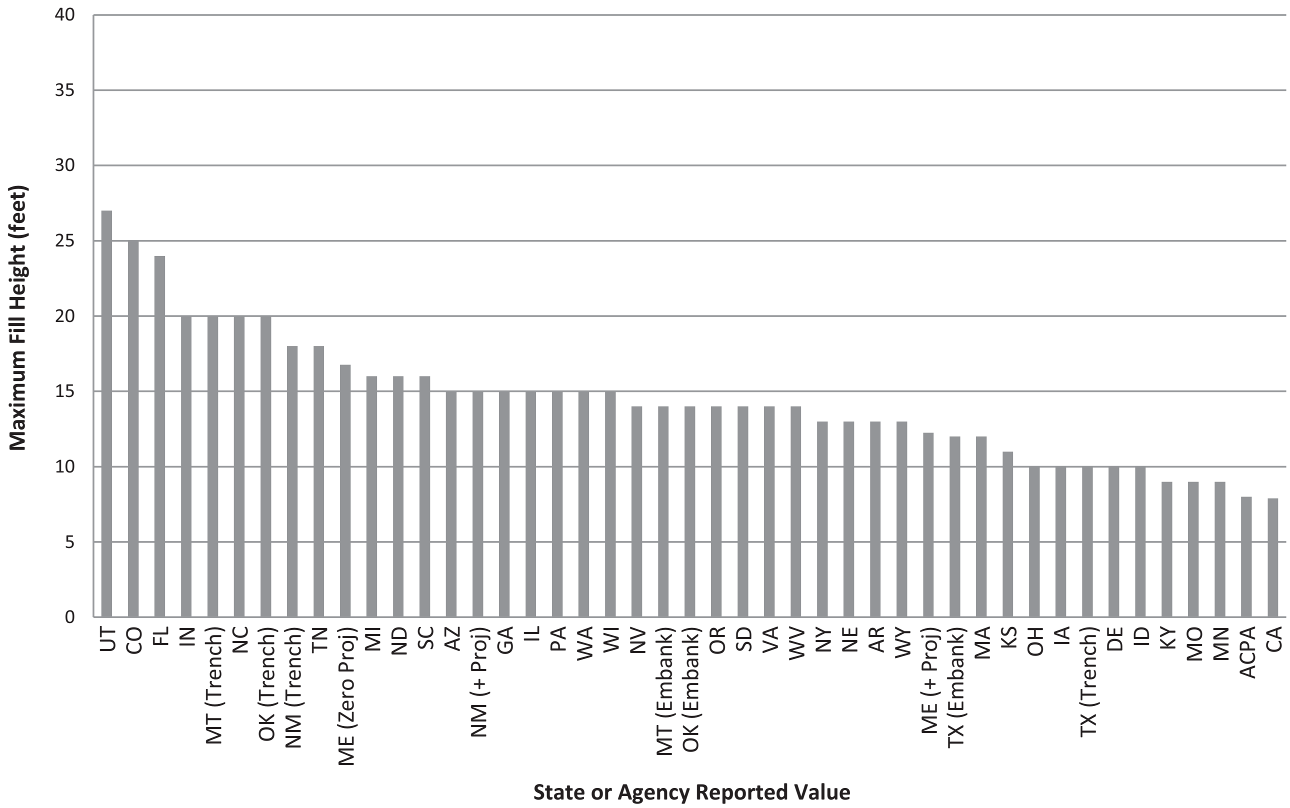


Figure 14. Distribution of maximum fill heights for 24" reinforced concrete pipe (1350 D, lowest quality bedding).

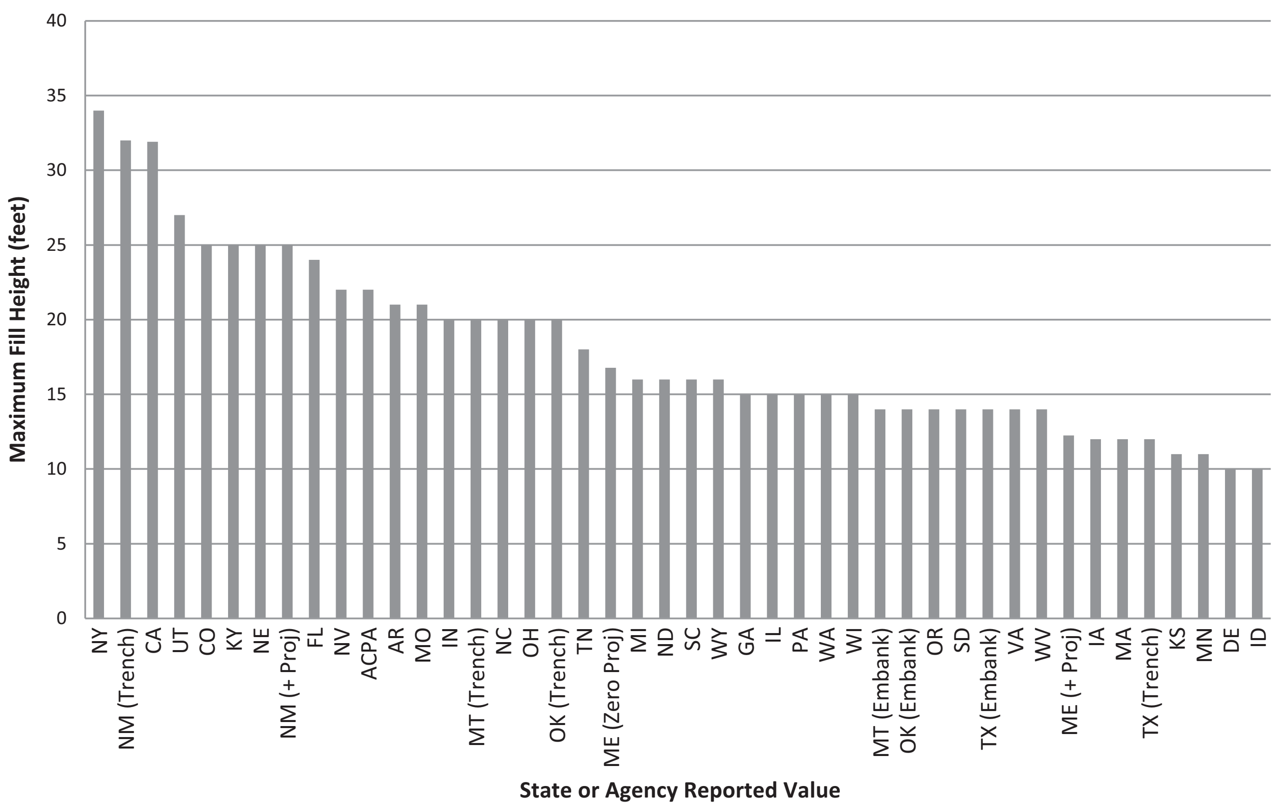


Figure 15. Distribution of maximum fill heights for 24" reinforced concrete pipe (1350 D, highest quality bedding).

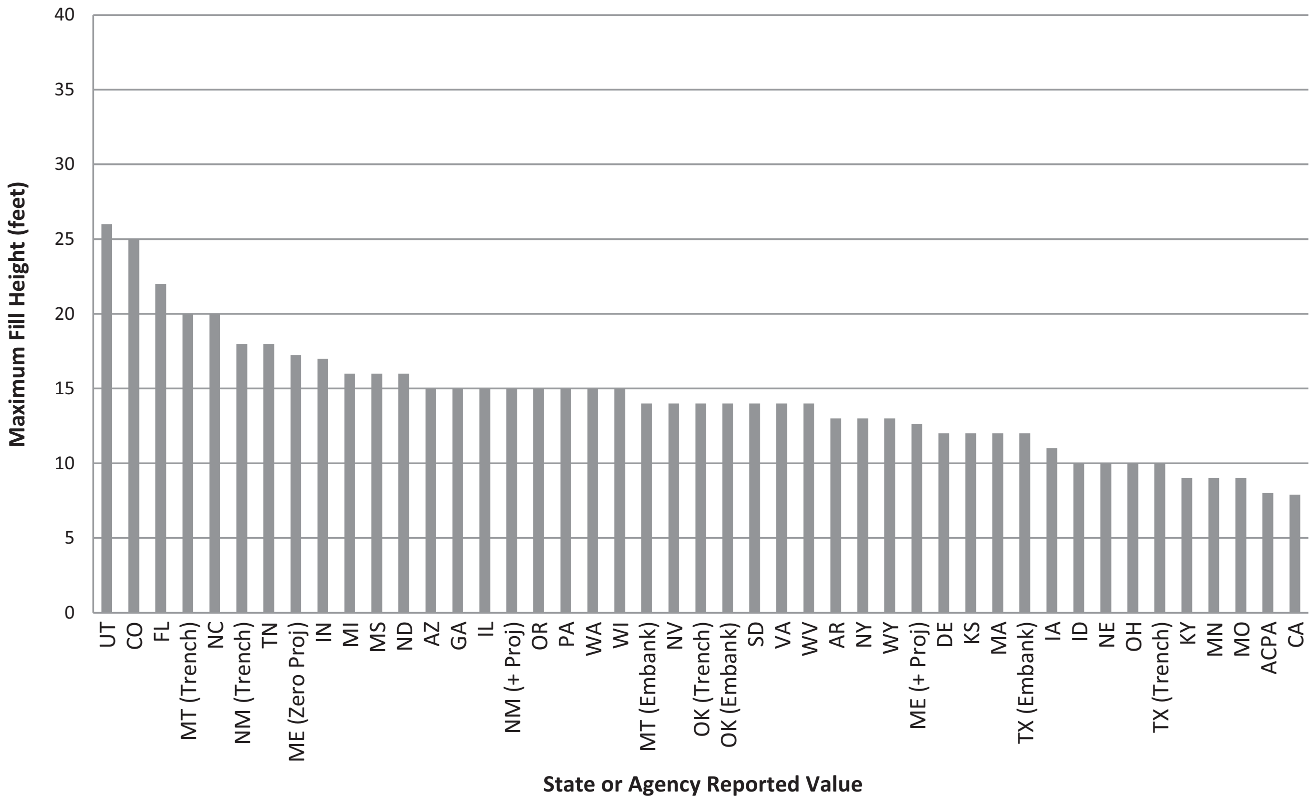


Figure 16. Distribution of maximum fill heights for 36" reinforced concrete pipe (1350 D, lowest quality bedding).

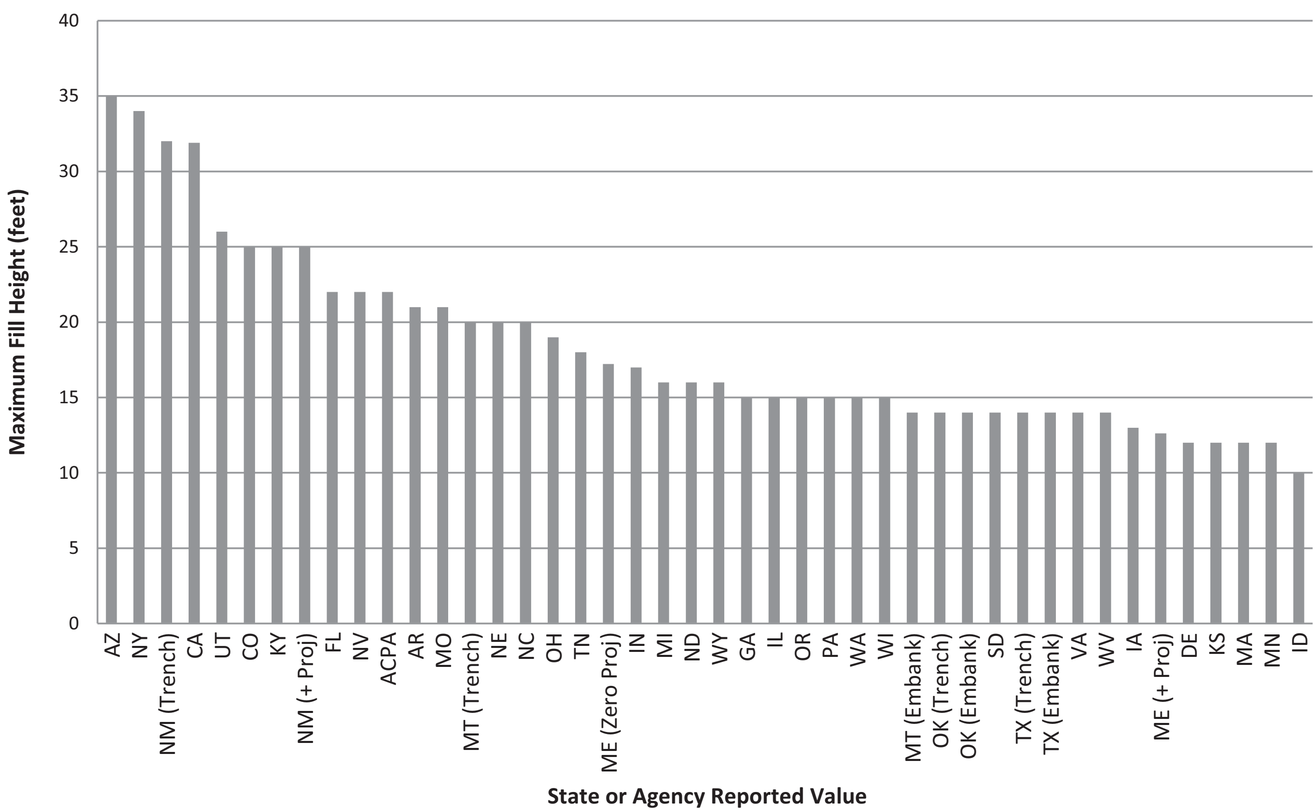


Figure 17. Distribution of maximum fill heights for 36" reinforced concrete pipe (1350 D, highest quality bedding).

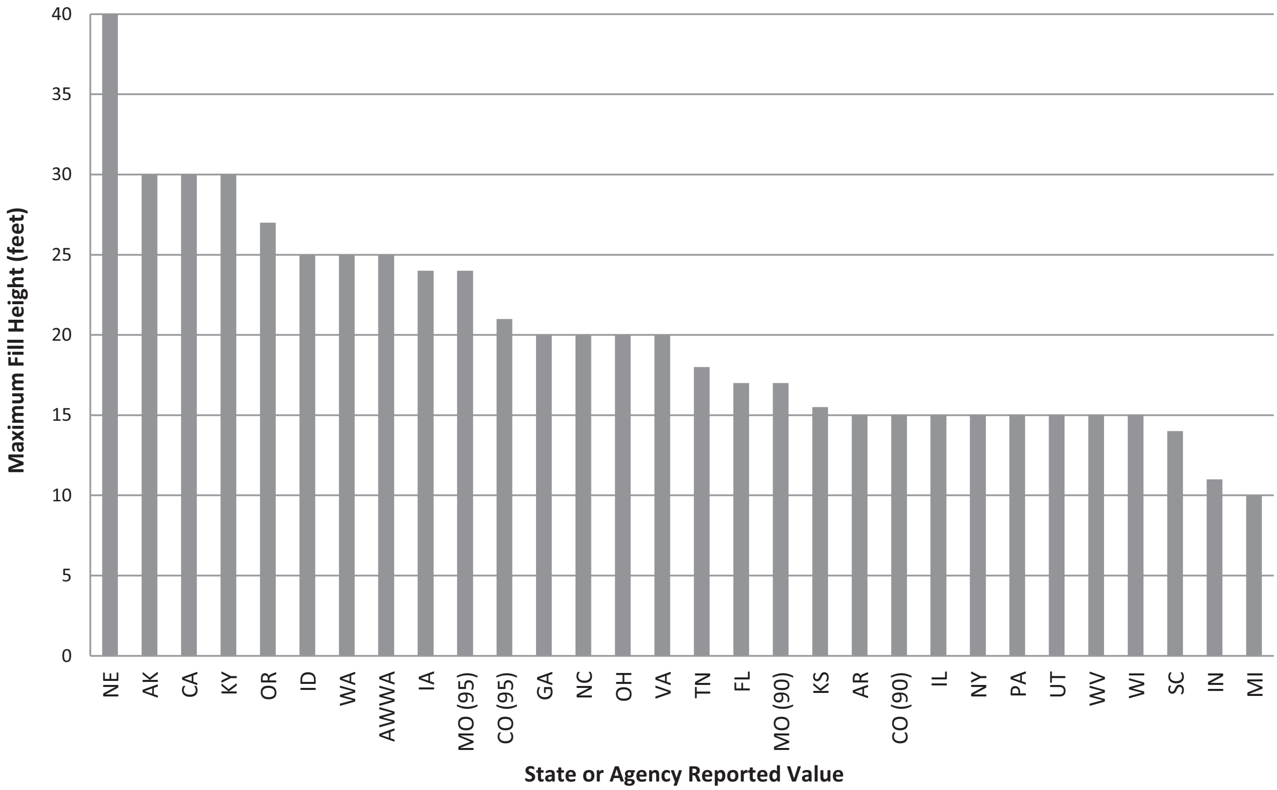


Figure 18. Distribution of maximum fill heights for 24" Type S HDPE pipe. (Note: Values in parentheses indicate % compaction.)

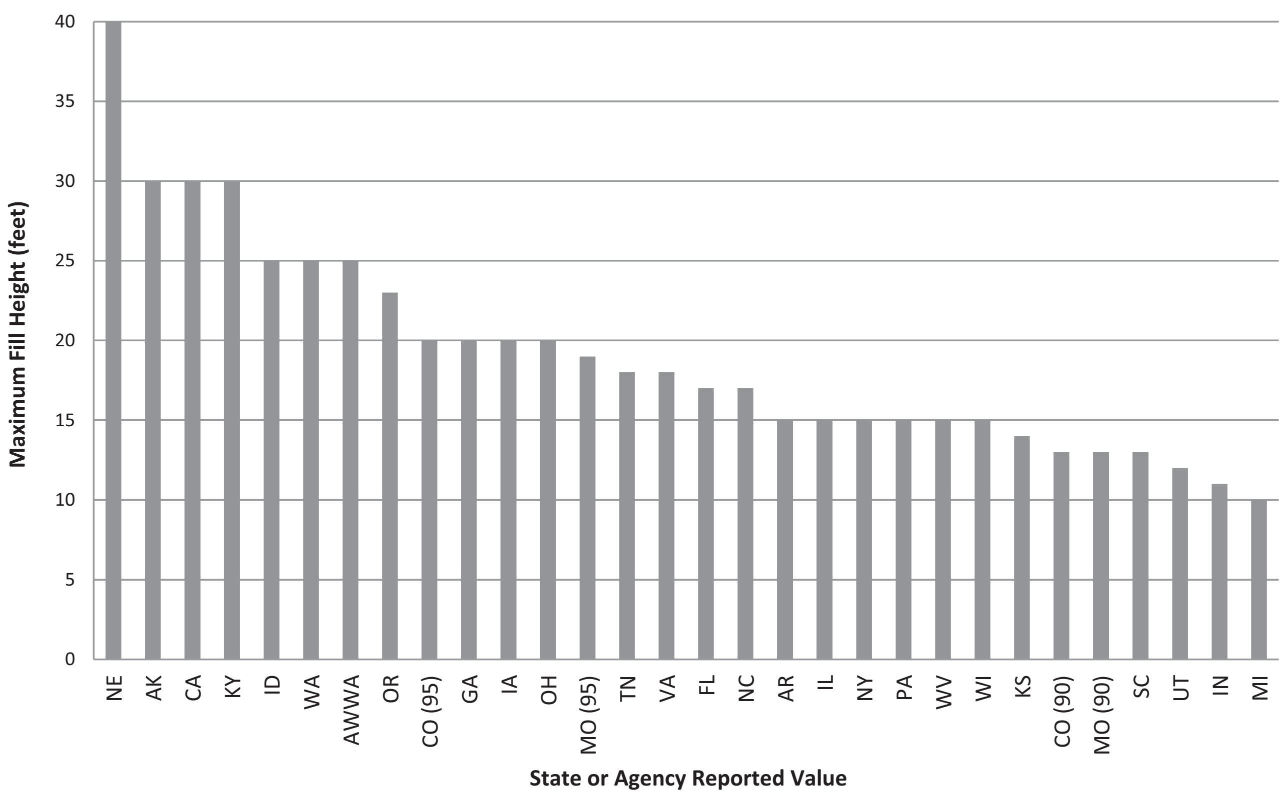


Figure 19. Distribution of maximum fill heights for 36" Type S HDPE pipe. (Note: Values in parentheses indicate % compaction.)

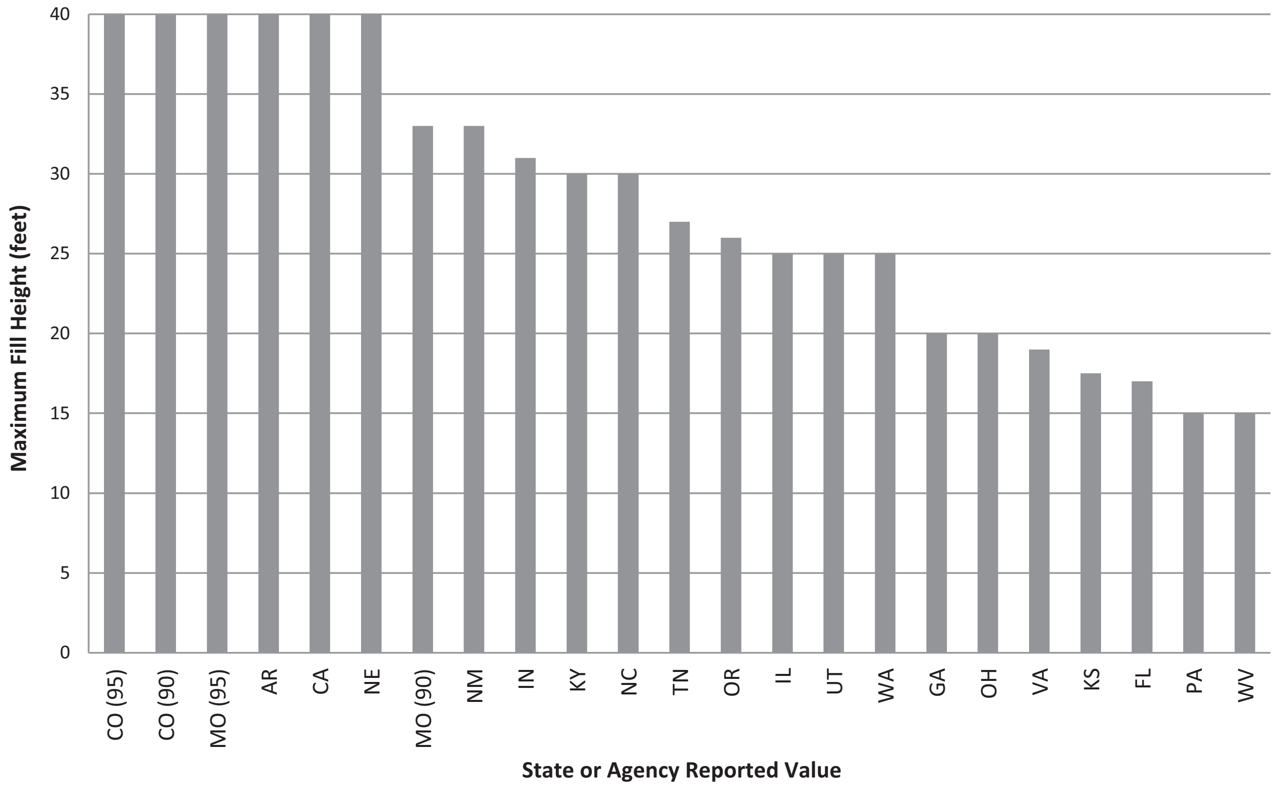


Figure 20. Distribution of maximum fill heights for 24" profiles wall PVC pipe. (Note: Values in parentheses indicate % compaction.)

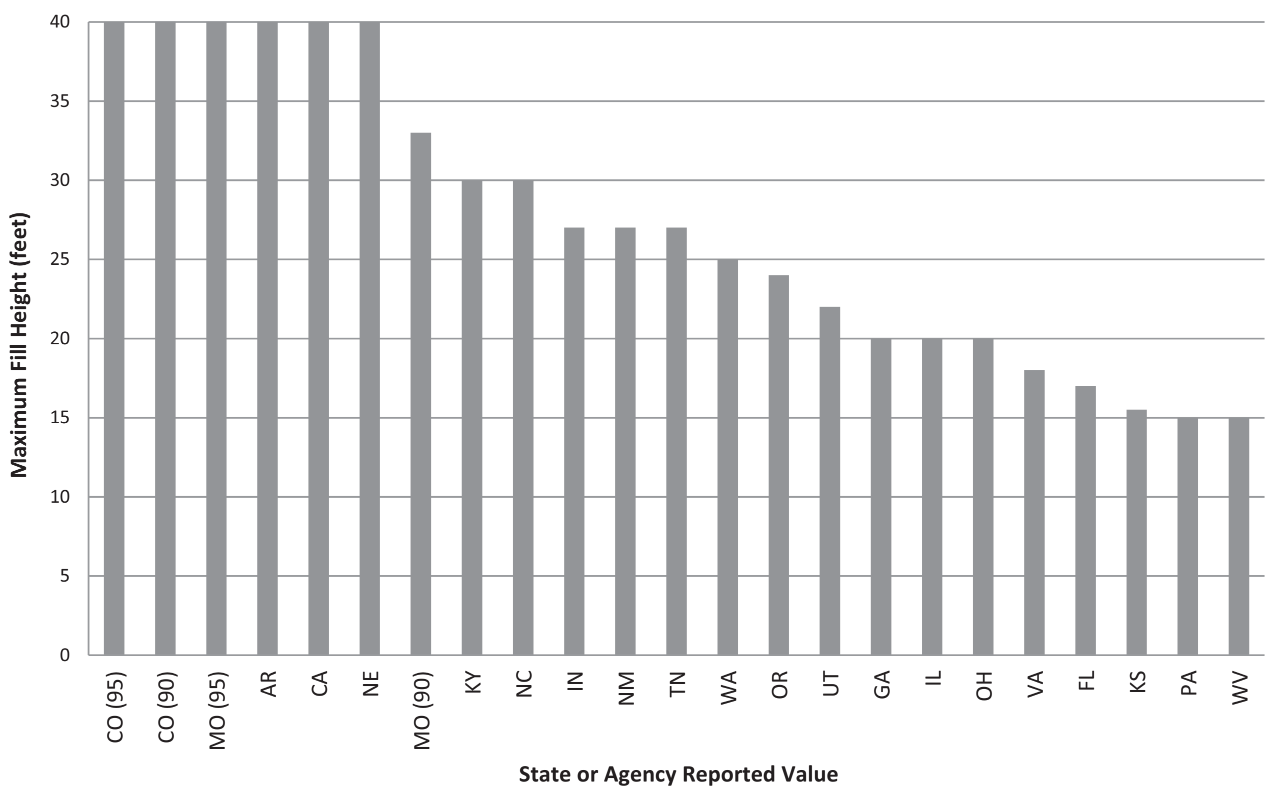


Figure 21. Distribution of maximum fill heights for 36" profiles wall PVC pipe. (Note: Values in parentheses indicate % compaction.)

Differences in allowable fill heights are thought to be the result of the following main factors:

- In agency structural evaluations, there are differences in how material factors such as pipe stiffness, corrugation geometries, and backfill/bedding details are considered. The following are some examples of the differences:
  - Variations in applied loading from trench versus embankment installations
  - Variations in installation and bedding/backfill specifications among agencies and among pipe materials
  - Changes in structural capacity with time due to pipe material degradation (e.g., metal corrosion, etc.)
  - Ignoring structural capacity of corrugation geometries
- The designs of rigid and flexible pipe systems have inherent differences in design methodology and in the factors of safety or risk tolerance typically applied in practice.
- There are variations in the basis for design (i.e., many state DOTs had not fully adopted the AASHTO LRFD Design requirements).
- The fill height tables presented in the standard guidelines and design manuals of many state DOTs do not specify the design bases or assumptions used in the development of the presented fill height tables.
- There are variations in the factors of safety and/or LRFD factors used to account for variations in construction quality oversight and specification across state DOT practice.

While the current study is not focused on providing a fully robust solution to the current biases that exist in practice, there is noted benefit to greater standardization and removal of bias. Given the range of different methodologies used in the development of fill height tables, some variation in the fill height tables was expected but the magnitude and range of variations was surprising. The lack of use of a clearly expressed and consistent methodology (despite one being available) is a cause for concern. Consistent implementation of the LRFD methodology in the form of fill height tables for typical installation conditions and configurations for all available pipe types would benefit designers, constructors, and manufacturers of highway drainage pipe products.

These factors combine to present a state of current practice that contains significant variation and bias in the evaluation of structural capacity of highway drainage elements that prevents national standardization and direct comparison of performance.

The following summary points have been developed from this review of fill height tables:

- While standardized design methodology is available from AASHTO and is mandated on federally funded projects, state practice generally does not follow the AASHTO guidance for structural adequacy evaluations because standardized fill height tables developed from these guidelines were not readily available at the time of the survey in 2011, and state agencies are continuing to use historic fill height tables.
  - Several states are currently working to address this issue as noted in their responses to the survey.
  - Some (but not all) manufacturers have issued fill height tables in compliance with the AASHTO LRFD design specifications that are available for use.
- Available fill height tables were developed with a range of design assumptions and specifications that often are not documented including variables such as the following:
  - **Design Methodology** (e.g., both direct and indirect methods for rigid pipes could be used, differing versions of AASHTO or state specifications are often implemented across pipe materials, and the design criteria is often not fully reported).
  - **Loading** (e.g., traffic loads, unit weight of fill)
  - **Bedding Materials** (e.g., material classifications [typically state specific and not AASHTO based])
  - **Bedding Conditions** (e.g., compaction requirements are often unknown or inconsistent)
  - **Installation Configuration** (e.g., trench, embankment, and so forth.)
- Not all available pipe products are independently considered, for example,
  - Corrugated metal pipe (CMP) with helical and annular corrugations and/or with varying corrugation profile geometries are often not considered separately.
  - The corrugation profile geometry of thermoplastic pipes is manufacturer specific and no national standards exist to group or classify the range of products in the marketplace with respect to LRFD limit states.
- No explicit consideration of joint materials and stress concentrations is made in typical practice. This would be acceptable if joints where always equal to or stronger than the equivalent barrel sections, but joints often present points of weakness in pipe installations, especially those with below standard installations.
- Variations in the degree of compaction are not always considered in fill height tables.
- Degradation of structural capacity due to corrosion and abrasion is generally not incorporated into fill height tables (PennDOT is noted to include this), despite AASHTO LRFD 12.6.9 requirements.
  - The AASHTO code does not provide specific guidance regarding the proper method(s) to account for degradation of structural capacity, and this likely is a driving factor in the limited application of structural degradation considerations in practice.
  - Durability is widely considered not to be fully developed for all pipe products and installation environments. It is an area requiring continued research and practical implementation.

3.4.3 Long Term Performance and Durability

A literature review of long term performance and durability of pipe systems was undertaken to evaluate the approaches used for estimating material service life of drainage systems for incorporation into the Recommended Practice. The intent of this project is not to provide an exhaustive review of durability, but to identify the key factors and methods needed for the implementation of a reliable Recommended Practice. *NCHRP Synthesis 474: Service Life of Culverts* will be published in spring 2015 and will provide a more comprehensive review of this topic.

This review examined the performance and durability of various pipe types including reinforced concrete, thermoplastic, and corrugated metal pipes. The following subsections briefly describe the major factors affecting durability for each pipe type, the current state of practice for addressing these factors, and existing methods for assessing the durability of a pipe. Software and online models for estimating material service life were also reviewed. There are a number of well established procedures for predicting the service lives of concrete and metal pipes related to material parameters and environmental and loading conditions, but prediction methods for thermoplastic pipe are less well developed.

The two primary mechanisms of degradation for properly specified and installed culvert pipe systems are corrosion and abrasion. The AASHTO LRFD Bridge Design Manual (Section 12.6.9) requires that the degradation of structural capacity due to corrosion and abrasion be considered in design, but does not provide specific methods for doing so. The specification further allows that if the design of a metal or thermoplastic culvert is controlled by flexibility factors (i.e., construction loads versus service loads) during installation, then the requirements for corrosion and abrasion protection may be reduced or eliminated, provided that it is demonstrated that the degraded culvert will provide adequate resistance to loads throughout the service life of the structure.

A summary of the most commonly accepted independent (i.e., not developed or published by a pipe trade organization) quantitative service life calculation methods for concrete and metal pipes is included in Appendix C. No known methods are in use to calculate the estimated material service life (EMSL) of thermoplastic pipes related to application conditions and loading. Extensive research has been undertaken, much of it sponsored by FDOT to better understand deterioration mechanisms of thermoplastic pipes and to develop appropriate material specifications to ensure long term performance. The EMSL of thermoplastic pipes is based on the material performance specifications and details of the resins used in the pipe manufacturing process. The materials are thus generally assigned a fixed EMSL regardless of the environmental parameters at the site. Thermoplastic culvert pipes for highway drainage applications are usually assigned EMSL values between 50 and 100 years.

Summary background information on several key culvert durability topics is presented below. The reader is referred to *NCHRP Synthesis 474: Service Life of Culverts* (to be published in spring 2015) for a more detailed summary of culvert durability issues.

3.4.3.1 Corrosion

Corrosion is the destruction of pipe material by chemical action. Most commonly, corrosion attacks metal culverts or the reinforcement in concrete pipe. Similar damage can occur to the cement in concrete pipe if it is subjected to highly alkaline soils or sulfates or to other pipe materials if they are subjected to extremely harsh or aggressive environments. For corrosion to occur, an electrolytic corrosion cell must be formed. This requires the presence of water, or some other liquid to act as an electrolyte, and materials acting as an anode, cathode, and conductor. As electrons move from the anode to the cathode, metal ions are released into solution, with characteristic pitting at the anode. The culvert will typically serve as both the anode and the cathode. Corrosion can affect either the inside or outside of a pipe or both. The potential for corrosion to occur, and the rate at which it will progress, is variable and dependent on a variety of factors. Depending on the particular corrosive environment encountered, increased pipe wall thickness, additional cover over reinforcing steel, or special coatings may be required to extend service life.

3.4.3.2 Abrasion

Abrasion is the gradual wearing away of the culvert wall due to the impingement of bedload. Abrasion will almost always manifest itself first in the invert of the culvert. As with corrosion, abrasive potential is a function of several items, including culvert material, frequency and velocity of flow in the culvert, and composition of the bedload.

Bedload is the leading cause of culvert abrasion. Critical factors in evaluating the abrasive potential of bedload material are the size, shape, and hardness of the bedload material and the velocity and frequency of flow in the culvert.

Generally, flow velocities less than 5 ft/s are not considered to be abrasive, even if bedload material is present. Velocities in excess of 15 ft/s, which carry a bedload, are considered to be very abrasive and some modifications to protect the culvert should be considered.

It is very difficult to look at a given culvert material and provide an absolute determination of how it will be affected by bedload abrasion. Perhaps the most useful method for making a reasonable determination is to look at the various types of culvert materials and make relative comparisons.

3.4.3.3 pH

The pH value is defined as the log of the reciprocal of the concentration of hydrogen ion in a solution. Values of pH in natural waters generally fall within the range of 4 to 10. A pH of less than 5.5 is usually considered to be strongly acidic, while values of 8.5 or greater are strongly alkaline. Studies performed in various states have been inconclusive in determining the exact role pH plays in corrosion. The presence of oxygen at the metal surface is necessary for the corrosion to occur and is independent of the pH. However, at the very least a pH reading that is either highly acidic or alkaline is indicative of a heightened potential for corrosion. The lowest pH levels (most acidic) are typically seen in areas that have received high rainfall over many centuries. The runoff and percolation will leach the soluble salts, with the resultant soil becoming acidic. Other likely sources of acidic runoff are mine wastes that often contain sulfuric and sulfurous acids. Milder acids can be found in runoff from marshy areas, which contain humeric acid, and mountain runoff that often contains carbonic acid.

Conversely, arid areas are much more likely to be alkaline due to soluble salts contained in groundwater being drawn to the surface through capillary action and then concentrating after evaporation occurs. Generally, soil or water pH levels between 5.5 and 8.5 are not considered to be severely detrimental to culvert life.

3.4.3.4 Resistivity

Resistivity of soil is a measure of the soil's ability to conduct electrical current. It is affected primarily by the nature and concentration of dissolved salts, and the temperature, moisture content, compactness, and presence of inert materials such as stones and gravel. The greater the resistivity of the soil, the less capable the soil is of conducting electricity and the lower the corrosive potential. The unit of measurement for resistivity is ohm-centimeters or, more precisely, the electrical resistance between opposite faces of a 1-centimeter cube. Resistivity values in excess of about 5,000 ohm-cm are considered to present limited corrosion potential. Resistivity values below the range of 1,000 to 3,000 ohm-cm will usually require some level of pipe protection, depending upon the corresponding pH level (e.g., if $pH < 5.0$, enhanced pipe protection may be needed for resistivity values below 3,000 ohm-cm; if $pH > 6.5$, enhanced pipe protection may not be needed unless resistivity values are below 1,500). As a comparative measure, resistivity of seawater is in the range of 25 ohm-cm, clay soils range from approximately 750 to 2,000 ohm-cm and loams from 3,000 to 10,000 ohm-cm. Soils that are of a more granular nature exhibit even higher resistivity values.

3.4.3.5 Chlorides

Dissolved salts containing chloride ions can be present in the soil or water surrounding a culvert. Chlorides will also be of concern at coastal locations or near brackish water sources. Dissolved salts can enhance culvert durability if their presence decreases oxygen solubility but, in most instances, corrosive potential is increased, as the negative chloride ion decreases the resistivity of the soil and/or water and destroys the protective film on anodic areas. Chlorides, as with most of the more common corrosive elements, primarily attack unprotected metal culverts and the reinforcing steel in concrete culverts if concrete cover is inadequate, cracked, or highly permeable.

3.4.3.6 Sulfates

Sulfates can be naturally occurring or may be a result of human's activities, most notably mine wastes. Sulfates, in the form of hydrogen sulfide, can also be created from biological activity, which is more common in wastewater or sanitary sewers, and can combine with oxygen and water to form sulfuric acid. Although high concentrations can lower pH, and be of concern to metal culverts, sulfates are generally more damaging to concrete. Typically, the sulfate in one or more various forms combines with the lime in cement to form calcium sulfate, which is structurally weak. Concrete pipe is normally sufficient to withstand sulfate concentrations of 1,000 parts per million (ppm) or less. For higher concentrations of sulfates, higher strength concrete, concrete with lower amounts of calcium aluminate (under 5%), or special coatings may be necessary.

3.4.3.7 Available Software Durability Evaluation Tools

The literature review identified three software programs that have been developed by transportation agencies to automate the calculation of estimated service life for pipe systems:

- HiDISC 1.0 developed for the MTO (not yet publicly released)
- CSLE (Culvert Service Life Estimator) 2013 developed by FDOT
- AltPipe v 6.08 developed by Caltrans

HiDISC and CSLE are stand-alone software programs while AltPipe is an online tool. Appendix C includes screenshots showing the use of these programs for a non-aggressive case.

3.4.4 Inspection and Post-Installation Certification

Experience has shown that one of the critical issues impacting the performance (short and long term) of pipe systems is the quality of the installation. Drainage systems that are appropriately designed and properly installed will generally perform well throughout the design life of the pipe system.

Post-installation inspection of a buried pipe system is one phase of a comprehensive quality assurance program. Mill certificates for all pipe materials should be checked in advance and conformance to relevant project specifications and reference standards (e.g., ASTM/AASHTO) confirmed. Source acceptance test results for all imported materials should be checked against project specifications. Inspections should be performed on the pipe, bedding, and backfill materials prior to and during installation. The agency's specifications for compaction and general requirements for workmanship during construction should be enforced. Some agencies have a program of periodic routine systemwide inspections for in-service pipe systems. While this is not considered essential, it can identify potential future serviceability problems that can be addressed by routine maintenance rather than by emergency repairs. The inspection of system materials prior to installation and inspection during construction are summarized in the following subsections followed by a more detailed discussion of post-installation inspection procedures.

Guidelines for routine systemwide inspection programs of in-service pipe systems can be found in the FHWA Report No. FHWA-IP-86-2, Culvert Inspection Manual (FHWA 1986). As new pipe products (materials, coatings, and rehabilitative liners) and remote access inspection technologies have been introduced since the Culvert Inspection Manual was developed, there is a need for updated culvert inspection guidelines. An update and review of inspection procedures and technologies is proposed to be addressed through NCHRP Project 14-26, Culvert and Storm Drain System Inspection Manual, which is scheduled for completion in fall 2015.

The AASHTO LRFD Bridge Construction Specifications provide excellent baseline recommendations for inspection requirements for the three main categories of pipe materials (Metal Pipes in Section 26, Reinforced Concrete Pipes in Section 27, and Thermoplastic Pipes in Section 30) that can also be applied to other flexible and rigid pipe material systems.

3.4.4.1 Inspection of Pipe Materials

In general, state agencies have well-developed and documented policies for evaluating and ensuring the quality of pipe materials delivered to project sites. These procedures often include the following:

- Qualification of manufacturer and manufacturing facility and review of mill certificates
- Inspection of deliveries, which may include inspection of the following:
  – Identification markings
  – Date of manufacture
  – Shipping papers
  – Diameter
  – Net length of fabricated pipe
  – Evidence of poor workmanship
  – Identification of damage during shipping and handling
  – Measurement of surface cracks (for example with leaf gages)
- Taking samples of pipe for additional testing (chemical, mechanical, coatings)

3.4.4.2 Inspection During Construction

Inspection of the pipe system materials and workmanship during construction allows corrections to be made in assembly and backfill practices before construction is complete, and is of particular importance for deeply buried, high traffic, or other critical and/or costly to repair installations. The timing and frequency of such inspections should depend on the significance of the structure and depth of fill. In general, inspections should be conducted when materials arrive at the job site, during pipe installation, during backfilling, and prior to construction of final finishes (e.g., paving).

Inspections during construction may include examination of the following:

- Foundation material
- Trench geometry and dimensions
- Groundwater conditions
- Bedding material
- Line and grade
- Assembly techniques
- Structure backfill and compaction methods
- Joint assembly and materials
- Pipe deflection (during construction)
- Damage to pipe coatings

3.4.4.3 Post-Installation Inspection

Post-installation inspection allows for timely identification of potential installation problems and allows for corrective action to be taken, if needed, within the scope of the construction contract. The AASHTO LRFD Bridge Construction Specifications recommend that final post-construction inspections for culvert approval be completed no sooner than 30 days after completion of installation and final fill so that defects under initial conditions can have time to present themselves. The AASHTO construction specifications commentary expands on this recommendation by stating that soil consolidation continues with time after installation of the pipe. While 30 days will not encompass the timeframe for complete consolidation of the soil surrounding the pipe, it is intended to give sufficient time to observe some of the effects that this consolidation will have.

Post-installation inspection can be carried out in a number of ways, with the most common methods being the following:

- Visual inspection performed manually (usually for larger diameter pipes, typically greater than 36 in.)
- Visual inspection performed remotely by video inspection (e.g., closed-circuit television [CCTV])
- Mandrel testing
- Laser profiling, upcoming ASTM F36 method
- Non Destructive Inspection/Testing (NDI/NDT) techniques

Current post-installation inspection requirements of pipe systems across state agencies vary more significantly than current practices for the other stages of inspections. This difference is due in part to the continued introduction of new pipe materials, design methods, and remote access inspection techniques within the industry. Improving the consistency of post-installation inspection practices will mitigate risks associated with broadening the use of alternative pipe types.

3.4.4.4 AASHTO LRFD Bridge Construction Specifications

Standard post-installation inspection recommendations are found in the following subsections of the AASHTO LRFD Bridge Construction Specifications:

- Metal Pipes (Section 26)
- Reinforced Concrete Pipes (Section 27)
- Thermoplastic Pipes (Section 30)

3.4.4.4.1 AASHTO Visual Inspection Recommendations for Flexible Pipe Systems. The recommended inspections for flexible pipe system installations include checks for the following:

- Alignment
- Joint separation
- Cracking at bolt holes
- Localized distortions
- Bulging, flattening, and racking
- Minimum cover levels (for shallow installations)
- Deflection Testing

3.4.4.4.2 AASHTO Visual Inspection Recommendations for Reinforced Concrete (and Other Rigid) Pipe Systems. Reinforced concrete pipes do not deflect appreciably before cracking or fracturing, so deflection testing is of limited value. Visual inspection of pipe interiors and joints is the primary means of inspection for rigid pipes. During a visual inspection, observations of the following should be made:

- Misalignment
- Joint defects
- Longitudinal cracks
- Transverse cracks
- Spalls
- Slabbing
- End-section drop off

3.4.4.4.3 Other Inspection Techniques. A wide range of other less commonly used culvert inspection techniques are available, several of which are listed as follows:

- Destructive Core Sampling and Evaluation
- Ground Penetrating Radar (GPR) (Applied from ground surface and from within pipes)
- Impact Echo (IE) Testing
- Infrared (IR) Thermography
- Mechanical Impedance Testing
- Microdeflection Testing
- Natural Frequency Measurement
- Pigs (basic mandrels through Instrumented “Smart” Pigs)
- Spectral Analysis of Surface Waves (SASW)
- Ultrasonic Testing
- Ultra Wide Band (UWB) Radar

3.4.4.5 Commentary on the State of Practice for Inspections

The state of knowledge with respect to short and long term inspection for highway culverts has been benefited tremendously in recent decades by significant improvements in a range of inspection technologies. Most notably improvements in CCTV, remote control robotics, laser profiling, optical scanning, and other remote techniques make in line inspections of culverts easier, less expensive, and more reliable than ever before. Many agencies routinely use a range of remote and man-entry inspection techniques during installation, post-installation, and for long term monitoring and inventory management. It is noted that some forms of inspection require or are benefited from training and certification programs such as National Association of Sewer Service Companies (NASSCO), and agency-specific training such as that provided by FDOT, Ohio DOT, and others.

The survey response graphs included in Chapter 3 and the following observations were made based on the results of the NCHRP Project 10-86 DOT survey:

- For rigid pipe systems: visual inspection is the most common, followed by video inspection and laser profiling.
- For flexible pipe systems: mandrel testing is the most common, followed by visual inspection, video inspection, and laser profiling.
- Leak testing is performed equally (although infrequently) on flexible and rigid pipe systems.
- Video inspection and laser profiling are performed equally on rigid and flexible pipe systems.
- Video inspection is approximately 60% more common than laser profiling.
- Rigid pipe systems are less likely to be inspected than flexible pipe systems.

Two ongoing NCHRP Projects: 14-19 on Culvert Rehabilitation to Maximize Service Life While Minimizing Direct Costs and Traffic Disruption and 14-26 Culvert and Storm Drain System Inspection Manual will provide updated summaries of culvert inspection techniques.

CHAPTER 4

Summary of Gaps in Knowledge and Practice

This chapter summarizes noted gaps in the current state of practice related to the design and subsequent bidding of gravity drainage pipes for roadway applications. NCHRP Project 10-86 was tasked with identifying gaps that had the potential to substantially affect the development and implementation of the Recommended Practice. The techniques used to identify critical gaps included the following:

- Consideration of the current knowledge gaps identified in the draft report of NCHRP Project 20-07 (White and Hurd 2011). These relate to the definition and selection of DSL, lack of a comprehensive quantitative model for predicting pipe service life, and lack of an approach to defining levels of joint performance.
- Review of literature including state practice guidelines and specifications with regard to DSL assessment for pipe selection and the data currently available for assessing long term pipe failure mechanisms, and the rates of deterioration.
- Use of a survey of state DOTs (state drainage and material engineers) as outlined in Chapter 3 to solicit, amongst other things, broader feedback on the main concerns with predicting pipe service life and any recurring problems identified with premature pipe failures.
- Discussions with state agencies, the Province of Ontario, and amongst the research team of technical resources (e.g., with Dr. Ian Moore) to determine limitations and shortcomings of existing drainage pipe design and selection procedures.

Gaps in practice can typically be grouped into one of the following categories:

- **Knowledge Gaps**—areas where there is a deficiency in design theory/methodologies or performance data to support rigorous and robust design and performance decisions.
- **Implementation Gaps**—areas where there is clear and technically valid information (design method, performance data, etc.) to support use of a design method, evaluation criteria, pipe product, and so forth, but implementation has not yet been instituted.

4.1 Knowledge Gaps

Knowledge gaps are areas where the state of knowledge has not reached maturity and/or consensus has not been reached on the appropriate approach to a given design problem or in the evaluation of a particular aspect of performance. To date, the following critical knowledge gaps have been identified that impact the design and bidding of drainage pipe systems:

- **Standardization of DSL**—Standard (universal) and objective guidelines for defining service life requirements for various drainage pipe system applications are not defined in AASHTO.
- **Service Life Prediction and Evaluation (Durability)**—the prediction and evaluation of drainage pipe system (pipe material, backfill, etc.) service life is a complex process involving the evaluation of chemical (corrosion) and mechanical (abrasion) resistance (material properties) and loading (service conditions).
- **Time-Dependent Performance Data**—in general there is a lack of statistical data of long term field performance for the full range of drainage system and service conditions.
- **Pipe Joint Evaluation**—the evaluation of structural and hydraulic performance impacts from various pipe joint systems results in both knowledge and implementation gaps.
- **Installation Quality**—a clear and universally accepted methodology to quantify the impacts of installation quality on drainage system performance is not known to exist, and sufficient performance data to generate such an evaluation system may not exist for all pipe systems and installation conditions.

It is noted that the hydraulic and structural design of new (virgin) drainage pipe systems is generally well understood and the methodologies presented in reference documents (e.g., AASHTO LRFD Bridge Specifications; Chapter 12) are accepted as appropriate. However, while knowledge gaps related to these functions do not exist, implementation gaps related to these basic design functions do exist as detailed below.

4.1.1 Standardization of DSL

Establishing the minimum required life at an adequate level of service for a pipe system is a necessary guideline to consider for selecting alternative pipe systems. This issue recognizes that different pipe types will deliver different service lives under defined conditions, but that not all highway applications require the same service life or level of service. While some DOTs have guidelines on defining DSL, there currently is not a standard approach for this process. There are a number of different aspects to this. On a simple level, most agencies relate DSL to the highway classification or the strategic importance of the route. Thus design service lives of 25, 50, 75 or 100 years can be assigned. Other factors that need to be considered are the ease of replacement of a particular pipe system. For example, if a cross culvert is at the base of a high rockfill embankment, and replacement would require the construction of a temporary detour, the DSL may need to be increased irrespective of the road classification. The research team is not aware of any comprehensive life cycle costing studies done on the differential between a 25-year pipe design and a 75-year pipe design.

4.1.1.1 Future Considerations

The development of a standardized set of objective guidelines for use in setting DSL requirements would likely serve to benefit the industry and may warrant consideration by AASHTO.

4.1.2 Service Life Prediction and Evaluation (Durability)

The potential for changes in system material properties (pipes and surrounding materials) over time (durability) serve to impact structural and hydraulic performance of drainage systems. Additionally, the durability of system components is impacted by a range of chemical and mechanical loading processes that typically fall along the periphery of drainage system designer knowledge and expertise. As such, it is understandable that this area is the least mature and most variable with regard to available design methods, compilations of field and laboratory performance data, and integration in practice. The process is further complicated in practice by the fact that most prediction models assume the pipe system is correctly installed and are invalid if this is not the case.

The knowledge gaps related to pipe durability are well known as reported in a wide range of reference documents including MTO (2007) and *NCHRP Synthesis 254* (1998) (*NCHRP Synthesis 474* is an update to *NCHRP Synthesis 254* that will be published in spring 2015). There is also significant ongoing research at universities, within state DOTs, and by pipe manufacturers and trade associations aimed at improving the knowledge base regarding durability.

4.1.2.1 Future Considerations

The Recommended Practice developed in this study acknowledges the data gaps that exist in evaluating durability and quantifying EMSL. Because the state of knowledge in this area is rapidly changing and likely will continue to change and adapt as new and improved materials, construction techniques, and post-installation verification techniques are implemented, the path forward is to ensure that the developed practice includes the following:

- Clear definitions and typical ranges for critical properties (pH, resistivity, sulfide concentrations, chloride concentrations, bedloading, etc.).
- Inclusion of a range of current and accepted methods for evaluating EMSL with a discussion of limitations and applicability.
- Flexibility to allow state specific and/or new developments in evaluation methods to be easily implemented into the process.
- Suggested methods for measuring relevant properties/parameters.

4.1.3 Time-Dependent Performance Data

In general, there is a need for additional evaluations of time-dependent performance data on all drainage systems. Drainage systems and pipe products that have longer histories have significantly more data available, but often these collections of data are potentially biased as a result of being presented by industry trade organizations and/or they do not cover the full range of installation conditions.

For newer pipe products and systems the need for evaluation and unbiased compilation of performance data is significantly greater and leads to the exclusion of newer pipe products in some jurisdictions.

4.1.3.1 Future Considerations

The need for continued and additional studies to collect and analyze drainage system performance data is well known. For this project, the developed Recommended Practice relies on available studies and a flexible framework intended to allow incorporation of changes in performance criteria and data as new information is published.

4.1.4 Pipe Joints

The responsibility to provide information regarding the impact of pipe joint systems typically falls on the manufacturer. While some pipe systems and products provide a full range of information to allow the adequate incorporation of joint performance into design, this is not universal amongst available pipe products and joint systems. Additionally, the performance of many joint systems is strongly dependent on the quality of installation (i.e., proper vs. improper installation) and the performance of improperly installed joints is in general not well documented or quantifiable.

Instances where joint performance data and/or evaluation tools are not available in the literature (even if they are available internally within pipe manufacturer's literature) are considered knowledge gaps in the current study.

The knowledge gaps related to pipe joint systems are evident by the proportionally large percentage of failures (or other service impacts) that are related to pipe joints. Joints have the potential to impact both the hydraulic and the structural performance of the pipe material, and to further impact the performance of the pipe system through leaks that can lead to degradation or erosion of bedding and embedment materials. Infiltration of soil particles into pipes can also cause an increase in abrasion.

4.1.4.1 Future Considerations

The following are potential future considerations related to the existing knowledge and data gaps in evaluating joint performance:

- Pipe manufacturers should be encouraged (and/or required) to provide technical information regarding the impacts on hydraulic (Manning's *n*) and structural (impact on fill height tables) performance (if any) for each joint system, assuming proper installation is followed.
- As it is likely impractical to fully and accurately quantify the impacts of poor or improper joint installation on performance, the recommended path forward is for state agencies and other owners and their representatives to institute and require the following:
  – Clear specification of joint requirements in contract documents
  – Contractor pre-qualifications regarding experience installing various joint systems
  – Development and implementation of adequate inspection protocols to provide greater assurance of high quality and proper joint installations.

The structural design of joints to withstand variations in construction, support, and loading conditions is the topic of NCHRP Project 15-38. The results of that project will improve the state of knowledge on this topic.

4.2 Implementation Gaps or Inconsistencies

4.2.1 Introduction

Implementation gaps are areas where typical practice does not consistently follow known best practices and/or regulatory requirements (i.e., Code of Federal Regulations (CFR), AASHTO design specifications, and so forth). The following implementation gaps have been identified to date that are anticipated to impact the alternative bidding of drainage systems:

- Variations in hydraulic design criteria
- Out of date/inconsistent fill height tables
- Site specific consideration of durability
- Consistent and timely evaluation of new pipe products
- Unwarranted exclusion of pipe systems (historical or other bias)

4.2.2 Variations in Hydraulic Design Criteria

4.2.2.1 Variations in Manning's n *Value Recommendations*

The Manning's equation is an empirical relationship commonly used to calculate barrel friction losses in pipe system and design. The Manning's *n* value is based on either hydraulic test results or resistance values calculated using a theoretical equation such as the Darcy equation and converting to a Manning's *n*. The use of the Manning's equation for culvert design is the predominant means of evaluating the hydraulic adequacy of various pipe materials for a given drainage application used in practice.

Section 3.4.1.2 presented summary plots showing the ranges of Manning's *n* values across several pipe types for the references reviewed. The observed range in values indicates that Manning's *n* values are not standardized across the practice and that this represents an implementation inconsistency in current practice.

4.2.2.2 Changes in Hydraulic Performance Over Time

Abrasion, corrosion, and bio-sliming (i.e., accumulation) of pipe materials are known to potentially influence the hydraulic performance of pipes over their service life. However, as identified in the review of hydraulic design practice, clear methods to evaluate and incorporate this potential change in performance over time do not exist. As expected in an area without a clear standardized evaluation method, typical practice regarding incorporation of these factors is quite variable.

A relatively wide range of Manning's *n* values is recommended for use in hydraulic design and adequacy evaluations (as summarized in Figures 2 through 8) that vary over a wide range of risk tolerances and do not typically consider the expected length of service. Practice ranges widely, from agencies recommending no change in Manning's *n* from the measured virgin material values, to others that recommend potentially conservative upper end values that would only occur in service through significant material changes over the service life of the drainage element. The relevance of these service life changes in Manning's *n* need to be evaluated further to establish whether indeed they need to be considered in an alternative pipe selection process or whether they would have no material impact on the outcomes.

4.2.2.3 Future Considerations

Additional research and review of available service data would be beneficial to the design and adequate evaluation of time-dependent impacts on hydraulic performance. If available, information could be requested from manufacturers; however, it is unlikely that this information would be available for all pipe types or that a consistent methodology would have been used in evaluating performance.

4.2.3 Out of Date/Inconsistent Fill Height Tables

As summarized in Section 3.4.2.2, typical practice for the structural evaluation of drainage systems is to use fill height tables to screen combinations of pipes and installation conditions for adequacy based on the known loading conditions. This approach is technically valid, is quick, and is not subject to significant errors because the use of such tables greatly simplifies what can be complicated analyses. As such, the use of fill height tables is expected to remain the predominant method for structural evaluations of drainage systems.

The inconsistency of the preparation, use, and variables for structural design and fill height tables results in an implementation gap that affects the current state of the practice, and prevents national standardization and in-service tracking of structural pipe system performance.

These factors combine to present a state of current practice that contains significant variation and bias in the evaluation of structural capacity of highway drainage elements, and that prevents national standardization and direct comparison of performance.

4.2.3.1 Future Considerations

The research team worked with the pipe industry representatives to develop nationally standardized structural fill height tables across all pipe types, but was unsuccessful in accomplishing that task fully within the project time constraints. The development of nationally standardized baseline fill height tables based on the AASHTO LRFD code and a set of clear and transparent design criteria would likely be of benefit and save resources spent repeating the design processes across all agencies in the United States. Following the development and distribution of such standard tables, state agencies could then consider variations from the standard values for state specific or design specific conditions (e.g., increased factors of safety for critical structures and variations in available bedding classes) at reduced effort and cost.

It is the team's opinion that the development of standardized fill height tables is a key step in providing for equitable comparison and evaluation of highway drainage elements and would be of great value to the technical community. Additionally, it would provide a clear baseline of standard practice and methodology for new pipe products, which would help ease integration of new products into practice.

It is noted that TRB Standing Committee AFF70 identified as one of the key research needs to standardize structural design methods for alternate pipe materials based on equivalent risk factors (TRB 2009). The research statement and objective from that identified research need reads as follows:

> *"The AASHTO LRFD Bridge Design Specification use different load and resistance factors for the design of pipes made from different materials. Seemingly, this practice results in different factors of safety between designs of the concrete, metal and plastic pipes involved. In some instances, the apparent safety factors appear to range from roughly 1.2 to 5.0. This is a historic practice that may or may not be justified by the loads, known strength of the pipe materials and installed backfill soils involved.*
>
> *Load factor evaluations need to account for current day inspection controls, deflection testing, etc. Effective means of offsetting likely variations in design assumptions need to be identified, evaluated and, where appropriate, included in future specifications. Resistance factors are to be developed on the basis of inconsistencies that may actually occur within the pipe and backfill materials as specified as well as the accountability of the materials involved."*
>
> *"Evaluate the basis of the various AASHTO pipe design specifications (methods), their degree of technical substantiation as well as their dependency on (any) differing loading assumptions, the effect of variations in specified backfill materials and the dependency of the pipe's performance on contractor workmanship.*
>
> *Develop design methods with equivalent risk factors for pipes of alternate materials. Appropriate soil and live load design assumptions as well as soil support, shape control and pipe material strength variations are significant factors."*

4.2.4 Site Specific Consideration of Durability

As introduced and summarized in Section 3.4.3, the AASHTO LRFD Bridge Design Manual requires that the two main mechanisms of durability (corrosion and abrasion) be considered in design highway drainage systems. While multiple methods for calculating site and pipe system specific EMSL values exist (see Section 3.4.3 and Appendix C), a survey of North

American DOTs completed during *NCHRP Synthesis 474: Service Life of Culverts* (an update to *NCHRP Synthesis 254* that will be published in spring 2015) indicated the following state of practice trends show an apparent implementation gap in applying site specific durability evaluations.

- Assumed agency-wide values are still the predominant method for estimating EMSL during design of all pipe types. Quantitative methods are more commonly used for pipes with a longer history of use (concrete and metal), and are more rare for pipe materials with a shorter history of use.
- For agencies that complete quantitative EMSL evaluations, corrosion and abrasion were the most common factors considered, followed by settlement and stress cracking, and other factors were generally not considered.
- The tools and aids used to calculate EMSL typically include some combination of assumed values, agency-specific data, and industry supplied data. Software programs are still relatively infrequently used to predict EMSL values.
- There is near universal application of assumed values of EMSL for all pipes other than concrete and metal, which is believed to primarily result from the limited methodologies to complete project specific evaluations of MSL for thermoplastic and other non-concrete/metal pipe types.
- One-third of agencies reported maintaining maps indicating regions of environmentally aggressive conditions.

4.2.4.1 Future Considerations

The Recommended Practice developed acknowledges that knowledge and implementation gaps exist in evaluating durability and quantifying EMSL. Because the state of knowledge in this area is rapidly changing and likely will continue to change and adapt as new and improved materials, construction techniques, and post-installation verification techniques are implemented, the suggested path forward is to ensure that practice moves toward more widely including the following:

- Continuation of the increasing trend to collect site specific environmental and geotechnical data from the native soil, backfill, flow, and groundwater data necessary to implement site specific durability methods.
- Consideration by AASHTO to include a range of current and accepted methods for evaluating EMSL with a discussion of limitations and applicability.
- Continued information sharing amongst state DOTs with successful and robust site specific durability evaluation practices.
- Continuation of the significant on-going research related to the durability assessment of thermoplastic and other newer pipes types.

4.2.5 Consistent and Timely Evaluation of New Pipe Products

This gap is typically temporary and exists from the time of new product development until sufficient product information and performance data exist to encourage implementation in practice. However, the timing to reach maturity and the requirements to reach acceptance are often highly variable across state agencies (often related to the local need and competitiveness of each new product).

While temporary implementation gaps are necessary and important through the final development and implementation of new products, a unified, consistent and clear system of requirements to allow new products to gain approval status (or to be determined to be unsuitable for widespread use) with federal and state agencies would be beneficial to the pipe manufacturing industry and would take significant burden off individual states to have to conduct individual (often repetitive) state specific review and approvals of all new products. New products can represent improved performance and cost savings where they can be introduced into use for appropriate applications.

Based on qualitative historic evidence in the piping and other industries, the adoption of an open and clear system applicable on a national level for evaluation (approval/rejection) of new or updated pipe products would increase competition and be beneficial to both industry and state agencies.

4.2.5.1 Future Considerations

The most practical solution to this challenge would be the greater use and adoption of the National Technical Product Evaluation Protocol (NTPEP) process or another similar nationally coordinated process to provide a common and clear framework for independently evaluating new pipe products. NTPEP evaluations are often completed in conjunction with specific state DOTs to run field trials under agreed protocols.

4.2.6 Unwarranted Exclusion of Pipe Systems (Historical or other Bias)

One of the main objectives of this study is to provide a framework that allows for the reduction or elimination of bias in the bidding and design of drainage systems. It is the intent of the research team that this known implementation gap will be improved through development and implementation of the Recommended Practice.

CHAPTER 5

Introduction to the Recommended Practice

The Recommended Practice in AASHTO format developed during the execution of NCHRP Project 10-86 is presented in this report with commentary as Appendix A. Worked examples of the Recommended Practice are presented in Appendix B to aid designers in the use of the Recommended Practice. Appendix B is not published herein but is available on the NCHRP Project 10-86 webpage at www.trb.org.

This Recommended Practice is intended to guide agencies and industry in implementing a performance-based process for contractor selection and delivery of drainage pipe systems on highway construction projects. The Recommended Practice provides guidelines and procedures for (1) agency definition of drainage requirements and (2) contractor bidding of drainage pipe systems to meet those requirements.

5.1 Overview

The evaluation and selection of suitable, and cost-effective drainage pipe systems for highway projects involves consideration of a range of engineering suitability criteria, installation requirements, and construction and post-construction maintenance costs. The availability of a streamlined, rational, and reliable design approach that identifies a wide range of appropriate pipe system alternatives on a consistent and unbiased basis would allow owners and agencies to take advantage of increased product competition with lower overall costs for procuring highway drainage systems. In addition, if such an alternative drainage pipe design and selection system also took serviceable life and durability into account, it would allow the appropriate pipe systems to be matched to the functional requirements of the highway, resulting in improved drainage system performance and lower long term maintenance costs. This Recommended Practice aims to achieve these objectives.

By delivering a consistent and technically sound design and selection process for drainage pipe systems this Recommended Practice also provides agencies the ability to systematically track bid selections and drainage pipe system inventories and performance records for input into asset management systems. Additionally, as agencies systematically track design evaluations and compare them over time to actual in-service performance, it will provide the opportunity to continually improve the state of knowledge regarding service life prediction and evaluation methods.

5.2 Scope of the Recommended Practice

This Recommended Practice presents a methodology to guide transportation agencies in implementing a performance-based process for selecting alternative drainage pipe systems on highway construction projects and is intended for use by transportation agencies, design consultants, and contractors.

The Recommended Practice is intended to provide a systematic, rational, comprehensive, and technically sound process for the evaluation of alternative highway drainage pipe systems, which includes the pipe dimensions, material and joints, bedding, embedment, and backfill.

The Recommended Practice uses recognized methods for pipe system selection, design, and post-construction acceptance based on performance-based criteria including hydraulics, structural capacity, durability, and environmental compatibility.

The Recommended Practice also provides guidance for post-installation inspection and agency acceptance of drainage pipe systems.

The Recommended Practice is not intended to provide specific guidance for every potential design decision that may arise during a drainage project. Instead, the intent is to provide guidance and recommendations for evaluating suitable alternatives for the majority of routine highway drainage applications.

The Recommended Practice is intended to be as inclusive and flexible as possible so as to address specific agency needs and requirements. Agency-specific regulatory policies and practices can be considered within the framework of this Recommended Practice.

The Recommended Practice indicates which related design issues are not inherently addressed, so that these issues may be addressed outside of this methodology. The Recommended Practice is applicable to circular, elliptical and arch-shaped culverts and storm sewers where a number of alternative pipe systems are readily available for selection as suitable alternatives. Box culverts, large span structures, and pressurized pipes are not specifically addressed or intended to be evaluated through the Recommended Practice.

5.3 Summary of the Recommended Practice

The Recommended Practice is intended to be transparent with all inputs, methodologies, and evaluation results clearly defined and presented. The process recommends undertaking evaluations using each agency's full inventory of pipe systems, including incorporation of available variations in installation type and backfill material and compaction. Pipe systems are technically evaluated as to their suitability in each of three main design functions: hydraulic, structural, and durability.

The Recommended Practice recommends evaluating the widest practical range of drainage pipe system options against the system performance requirements for each highway drainage application. This decreases the potential for bias in the selection of pipe system alternatives included in the bid documents. An inventory of available pipe systems within a jurisdiction may not currently be available and may have to be developed by the agency.

The Recommended Practice should be applied to each drainage application individually, so that site specific conditions affecting the performance and projected service life can be adequately considered.

The Recommended Practice is intended to promote technical evaluation of entire pipe systems as opposed to separately evaluating pipe system components. This allows acceptable combinations of backfill material, joint type, installation criteria, pipe linings, and so forth to be considered as separate alternatives. This may require agencies to develop a wider range of specifications to cover the construction aspects of these variations.

The Recommended Practice is intended to be flexible to account for individual state policies and procedures as well as potential future changes in policy, regulation, or availability of new pipe products and evaluation methods.

The Recommended Practice follows a systematic five-phase approach to evaluating, bidding, inspecting, and tracking alternative drainage pipe systems. The five phases (identified numerically) each consist of multiple steps (identified alphabetically), as illustrated in Figure 22:

Phase 1—Data Gathering and Project Definition
Phase 2—Technical Evaluation
Phase 3—Final Design and Policy Checks
Phase 4—Reporting Results and Incorporating Alternatives into Bid Documents
Phase 5—Construction Quality Control, Inventory Management, and Performance Feedback, with these latter components forming part of a highway drainage asset management system.

The Recommended Practice promotes the implementation of a thorough and inclusive performance-based evaluation process that considers all technically suitable alternatives for a given highway drainage application, leaving economic judgment of the most cost-effective suitable alternative to be determined through competitive bid.

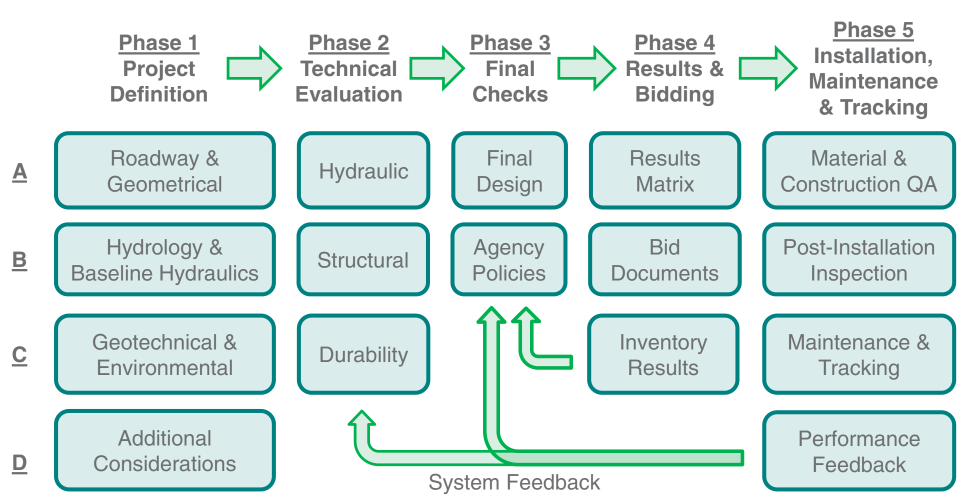


Figure 22. Primary steps in the Recommended Practice.

Successful evaluation of a large number of pipe system options, as completed during application of the Recommended Practice requires a systematic process for completing and tracking the results of each evaluation phase.

To achieve the goals of systematically and clearly presenting the large number of technical and policy evaluations involved in the Recommended Practice, a matrix approach was developed to track and report the pipe system selection process.

The matrix approach consists of all pipe system types compiled into rows, with circular equivalent pipe sizes listed in columns. Three individual matrices for each of the technical evaluation steps: hydraulic ("H"), structural ("S"), and durability ("D") are constructed and serve as the pallet for completing the individual steps of the Recommended Practice. A composite matrix with four sub-cells for each pipe system type and size combining the three technical evaluation steps with the final design and policy check ("F") stage is then used to create the overall Recommended Practice results matrix. Schematics of the individual and overall composite results matrix are shown in Figures 23 and 24.

This matrix format illustrates the results from each step in the systematic process with a "go" or "no-go" decision for each

Hydraulic

Pipe System	Pipe Inside Diameter (in.) 18	24	30	36
Pipe System A	X	H	H	H
Pipe System B	X	H	H	H
Pipe System C	X	H	H	H
Pipe System D	X	H	H	H
Pipe System E	X	H	H	H
Pipe System F	X	X	H	H
Pipe System G	X	X	H	H
Pipe System H	X	X	H	H
Pipe System I	X	X	H	H
Pipe System J	X	X	H	H
Pipe System K	X	X	H	H
Pipe System L	X	X	H	H
Pipe System M	X	X	H	H
Pipe System N	X	X	H	H
Pipe System O	X	X	H	H
Pipe System P	X	X	H	H
Pipe System Q				
Pipe System R	X	H	H	H
Pipe System S		H	H	H
Pipe System T	X	H	H	H
Pipe System U	X	H	H	H
Pipe System V	X	H	H	H
Pipe System W	X	H	H	H

Structural

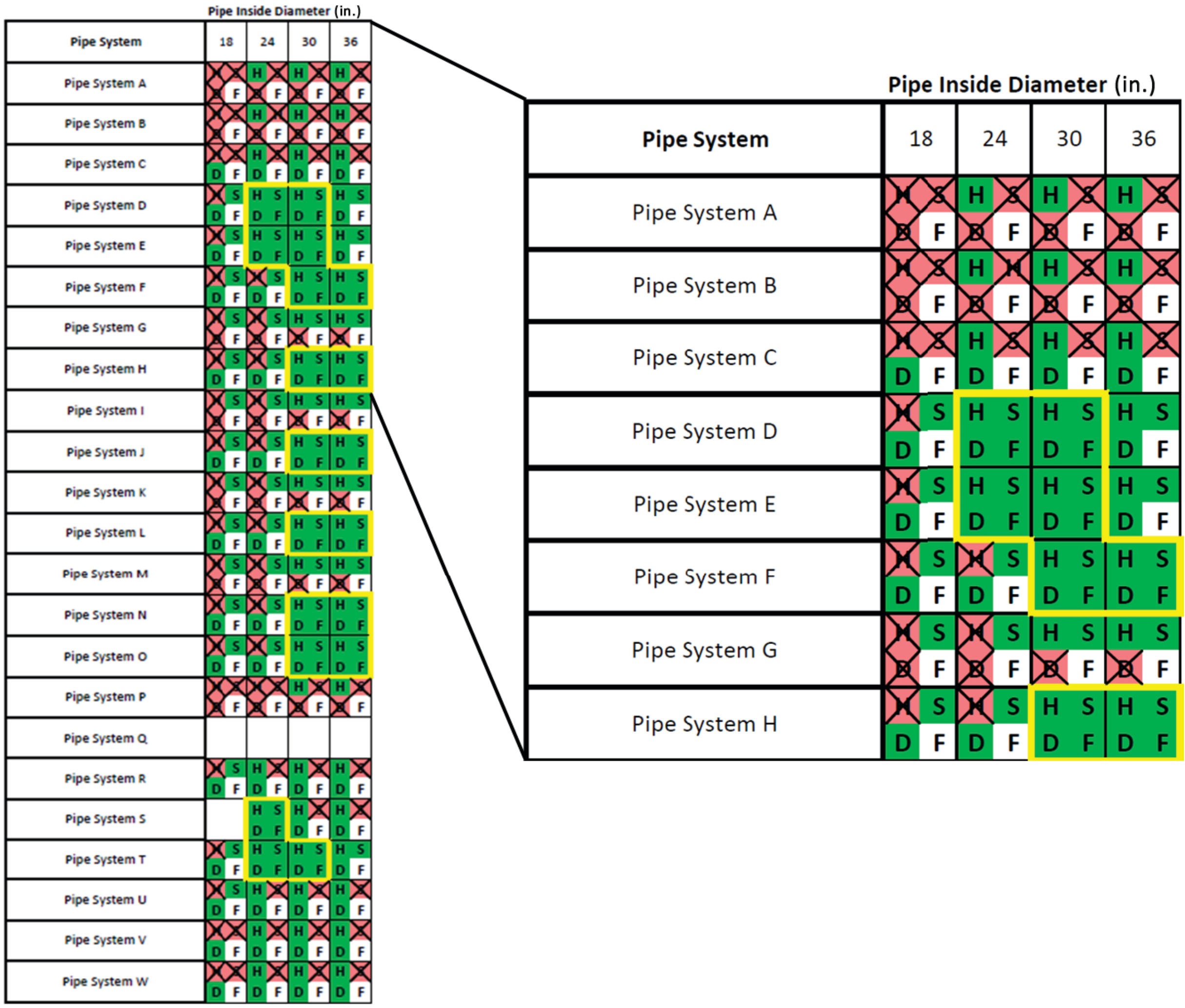
Pipe System	Pipe Inside Diameter (in.) 18	24	30	36
Pipe System A	X	X	X	X
Pipe System B	X	X	X	X
Pipe System C	X	X	X	X
Pipe System D	S	S	S	S
Pipe System E	S	S	S	S
Pipe System F	S	S	S	S
Pipe System G	S	S	S	S
Pipe System H	S	S	S	S
Pipe System I	S	S	S	S
Pipe System J	S	S	S	S
Pipe System K	S	S	S	S
Pipe System L	S	S	S	S
Pipe System M	S	S	S	S
Pipe System N	S	S	S	S
Pipe System O	S	S	S	S
Pipe System P	X	X	X	X
Pipe System Q				
Pipe System R	S	X	X	X
Pipe System S		S	X	X
Pipe System T	S	S	S	S
Pipe System U	S	X	X	X
Pipe System V	X	X	X	X
Pipe System W	X	X	X	X

Durability

Pipe System	Pipe Inside Diameter (in.) 18	24	30	36
Pipe System A	X	X	X	X
Pipe System B	X	X	X	X
Pipe System C	D	D	D	D
Pipe System D	D	D	D	D
Pipe System E	D	D	D	D
Pipe System F	D	D	D	D
Pipe System G	X	X	X	X
Pipe System H	D	D	D	D
Pipe System I	X	X	X	X
Pipe System J	D	D	D	D
Pipe System K	X	X	X	X
Pipe System L	D	D	D	D
Pipe System M	X	X	X	X
Pipe System N	D	D	D	D
Pipe System O	D	D	D	D
Pipe System P	X	X	X	X
Pipe System Q				
Pipe System R	D	D	D	D
Pipe System S		D	D	D
Pipe System T	D	D	D	D
Pipe System U	D	D	D	D
Pipe System V	D	D	D	D
Pipe System W	D	D	D	D

Notes:
1. H denotes hydraulic; S denotes structural; and D denotes durability.
2. Cells highlighted in green pass the relevant design check.
3. Cells with an "X" and highlighted in red fail the relevant design check.

Figure 23. Individual results matrices for technical evaluations.



Notes:
1. H denotes hydraulic; S denotes structural; D denotes durability; and F denotes final design check.
2. Cells highlighted in green pass the relevant design check.
3. Cells with an "X" and highlighted in red fail the relevant design check.
4. Pipe system options that pass all four technical evaluations (with the H, S, D, and F cells all highlighted in green) represent pipe systems that are acceptable design options. A yellow border is used to further highlight and identify acceptable design options.

Figure 24. Overall composite results matrix for the Recommended Practice.

pipe option. Matrix cells for which that type and size of pipe are not available are left blank to indicate lack of availability as the reason for elimination of that option.

In addition to the systematic advantages of the matrix approach, the visual presentation of the evaluation results from adjacent sizes in adjacent columns and for similar pipe system types in adjacent rows allows for rapid visual assessment of trends in the presented results. The ability to perform a visual review of trends in the results provides significant advantage for identifying errors in calculation or transcription in the Recommended Practice process and also identifying gaps or areas of improvement in technical methods and/or agency policies.

While not required as part of implementation, the Recommended Practice is intended to facilitate database tracking of an in-service drainage pipe system inventory to allow for more systematic and efficient maintenance, renewal, and replacements in line with the goals of the Second Strategic Highway Research Program (SHRP2) and other ongoing AASHTO and agency initiatives.

The Recommended Practice could also aid in tracking drainage pipe system failures, failure causation mechanisms, and achieved in-situ service life values across each adopting agency's' drainage pipe system inventory. For example, if a specific culvert fails within 15 years of installation, it could be back-analyzed using the Recommended Practice to confirm that that specific pipe should not have been selected for that site and application. The tracking of failures and the loss of service life mechanisms, in combination with the tracking of estimated and actual material service lives will allow for research and data-mining to improve and calibrate existing culvert design methods through feedback loops within the Recommended Practice. Specifically, the developing research topics of service life prediction and failure modes can be significantly improved through the tracking and sharing of actual drainage pipe system service life data across and within AASHTO agencies.

The Recommended Practice could also form the basis to simplify and facilitate a highway drainage asset management system by tracking and integrating system feedback based on the transparent processes included in the Recommended Practice. The independent parallel assessment for each functional/technical category used in the Recommended Practice allows the designer to observe why a pipe system was determined to be unsuitable. Regular agency review of technical evaluation results and trends in bidding and field performance are encouraged for incorporation into agency policy reviews and updates.

5.4 Recommended Use

The selection and design of drainage pipe systems for use in transportation projects depends on both economic and technical considerations. Individual agencies currently develop and maintain independent policies to guide the design, bidding, post-construction inspection, and long term asset management of highway drainage pipe systems. This Recommended Practice is intended to provide a national AASHTO standard for agency implementation of drainage pipe system evaluation and alternative bidding to foster greater harmonization and standardization across AASHTO agencies. With implementation, it should serve to reduce costs through more efficient design, identification of cost-effective solutions, and increased local competition between contractors and suppliers. It should also encourage the development of better pipe products and the formation of a national marketplace for drainage system pricing as policies become more nationally standardized.

The current functionality of the Recommended Practice is that it selects pipes that have an EMSL that is longer than the desired DSL. However, as EMSL methods improve, the Recommended Practice could facilitate application of a life cycle costing approach to pipe selection whereby even pipes with EMSLs less than the DSL could be selected provided their service life could be extended by in-situ remediation. This would allow even more options to be considered and could facilitate a "staged-construction" approach to drainage design.

Traditionally, transportation agencies have used a "means and methods" approach for selection and specification of products such as drainage pipe systems. In this approach, the agencies specify a particular drainage pipe system during the design process and the cost of the specified system is included in the contractors' bids for the project. This system often restricts or impedes competition by eliminating many technically suitable alternatives. The inclusion of multiple equivalent options during the bid phase of projects has been shown to reduce costs through increased competition.

This Recommended Practice presents a methodology to guide transportation agencies in implementing a performance-based process for evaluating alternative drainage pipe systems with the intent to increase competition and reduce costs while maintaining safety and performance standards. The Recommended Practice contains elements to guide development of a holistic program that would allow for systematic inventory management and tracking of results that could improve service life predictions and lead to better management of highway drainage assets.

The Recommended Practice applies rational performance-based criteria to the selection of pipe systems. It is not intended to be a stand-alone design document, but rather a design guidance and process framework when used in conjunction with other resources including AASHTO LRFD, FHWA Hydraulic Design procedures, and agency policies and design manuals. This methodology promotes the implementation of the latest national standards and other state-of-the-practice design evaluation methodologies with the intent of being as comprehensive as possible while also allowing the flexibility to incorporate agency-specific standards or requirements. The matrix approach developed for technical evaluations within the Recommended Practice is intended to provide clarity of design decisions and to allow for data tracking and mining for future agency use or for research to improve policies and methods.

The Recommended Practice methodology presents a simplified systematic process for identifying drainage pipe systems for a specific defined application based on the application of hydrological, hydraulic, structural and durability principles. However, it is expected that the Recommended Practice be applied only by engineers experienced in drainage pipe design principles and that the use of the Recommended Practice will not eliminate the need for the results to be reviewed and checked by a drainage design engineer. The Recommended Practice incorporates a final design check step to allow for more detailed analyses, where necessary, beyond the basic evaluations and to allow for agency- or project-specific provisions to be applied.

The Recommended Practice addresses the design of circular and standard elliptical and closed arch (i.e., pipe arch) drainage elements. Large and special design drainage pipe systems such as box culverts, large span open bottom arches, pressure pipes, and so forth are not directly addressed or incorporated. Above all, the Recommended Practice is intended as a streamlined process for the design of routine highway culvert and storm sewer systems.

CHAPTER 6

Preparatory Agency Actions Prior to Implementation of the Recommended Practice

To optimize the benefits of implementing the Recommended Practice, initial preparatory work and internal review is recommended.

6.1 Identification of Agency Goals, Requirements, Constraints, and Opportunities

Before implementing a new or revised alternative pipe system bidding practice, it is recommended that an agency identify the requirements, constraints, and opportunities associated with any new or revised system, and select a system that will most effectively meet the agency's goals.

6.2 Pipe System Inventory

To complete technical evaluations it is necessary to define the characteristics of each pipe system within the inventory including the following:

- Pipe size
- Pipe shape
- Pipe profile
- Pipe material type
- Pipe coating or lining condition
- Pipe structural class (presented as min and max allowable fill height)
- Pipe joint type
- Pipe roughness (Manning's *n* value)
- Pipe abrasion resistance
- Installation type (embankment or trench)
- Installation class (as per AASHTO, ASTM, or agency-specific classifications defining backfill and bedding geometry, materials, and compaction requirements)

An inventory of pipe systems within a jurisdiction may not be available and may have to be developed by the agency. Comparing the allowable pipe system inventory with other AASHTO agency inventories and with available pipe systems in the marketplace is recommended prior to Recommended Practice implementation and at regular intervals thereafter. Considering piggyback approvals based on research and pilot verification efforts by other AASHTO agencies and leveraging of the NTPEP system are recommended to expand the inventory of approved pipe systems to include the widest possible range of pipe materials and installation conditions appropriate.

6.3 Pipe System Codes

The adopting agency needs to maintain a detailed inventory of available pipe systems approved for use on agency projects. To help promote standardization and efficiency in dealing with the large number of pipe system variations available for use in highway drainage systems, the Recommended Practice recommends developing and integrating a pipe system identification code (PSIC) for use in uniquely identifying each available pipe system alternative. The unique PSIC code for each available pipe system option can either be agency specific or follow from the example nomenclature presented below. The use of a PSIC to uniquely identify pipe systems is intended to allow for simpler and clearer presentation of pipe systems within the Recommended Practice matrix, on construction documents, and on as-built drawings to identify the full range of pipe system characteristics.

6.4 Inventory Database

While not a requirement for implementation of the Recommended Practice, it may be advantageous for the adopting agency to enhance the benefits of implementation by maintaining a detailed inventory of in-service drainage pipe systems. To help promote standardization and to allow for potential multi-agency data gathering and research, the Recommended

Practice can be expanded to include an inventory database which would include the following items at a minimum, noting that many agency inventories may have additional items:

- Functional classification: arterial, collector, local, and so forth
- Roadway number
- Drainage system type: culvert or storm sewer
- Station of culvert inlet or station range for storm sewers
- Pipe system ID
- Installation date: month and year
- Original DSL in years
- Current estimated service life or achieved service life to failure
- Failure causation mechanism(s)

This inventory could also form the basis for an asset management system for drainage pipe systems to assist with establishing long term pipe replacement and rehabilitation budgets. The tracking of original DSL, current estimated service life (from regular maintenance inspections), achieved service life to failure, and failure causation mechanisms is intended to allow for evaluation and improvement through calibration of durability prediction methods over time.

CHAPTER 7

Project Definition

7.1 Roadway and Geometrical

The initial phase of use for the Recommended Practice is to define the project details. The fundamental roadway and geometrical parameters are compiled so that they are available for use in the design evaluations completed in Phases 2 and 3.

The following are the recommended roadway and geometrical design parameters:

- Unique project, bid, or agency-wide identifier
- Type of installation or pipe function (culvert or storm sewer)
- Location
- Roadway functional classification
- DSL
- Culvert length
- Minimum fill height
- Maximum fill height
- Maximum size (considering vertical and lateral conflicts)
- Minimum size (considering maintenance, future rehabilitation)
- Upstream invert elevation
- Downstream invert elevation
- Design slope
- Skew
- Breaks in slope or alignment
- Installation condition (embankment/trench)

7.1.1 DSL

The general principle for the use of a DSL-based system is that the higher the road classification and the higher the consequences from premature failure of a drainage system, then the longer the DSL should be. Other factors that could influence the DSL would be the height of embankment fill above the pipe which can necessitate full road closures to allow pipe replacements. Typically agencies use DSL values of 25, 50, 75 and 100 years, with design lives of 75 and 100 years being reserved for high volume freeways, and 25 years being used for entrance culverts and similar pipes.

7.2 Hydrology and Waterway

The fundamental hydrologic, waterway, and hydraulic parameters are compiled in this stage for use in the design evaluations completed in Phases 2 and 3 of the Recommended Practice. At least one baseline hydraulic design for the drainage application being evaluated is also required to be undertaken outside of the Recommended Practice to provide a starting point for the Phase 2 and 3 design evaluations of available alternatives.

The basic hydrologic design parameters are as follows:

- Drainage area
- Design flow rate
- Design storm
- Check storm
- Allowance for future watershed changes

A hydrological analysis to define the drainage system flow requirements is required to be completed outside of the Recommended Practice, typically using procedures outlined in the most recent version of the following documents:

- FHWA Highway Hydrology—HDS
- AASHTO Model Drainage Manual

In addition, hydraulic design parameters such as those listed below need to be defined, with guidance provided in FHWA Hydraulic Design of Highway Culverts—HDS 5:

- Allowable headwater criteria
- Minimum allowable flow velocity

- Maximum allowable flow velocity
- Joint rating: soil tight, silt/fines tight, or water tight
- End treatments
- Section variations (e.g., bends, junctions, wyes, transitions)
- Aquatic organism passage requirements

Two default options for baseline pipe roughness categories are defined below, noting that agencies may use alternate default category names and representative minimum Manning's n values as preferred.

The recommended default pipe roughness categories are as follows:

- Smooth ($n = 0.012$)
- Corrugated ($n = 0.024$)

If a more rigorous category classification scheme is desired, the following four categories are recommended:

- Ultra smooth ($n = 0.009$)
- Smooth ($n = 0.012$)
- Corrugated ($n = 0.024$)
- Structural plate (0.036)

The baseline hydraulic design for each of the generic baseline pipe roughness categories is performed through use of the FHWA HY-8 Hydraulic Analysis Program or other means.

In the absence of minimum flow requirements and other special hydraulic considerations, the classification of the drainage application as inlet or outlet controlled can be used to streamline the baseline hydraulic evaluations. Starting with analysis of the roughest category first, if the system is found to be inlet controlled, all smoother baseline categories can be set to that same size without requiring independent analysis. If an evaluation results in outlet controlled conditions, the next roughness category evaluation would be completed to determine the potentially smaller baseline pipe size requirements for that roughness condition.

It is noted that variations in barrel roughness impact outlet velocity and thus outlet scour, potentially resulting in variations to the required engineering controls at the outlet to achieve equivalent performance.

7.3 Environmental and Geotechnical

Collection of site-specific environmental and geotechnical data from the native soil, backfill, flow, and groundwater is necessary to estimate the material service life of drainage pipe systems.

7.3.1 Definition of Site Environmental Parameters

Data on the soil, backfill, and water should be collected in accordance with the most recent versions of the following standards:

- Soil pH: AASHTO T 289 or ASTM G51
- Water pH: ASTM D1293 or ASTM D5464
- Soil resistivity: AASHTO T 288
- Water resistivity: ASTM D1125
- Chloride concentration: AASHTO T 291 or ASTM D512
- Sulfate concentration: AASHTO T 290 or ASTM D516
- Flow rate: ASTM D3858 or ASTM D5243

Relevant standardized test procedures adopted by state transportation agencies may also be used to collect site-specific environmental data. Alternatively, many agencies make use of field kits that are specifically designed for this purpose and are useful in supplementing the data from laboratory testing.

Data collected at a single location at a specific time may not be representative of conditions that exist at a site over the lifetime of the drainage pipe system. To account for potential seasonal and other variations in water characteristics, collection of environmental data at multiple locations and at multiple times during the year should be considered depending on the scale of the project. Changes in surrounding land use (e.g., fertilizer impacted runoff from nearby agricultural lands, roadway salting efforts in the winter) and flow characteristics should also be considered.

Test values can be seasonally affected by such factors as rainfall, flooding, drought decaying vegetation, and man-made influences (e.g., fertilizer or road salt runoff). Whenever possible, environmental tests should be taken during periods considered representative of critical environmental conditions.

In addition to the collection of soil and water environmental data to allow completion of the quantitative durability evaluations in Phase 2, it is strongly recommended that the in-service performance of nearby drainage systems be recorded and used to back-calculate estimated environmental conditions for the observed service life conditions through reverse application of the methods discussed in Phase 2.

Based on comparison of the field measured and back-calculated environmental conditions the designer would choose the critical value in each category to bring forward through the remainder of the Recommended Practice.

7.3.2 Geotechnical Information

A geotechnical investigation should be performed in accordance with AASHTO Standard Recommended Practice R13-03 "Conducting Geotechnical Subsurface Investigations" and agency-specific guidance. It is convenient to include the geotechnical data needed for drainage system design in the scope of a pavement rehabilitation investigation.

The focus of the investigation for drainage system design should be on the following:

- Determining the ground conditions that will act in support of the drainage pipe system
- Determining the suitability of native materials to be used in construction
- Compaction characteristics of construction materials
- Potential for abrasive bedload to be generated from watershed soils
- Collecting samples for the testing listed in Section 7.5.2 of the Recommended Practice

7.3.3 Additional Considerations

Additional design drivers are considered in Phase 1D and may cause the drainage application to be designed outside of the Recommended Practice, and/or for additional design constraints to be placed on the technical evaluations.

- Earthquake hazards including liquefaction, fault crossings, and so forth
- Ecological factors upstream, downstream, or within the culvert
- Minimum and maximum temperatures, and resulting extreme temperature impacts
- Ground freezing and other cold weather considerations
- High maximum temperatures can impact the material service life of thermoplastics and other pipe materials and may require special design considerations
- Erosion and scour potential
- Fire risk and consequence
- Roadway chemical spill risk and consequence
- Other geologic, environmental, or man-made conditions

Assign an abrasion level for use during Phase 2 by using the data collected in Phases 1B and 1C.

7.4 Inventory of Available Pipe Systems

Following completion of Phases 1A through 1D, the design engineer should refer to the agency inventory of available and approved pipe systems to set the listing of pipe systems to be included in the matrix and to be evaluated as part of the current application of the Recommended Practice. This Recommended Practice phase is included to promote recording of the inventory used in the Recommended Practice for a given project or drainage application as agency inventories will likely change over time.

The range of sizes evaluated in each application of the Recommended Practice should be sufficient to capture all suitable alternative pipe systems, but be limited to those systems that are practical for a given drainage application. It may be beneficial to evaluate pipe systems within two sizes above the baseline designs during application of the Recommended Practice so as to increase the bidding options.

The evaluation of non-circular shapes (pipe arch, horizontal elliptical, vertical elliptical) is not required for many standard drainage applications. However, these alternate shapes and/or the use of multiple barrels are common practice and require evaluation when applicable. It is recommended that the potential need for non-circular shapes be identified during Phase 1 through evaluation of the baseline hydraulic design and the roadway and geometrical data, with alternate shapes included in the Recommended Practice evaluations if it is determined that non-circular shapes may be required.

In line with standard design practice, if the Phases 1A through 1D evaluations do not identify a potential need to use non-circular shapes, it is recommended that these shapes not be evaluated to simplify and streamline the implementation of the Recommended Practice.

Multiple barrel drainage systems can be evaluated using the Recommended Practice through analysis of an individual component with the Recommended Practice process, noting that the chosen option (size and number of barrels) must meet the geometric constraints defined in Phase 1A.

CHAPTER 8

Hydraulic Evaluation

During Phase 2A the user compares each evaluated pipe system's hydraulic capacity to the hydraulic requirements of the drainage application. The Recommended Practice recommends conducting these evaluations not through detailed hydraulic design of each pipe system, but rather through comparison of pipe size (equivalent circular diameter) and pipe roughness.

While independent rigorous hydraulic capacity evaluation for each pipe system is not considered necessary for most applications, verification of equivalency or the adequacy of the defined pipe roughness categories to adequately achieve all hydraulic requirements can be conducted in Phase 3A for critical drainage applications if desired.

Minimum pipe diameters for standard roughness categories were established in Phase 1B. If the range of pipe roughness in the pipe system inventory can be adequately represented through grouping into one of the Manning's *n* categories defined in Phase 1B then no further hydraulic evaluation is required and pipe systems are considered hydraulically acceptable if they meet the minimum and maximum pipe size requirements defined for the representative roughness category.

If it is desired to hydraulically evaluate each pipe system's specific Manning's *n* value or to define the pipe size requirements for additional pipe roughness categories not previously set in Phase 1B, these evaluations are recommended to be performed in Phase 2A using hydraulic equivalency charts.

Starting from the baseline hydraulic designs completed in Phase 1B, the Manning's equation may be used to determine the equivalent hydraulic capacity of different pipe materials under the drainage system flow conditions. An example hydraulic equivalency equation and chart are shown in Figure 25.

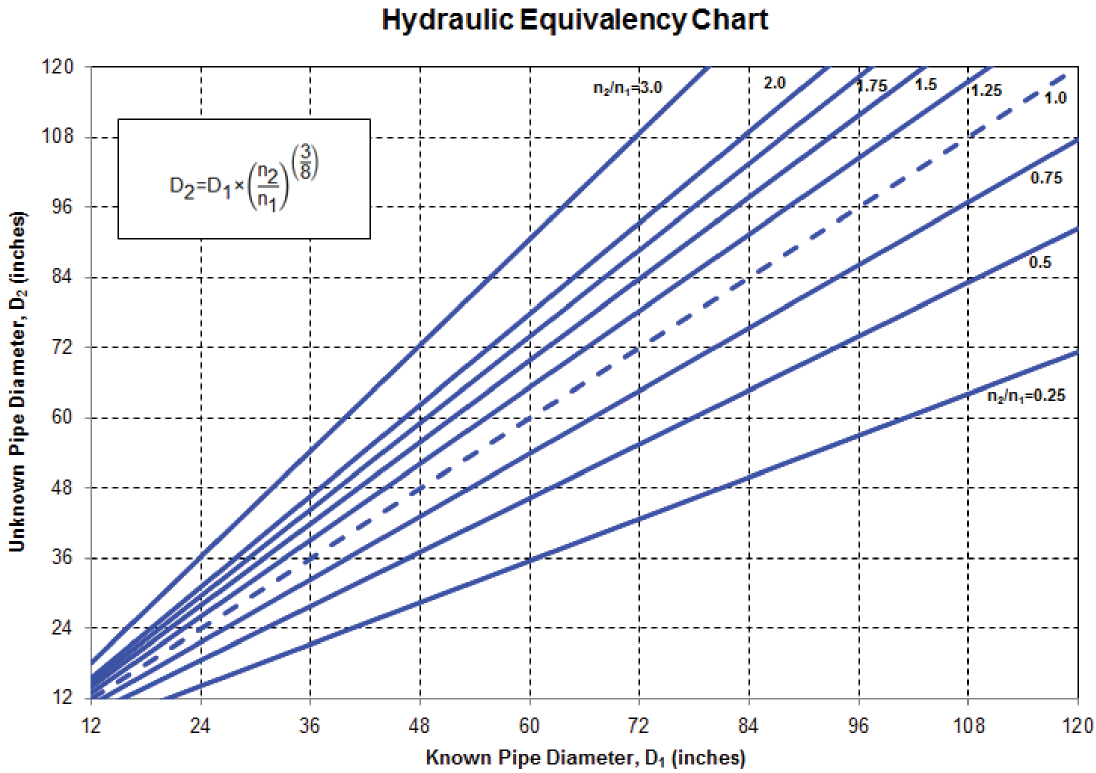
The completion of the hydraulic evaluation step results in each pipe system option being rated as either hydraulically acceptable or unacceptable. This rating is then carried forward to the reporting and presentation of results stage.

The systematic matrix approach of the Recommended Practice is used for tracking the results of each evaluation phase.

While many of these aspects are accounted for in the evaluation of the baseline hydraulic design, the following design aspects are not incorporated directly into the Recommended Practice. These design considerations should either be set in Phase 1 or accounted for in the final design and policy checks completed in Phase 3:

- Flow control and measurement
- Low head installations
- Siphons
- Aquatic organism passage
- Scour at inlets/outlets
- Sedimentation and debris control
- Multiple barrels
- Perforated pipes

As with the other technical evaluation steps, the results matrix presents the evaluation results from the hydraulic evaluation stage. The hydraulic matrix is denoted with "H" identifiers within the box for each pipe system type and highlighted green in cases calculated to be suitable, or highlighted red and crossed out for pipe system options that do not meet the design criteria.



Note
1. Chart based on Manning equation assuming pipe, full flow conditions, constant slope, and constant total flow
2. Actual flow conditions may vary and warrant a more detailed analysis

Figure 25. Hydraulic equivalency chart.

CHAPTER 9

Structural Evaluation

Phase 2B of the Recommended Practice consists of evaluating the structural capacity of each pipe system in the pipe system inventory using the most recent version of the AASHTO LRFD Bridge Design Specifications.

The use of previously prepared minimum and maximum fill height tables is the most practical and efficient means of performing the structural evaluations.

Structural capacity must be checked for each allowable pipe system combination of material type, material class/thickness, bedding and backfill material, bedding and backfill compaction, and installation condition.

In manual applications of the Recommended Practice (without the benefit of software automation), it is recommended that users evaluate pipe system options starting with the lowest available structural class, because structural classes above the minimum approved class are typically acceptable (except in the rare case when the additional wall thickness of the higher class pipe results in a geometric conflict).

Structural evaluation methods (e.g., fill height tables) not in accordance with the current AASHTO LRFD Bridge Design Specifications should not be used in this stage of the Recommended Practice. Such fill height tables should be applied in Phase 3 if agency policy is divergent from current AASHTO standards.

The use of national standards in the technical evaluation stage is one key component of the Recommended Practice, in that it is intended to clearly rely on AASHTO-approved procedures. The intent of completing initial technical evaluations using the latest national standards is to maintain the integrity of the Recommended Practice. Where agencies have not adopted national standards, agency-specific evaluations can be implemented as part of Phase 3.

As with the other technical evaluation steps, a results matrix is used to present the evaluation results from the structural evaluation stage. The structural matrix is denoted with “S” identifiers within the box for each pipe system type and highlighted green in cases calculated to be suitable, or highlighted red and crossed out for pipe system options that do not meet the design criteria.

CHAPTER 10

Durability Evaluation

Phase 2C of the Recommended Practice consists of durability evaluations across all available material pipe types in the user's pipe system inventory.

10.1 Overview of Approach

Highway drainage pipe systems deteriorate over time due to in-service loading and environmental exposure. Processes such as abrasion and corrosion can lead to impairment of structural and hydraulic performance and reduce the service life of drainage pipe systems. A key requirement of a rational process to allow bidding of alternative drainage pipe systems is an ability to predict the service life of a drainage pipe system, that is, the EMSL.

Different methods for estimating EMSL are available in the technical literature and there is no widespread consensus on the most accurate method for any given pipe material type. Different methods will provide different levels of accuracy depending on how similar the conditions are between the pipe systems being evaluated and the pipe systems and conditions included in the development of the method. Additional details regarding application of the recommended EMSL evaluation methods are provided in Appendix C.

Highway drainage structures are designed with the goal of providing a minimum DSL. Different drainage pipe system materials respond to environmental conditions in different ways, and thus have different definitions for when the end of the service life is reached.

For a design to be technically acceptable, the EMSL must be greater than or equal to the DSL.

Durability performance of existing drainage structures in the same watershed or under similar environmental conditions may also be used as a guide to anticipated durability performance. An inspection program and data management system would facilitate the use of in-service durability performance results in the durability evaluation of new systems. Such comparative evaluations are to be considered a complimentary approach, and should be used in conjunction with the quantitative methods described in this chapter.

Durability evaluation in the Recommended Practice is performed in the sequence shown in Figure 26.

10.1.1 Step 1a—Perform Abrasion Evaluation

This step requires use of Table 2 in the Recommended Practice to determine what limitations, if any, on pipe material selection are a result of the abrasion level determination made in Phase 1.

Abrasion potential is a function of several factors, including pipe material, frequency and velocity of flow in the pipe, and composition of the bedload.

The most comprehensive abrasion evaluation methodology is the method developed by Caltrans (White and Hurd 2011). Caltrans defines six levels of abrasion for preliminary estimation of abrasion potential based on flow velocities and bedload characteristics.

Only some of the more relevant factors are considered in Table 2 and additional factors may need to be considered when assessing abrasion potential.

10.1.2 Step 1b—Perform Baseline EMSL Evaluation

Apply the appropriate service life prediction model for the specific pipe material type. While this topic is the subject of on-going research and refinement, the Recommended Practice relies on a range of prediction models that are currently in use, with the recognition that these will be improved over time as more agencies adopt alternative drainage pipe bidding systems and additional applied research is undertaken. Due to the complexity of different pipe materials' performance and associated deterioration mechanisms, not all current prediction models have the same degree of reliability and so caution must be exercised in their application.

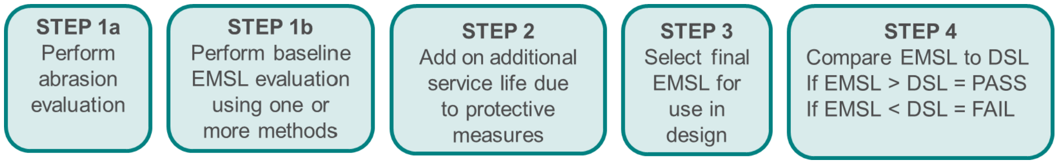


Figure 26. Durability evaluation procedure.

Table 2. Recommended abrasion guidance (from the Recommended Practice).

Level	Pipe Material Guidance
1	No restrictions on material types due to abrasion.
2	Generally, no abrasive resistant protective coatings needed for steel pipe. Polymeric, polymerized asphalt, bituminous coating, or an additional gauge thickness of metal pipe may be specified if existing pipes in the same vicinity have demonstrated susceptibility to abrasion and thickness for structural requirements is inadequate for abrasion potential.
3	Steel pipe may need an abrasive resistant protective coating or additional gauge thickness if existing pipes in the same vicinity have demonstrated susceptibility to abrasion and thickness for structural requirements is inadequate for abrasion potential. Aluminum pipe may require additional gauge thickness for abrasion if thickness for structural requirements is inadequate for abrasion potential. Aluminized steel (Type 2) not recommended without invert protection or increased gauge thickness (equivalent to galv. steel) where pH < 6.5 and resistivity < 20,000.
4	Steel pipe will typically need an abrasive resistant protective coating or may need additional gauge thickness if thickness for structural requirements is inadequate for abrasion potential. Aluminum pipe not recommended. Aluminized steel (Type 2) not recommended without invert protection or increased gauge thickness (wear rate equivalent to galv. steel) where pH < 6.5 and resistivity < 20,000 if thickness for structural requirements is inadequate for abrasion potential. Increase concrete cover over reinforcing steel for reinforced concrete box (RCB) (invert only). Reinforced concrete pipe (RCP) generally not recommended. Corrugated and high density polyethylene (HDPE) (Type S) limited to > 48" min. diameter. Corrugated HDPE Type C not recommended. Corrugated PVC limited to > 18" min. diameter.
5	Aluminum pipe not recommended. Aluminized steel (Type 2) not recommended without invert protection or increased gauge thickness (wear rate equivalent to galv. steel) where pH < 6.5 and resistivity < 20,000 if thickness for structural requirements is inadequate for abrasion potential. Closed profile and Standard Dimensional Ratio (SDR) 35 polyvinyl chloride (PVC) liners are allowed but not recommended for upper range of stone sizes in bedload if freezing conditions are often encountered, otherwise allowed for stone sizes up to 3 in. Most abrasive resistant coatings are not recommended for steel pipe. A concrete invert lining or additional gauge thickness is recommended if thickness for structural requirements is inadequate for abrasion potential. See lining alternatives below. Increase concrete cover over reinforcing steel for RCB (invert only). RCP generally not recommended.
6	Aluminum pipe not recommended. Aluminized steel (Type 2) not recommended without invert protection or increased gauge thickness (wear rate equivalent to galv. steel) where pH < 5.5 and resistivity < 20,000. None of the abrasive resistant protective coatings are recommended for protecting steel pipe. A concrete invert lining and additional gauge thickness is recommended. See lining alternatives below. Corrugated HDPE not recommended. Corrugated and closed profile PVC pipe not recommended. RCP not recommended. Increase concrete cover over reinforcing steel recommended for RCB (invert only) for velocities up to 15 ft/s. RCB not recommended for bedload stone sizes > 3 in. and velocities greater than 15 ft/s unless concrete lining with larger, harder aggregate is placed (see lining alternatives below). SDR 35 PVC liners (> 27 in.) allowed but not recommended for upper range of stone sizes in bedload if freezing conditions are often encountered, otherwise allowed for stone sizes up to 3 in.

Source: Caltrans Highway Design Manual, Table 855.2A.

10.2 Principles and Definitions

DSL requirements are typically based on the type of highway facility and the attendant difficulty of providing repair or replacement. Failure to understand and address the potential effects of aggressive soil/effluent conditions or highly abrasive bedload can shorten the actual service life of a culvert.

The following are some of the influences that must be included in any estimation of service life:

- pH (hydrogen-ion concentration) of the surrounding soil, groundwater, and streamflow
- Resistivity, chloride, and sulfate concentrations in the soil
- Resistivity, chloride, and sulfate concentrations in the groundwater and streamflow
- Size, shape, hardness, and volume of bedload
- Volume, velocity, and frequency of streamflow in the culvert
- Material characteristics of the pipe barrel and any linings for coatings
- Anticipated changes in the watershed upstream of the culvert (such as development, mining, and logging activities)
- Possible effects of severe climates

Tests performed on concrete pipe have generally shown excellent wear characteristics. Although high velocity flow will induce abrasion regardless of the size of bedload particles, tests performed on concrete pipe have shown that cobble and larger sizes will induce higher wear rates than sands and gravels. Larger rocks apparently impact with enough force to break away minute particles of the wall. The use of high quality aggregate (i.e., aggregate that is harder than the anticipated bedload hardness) in the concrete mix can greatly enhance the resistance to wear of the concrete. Likewise, manufacturing methods that lead to a denser concrete mix, such as roller compacted or spun concrete, or higher compressive strength concrete can exhibit increased resistance to wear. Where velocities are known to be high and a bedload is present, additional concrete cover over the reinforcing steel is recommended. The presence of a very high or very low pH environment will accelerate the abrasive effects of any bedload conditions.

Steel culverts are the most susceptible to the dual action of abrasion and corrosion, particularly where thinner walled pipes are used. Abrasion accelerates the normal rates of corrosion by removing protective surface coatings (e.g., an applied protective coating or a previously corroded surface) and exposing fresh metal to renewed corrosion. Once the thin protective coating on a steel pipe is worn away, whether it is zinc or another substance, exposure to low resistivity and/or low pH environments can dramatically shorten the life of a steel culvert. Although aluminum culverts are occasionally specified to combat corrosion, plain aluminum is typically not recommended for abrasive environments because tests indicate that aluminum can abrade as much as three times the rate of steel. Abrasive effects are typically countered in metal pipes by using protective coatings, invert paving, added metal thickness, or a combination of these measures.

Plastic culvert materials (both PVC and HDPE) exhibit good abrasion resistance. Since plastic is not subject to corrosion, it will not experience the dual action of corrosion and abrasion. Plastic pipes, like metal pipes, have relatively thin walls and thus the rate of wear must be carefully evaluated with the material thickness. The documented abrasive resisting capabilities of plastic pipe are primarily based on tests using small aggregate sizes (gravels and sands) flowing at velocities in the range of 2 to 7 ft/s. The effects of large bedload particles (cobbles and larger) and/or high velocity flows are not well defined as a result of limited data. Additionally, because of their more recent emergence as a culvert product, plastic pipes have generally not had rehabilitative strategies developed specifically for them. Some of the more popular current strategies (e.g., invert paving) are not effective with plastic pipes because of the smooth surface of the plastic and an inability to achieve a satisfactory bond.

Although generally unpredictable from a design standpoint, there are other physical factors besides corrosion and abrasion that can shorten the life of drainage culverts. The loss of structural integrity can sometimes be traced to a defect in the manufacture of the pipe, improper construction techniques, or the effects of a large storm event. More commonly, though, the loss of structural integrity occurs over many years and is related to such factors as soil piping, seepage, soil movement, scour, and backfill soil loss. These processes can gradually reduce the culvert strength and support and make it susceptible to catastrophic events such as floods.

Plastic pipe materials are also subject to certain limiting conditions that are a less significant consideration in selecting other culvert types. Among these conditions are use under deep fills, extended exposure to sunlight (specifically ultraviolet radiation) for some types of plastic, and a higher potential for damage from improper handling and installation.

Plastic pipe is also flammable. When used where the potential for roadside brush fires is high, end treatments using concrete headwalls or specially attached end sections will limit the possibility of fire damage.

However, due to their light weight and corresponding ease of handling, plastic pipes lend themselves to installation in remote and/or hard to reach locations where other materials would not be suitable, and they usually have a more rapid installation than heavier products.

Both PVC and HDPE come in ribbed and/or corrugated shapes and smooth, solid-wall profiles; however, culvert and storm drain applications will generally call for the higher strength attained by the ribbed or corrugated designs. Even with the higher strength plastic profiles, material creep is possible, and care must be taken to provide a uniform, compacted backfill around the culvert. In flexible pipe installations, the full strength of the culvert installation relies heavily on the support obtained from the backfill material. Minimum cover applications must also be evaluated carefully when selecting this material.

10.3 Concrete Pipe Systems

10.3.1 DSL

The service life of reinforced concrete pipe is typically the period from installation until reinforcing steel is exposed, or a crack signifying severe distress develops.

10.3.2 Evaluation Methods

The following table lists methods that can be used to determine EMSL values for reinforced concrete pipes. The EMSL values obtained using these different methods can vary widely so the Recommended Practice selects the lowest EMSL value from the methods used. The limitations and range of parameters for which each method is applicable are summarized in the following table:

Methods for Determining EMSLs for Reinforced Concrete Pipe

Durability Method	Reference	Notes
Ohio DOT Model	Potter 1988	Based on large data set over wide range of pH and size values. Includes an abrasive component
Hurd Model	Potter 1988	Method developed for large diameter pipes in acidic environments
Hadipriono Model	Potter 1988	Method includes wide pH range
Florida DOT Model	*Florida DOT, Optional Pipe Materials Handbook, 2012*	Considers corrosion to be the only mechanism of degradation

Concrete culverts are constructed in a large variety of round, elliptical, arch, and rectangular box sizes and have the ability to withstand a wide range of loading and environmental conditions. There are no definitive design methods for estimating concrete culvert service life. As a result, the designer is required to make judgments about the severity of the environmental conditions and the offsetting nature of a variety of design accommodations.

One method of accommodating a harsh environment is the addition of extra sacrificial concrete cover over the reinforcing steel. Typically, where severe abrasion is anticipated, at least 2 in. of additional concrete cover is recommended.

Sulfate-resisting concrete or high density concrete should be used where acids, chlorides, or sulfate concentrations in the surrounding soil or water are detrimental. Generally, if soil and/or water have a pH of 5.5 or less, concrete pipe should be required to have extra cover over the reinforcing steel or a protective coating, and cast-in-place pipe should not be used.

Additional concrete cover is also used to protect reinforcing steel in reinforced concrete pipe in situations where they are exposed to aggressive soils or water. The concrete cover can be increased to inhibit moisture from penetrating to the steel.

10.4 Steel Pipe Systems

The design of metal culverts starts with the selection of the proper thickness to handle the loading conditions. Where corrosion and/or abrasion are expected, design charts and empirical data are used to determine if additional metal thickness (heavier gage) or some type of protective coating will extend the service life to an acceptable range.

With perhaps the greatest variety of shapes and sizes available, including round, elliptical, and arch, there will typically be some metal culvert to fit a given culvert installation. Since metal culverts have been in service for many years, its history of use has enabled researchers to develop relatively well-defined parameters to govern its use and estimated life. Currently, there are more well-defined methods to estimate the service life of steel culverts than any other type of material. Unfortunately, these existing methods deal much more with the potential effects of corrosion than abrasion.

The basic assumptions used to determine service life for standard metal pipes may also be extended to metal structural plate pipes (AASHTO M 167/M 167M for steel and M 219/M 219M for aluminum). One advantage of metal plate is the ability to specify thicker plates for installation in the invert of the structure while keeping the rest of the plates thinner (meeting structural loading requirements only) for economy. This provides greater protection where corrosion and abrasion will typically be most severe.

Protective coatings have been used for many years primarily to protect steel culverts against the effects of corrosive action. Only recently have products become available that exhibit adequate bonding and wearability characteristics that make them attractive for abrasion resistance. Selection of an appropriate coating will require consideration of the pH and resistivity ranges to be encountered (both on the soil and water side of the culvert) and the potential for abrasion. Soil side protection of culverts will often provide up to 25 years of additional service life where conditions are not unduly severe. However, where the primary concern is on the water side, due to the dual action of abrasion and corrosion, additional service life may be as little as 1 to 2 years. Often, a combination of protective coatings is used to increase the expected years of life. Any applied coating is only as good as its bond with the base culvert material.

Zinc galvanizing consists of the application of a thin layer of zinc to the steel by a hot-dip process. This most common protective coating is not particularly abrasion resistant and has been shown to provide corrosion protection primarily when the site pH is within a range of 5.5 to 8.5.

Similar to galvanizing, aluminizing is the hot-dip application of a thin layer of aluminum to both sides of the steel sheet. Unlike galvanizing, the aluminizing process (Type 2 only—conforming to AASHTO M 274M) creates an alloy layer between the exterior aluminum and the steel. The result is a protective coating with abrasive resistant characteristics that are similar to zinc galvanizing.

From a corrosion resistance standpoint, aluminized steel pipe (Type 2) is typically recommended for use when pH values are between 5.0 and 9.0, and resistivity is above 1,500 ohm-cm. Recent data from industry evaluations of in-field performance of culverts with over 40 years of service verify that, within the prescribed environmental limits, aluminized steel pipe (Type 2) can provide effective corrosion resistance.

10.4.1 DSL

The DSL of corrugated metal pipes will normally be the period in years from installation until deterioration reaches the point of either perforation of any point on the culvert or some specified percent of metal loss. Different methods used to estimate service life use different definitions of service life.

10.4.2 Evaluation Methods

10.4.2.1 Galvanized Steel Pipes

A number of methods are available for estimating the EMSL of galvanized steel pipe. The California method is the most widely accepted and is recommended for use if no state- or location-specific research is available that indicates another method is more suitable. The other methods are modifications of the original California method. The following table lists the methods that can be used to determine EMSL values for plain galvanized steel pipes:

Methods for Determining EMSLs for Plain Galvanized Steel Pipe

Durability Method	Reference	Notes
California Method	*California Test 643, Method for Estimating the Service Life of Steel Culverts, 1999*	Includes combined effects of corrosion and abrasion. Based on soil/water pH and resistivity. Service life of pipe considered to be until time of first perforation.
American Iron and Steel Institute (AISI) Method	*Handbook of Steel Drainage and Highway Construction Products, AISI, 1994*	Modification of California Method. Service life of pipe considered to be until 25% thickness loss in the invert.
Federal Lands Highway Method	*Federal Lands Highway, Project Development and Design Manual, 2008*	Modification of California Method. Increase the EMSL by 25% after first perforation.
Colorado DOT Method	*CDOT-2009-11, Development of New Corrosion/Abrasion Guidelines for Selection of Culvert Pipe Materials, 2009*	Calibration of California Method to state-specific conditions with a limited data set.
Florida DOT Method	*Florida DOT Optional Pipe Materials Handbook, 2012*	Modification of California Method to include a minimum steel thickness of 16 gage.

10.4.2.2 Aluminized Type 2 Steel Pipe

The following table lists the methods that can be used to determine EMSL values for aluminized Type 2 steel pipes:

Methods for Determining EMSLs for Aluminized Type 2 Metal Pipe

Durability Method	Reference	Notes
Florida DOT Method	*Florida DOT Optional Pipe Materials Handbook 2012*	Based on anticipated soil/water pH and resistivity

10.5 Aluminum Pipe Systems

The following table lists the methods that can be used to determine EMSL values for aluminum pipes:

Methods for Determining EMSLs for Aluminum Pipe

Durability Method	Reference	Notes
Florida DOT Method	*Florida DOT Optional Pipe Materials Handbook 2012*	Based on estimated corrosion rates due to pH and resistivity

When installed within acceptable pH and soil resistivity ranges (typically 4.0 to 9.0 and > 500 ohm-cm, respectively) aluminum pipe (AASHTO M 196/M 196M) can provide a significant advantage over plain, galvanized steel pipe from a corrosion standpoint. It is therefore possible to use aluminum pipe in lieu of a thicker walled or coated (and thus more expensive) steel pipe.

Because aluminum is softer than steel, it is more susceptible to the effects of abrasion. This is particularly true for higher velocity flows that produce a scraping action, as opposed to lower velocity flows that allow the bedload to roll over the culvert surface. Where high velocity flows (15 ft/s or greater) carrying a bedload are prevalent, use of aluminum should be carefully evaluated. As with all metal pipes, invert loss is caused by a combination of abrasion and corrosion and, thus, the severity of both conditions must be considered.

10.6 Thermoplastic Pipe Systems

The most commonly used thermoplastics are PVC and HDPE. These materials are largely resistant to the chemical and corrosive elements typically found in soils.

Empirical data regarding the durability of thermoplastic pipes is limited when compared with the data available for pipe material types that have longer histories of service.

Slow crack growth and oxidative/chemical failure have been identified as the primary long term failure mechanisms for corrugated HDPE pipes, but no methods based on service histories have yet been developed for serviceable life predictions for these materials.

The long term performance of thermoplastic pipes is highly dependent on the quality of the installation. Estimated service lives assume that pipes are installed in compliance with specifications and that such compliance is confirmed by post-installation inspection.

Agencies typically assign an estimated service life of between 50 and 100 years for thermoplastic pipes manufactured in accordance with the relevant AASHTO standards and installed in accordance with relevant specifications.

10.7 HDPE Pipe Systems

10.7.1 DSL

The service life of thermoplastic pipe may be considered at an end when excessive cracking, perforation or deflection has occurred.

Generally constructed with helical, annular corrugated, or ribbed profiles according to either AASHTO M294 or ASTM F894, HDPE pipes are available in round configurations only.

Due to its ability to withstand corrosive attack, HDPE pipe has found wide use in mining applications and other severe environment locations. Where HDPE has its major weakness is where high temperatures are of concern. Material creep can occur where water temperatures exceed 140°F (extremely rare for culvert or storm drain applications). HDPE compounds used in pipe manufacture are combined with ultra-violet inhibitors that help retard ultraviolet degradation and are not subject to the long term exposure problems that some other plastics can experience.

Joints for HDPE pipe are available in both band type (split couplers) and tongue and groove designs. It is often recommended that a factory applied neoprene gasket or construction applied filter fabric wrap be used at the joints to enhance the soil tightness of the split coupler design.

10.8 PVC Pipe Systems

10.8.1 DSL

The service life of thermoplastic pipe may be considered at an end when excessive cracking, perforation, or deflection has occurred.

Generally similar in application to the more commonly used HDPE pipe, PVC pipe (AASHTO M304) is equally resistant to corrosive environments and only slightly more susceptible to abrasion, particularly where pH is very low (<4). However, considering the typically greater pipe wall thickness of PVC compared with HDPE, service life can be equal if not longer.

Typically available in a ribbed, corrugated, or profile wall (either open or closed cell) design, PVC's higher stiffness will generally allow its use under deeper embankments than HDPE pipe of similar configuration. PVC pipe for culvert and storm drain applications is available only in round configurations.

PVC pipe products do not usually incorporate a high level of ultraviolet light inhibitors; thus, they can be susceptible to long term breakdown when continuously exposed to sunlight. Typically, this translates to brittle material (impact resistance is reduced, but tensile strength is only minimally affected) at exposed culvert ends, and is one reason why PVC is more popular in storm drains than in culvert applications. Exposure issues can be overcome to a large degree if concrete endwalls are used or where corrugated metal pipes are used at the exposed culvert ends. PVC pipe will also become brittle from exposure to cold (less than 37°F) temperatures. This requires that extra care be taken when handling the pipes if installations will take place during the winter season.

10.9 Other Rigid Pipe Materials

The following other (non-concrete) rigid pipe materials are used to a lesser extent in highway drainage practice for new installations and/or are present in historic in-service inventories:

- Ductile iron pipe
- Fiberglass pipe
- Vitrified clay pipe

The EMSL values for these materials can be established by past performance history or by application of the above listed methods for pipes with equivalent component materials. In the absence of reliable prediction models, it would be prudent to assign conservative EMSL values, in consultation with the pipe suppliers, until further research and documented case studies are available or until evaluation methods become available and widely accepted.

10.10 Other Flexible Pipe Materials

The following other (i.e., non-metal, HDPE, or PVC) flexible pipe materials are used to a lesser extent in highway drainage practice for new installations and/or are present in historic in-service inventories:

- Metal reinforced HDPE pipe
- Polypropylene pipe
- Fiberglass pipe (can be rigid or flexible dependent on installation)

The EMSL values for these materials can be established by past performance history or by application of the above listed methods for pipes with equivalent component materials. In the absence of reliable prediction models, it would be prudent to assign conservative EMSL values, in consultation with the pipe suppliers, until further research and documented case studies are available or until evaluation methods become available and widely accepted.

10.10.1 Step 2—Add-On Additional Service Life Due to Protective Measures

Coatings and or invert protection are often applied to culvert pipes (predominantly to metal pipes) to increase their service life. Many different coatings exist, the main types of which are listed below:

- Asphaltic/Bituminous
- Fiber-bonded bituminous
- Asphaltic mastic
- Polymerized asphalt
- Polymeric sheet
- Concrete

Guidance on the additional service life due to the application of coatings on corrugated steel pipes can be found in the most recent version of the National Corrugated Steel Pipe Association (NCSPA) Pipe Selection Guide (NCSPA 2010). Predetermined service life add-on values depend on the abrasion characteristics and type of coating. Add-on service life year values typically range from 10 to 80 years. A table summarizing recommended service life add-ons for supplemental pavings and coatings recommended by the metal pipe industry (NCSPA 2010) is shown in Figure 27.

10.10.1.1 Asphaltic Coatings

Several different types of asphaltic-based coatings are currently being used. Most do not provide extensive protection against abrasion but can be applied to both metal and concrete culverts. Coating thickness is typically measured over the inner crests of the corrugations on metal pipe. Because of the limited abrasion resistance, these coatings provide their greatest benefit where soil side corrosion is the most likely item of concern or where bedload is not present.

Besides limited abrasion resistance, most asphalt coatings experience problems where the culvert is exposed to sunlight. Ultraviolet rays and temperature extremes often result in the development of cracks that expose the bare metal and eventually break the bond of the coating. However, asphalt does not appear to be affected by the various ranges of pH typically encountered in culvert installations.

Asphalt coatings can be flammable. Where the risk of fire is high, concrete end walls or other "insulating" end treatments should be considered. All asphalt coatings require that special

SERVICE LIFE ADD-ONS FOR SUPPLEMENTAL PAVINGS AND COATINGS				
COATING MATERIAL	FHWA ABRASION LEVEL			
	1	2	3	4
	Add-on Service Life (Years)			
Asphalt Coated	10	10	N/R	N/R
Asphalt Lined and Paved	30	30	30	30
Polymerized Asphalt Invert Coated	45	45	35	N/R
Polymer Coated and Paved	80+	80+	80+	30
Polymer Coated with Polymerized Asphalt Invert Coated	80+	80+	80+	30
High Strength Concrete Lined	75	75	50	N/R
Concrete Paved	80+	80+	80+	50

Figure 27. NCSPA recommended values for service life add-ons provided by supplemental pavings and coatings (NCSPA 2010).

care be taken during the application process. The pipe must be cleaned thoroughly and brought to an elevated temperature to ensure proper bonding to the culvert. Special care should also be taken during shipping and installation to ensure that the coating is not damaged or removed.

10.10.1.2 Bituminous

The most common asphalt coating is the hot-dip application (ASTM A 849) of bituminous material (AASHTO M 190M). This type of coating often covers the entire inside and outside of the culvert and provides corrosion protection. Typical minimum application thickness is 0.05 in. This typical application provides very little protection against abrasion, and where flow velocities exceed 6.5 ft/s will provide almost no additional service life. To improve the abrasive characteristics of bituminous coatings, the addition of extra thickness of bituminous material over the entire inside (bituminous lining) or only the invert area (bituminous invert paving) may be specified. This type of treatment will typically involve asphalt paving to provide a minimum thickness of ⅛ in. above the crest of the corrugations for at least 25 percent of the circumference of round pipe and 40 percent of the circumference for pipe arch.

Due to both the air quality concerns over the hot-dipping process and the water quality concerns related to bitumen impact on fish habitat, some regulatory agencies have placed restrictions on the use of bituminous coatings, and their use in practice is decreasing.

10.10.1.3 Fiber Bonded Bituminous

To create better bonding characteristics so that the bituminous coating will better withstand severe environments, a fiber mat is embedded into molten zinc galvanizing while it is being applied to steel sheets. Asbestos has been used as the fiber material but is generally being replaced with newer materials, such as aramid (ASTM A 885). Bituminous material is then applied in the standard fashion, developing a strong bond with the protruding fibers.

Although still not highly resistive to abrasion, this process does enhance the corrosion resistance of metal pipes in severe conditions. Marine environments are typical of the conditions that can make fiber bonded pipe cost-effective.

10.10.1.4 Asphalt Mastic

Asphalt mastic (AASHTO M 243M) is typically not used in conjunction with lining or invert paving. Asphalt mastic can be substituted for bituminous coatings and is applied (ASTM A 849) to the same minimum thickness with a spray application. Like bituminous coatings, there are environmental concerns regarding its use and abrasion resistance is minimal.

10.10.1.5 Polymerized Asphalt

Polymerized asphalt (ASTM A 742/A 742M) is primarily an abrasion resistive coating that will provide some corrosion resistance benefits for metal pipes. Applied in a hot-dip process (ASTM A 849) to a minimum thickness of approximately 0.05 in., polymerized asphalt is applied to only a 90 degree portion of the pipe that is centered about the invert.

Independent testing has indicated a service life extension of several times that of bituminous coatings. Since only a portion of the pipe is coated, extensive soil side corrosion concerns, continuous immersion, or use near saltwater environments may pose problems. However, the polymerized asphalt is compatible with other asphalt coatings in combination and has received acceptance from some environmental regulatory agencies.

10.10.1.6 Polymeric Sheet Coating

Protection to metal culvert pipes can be provided by polymer coatings, which have good corrosive resisting properties. A laminate film is applied over the protective metallic coating (typically galvanizing) and is generally 10 to 12 mils thick (0.01 to 0.012 in.). The coating is often applied on both sides of the pipe (water and soil sides) but can also be applied to only one side, and is applied to the steel prior to corrugating. Polymer coatings also typically provide more abrasion resistance than bituminous coatings provide.

Independent studies of the durability of these coatings are not available and guidance on the use of polymeric coatings is given by industry and trade groups representing manufacturers and suppliers of polymer coatings. The NCSPA 2012 report on the performance of polymer coated steel pipes does however present performance inspection data across a wide range of environments from studies conducted in parallel with a number of state agencies.

pH, resistivity, and abrasion level (FHWA) are typically used to determine the most appropriate coating type for a specified service life. Polymer coatings are not recommended for use in applications where the FHWA abrasion level is greater than 3.

One drawback of polymer coatings is that they are susceptible to damage from impacts and gouging, with the damage to the coating typically occurring during construction and installation. Where damage has occurred, the pipe wall will not be supplementarily protected leading to localized increased rates of corrosion. Corrosion will typically not spread away from the area of initial localized damage. A solution to this problem is to apply a touch-up after construction, however, the quality and consistency of these repairs remains a concern for many agencies.

10.10.1.7 Concrete Coatings

Primarily used with metal culverts (ASTM A 849) to act as sacrificial material for abrasion resistance, concrete can be placed in the invert area of the pipe to a thickness of between 3 and 6 in. The thickness and width of coverage are variable, based on typical flow depth and anticipated abrasive potential. Although the concrete may be placed directly against clean pipe material, steel reinforcing bars or wire fabric is often welded to the metal pipe before concrete placement.

10.10.2 Step 3—Select Final EMSL

This step requires selection of EMSL Values for use in design evaluations. Where more than one method of estimated EMSL is used, to allow for automation in the process, the Recommended Practice selects the lowest EMSL values for use in design.

10.10.3 Step 4—Compare EMSL to DSL

The EMSL design value obtained from the previous step is then compared with the DSL. If the EMSL is greater than the DSL, then the pipe option is determined to be acceptable from a durability standpoint. If the EMSL is less than the DSL, the pipe option does not meet the durability evaluation criteria and is eliminated.

Failure of individual pipe systems to meet durability requirements will not disqualify entire pipe classifications, as other similar pipe system options that provide higher EMSL values based on increased wall thickness, additional/different coating, improved concrete mix design, or other factors will be independently assessed against the DSL.

No currently available method provides the designer with an exact estimate of service life. One of the best ways to estimate service life is to investigate existing drainage facilities near the project site. Unless upstream watershed characteristics have been altered since existing culverts have been installed, to include new aggressive conditions, investigations that show a particular pipe product has successfully met or exceeded its DSL (or has shown such minor deterioration over a lesser period of years to indicate the capability of attaining or surpassing the DSL) in a like environment will give the designer more useful information than other service life analyses.

Service life can also be affected by debris damage or erosion caused by major storm events, improper manufacture or handling of the culvert, and incorrect laying or backfilling of the culvert. These issues may often be the cause of culvert distress or failure, but are difficult to predict and are not currently accounted for in estimating service life.

CHAPTER 11

Final Check and Policy Application

Phase 3 of the Recommended Practice is to perform final design checks on the output from Phase 2, and to compare the results of the Recommended Practice with existing agency policies. It is anticipated that only pipe system options meeting the requirements of all three technical evaluation stages will be carried forward into Phase 3 for completion of final design and policy checks.

11.1 Final Design Checks

Output from Phase 2 should be reviewed by the engineer to

- Identify possible errors and inconsistencies.
- Develop alternative designs that are outside the scope of the standard Recommended Practice (e.g., multiple barrels, aquatic organism passage).
- If desired, hydraulic design checks can be considered during this final check phase if generalized Manning's *n*, equivalency charts, or other generalizations were applied for efficiency in the initial technical evaluations.

The engineer should record why any options considered technically valid through the technical evaluations are not being forwarded into Phase 4. The engineer should record why any options not proposed by the Recommended Practice are being added for inclusion in Phase 4.

11.2 Agency Policy Checks

The engineer should compare the output from Phase 2 and any adjustments made during final design checks with the drainage pipe system options allowed by the agency for the given application. Policy may dictate or restrict pipe size, pipe class, pipe material, backfill type, minimum or maximum fill height, and so forth as a matter of policy and those systems evaluated to meet the technical design criteria but not meet policy guidelines will be eliminated from further consideration in this phase.

If AASHTO or FHWA standards have not been implemented as agency policy for hydraulic, structural, and/or durability evaluations, the previous evaluations should be checked against current agency policy in this stage. The intent of separating agency-specific policy evaluations from the initial technical evaluations is to promote greater standardization and adoption of national standards, and/or to identify areas for refinement of national standards to meet the range of needs expressed by all AASHTO agencies.

The reason for elimination of a pipe drainage system in the final policy check phase should be recorded to provide full transparency in the design process. It is recommended that adopting agencies regularly review the list of final check eliminations to allow for evaluation and optimization of agency policies.

11.2.1 Presentation of Results

As with the technical evaluation steps, a results matrix is used to present the evaluation results from the final design and policy check stage. The final check matrix is denoted with "F" identifiers within the box for each pipe system type and highlighted green in cases calculated to be suitable for inclusion in bid documents, or highlighted red and crossed out for pipe system options that do not meet all the design and policy criteria.

CHAPTER 12

Results and Bidding

12.1 Summary and Reporting of Evaluation Results

One of the defining principles of the Recommended Practice is to promote transparency in the design and selection of drainage pipe systems. Transparency in the process is achieved by presentation of technical and policy evaluations in a systematic and clear manner across the full range of available pipe systems.

The output from the evaluations performed as part of the Recommended Practice consists of a large amount of data and the summary and reporting of this information is best managed through a systematic process. It is proposed that the pipe system evaluation results be presented via a graphically coded matrix to allow the design engineer, technical reviewers, and other users of the Recommended Practice (bidders, contract managers, estimators, agency engineers, and construction inspectors) to conduct a visual review of the results.

Transparency and data organization are achieved in the Recommended Practice through the use of the results matrix, which provides a clear and systematic process for recording the adequacy of each pipe system considered versus the various technical and policy criteria. The matrix approach provides a means to conduct a rapid evaluation and check of results through visual recognition and review of patterns within the matrix results. Adjacent rows contain similar pipe systems, and adjacent columns contain similar sizes such that continuous zones of pass and fail for the various technical and final criteria should be apparent in the final results matrices.

The final results from the application of the Recommended Practice can be converted into a streamlined tender code for bidding purposes, as detailed in Section 11 of the Recommended Practice.

In addition to the results matrices that depict the end result of the three technical evaluations and overall final and policy evaluation, it is important that calculations and other back-up design and decision information relied on are recorded and stored for future reference in line with other document control standards for engineering designs. The Recommended Practice does not specifically recommend the level or manner in which back-up information is stored, but rather recommends storage and record keeping in line with existing agency standards and protocols.

The main purpose of providing good documentation is to define the design procedure that was used and to show how the final design and decisions were determined. Documentation should be viewed as the record of reasonable and prudent design analysis based on the best available technology.

12.2 Incorporation of Alternatives into Bid Documents

Each agency typically has a detailed and multi-faceted system for bidding highway projects that involves cooperation and coordination amongst multiple agency departments and often coordination with multiple national review and funding agencies. As such, the Recommended Practice is intended to maintain flexibility for each adopting agency to develop the optimum manner for integration of results from the Recommended Practice into bid and tender documents.

12.2.1 Tender Code

The result of the Recommended Practice is a complete list of technically acceptable pipe system alternatives for a specific drainage application. To facilitate management of long lists of alternative pipe type data, the information can be summarized into a concise alphanumeric code format suitable for use by designers, consultants, estimators, contractors, pipe suppliers, and project managers. This code is termed the tender code. While it is not necessary to use the code with the Recommended Practice, it may be a helpful option for some user agencies.

The tender code is divided into three main parts: a minimum pipe diameter for smooth pipe (generic Manning's *n* of 0.012),

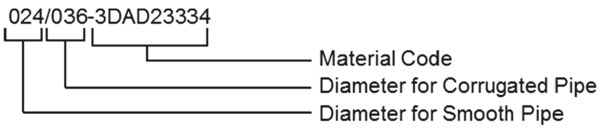


Figure 28. Format of a tender code.

a minimum pipe diameter for corrugated pipe (generic Manning's *n* of 0.024), and a material code. The use of these generic Manning's *n* numbers is recommended; however, other Manning's *n* values could be used. An example tender code is shown in Figure 28.

12.2.1.1 Diameter for Baseline Smooth Pipe

The first element of the code is a three digit number specifying the minimum equivalent circular diameter for the baseline smooth circular pipe case using a Manning's *n* of 0.012.

12.2.1.2 Diameter for Baseline Corrugated Pipe

The second element of the code is a three digit number specifying the minimum equivalent circular diameter for the baseline corrugated circular pipe case using a Manning's *n* of 0.024.

12.2.1.3 Material Code

The material code is a nine digit code that specifies what materials are allowed. Each digit position represents a different pipe material. The value in each position specifies a particular class of pipe, wall thickness, or stiffness rating. Figure 29 below shows all the options for the material code portion of the tender code.

The material code is interpreted in the following way:

- A zero in any position indicates that a particular pipe material is not technically suitable or allowed across all pipe system combinations evaluated for that pipe material type.
- An "X" in any position indicates that that pipe material type was not evaluated during the performance of the Recommended Practice.
- The minimum class technically suitable across the range of installation conditions is always specified, with higher classes being allowed. For example, if a Class 2 pipe is specified as the minimum, a Class 3 pipe would also be deemed acceptable.
- To streamline the tender code into a manageable length, only the minimum pipe class is listed for each pipe material type. Because of this presentational efficiency, bidders will need to confirm the installation requirements to use the minimum listed pipe class, and may want to bid the system with a higher class pipe that may have less stringent installation requirements.
- The 1st digit represents concrete pipe. Five classes of reinforced concrete pipe can be specified with the numbers 1 through 5. Unreinforced concrete can be specified using the letter "U" and the need for a special design is indicated with the letter "S."
- The 2nd digit represents HDPE pipe. Three different wall profiles are allowed: profile, corrugated, and solid wall. Profile wall pipe is specified using one of six ring stiffness

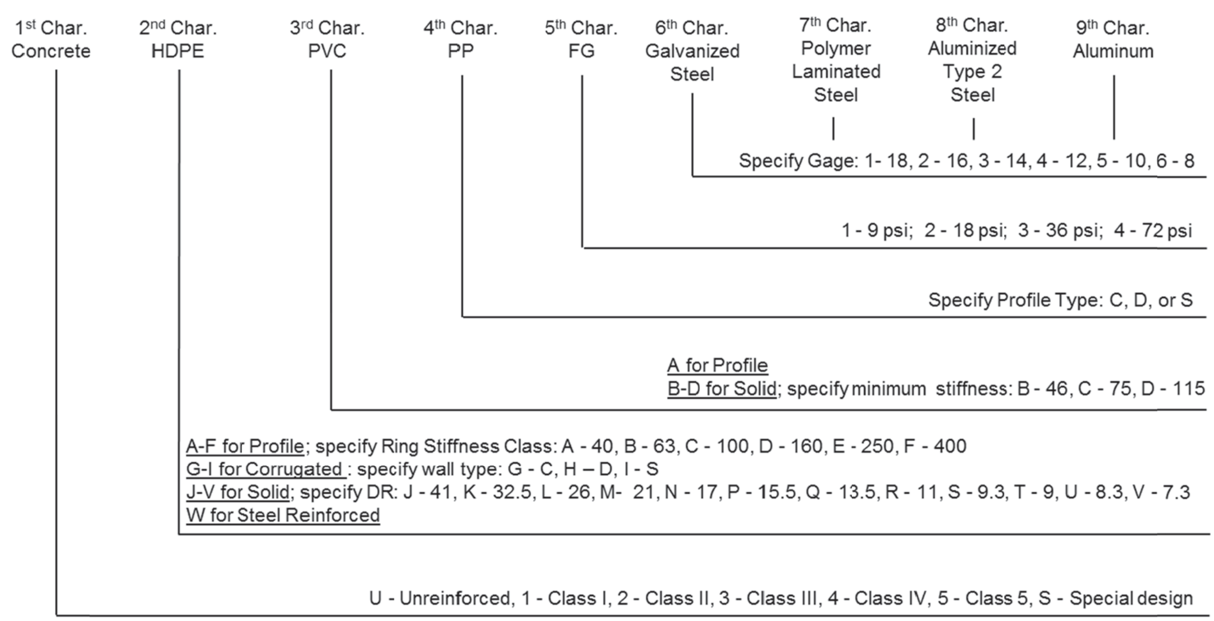


Figure 29. Material code summary.

constants (RSC). Corrugated wall pipe is specified using one of three profile shapes defined in AASHTO M294 as Type C, Type D, and Type S. Solid wall pipe is specified using one of twelve dimension ratios (DRs). A minimum DR is specified. A letter is used to represent each pipe option as shown in Figure 29. For example, a "D" would indicate that a profile wall pipe with a minimum RSC of 160 was being specified. A "W" indicates that steel reinforced polyethylene is being specified. Note that the letter "O" is not included in the code so as not to be confused with the number zero.

Three different systems are used for specifying the dimensions of solid wall HDPE pipe. Any of these systems can be used with this code system.

- The 3rd digit represents PVC pipe. Profile wall pipe can be specified using the letter "A" and solid wall pipe can be specified using the letters "B" through "D" corresponding to three different pipe stiffness classes.
- The 4th digit represents polypropylene (PP) pipe. This pipe is specified using one of three profile shapes, defined in AASHTO MP-21 as Type C, Type D, and Type S.

  Polypropylene pipe is currently not listed as an available pipe type in the AASHTO LRFD Bridge Design Specifications.
- The 5th digit represents glass fiber reinforced pipe and can be specified in one of four pipe stiffness classes; 9, 18, 36, and 72 psi.
- The 6th, 7th, 8th, and 9th digits represent galvanized steel, polymer laminated steel, aluminized Type 2 steel, and aluminum pipe, respectively. Each of these material options is specified by the minimum gage thickness of the wall.

It is noted that to provide a code of realistic length for incorporation and use in bid documents some details regarding the suitability of particular pipe system options such as installation class, installation type, pipe lining, pipe roughness values, other than baseline smooth and corrugated are not uniquely identified in the code. Bidders will be required to refer to the final results matrix (or conduct independent evaluations) to determine which combinations of those factors are suitable for the given performance criteria.

If bidders wish to use larger pipe systems than the minimum specified in the tender documents, it is recommended that a submittal process be used to evaluate these cases.

12.2.2 Tracking of Bid Results

The Recommended Practice strongly recommends that agencies record and database bid results such that regular and systematic evaluations of bid results can be made that allow for evaluation of the impact of Recommended Practice implementation, and also to provide insight into bid trends to direct and guide policy updates as appropriate.

CHAPTER 13

Installation, Maintenance, and Tracking

One of the main objectives of the Recommended Practice is to encourage highway agencies to allow contractors to bid on a wider range of alternative pipe products and systems. Without an associated appropriate and adequate post-installation inspection protocol, the risk of premature failure of pipe systems will increase. In this context, post-installation inspection is not an optional extra for the Recommended Practice and must be seen as an essential component of implementation. All the pipe system evaluation components within the Recommended Practice are based on the assumption that the pipe system was installed in compliance with agency specifications.

Phase 5 of the Recommended Practice describes recommended steps and actions related to overall quality control, inspection, and tracking. Recommended actions for the five main steps in this phase are described in the following subsections.

13.1 Material and Construction Quality Assurance

13.1.1 Material Quality Assurance

The standard of practice includes checks of all construction materials for conformance with the relevant AASHTO and state agency standards. Qualification of manufacturer and manufacturing facility should be performed, together with review of certificates. Inspection of deliveries, which may include inspection of identification markings, date of manufacture, shipping papers, diameter, net length, evidence of poor workmanship, damage during shipping or handling, and measurement of surface cracks, should also be performed.

13.1.2 Construction Quality Assurance

Federally funded roadway construction projects are supposed to be performed in accordance with AASHTO standards, in particular the AASHTO LRFD Bridge Construction Specifications.

Inspection of the pipe system materials and workmanship during construction allows corrections to be made in assembly and backfill practices before construction is complete, and is of particular importance for deeply buried and high traffic installations. The timing and frequency of such inspections should depend on the significance of the structure and depth of fill. In general, inspections should be conducted when materials arrive at the job site, during pipe installation, during backfilling, and before construction of final finishes. Inspections during construction may include examination of the following:

- Foundation material
- Trench geometry and dimensions
- Groundwater conditions
- Bedding material
- Line and grade
- Assembly techniques
- Structure backfill and compaction methods
- Joint assembly and materials
- Pipe deflection (during construction)
- Damage to pipe coatings

13.2 Post-Installation Inspection and Approval

Different pipe materials may require different post-installation inspection and approval procedures due to the inherent differences in the modes of material behavior. Pipe materials are recommended to be inspected in accordance with the appropriate chapter of the AASHTO LRFD Bridge Construction Specifications:

- Metal Pipe—Chapter 26
- Concrete Pipe—Chapter 27
- Thermoplastic Pipe—Chapter 30

13.3 Long Term Inspection and Maintenance

Inspection of drainage pipe systems should be performed in accordance with the FHWA Culvert Inspection Manual (1986).

NCHRP Project 14-26, Culvert and Storm Drain System Inspection Manual, is revising this guidance and is expected to be complete in fall 2015.

13.3.1 Tracking of Actual Performance

Collection of performance data will assist designers, researchers, and policy makers to refine durability evaluation models and pipe selection criteria. Collection of this data should be performed using the guidance from the Asset Management Data Collection Guide (AASHTO 2006).

At a minimum the following information on each culvert should be recorded during each major inspection:

- Environmental parameters of surface water flow in the system
- Condition assessment
- Deflection (for flexible pipe) or joint (for rigid pipe) inspection

13.4 Performance Feedback

State agencies are encouraged to consider tracking and evaluation of findings from implementation of the Recommended Practice and other aspects of highway drainage design, construction, and maintenance to allow for continual improvement and refinement of agency policies. Additionally, sharing performance feedback through national surveys, AASHTO and TRB committees, and other mechanisms helps advance the state of knowledge and practice.

CHAPTER 14

Implementation of the Recommended Practice

Implementing an alternative pipe system selection and bidding process gives contractors the ability to choose from among alternative drainage pipe systems that are of satisfactory quality and are equally acceptable to the owner. This will promote competition and lower costs, and is the primary driver pushing the implementation of such a system. The previous federal mandate (23 CFR 635.411) that required competition with respect to the specification of alternative types of drainage pipe systems judged to be of satisfactory quality and equally acceptable on the basis of engineering and economic analyses was eliminated with the signing of MAP-21 in July 2012. Specifically, 23 CFR 635.411 was revised to ensure that states have the autonomy to determine culvert and storm sewer material types. Regardless of this change to the federal regulations that eliminates the mandatory requirement for competition with respect to alternative types of drainage pipe systems on projects receiving federal funding, the underlying economic and technical merits of alternative pipe bidding that gave rise to the original desire to increase competition through alternative bidding have not changed.

14.1 Implementation Strategy

The overarching strategy for successful adoption of the Recommended Practice is to provide key decision-makers in stakeholder organizations with a credible and persuasive value proposition. The value proposition will clearly and specifically communicate how their organizations will benefit from adopting the Recommended Practice.

Providing relevant examples of the benefits and costs associated with adopting the Recommended Practice will be essential to developing a credible value proposition. This leads to a multi-stage implementation strategy, with the initial phase focused on those stakeholders that will likely derive the most value from adopting the Recommended Practice, and progressively focusing on stakeholders who may perceive the Recommended Practice as providing lesser value to their organizations.

14.2 Key Benefits of Adopting the Recommended Practice

The Recommend Practice has several key characteristics that are intended to provide value to stakeholders:

- Comprehensive framework for increasing competition in pipe system selection with a resulting reduction in overall costs to the agency
- Streamlined, technically sound, and consistent approach to pipe system selection
- Integrated use of best available practices
- Expandable framework enabling modifications when new methods and materials are developed
- Flexible framework enabling extensive customization to address individual agency needs

14.3 Stakeholder Identification

Different stakeholder groups will provide varied opportunities and challenges to successful widespread adoption of the Recommended Practice. Thus, identifying stakeholders who will be involved in decisions directly impacting the successful adoption of the Recommended Practice is an important element of implantation.

The following stakeholder organizations and personnel groupings have been identified as important to successful adoption of the Recommended Practice:

- State and local transportation agencies
  - Engineering departments
    - Materials
    - Geometric Design
    - Drainage
    - Structural
    - Geotechnical
  - Maintenance departments
  - Programming, estimating, and contracts departments

- Owner agencies, associations, and policy makers
  - AASHTO (including subcommittees)
  - ACEC
  - ASCE
  - ASTM
  - FHWA
  - NAS/TRB/NCHRP
- Industry
  - Trade and industry associations
    - American Concrete Pipe Association (ACPA)
    - American Water Works Association (AWWA)
    - National Corrugated Steel Pipe Association (NCSPA)
    - Plastic Pipe Institute (PPI)
    - Uni-Bell PVC Pipe Association
  - Pipe manufacturers
  - Pipe suppliers
  - Contractors and pipe installers
- Engineering consulting and design firms
- Academic practitioners and researchers

14.4 Implementation Steps

The following subsection outlines the current thinking on how best to develop the implementation plan. The implementation process outlined in the following subsections highlights the importance of engaging across all stakeholder groups, and proposes to engage the identified stakeholder groups at appropriate points throughout the implementation plan.

The following subsections are organized by stakeholder groups. This layout is intended to provide an accessible framework to facilitate panel and other stakeholder input, and to approximate the chronological order in which the plan may be developed. The actual implementation will be a fluid process without sharply defined stages and groups.

14.4.1 Early Adopter State DOTs

This implementation stage is focused on those DOTs that have been involved in any aspect of this project, and those DOTs that have expressed a particular interest in the results of the project regardless of their involvement to date.

The goal in this stage will be to demonstrate the potential value derived from use of the Recommended Practice and to assist these early adopter DOTs in implementing the Recommended Practice on a limited number of projects. It is suggested that an online webinar be conducted early in this phase to summarize the technical, financial, and performance benefits of the Recommended Practice. The lessons learned from the feedback from this first stage and the demonstrated benefits from using the Recommended Practice on the pilot projects will be used to modify subsequent stages as needed.

Potential steps to focus on these stakeholders are as follows:

- Maintain relationships developed through the pilot project phase of NCHRP Project 10-86.
- Host recorded webinars to disseminate information and provide practical help with implementation. These recorded webinars can be accessed at a later date at the convenience of the stakeholder.
- Provide a practical manual or guidebook for use as a quick-reference supplement to the final project deliverable to aid in implementation.
- Conduct in person or small group web meetings to discuss and assist with implementation.

The parties executing the implementation plan stage would likely engage in some or all of the following steps:

- Preparation of materials outlining the value to be derived from adoption
- Presentation and discussion of the materials through webinars or live meetings
- Preparation of materials to assist in actual implementation (practical manual or guidebook to use as a quick-reference supplement to the final project deliverable)
- Support, as needed, to implement the Recommended Practice on a limited number of projects

14.4.2 Additional DOTs

This stage is focused on providing information and training to additional DOTs who were initially hesitant to adopt the Recommended Practice. The likely target audience will be local agencies, drainage design engineers, materials engineers, and estimating/contracts personnel from DOTs that have not yet adopted the Recommended Practice. The plan should address how best to promote the Recommended Practice on the basis of it delivering more cost-effective drainage solutions with a minimal amount of staff re-training.

Lessons learned from the implementation of the Recommended Practice with the early adopter DOTs will be applied. Benefits derived from the Recommended Practice by the early adopter DOTs will be collated into a clearly communicable package.

Potential steps for these stakeholders to focus on include the following:

- Information provided to inform and allow for internal dissemination within DOTs
  - Electronic and printed materials and brochures
  - Written testimonials from early adopter DOTs
  - Presentations, recorded and hard copy, prepared to facilitate internal discussion on the Recommended Practice

(assuming that a champion at a specific DOT can be identified)
- Training opportunities
  – Hosted and recorded webinars
  – Workshops at conferences and conventions

14.4.3 Industry Stakeholders

As the Recommended Practice is implemented by the early adopter DOTs, it will be necessary to provide information and training to other industry stakeholders. The target audiences include trade association representatives, contractors, pipe manufacturers, and pipe suppliers. The implementation plan should seek to engage these groups through exposure to the details and benefits of the Recommended Practice.

The promotion of the Recommended Practice will be achieved through the following:

- Technical conference presentations
- Hosted webinars
- Printed materials
- Distribution of white papers
- Local industry and professional meetings
- Articles in trade publications

14.4.4 Owner Agencies, Associations, and Policy Makers

Potential steps for these stakeholders to focus on include the following:

- Engagement of AASHTO subcommittees (Standing Committee on Materials)
- Presentations at conferences and conventions
- Articles in academic journals
- Articles in trade publications

14.4.5 Engineering, Consulting, and Design Firms

Potential steps for these stakeholders to focus on include the following:

- Presentations at conferences and conventions
- Articles in academic journals
- Articles in trade publications

14.5 Academic Practitioners and Researchers

Potential steps for these stakeholders to focus on include the following:

- Presentations at conferences
- Articles in academic journals
- Opportunities to include research results in future updates to the Recommended Practice
- Sponsored events at conferences
- Providing copies of the Final Report on NCHRP Project 10-86 (published as *NCHRP Report 801*) to faculty and researchers involved in highway drainage to stimulate further research relating to the Recommended Practice

14.6 Trial of the Recommended Practice Through Pilot Projects

As part of NCHRP Project 10-86, a review of current practices and trialing of the newly developed Recommended Practice to alternative bidding were undertaken. The piloting was intended to trial the Recommended Practice across a range of agency policies on real highway projects. The Recommended Practice was applied using the current policies from nine different agencies. It incorporated, within a single framework, the wide variety of factors and criteria required to successfully bid alternative pipe systems. The successful trials illustrate that the Recommended Practice facilitates an alternative pipe system selection procedure that is flexible and technically sound. This was demonstrated clearly when previously unspecified pipe system alternatives were identified.

The trial evaluations indicated that differences across current agency practices were shown to materially affect the proposed alternative pipe systems. This is a reflection of the differences in local experience; the variations in local climate, terrain, and subsurface conditions; the risk tolerance of given agencies toward various design criteria; and the structure of alternative pipe selection processes. The variation between agencies in the criteria and reference values used for alternative pipe system selection and the variable treatment of pipe system types in standardized codes (e.g., AASHTO) present hurdles to using the Recommended Practice as a single nationally applicable tool that does not require individual agency modification. Even with the variability observed in the current state of practice across United States transportation agencies, the Recommended Practice to alternative bidding can effectively be implemented as a standard framework at this time. Additionally, the Recommended Practice was developed with the intent of allowing for future refinement and development of a nationally standardized fully developed design and bidding tool, if further standardization is achieved across certain aspects of pipe design policies.

14.6.1 Pilot Project Agencies

A number of state agencies were approached for potential participation in the pilot project phase of NCHRP Project 10-86.

Participating agencies were chosen based on their interest and willingness to participate and in an attempt to access a wide range of agency policies applied to diverse drainage, climatological, and environmental conditions; technical evaluation criteria; and bidding practices. Specifically, variations in agency approach to design, alternative/optional bidding, post-installation inspection, geographic location, and other factors were considered in approaching and selecting agencies for participation. The following agencies participated in full pilot projects and in baseline pilot projects.

14.6.1.1 Full Pilot Projects

- Pennsylvania DOT (PennDOT) Project 79484 in Northumberland County, Pennsylvania, with a pre-bid estimated construction cost of approximately $2.1 million. It included pipe diameters ranging from 15 in. to 24 in. as well as elliptical pipe elements.
- Missouri DOT (MoDOT) J5P0951B Project in Osage County, Missouri, had an estimated construction cost of approximately $25.5 million. It included pipe diameters ranging from 15 in. to greater than 54 in. and a number of special design installations.

14.6.1.2 Baseline Pilot Projects

The following agencies agreed to participate in the baseline pilot projects:

- California Department of Transportation (Caltrans)
- Florida Department of Transportation (FDOT)
- Michigan Department of Transportation (MDOT)
- Ministry of Transportation Ontario (MTO)
- Nebraska Department of Roads (NDOR)
- New York State Department of Transportation (NYSDOT)
- Virginia Department of Transportation (VDOT)

The research team selected the MoDOT J5P0951B Project as the reference project for use in the desktop baseline pilot project assessments because it contained a wide range of drainage requirements. The baseline pilot projects consisted of applying the current procedures for pipe system design from each baseline pilot project agency to the MoDOT project. Also, limited number of additional and targeted supplemental reference evaluations were added to the pipe systems within the MoDOT reference project to more fully evaluate certain technical considerations. These additional reference evaluations were targeted to expand the range of evaluations to include a broader range of hydraulic, structural, and durability conditions. The inclusion of additional durability assessments for the baseline pilots was key as the original MoDOT project showed benign durability conditions within allowable limits for all agencies. Additional evaluations assuming low, medium, and highly aggressive environmental conditions were added to challenge the ability of the Draft Recommended Practice to eliminate low durability pipe systems in certain instances.

The research team would like to gratefully acknowledge the participation of all pilot project agencies and parties involved in survey and trials of NCHRP Project 10-86. Many agencies provided their time and willing partnership during the project. In particular, MoDOT and PennDOT made projects available for piloting of the Draft Recommended Practice. This provided significant and helpful feedback. Some of the key findings and insights garnered from the pilot projects are summarized by topical group below.

14.6.2 Summary Discussion of Results from Pilot Projects

A number of key findings and lessons were obtained from performance of the Recommended Practice trials during the pilot project phase of NCHRP Project 10-86. Summary findings included the following:

- The Recommended Practice matrix approach was found to be
  - Systematic and Structured—A key when evaluating full drainage system inventories
  - Transparent—Results of all steps are presented
  - Flexible—Easily adapted for use with all pilot agencies
- Hydraulic design is mature and practice is standardized
- Use of baseline Manning's *n* values simplifies evaluation of full inventories and is considered necessary for manual application of alternative bidding
- Structural design is mature, but application is highly variable in practice
  - LRFD structural design is not widely implemented
  - Complications with thermoplastic pipe exist based on the lack of meaningful structural pipe classes.
- Science and application of durability methods are not fully mature
  - Significant variation in EMSL between different methods
  - Considerable variation in basis for RCP and CMP methods
  - No widely accepted methods for estimating EMSL of thermoplastic pipes. Single values often assumed regardless of environment or pipe
  - Interim approach for the Recommended Practice is to use a range of durability methods but encourage further development
- Durability is evaluated at some level by most agencies
  - Site specific environmental parameters (pH, resistivity, sulfates, chlorides) are universal parameters considered for corrosion and degradation

- Abrasion is typically evaluated on a qualitative basis
- Methods to couple evaluation of abrasion and corrosion are not widely used. Increase in EMSL from coatings is not standardized
- The effectiveness of an alternative bidding protocol is predicated on the use of a broad inventory of pipe systems
- Short hand inventory codes, similar to those used by MTO and NDOR provide benefit and facilitate tracking and transfer of design output into bid documents and quantity sheets
- Post-installation inspections are an essential part of alternative pipe bidding to reduce risk of premature pipe system failure
- The inspection requirements defined in current AASHTO guidance are thorough and robust and are recommended for increased adoption
- Inspection methods that provide objective continuous records of quality indicators along the length of the pipe are preferred and are to be encouraged
- Agencies that impart standard application of post-installation requirements typically allow a wide range of pipe systems
- Widespread adoption of alternative bidding will likely require automation (most likely a software application)
  - Existing automated routines, e.g., Caltrans, FDOT, and MTO, each have some good features but none is completely flexible or adaptable to all agencies
- Widespread and standardized adoption would be aided by further national standardization of design criteria and pipe system requirements
  - Development and maintenance of a national pipe product inventory
  - Harmonized and standardized backfill requirements
  - Harmonized and standardized installation requirements
  - Development of structural thermoplastic pipe classes

The differences between current agency practices can materially affect the proposed alternative pipe systems. This is a reflection of the differences in local experience, the risk tolerance of given agencies toward various design criteria, and the variability in agency structures for alternative pipe selection. The variation between agencies in the criteria and reference values used for alternative pipe system selection present a hurdle to using the Recommended Practice as a single nationally applicable tool. With the variability observed in the current state of practice across U.S. transportation agencies, the Draft Recommended Practice can effectively be implemented as a standard framework at this time, with the Recommended Practice developed to allow for future refinement and development of a nationally standardized fully developed design and bidding tool if further standardization is achieved across certain aspects of pipe design policy. The standard framework provided by the Recommended Practice can be easily adopted with agency-specific guidelines to create agency-specific tools.

The Recommended Practice provides a standardized framework to ensure technical robustness, completeness, and transparency, while maintaining the ability of agencies to use their local experience to assist in alternative pipe system selection. The clarity in evaluation criteria provided by the Recommended Practice matrix approach should facilitate an agency's ability to more easily update policies in line with changes in applicable codes and material advances.

14.6.2.1 Potential Barriers to Implementation

The following were identified as potential barriers to the implementation of the Recommended Practice:

- Lack of harmonized standards
  - Installation conditions and backfill vary greatly across agencies (AASHTO code also varies classifications based on pipe type)
  - DSL requirements vary
- Fill height tables based on AASHTO LRFD are onerous to develop and are not nationally applicable or available for all pipe systems
  - The lack of standard LRFD compliant structural classification for thermoplastic pipes creates confusion and complications
  - With no standardization of input parameters, fill height tables are often based on a mixture of criteria and codes that is not always compatible with equitable pipe system selection
- The lack of a recognized national pipe inventory and acceptance criteria limits the formation of a "national market" and requires agency-specific acceptance of new products
- While the NTPEP program provides an avenue for collaborative national evaluation of highway materials, there is still limited overlap between agency processes to approve new pipe products
  - If process could be defined in terms of component material's characterization, controlled field trials, and monitored performance on trial highway projects, for example, it would encourage greater product innovation as there would be more certainty as to what was needed to gain acceptance in the marketplace
- Alternative bidding will require additional design effort
  - The Recommended Practice needs to be streamlined, easy to follow, and standardized to limit the additional design burden. An automated design tool is likely required to achieve widespread adoption
  - A goal of alternative bidding procedure is to offset any additional design effort through cost savings realized by increased competition in highway drainage items

The Recommended Practice has been designed in such a way that the results of future advances in research, standardization, and practice can be readily incorporated. The Recommended Practice retains an agency's flexibility to manage risk for each design component as per agency preference but makes a clear distinction between disqualifications made for technically justifiable reasons and disqualifications made for agency or designer preference. In summary, portions of the current state of practice within national and individual agency specifications and guidelines result in barriers to widespread use of tools without the need for agency-specific specialized modifications and limit the ability to generate nationwide charts and design aids.

14.6.2.2 Benefits of Alternative Pipe Bidding System

The successful trials of the Recommended Practice during the pilot project phase illustrate that the Recommended Practice framework facilitates an alternative pipe system bidding procedure that is flexible and technically sound. This was demonstrated clearly when previously unspecified pipe system alternatives were identified when the Recommended Practice was applied.

The Recommended Practice was applied using policies from nine different agencies and has been able to incorporate, within a single framework, the wide variety of factors and criteria required to successfully bid alternative pipe systems.

Pilot project transportation agencies that have implemented some form of alternative pipe system bidding have noted increased competition across pipe system types. A case study of a similar system to the Recommended Practice can be found by observing the benefits seen at the MTO since development of its alternative bidding procedure in 2007 and the subsequent roll out of the system in 2009.

Through personnel communication with the principal investigator, Mr. Art Groenveld, Senior Engineer, Drainage Design, MTO, noted the following insights based on the implementation of the alternative bidding over a period of several years:

- Comprehensive Alternative Pipe Selection Procedure implemented in 2007
- First drainage projects through the system in 2009
- Estimate drainage component costs reduced by ~10%
- Positive feedback from contractors—product codes easy to understand
- Negative feedback from one pipe supply sector
- Minor increase in consulting engineering design charges
- MTO is actively pursuing further streamlining via HiDISCD software

14.7 Automation of Alternative Bidding

Manual application of the Recommended Practice across all (or the majority of) available pipe types for each drainage system item in a project was shown to increase design time from current practice. The increased design effort is principally a result of two factors (1) the wide range of agency policies and procedures that the Recommended Practice was designed to address and (2) the wide range of available pipe systems. The matrix approach and flow process adopted were devised to facilitate eventual automation.

Several agencies (e.g., Caltrans, FDOT, and MTO) have made significant progress in automating alternative/optional pipe system evaluations and these systems are currently in active use. This confirms that the process of alternative pipe system selection can be successfully streamlined and automated.

The NCHRP Project 10-86 Recommended Practice was intended to provide a streamlined, rational, and reliable design approach to identify a wide range of technically appropriate pipe system alternatives on a consistent and unbiased basis with the intent of increasing product competition and reducing overall costs for procuring highway drainage systems. Such a process is ideally suited for further streamlining through use of a software design tool, and the NCHRP Project 10-86 panel and the research team believe that the availability of an accessible and easy-to-use tool to trial the Recommended Practice would greatly enhance acceptance and implementation of it. Most design engineers readily adapt to new software, and this option would encourage more rapid implementation.

CHAPTER 15

Future and Parallel Research

Through the course of NCHRP Project 10-86, it became clear that an increased level of standardization of specific components of highway drainage systems would simplify the implementation of national design and bidding standards including the Recommended Practice. In particular, addressing the following issues would improve the current practice as it relates to bidding alternative drainage systems:

- Standardized backfill and installation requirements
- Standardized DSL requirements
- National pipe system inventory
- Standardized structural design elements and criteria

Each of these topics is described in the following subsections. They are also the basis for future consideration by the highway drainage community.

15.1 Standardized Backfill and Installation Requirements

Highly variable backfill standards exist across North American transportation agencies. In addition, AASHTO standards include different pipe system backfill classifications and design bases for different pipe material types (concrete, metal, and plastic). Note that the ASTM standards are more streamlined (but vastly different) in this area. Specification of alternative backfills is thus both agency and pipe-type specific, which complicates comparison and evaluation of multiple backfill options during alternative or optional bidding. One possible approach to standardizing backfill requirements is to base the specification partly on a stiffness modulus value that can be measured in-situ and that has been shown through research and experience to produce a satisfactory installation. Due to the different ways that flexible and rigid pipes interact with embedment materials, different modulus values would be expected for the different pipe types. Modulus values should be based on the expected pipe system performance over the design life of the installation.

15.2 Standardized DSL Requirements

Lack of nationally accepted DSL requirements for each roadway classification and variable definitions and bases for determining DSL mean that pipe suppliers and contractors have to accommodate a diverse range of requirements. This hampers the optimization and standardization of products. The development of standard national definitions for DSL would likely benefit the industry and increase competition by creating a more consistent national market. This would also encourage pipe manufacturers and suppliers to market their products on the basis of service life delivery and to improve products to meet agency defined design lives.

15.3 National Pipe System Inventory

A review of new product evaluation procedures currently used by state DOTs was recently completed (White and Hurd 2011). It also presented a recommendation for a three-phase approach for determining if a new product submitted by a vendor is acceptable. This New Product Evaluation (NPE) Protocol comprises an initial evaluation, evaluation of previous performance, and field and laboratory testing. This document could be used as a basis for developing a standard new pipe product evaluation process and guidance on compiling and maintaining lists of all acceptable pipe products. A key component of a pipe system evaluation process is previous field performance, and there is currently no mechanism to allow this information to be compiled and shared between agencies.

The absence of a recognized national pipe inventory and standard acceptance criteria limits the formation of a "national market" and requires agency-specific acceptance of new products. Greater use of AASHTO's NTPEP or other similar programs could greatly benefit the development of more national product acceptance. Use of an approval process defined in terms of component material's characterization, controlled field trials, and monitored performance on trial highway projects would encourage greater product innovation because there would be more certainty as to what was needed to gain acceptance in the marketplace.

15.4 Standardized Structural Design Elements and Criteria

Increased standardization across structural design elements (most specifically across backfill criteria) could greatly simplify and standardize structural evaluations of pipe systems. Several key elements for consideration in greater standardization are highlighted below.

- Performing calculations in accordance with AASHTO LRFD Bridge Design Specifications is a technically involved task and the lack of universal fill height tables is a barrier to implementing a nationally standardized framework for alternative pipe bidding. Alternative bidding can move forward on an agency-by-agency basis but standardization of the AASHTO code (potentially going as far as providing baseline standard fill height tables within the AASHTO code if input criteria become more standardized) would simplify development and implementation of the Recommended Practice.
- With no widespread adoption of standardized input parameters, fill height tables are often not compatible with equitable pipe system selection.
- The thermoplastic pipe industry has not standardized the structural classification of their products with respect to LRFD structural design. Structural capacity is currently manufacturer-specific and the lack of target specification classes creates confusion in the design and specification of these products. This lack of meaningful pipe classes is believed by the research team to be a component that is potentially reducing the acceptance and wider use of thermoplastic pipes. It is noted that discussions in the thermoplastic pipe industry have occurred on this topic but currently have not resulted in the development of meaningful structural classifications within the LRFD design framework.

15.5 Links to Other Research and Identified Research Needs

Widespread adoption of a national alternative bidding approach for pipe drainage systems would coordinate well with other identified research needs across the industry. In particular, two TRB committees (AFS40, Subsurface Soil-Structure Interaction; and AFF70, Culverts and Hydraulic Structures) have identified a number of research needs directly related to issues identified during the course of NCHRP Project 10-86.

15.5.1 Design of Bedding Thickness and Backfill Envelopes for Underground Structures

This research need highlights the fact that a number of pipe materials and backfills have recently proliferated without a corresponding update of backfill requirements. Further evaluation of the influence of installation procedure and bedding conditions on the backfill properties that affect structural performance is needed. Adopting the Recommended Practice would allow for a range of backfill options to be specified in conjunction with different pipe materials. Tracking and synthesizing the performance of these pipe-backfill systems would be facilitated by having a standardized framework, such as the NCHRP Project 10-86 Recommended Practice.

15.5.2 Modulus-Based Quality Control in Culvert Backfill Installation

There is a need for an improvement in how backfill quality is measured and how specifications can be revised to reflect new technologies available for measuring soil modulus. The primary objectives of this identified need are as follows:

- Correlate field gage soil modulus measurements to tabulated modulus values based on soil type coupled with Proctor density.
- Investigate usefulness of soil modulus gages in the marketplace for assessing culvert backfill properties.
- Collect soil modulus data for a range of soil, culvert, and construction methods to assess modulus values and variability.
- Develop recommendations for establishing compaction target values.
- Develop a standard test method for soil modulus for incorporation into AASHTO specifications.

A standardized framework such as the Recommended Practice would allow for easier and faster implementation of ongoing or new research, such as modulus-based quality control of backfill. With improved methods of backfill quality control some of the agency concerns about dealing with large numbers of pipe system options would be alleviated.

15.5.3 Long Term Performance of Buried Pipe Systems

There is a need to develop a basis for evaluation of the projected longevity of the large number of buried pipes currently installed. There is an associated need to incorporate long term performance considerations in the design of future pipe installations. These factors directly relate to improving the way that culvert pipes are currently designed and specified as well as installed and maintained.

This project has identified that there is considerable uncertainty in existing methods used to estimate material service life, and that methods do not exist for all pipe types. Having a standardized framework, such as the Recommended Practice, would allow new methods to achieve widespread adoption in practice.

A great deal of guidance has been developed on culvert durability, inspection procedures, and rating systems. This information has been used by DOTs as well as local agencies to estimate service life and level of deterioration of their drainage infrastructure. In addition, a number of highway agencies have implemented culvert inspection programs, which incorporate formalized inspection scheduling and documentation. Most of these programs, however, are not tailored to a national audience, are not comprehensive in addressing all structural, hydraulic, geotechnical, and environmental issues, and do not produce condition and performance data compatible with culvert management strategies and systems.

In conjunction with this effort, there is a critical need for a comprehensive, state-of-the-art computerized tool for documenting and managing culvert and storm drain facilities once they are identified, evaluated, and rated. A drainage asset management system would serve as a database for culverts and storm drain pipe inventories and assist with recording locations, tracking evaluations of condition and performance, scheduling inspection and maintenance activities, and selecting and budgeting rehabilitation and replacement activities.

The Recommended Practice, in particular if implemented through a software tool, would be a complementary tool to any future development of a system for managing culvert and storm drain inventories. Such systems could be linked to provide information on field performance of pipe systems back into the pipe selection process. Over time, this would be significantly beneficial when evaluating culvert durability.

The Recommended Practice to alternative bidding combined with the potential implementation of a meaningful and standardized pipe system code classification could facilitate the tracking of performance data to aid future research projects, such as those mentioned above. The Recommended Practice retains an agency's flexibility to manage risk for each design component as per agency preference, but makes a clear distinction between pipe eliminations made for technically justifiable reasons and those made for agency or designer preference. In summary, certain aspects of current practice result in barriers to developing nationally applicable design tools.

CHAPTER 16

Conclusions

The primary objective of NCHRP Project 10-86 was to develop a Recommended Practice to assist transportation agencies and industry in implementing a performance-based process for design and selection of alternative culvert and storm water drainage pipe systems on highway projects. The procedure developed has been described as a Recommended Practice in standard AASHTO format.

This Recommended Practice was trialed using nine different agency policies across the United States and Canada and was proven to allow incorporation of the wide variety of factors required to successfully bid alternative pipe systems within a single framework. The successful trials of the Recommended Practice illustrated that the framework facilitates an alternative pipe system selection procedure that is flexible, comprehensive, and technically sound. This was demonstrated clearly when previously unspecified pipe system alternatives were identified when the Recommended Practice was applied to trial projects.

The Recommended Practice will have the following functions:

- Provide a systematic, rational, and technically sound process for the evaluation of pipe systems (incorporating pipe and backfill materials and their interaction);
- Aid designers and bidders in selecting appropriate and cost-effective pipe systems for specific applications and site locations. The Recommended Practice is considered suitable for use in conventional design-bid-build contracts and also in alternative delivery mechanisms, such as design-build;
- Incorporate a comprehensive evaluation of site characteristics (environmental, geotechnical, hydrogeological);
- Evaluate hydraulics, structural performance, and durability in a streamlined and technically sound manner;
- Use a novel matrix approach that facilitates clarity and transparency;
- Allow confidence in and tracking of post-construction performance;
- Be mindful of constructability, operational, and maintenance requirements;
- Have an expandable framework enabling modifications as new methods and materials are developed;
- Have an underlying framework that is flexible, which enables extensive customization to address individual agency needs; and
- Handle routine drainage pipe system design issues in an efficient manner and provide options for special design cases.

An agency's implementation of the Recommended Practice will require some customization. An inventory of approved pipe systems needs to be prepared and associated fill height tables developed for each pipe system option. The methods for estimated services life calculation need to be selected and, where possible, calibrated against local practice. The Recommended Practice has been developed with software automation in mind. This can be done by way of spreadsheets or more sophisticated database software. Widespread implementation of the Recommended Practice will require access to such an automated software tool so that the full process, from project data input to generation of quantity sheets for bidding, is streamlined and requires less engineering intervention than current drainage system design processes.

This project was intended to develop a national procedure for alternative bidding of highway drainage systems and has also put forward a range of standardization opportunities to additionally streamline and optimize drainage system design across the nation. The proposed Recommended Practice for Alternative Bidding of Highway Drainage Systems is intended to provide the following:

- Comprehensive framework for increasing competition in pipe system selection with a resulting reduction in overall costs to the agency
- Streamlined, technically sound, and consistent approach to pipe system selection

- Integrated use of best available practices
- Expandable framework enabling modifications as new methods and materials are developed
- Flexible framework enabling customization to address individual agency needs

The Recommended Practice provides a standardized framework to ensure technical robustness, completeness, and transparency, while maintaining the ability of agencies to use their local experience to assist in alternative pipe system selection. Risk associated with using new products and practices is mitigated through the use of such a framework. The clarity in evaluation criteria provided by the recommended matrix approach should facilitate an agency's ability to more easily update policies in line with changes in applicable codes and material advances.

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APPENDIX A

Recommended Practice for Bidding Alternative Drainage Pipe Systems

INTRODUCTION

The evaluation and selection of suitable and cost effective drainage pipe systems for highway projects involves consideration of a range of engineering suitability criteria, installation requirements, and construction and post-construction maintenance costs. The availability of a streamlined, rational and reliable design approach that identifies a wide range of appropriate pipe system alternatives on a consistent and unbiased basis would allow owners and agencies to take advantage of increased product competition with lower overall costs for procuring highway drainage systems. In addition, if such an alternative drainage pipe design and selection system also took account of serviceable life and durability, it would allow the appropriate pipe systems to be matched to the functional requirements of the highway, resulting in improved drainage system performance and lower long term maintenance costs. This Recommended Practice (RP) aims to achieve these objectives.

By delivering a consistent and technically sound design and selection process for drainage pipe systems this RP also provides agencies the ability to systematically track bid selections and drainage pipe system inventories and performance records for use as input to asset management systems. Additionally, as agencies systematically track design evaluations and compare them over time to actual in-service performance, it will provide the opportunity to continually improve the state of knowledge regarding service life prediction and evaluation methods.

This RP is intended to guide agencies and industry in implementing a performance-based process for contractor selection and delivery of drainage pipe systems on highway construction projects. The RP provides guidelines and procedures for (1) agency definition of drainage requirements and (2) contractor bidding of drainage pipe systems to meet those requirements.

1. SCOPE

1.1. This RP presents a methodology to guide transportation agencies in implementing a performance-based process for selecting alternative drainage pipe systems on highway construction projects and is intended for use by transportation agencies, design consultants, and contractors.

1.2. The RP is intended to provide a systematic, rational, comprehensive and technically sound process for the evaluation of alterative highway drainage pipe systems, which includes the pipe dimensions, material and joints, bedding, embedment and backfill.

1.3. The RP utilizes recognized methods for pipe system selection, design, and post-construction acceptance based on performance-based criteria including hydraulics, structural capacity, durability, and environmental compatibility.

1.4. The RP also provides guidance for post-installation inspection and agency acceptance of drainage pipe systems.

1.5. The RP is not intended to provide specific guidance for every potential design decision that may arise during a drainage project. Instead, the intent is to provide guidance and recommendations for evaluating suitable alternatives for the majority of routine highway drainage applications.

1.6. Full hydraulic design for the base case design will need to be performed by approved methods, such as HDS-5, outside the framework of the RP.

1.7. The RP is intended to be as inclusive and flexible as possible so as to address specific agency needs and requirements. Agency-specific regulatory policies and practices can be considered within the framework of this RP.

1.8. The RP indicates to the user which related design issues are not inherently addressed, so that these issues may be addressed outside of this methodology. The RP is applicable to circular, elliptical and arch-shaped culverts and storm sewers where a number of other pipe systems are readily available for selection as suitable alternatives. Box culverts, large span structures, and pressurized pipes are not specifically addressed or intended to be evaluated through the RP.

1.9. The RP is based on the research results described in the final report for NCHRP Project 10-86, including the content of its appendices. (This final report has been published as *NCHRP Report 801*: *Proposed Practice for Alternative Bidding of Highway Drainage Systems*). The RP should be used in conjunction with the findings, test methods, and specifications described therein.

1.10. This standard may involve hazardous materials, operations, and equipment. This standard does not propose to address all safety problems associated with its usage. It is the duty and responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. REFERENCED DOCUMENTS

2.1. AASHTO Standards

- LRFD Bridge Design Specifications
- LRFD Bridge Construction Specifications
- Model Drainage Manual
- Highway Drainage Guidelines
- Asset Management Data Collection Guide, Task Force 45 Report
- Standard Specifications for Transportation Materials and Methods of Sampling and Testing
- T 289, Determining pH of Soil for Use in Corrosion Testing
- T 288, Determining Minimum Laboratory Soil Resistivity
- T 291, Determining Water-Soluble Chloride Ion Content in Soil
- T 290, Determining Water-Soluble Sulfate Ion Content in Soil
- R 13, Conducting Geotechnical Subsurface Investigations

2.2. **ASTM Standards**

- G51, Test Method for Measuring pH of Soil for Use in Corrosion Testing
- D1293, Test Methods for pH of Water
- D5464, Test Method for pH Measurement of Water of Low Conductivity
- D1125, Test Methods for Electrical Conductivity and Resistivity of Water
- D512, Test Methods for Chloride Ion In Water
- D516, Test Method for Sulfate Ion in Water
- D3858, Test Method for Open-Channel Flow Measurement of Water by Velocity-Area Method
- D5243, Test Method for Open-Channel Flow Measurement of Water Indirectly at Culverts
- D420, Standard Practice for Conducting Geotechnical Subsurface Investigations

2.3. **Federal Highway Administration (FHWA)**

- Hydraulic Design of Highway Culverts, Hydraulic Design Series Number 5
- Culvert Inspection Manual, Supplement to the Bridge Inspector's Training Manual
- Federal Lands Highway, Project Development and Design Manual
- Durability Analysis of Aluminized Type 2 Corrugated Metal Pipe

2.4. **Transportation Research Board (TRB) and National Cooperative Highway Research Program (NCHRP)**

- *NCHRP Report 801: Proposed Practice for Alternative Bidding of Drainage Systems*
- *NCHRP Synthesis of Highway Practice 254: Service Life of Drainage Pipe*
- *NCHRP Web-Only Document 190: Structural Design of Culvert Joints*
- Report submitted to AASHTO for NCHRP Project 20-07, Task 264, Guidance for Design and Selection of Pipes

2.5. **State and Other Agency Publications**

- Florida DOT, Drainage Handbook, Optional Pipe Materials
- Colorado DOT, Development of New Corrosion/Abrasion Guidelines for Selection of Culvert Pipe Materials
- California Department of Transportation (Caltrans) Highway Design Manual
- Ministry of Transportation of Ontario (MTO), MTO Gravity Pipe Design Guidelines

2.6. **United States Army Corps of Engineers (USACE)**

- Technical Report GL-88-2, Life Cycle Cost for Drainage Structures

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3. TERMINOLOGY

3.1. Definition of Terms

Abrasion
Loss of section or coating of a culvert by the mechanical action of water conveying suspended bedload of sand, gravel, and cobble-size particles at high velocities with appreciable turbulence.

Backfill
The material used to refill a ditch or other excavation, material placed adjacent to or around a drainage structure, or the process of doing so.

Bedding
The soil or other material on which a pipe is supported.

Chloride Concentration
Chloride concentration is a measure of the number of chloride ions present.

Corrosion
Corrosion is the deterioration of pipe material by chemical action.

Design Service Life (DSL)
Design service life is the time duration during which a drainage pipe system is expected to provide the desired function with a specified level of maintenance established at the design stage.

Durability
Ability of pipe and fittings to remain in service during its design life without significant deterioration.

Embedment
Backfill materials of a pipe trench excavation that surround the pipe which includes the bedding, haunching and backfill.

Estimated Material Service Life (EMSL)
The number of years of service a particular material, system, or structure will provide before rehabilitation or replacement is necessary.

Haunch Zone
The zone of backfill on the sides of a pipe from the springline to the bottom of the pipe.

Inlet Controlled
A condition where the relation between headwater elevation and discharge is controlled by the upstream end of any structure through which water may flow.

Outlet Controlled
A condition where the relation between headwater elevation and discharge is controlled by the conduit, outlet, or downstream conditions of any structure through which water may flow. In culvert flow, outlet control exists for Flow Types II, III, IV, and VI.

pH
The pH value is the log of the reciprocal of the concentration of hydrogen ion in a solution.

Pipe System
A pipe system consists of all components of a culvert or drainage structure installation and how they interact including the following: the base pipe material; pipe joints; pipe lining or coating; bedding and backfill materials; bedding and backfill compaction; installation condition (e.g., trench or embankment); and end treatments.

Resistivity
Resistivity is a measure of electrical resistance, and is the inverse of conductivity.

Silt/Fines Tight Joint
A joint that is resistant to infiltration of particles that are smaller than particles passing the No.

200 sieve. Silt tight joints provide protection against infiltration of backfill material containing a high percentage of fines.

Soil Tight Joint
A joint that is resistant to infiltration of particles larger than those retained on the No. 200 sieve. Soil tight joints provide protection against infiltration of backfill material containing a high percentage of coarse grain soils.

Sulfate Concentration
Sulfate concentration is a measure of the number of sulfate ions present.

Water Tight Joint
A joint that provides zero leakage of water infiltration and exfiltration for a specified head or pressure application.

3.2. Abbreviations and Acronyms

AASHTO: American Association of State Highway and Transportation Officials

ACPA: American Concrete Pipe Association

ADT: Average Daily Traffic

AISI: American Iron and Steel Institute

ASCE: American Society of Civil Engineers

ASTM: formerly known as the American Society of Testing and Materials

Caltrans: California Department of Transportation

CIPP: Cured-In-Place Pipe

CLSM: Controlled Low-Strength Material

CMP: Corrugated Metal Pipe

CSP: Corrugated Steel Pipe

D: Durability

DOT: Department of Transportation

DSL: Design Service Life

EMSL: Estimated Material Service Life

F: Final

FDOT: Florida Department of Transportation

FHWA: Federal Highway Administration

H: Hydraulic

HDPE: High Density Polyethylene

LRFD: Load Resistance Factor Design

MTO: Ministry of Transportation Ontario

NCHRP: National Cooperative Highway Research Program

NCSPA: National Corrugated Steel Pipe Association

NTPEP: National Technical Product Evaluation Protocol

PP: Polypropylene

PPI: Plastic Pipe Institute

PSIC: Pipe System Identification Code

PVC: Polyvinyl Chloride

RCP: Reinforced Concrete Pipe

RCB: Reinforced Concrete Box

RSC: Ring Stiffness Constant

S: Structural

SDR: Standard Dimension Ratio

SHRP2: Second Strategic Highway Research Program

SIDD: Standard Installation Direct Design

SRSP: Spiral Rib Steel Pipe

TRB: Transportation Research Board

USACE: United States Army Corps of Engineers

4. SIGNIFICANCE AND USE

4.1. The selection and design of drainage pipe systems for use in transportation projects depends upon both economic and technical considerations. Individual agencies currently develop and maintain independent policies to guide the design, bidding, post-construction inspection, and long term asset management of highway drainage pipe systems. This RP is intended to provide a national AASHTO standard for agency implementation of drainage pipe system evaluation and alternative bidding to foster greater harmonization and standardization across AASHTO agencies. With implementation, it should serve to reduce costs through more efficient design, identification of cost effective solutions, and increased local competition between contractors and suppliers. It should also encourage the development of better pipe products and the formation of a more national marketplace for drainage system pricing as policies become more nationally standardized.

4.2. Traditionally, transportation agencies have used a “means and methods” approach for selection and specification of products such as drainage pipe systems. In this approach, the agencies specify a particular drainage pipe system during the design process and the cost of the specified system is included in the contractors’ bids for the project. This system often restricts or impedes competition by eliminating many technically suitable alternatives. The inclusion of multiple equivalent options during the bid phase of projects has been shown to reduce costs through increased competition.

4.3. This RP presents a methodology to guide transportation agencies in implementing a performance-based process for evaluating alternative drainage pipe systems with the intent of better matching pipe system performance characteristics to application-specific design requirements, to increase competition and reduce costs while maintaining safety and performance standards. The RP contains elements to guide development of a holistic program that would allow for systematic inventory management and tracking of results that could improve service life predictions and lead to better management of highway drainage assets.

4.4. The RP applies rational performance-based criteria to the selection of pipe systems. It is not intended to be a stand-alone design document, but rather a design guidance and process framework when used in conjunction with other resources including AASHTO LRFD, FWHA Hydraulic Design procedures, and agency policies and design manuals. This methodology promotes the implementation of the latest national standards and other state of the practice design evaluation methodologies with the intent of being as comprehensive as possible while also allowing the flexibility to incorporate agency-specific standards or requirements. The matrix approach developed for technical evaluations within the RP is intended to provide clarity of design decisions and to allow for data tracking and mining for future agency use or for research to improve policies and methods.

4.5. The RP methodology presents a simplified systematic process for identifying drainage pipe systems for a specific defined application based on the application of hydrological, hydraulic, structural and durability principles. However, it is expected that the RP be applied only by engineers experienced in drainage pipe design principles and that the use of the RP will not eliminate the need for the results to be reviewed and checked by a drainage design engineer. The RP incorporates a final design check step to allow for more detailed analyses, where necessary, beyond the basic evaluations and to allow for agency- or project-specific provisions to be applied.

4.6. The RP addresses the design of circular and standard elliptical and closed arch (i.e., pipe arch) drainage elements. Large and special design drainage pipe systems such as box culverts, large span open bottom arches, pressure pipes, etc. are not directly addressed or incorporated. Above all, the RP is intended as a streamlined process for the design of routine highway culvert and storm sewer systems.

4.7. The RP is not intended to provide detailed design solutions or guidance for the full range of highway drainage design issues. External references to address some of these associated issues are highlighted in the RP.

4.8. This RP is not meant to be an inflexible description of process and design evaluation requirements. Other evaluation methods and selection processes may be applied as appropriate.

5. SUMMARY OF PRACTICE

5.1. The RP is intended to be transparent with all inputs, methodologies, and evaluation results clearly defined and presented. The process recommends undertaking evaluations using each agency's full inventory of pipe systems, including incorporation of available variations in installation type, backfill material and degree of compaction. Pipe systems are technically evaluated as to their suitability in each of three main design functions: hydraulic, structural and durability.

5.2. The RP recommends evaluating the widest practical range of drainage pipe system options against the system performance requirements for each highway drainage application. This decreases the potential for bias in the selection of pipe system alternatives to be included in the bid documents. An inventory of available pipe systems within a jurisdiction may not currently be available and may have to be developed by the agency.

5.3. The RP should be applied to each drainage application individually, so that site-specific conditions affecting the performance and projected service life can be adequately considered.

5.4. The RP is intended to promote technical evaluation of entire pipe systems as opposed to separately evaluating pipe system components. This allows acceptable combinations of backfill material, joint type, installation criteria, pipe linings, etc. to be considered as separate alternatives. This may require agencies to develop a wider range of specifications to cover the construction aspects of these variations.

5.5. The RP is intended to be flexible to account for individual state policies and procedures as well as potential future changes in policy, regulation or availability of new pipe products and evaluation methods.

5.6. The RP follows a systematic five phase approach to evaluating, bidding, inspecting, and tracking alternative drainage pipe systems. The five phases (identified numerically) each consist of multiple steps (identified alphabetically) as illustrated in Figure 1:

Phase 1 - Data Gathering and Project Definition
Phase 2 - Technical Evaluation
Phase 3 - Final Design and Policy Checks
Phase 4 - Reporting Results and Incorporating Alternatives into Bid Documents
Phase 5 - Construction Quality Control, Inventory Management, and Performance Feedback

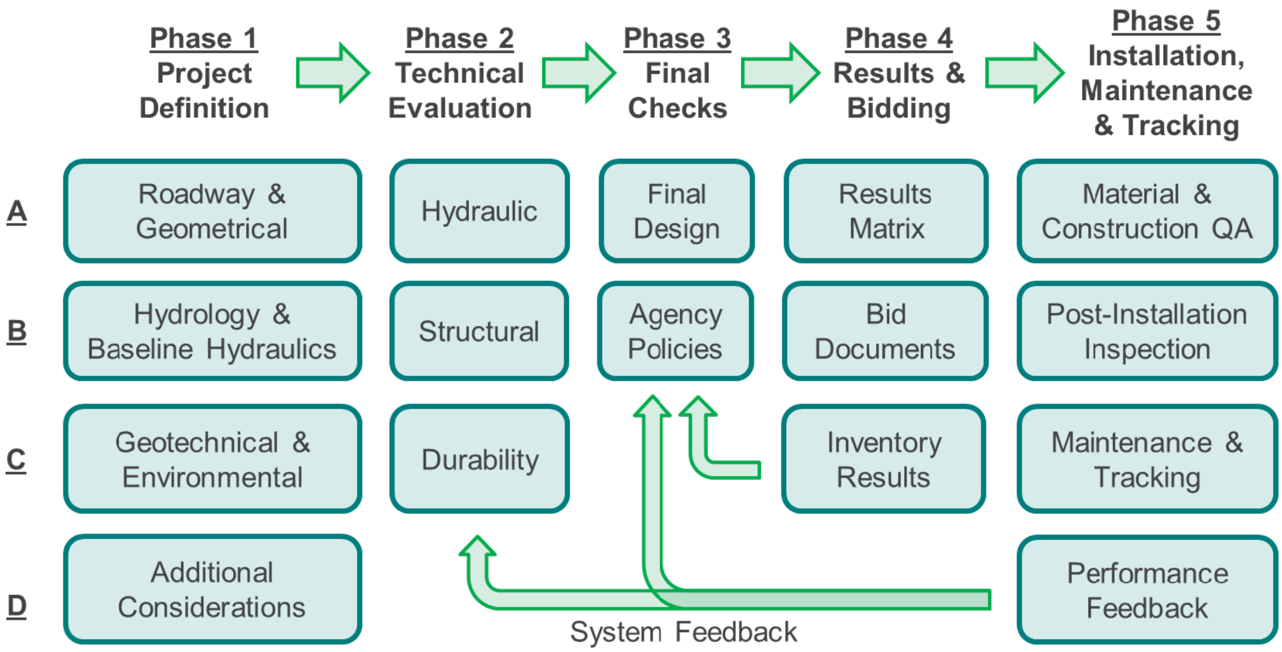

Figure 1 - Primary Steps in the RP

5.7. The RP promotes the implementation of a thorough and inclusive performance based evaluation process that considers all technically suitable alternatives for a given highway drainage application, leaving economic judgment on the most cost effective suitable alternative to be determined through competitive bid.

5.7.1. Successful evaluation of a large number of pipe system options, as completed during application of the RP requires a systematic process for completing and tracking the results of each evaluation phase.

5.8. To achieve the goals of systematically and clearly presenting the large number of technical and policy evaluations involved in the RP, a matrix approach has been developed to track and report the pipe system selection process.

5.8.1. The matrix approach consists of all pipe system types being compiled into rows, with circular equivalent pipe sizes listed in columns. Three individual matrices for each of the technical evaluation steps: hydraulic ("H"), structural ("S"), and durability ("D") are constructed and serve as the pallet for completing the individual steps of the RP. A composite matrix with four sub-cells for each pipe system type and size combining the three technical evaluation steps with the final design and policy check ("F") stage is then used to create the overall RP results matrix. Schematics of the individual and overall composite results matrix are shown in Figures 2 and 3.

5.8.2. This matrix format illustrates the results from each step in the systematic process with a "go" or "no-go" decision for each pipe option. Matrix cells for which that type and size of pipe are not available are left blank to indicate lack of availability as the reason for elimination of that option.

5.8.3. In addition to the systematic advantages of the matrix approach, the visual presentation of the evaluation results from adjacent sizes in adjacent columns and for similar pipe system types in adjacent rows allows for rapid visual assessment of trends in the presented results. The ability to perform a visual review of trends in the results provides a significant advantage in identifying calculation or transcription errors in the RP process and also to identify gaps or areas of improvement in technical methods and/or agency policies.

Hydraulic

	Pipe Inside Diameter (in.)			
Pipe System	18	24	30	36
Pipe System A	~~H~~	H	H	H
Pipe System B	~~H~~	H	H	H
Pipe System C	~~H~~	H	H	H
Pipe System D	~~H~~	H	H	H
Pipe System E	~~H~~	H	H	H
Pipe System F	~~H~~	~~H~~	H	H
Pipe System G	~~H~~	~~H~~	H	H
Pipe System H	~~H~~	~~H~~	H	H
Pipe System I	~~H~~	~~H~~	H	H
Pipe System J	~~H~~	~~H~~	H	H
Pipe System K	~~H~~	~~H~~	H	H
Pipe System L	~~H~~	~~H~~	H	H
Pipe System M	~~H~~	~~H~~	H	H
Pipe System N	~~H~~	~~H~~	H	H
Pipe System O	~~H~~	~~H~~	H	H
Pipe System P	~~H~~	~~H~~	H	H
Pipe System Q				
Pipe System R	~~H~~	H	H	H
Pipe System S		H	H	H
Pipe System T	~~H~~	H	H	H
Pipe System U	~~H~~	H	H	H
Pipe System V	~~H~~	H	H	H
Pipe System W	~~H~~	H	H	H

Structural

	Pipe Inside Diameter (in.)			
Pipe System	18	24	30	36
Pipe System A	~~S~~	~~S~~	~~S~~	~~S~~
Pipe System B	~~S~~	~~S~~	~~S~~	~~S~~
Pipe System C	~~S~~	~~S~~	~~S~~	~~S~~
Pipe System D	S	S	S	S
Pipe System E	S	S	S	S
Pipe System F	S	S	S	S
Pipe System G	S	S	S	S
Pipe System H	S	S	S	S
Pipe System I	S	S	S	S
Pipe System J	S	S	S	S
Pipe System K	S	S	S	S
Pipe System L	S	S	S	S
Pipe System M	S	S	S	S
Pipe System N	S	S	S	S
Pipe System O	S	S	S	S
Pipe System P	~~S~~	~~S~~	~~S~~	~~S~~
Pipe System Q				
Pipe System R	S	~~S~~	~~S~~	~~S~~
Pipe System S		S	~~S~~	~~S~~
Pipe System T	S	S	S	S
Pipe System U	S	~~S~~	~~S~~	~~S~~
Pipe System V	~~S~~	~~S~~	~~S~~	~~S~~
Pipe System W	~~S~~	~~S~~	~~S~~	~~S~~

Durability

	Pipe Inside Diameter (in.)			
Pipe System	18	24	30	36
Pipe System A	~~D~~	~~D~~	~~D~~	~~D~~
Pipe System B	~~D~~	~~D~~	~~D~~	~~D~~
Pipe System C	D	D	D	D
Pipe System D	D	D	D	D
Pipe System E	D	D	D	D
Pipe System F	D	D	D	D
Pipe System G	~~D~~	~~D~~	~~D~~	~~D~~
Pipe System H	D	D	D	D
Pipe System I	~~D~~	~~D~~	~~D~~	~~D~~
Pipe System J	D	D	D	D
Pipe System K	~~D~~	~~D~~	~~D~~	~~D~~
Pipe System L	D	D	D	D
Pipe System M	~~D~~	~~D~~	~~D~~	~~D~~
Pipe System N	D	D	D	D
Pipe System O	D	D	D	D
Pipe System P	~~D~~	~~D~~	~~D~~	~~D~~
Pipe System Q				
Pipe System R	D	D	D	D
Pipe System S		D	D	D
Pipe System T	D	D	D	D
Pipe System U	D	D	D	D
Pipe System V	D	D	D	D
Pipe System W	D	D	D	D

Figure 2 - Individual Results Matrices for Technical Evaluations

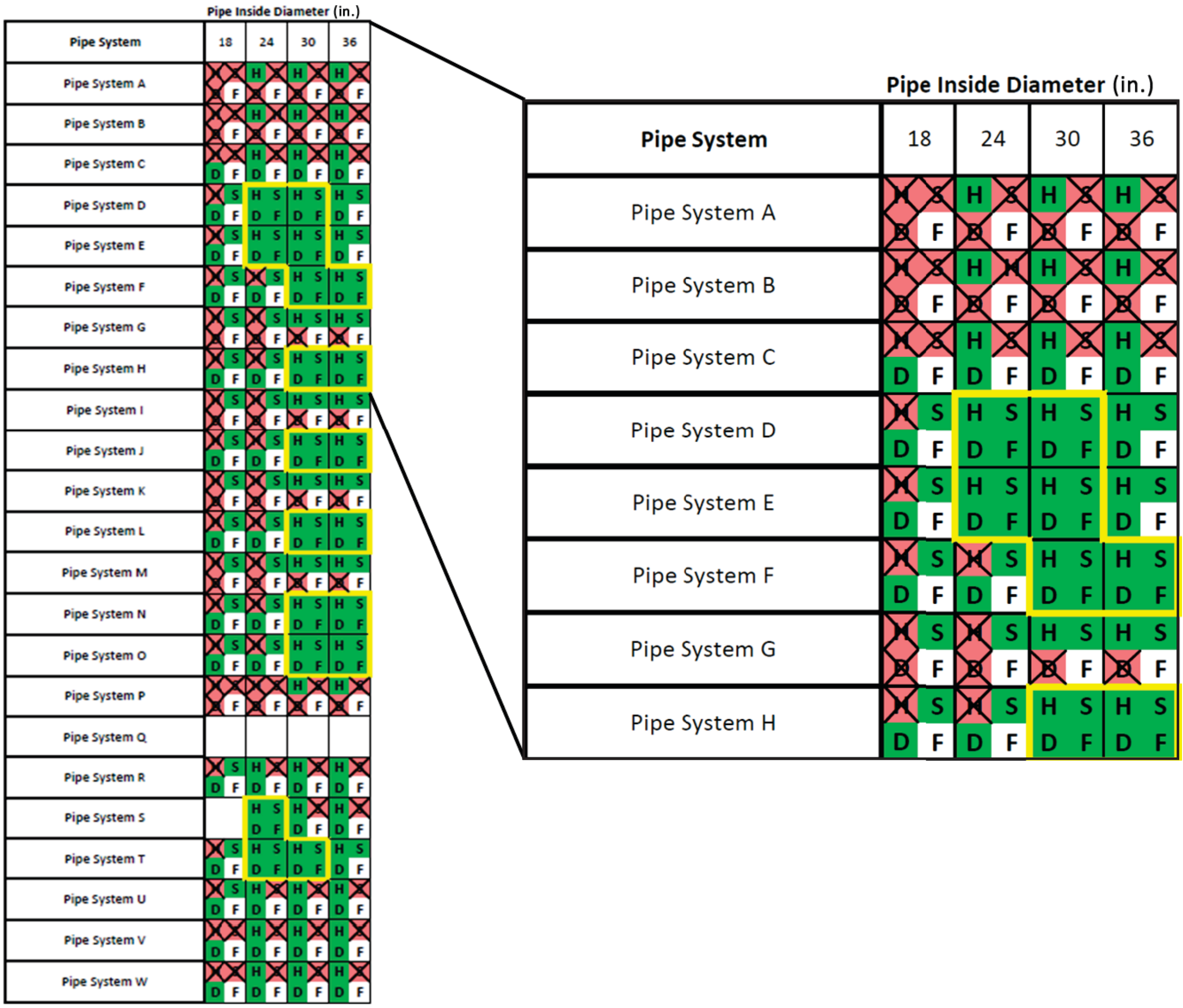

Figure 3 - Overall Composite Results Matrix for RP

5.9. **Note** - While not required as part of implementation, the RP is intended to facilitate database tracking of an in-service drainage pipe system inventory to allow for more systematic and efficient maintenance, renewal, and replacements in line with the goals of the Second Strategic Highway Research Program (SHRP2) and other ongoing AASHTO and agency initiatives.

5.10. **Note** - The RP could also aid in tracking drainage pipe system failures, failure causation mechanisms, and achieved in-situ service life values across each adopting agency's drainage pipe system inventory. For example, if a specific culvert fails within 15 years of installation, it could be back-analyzed using the RP to confirm that that specific pipe would not have been selected for that site and application. The tracking of failures and the loss of service life mechanisms, in combination with tracking the estimated and actual material service lives will allow for research and data-mining to improve and calibrate existing culvert design methods through feedback loops within the RP. Most specifically, the still developing research topics of service life prediction and failure modes can be significantly improved through the tracking and sharing of actual drainage pipe system service life data across and within AASHTO agencies.

5.11. **Note** - The RP could also form the basis to simplify and facilitate agency tracking and integration of System Feedback based on the transparent processes included in the RP. The independent parallel assessment for each functional/technical category used in the RP allows the designer to observe why a pipe system was determined to be unsuitable. Agencies are encouraged to incorporate the results and trends in bidding and field performance from their regular agency review of technical evaluation into agency policy reviews and updates.

6. PREPARATORY AGENCY ACTIONS PRIOR TO IMPLEMENTATION OF THE RECOMMENDED PRACTICE

6.1. To optimize the benefits of implementing the RP, initial preparatory work and internal review is recommended.

6.2. Identification of Agency Goals, Requirements, Constraints and Opportunities. Prior to implementing a new or revised alternative pipe system bidding practice it is recommended that agencies identify the requirements, constraints and opportunities associated with any new or revised system, and select a system that will most effectively meet the agency's goals.

6.3. Approved Pipe System Inventory. In order to complete technical evaluations it is necessary to define the characteristics of each viable pipe system including the following:

- Pipe Size
- Pipe Shape
- Pipe Profile
- Pipe Material Type
- Pipe Coating or Lining Condition
- Pipe Structural Class (presented as minimum and maximum allowable fill height)
- Pipe Joint Type
- Pipe Roughness (in terms of Manning's *n* value)
- Pipe Abrasion Resistance (Refer to Section 8.5)
- Installation Type, (Embankment or Trench)
- Installation Class (as per AASHTO, ASTM, or agency-specific classifications defining backfill and bedding geometry, materials, and compaction requirements)

6.3.1. An inventory of available pipe systems within a jurisdiction may not currently be available and may have to be developed by the agency. Comparison of the allowable pipe system inventory to other AASHTO agency inventories and the range of available pipe systems in the marketplace is recommended prior to RP implementation and at regular intervals thereafter. Consideration to piggyback approvals based on research and pilot verification efforts by other AASHTO agencies and leveraging of the NTPEP (National Technical Product Evaluation Protocol) system is recommended to expand the inventory of approved pipe systems to include the widest possible range of pipe materials and installation conditions appropriate.

6.3.2. **Note** - As noted above, the adopting agency needs to maintain a detailed inventory of available pipe systems approved for use on agency projects. To help promote standardization and efficiency in dealing with the large number of pipe system variations available for use in highway drainage systems, the RP recommends the development and integration of a Pipe System Identification Code (PSIC) for use in uniquely identifying each available pipe system alternative. The unique PSIC code for each available pipe system option can either be agency specific or follow from the example nomenclature presented below. The use of a PSIC to uniquely identify pipe systems is intended to allow for simpler and clearer presentation of pipe systems within the RP matrix (Figures 2 and 3), on construction documents, and on as-built drawings to identify the full range of pipe system characteristics.

6.3.3. The Recommended PSIC Format = PipeSize-PipeClass_Installation is outlined in Tables 1 through 3 and the examples in Table 4.

Table 1 - Pipe Identification Codes

Size	Equivalent Circular Size (Inches) e.g., 30 inch = 030
Shape Class	Pipe Arch = a; Circular/Round = c; Horizontal Elliptical = h; Vertical Elliptical = v
Profile	Smooth = M Type C = C, Type D = D, Type S = S; 1 ½" x ¼" = 1; 2 2/3" x ½" = 2; 3"x1" = 3; 5"x1" = 5; Spiral Rib = R
Material	Aluminum = AL; Aluminized Type II = AT; Ductile Iron = DI; Fiberglass = FG; Galvanized Metal = GV; Metal Reinforced HDPE = RP; HDPE = PE; Polypropylene = PP; Poly Vinyl Chloride = PV; Reinforced Concrete = RC; Steel Plate = SP; Unreinforced Concrete = UC; Vitrified Clay = VC
Structural Class(1)	Concrete → Classes I through V = 1 through 5, Special Design = S, and Unreinforced = U
	Metal → Wall Gage Thickness (18, 16, 14, 12, 10, 08, etc.)
	HDPE → A through W, depending on wall profile and stiffness or dimension ratio
	PVC → A through D, depending on wall profile and stiffness
	PP → C, D or S, depending on wall profile
	FG → 1 through 4, depending on stiffness
Joint Type	Soil Tight = S, Silt Tight = M; Water Tight = W; Riveted = R; Lock Seam = L
Lining	No Lining = nl Asphalt Coated = ac; Asphalt Paved Invert = ap; Asphalt Coated Smooth Lined = as; Concrete Paved = cp; Polymer Coated = pc; Polymer Coated and Paved = pp

(1) Refer to Figure 6 for explanation of structural class identification codes.

Table 2 - Installation Identification Codes

Installation Class	As per AASHTO LRFD Bridge Specs, Chapter 12 • Concrete – Type I to IV (1 to 4) • Metal – No variation specified in AASHTO (Use 2 as default) • Thermoplastic – Sn-100 to Cl-85
Installation Type	Embankment = E; Trench = T

Table 3 – Compiled Pipe System Identification Code (PSIC)

Pipe Size			Dash	Pipe Material				Under score	Installation	
Size (ID in Inches)	Shape Class	Profile	-	Material	Structural Class	Joint Type	Lining	_	Class	Type
###	x	# / X	-	XX	# / X / X	X	xx	_	# / Xx-###	X
Three Number Code	Single Letter Code	Alpha-numeric Code	-	Two Letter Code	Mixed Code	One Letter Code	Two Letter Code	_	Mixed Code	One Letter Code

Table 4 - Examples of the PSIC Concept

Example PSIC #1: 30 Inch Circular Smooth Walled, Concrete, Unlined, Class III, Water Tight Pipe Installed within a Class II Embankment installation
Example PSIC #1: 030cM-RC3WnI_2E
Example PSIC #2: 53" x 41" (Equiv. 48" Inch) 3"x1" Pipe Arch, Aluminized Type II, 12 gauge, Lock Seam, Concrete Paved Invert, Installed within a Class II Trench installation
Example PSIC #2: 048a3-AT4Lcp_2T

6.4. Service Performance Criteria. While many agencies have adopted the concept of Design Services Life (DSL) for pipe systems, there is currently no universally accepted method or guidance for establishing it. The general principle for the use of a DSL based system is that the higher the road classification and the higher the consequences from premature failure of a drainage system, then the longer the DSL should be. Typically agencies use DSL values of 25, 50, 75 and 100 years, with design lives of 75 and 100 years being reserved for high volume freeways, and 25 years being used for entrance culverts and similar pipes.

6.5. **Note-** While not a requirement for implementation of the RP, it may be advantageous for the adopting agency to enhance the benefits of implementation, by maintaining a detailed inventory of in-service drainage pipe systems. To help promote standardization and to allow for potential multi-agency data gathering and research, the RP can be expanded to include an inventory database which would include the following items at a minimum, noting that many agency inventories may have additional items.

- Functional Classification: arterial, collector, local, etc.
- Roadway Number
- Drainage System Type: Culvert or Storm Sewer
- Station of Culvert Inlet or Station Range for Storm Sewers
- Pipe System ID (as defined in Section 6.3.2 or similar)
- Installation Date: Month and Year
- Original Design Service Life in Years
- Current Estimated Service Life or Achieved Service Life to Failure
- Failure Causation Mechanism(s)

6.5.1. **Note** - This inventory could also form the basis for an asset management system for drainage pipe systems, to assist with establishing long term pipe replacement and rehabilitation budgets. The tracking of original design service life, current estimated service life (from regular maintenance inspections), achieved service life to failure, and failure causation mechanisms is intended to allow for evaluation and improvement through calibration of durability prediction methods over time.

6.5.2. **Note** - In addition to the primary objective of providing a framework for the bidding of alternative drainage pipe systems, the RP incorporates several features that can deliver additional benefits from implementation if integrated into broader agency wide efforts to optimize design, bidding, construction, inspection, and maintenance procedures.

6.6. **Note** - Incorporation of Automation. The RP is suitable for application as a manual process, but the repetitive nature of completing calculations across multiple pipe system options lends itself to partial or full automation through spreadsheets, stand-alone software, or other efficiency schemes. Several agencies have incorporated partial automation into their current processes for evaluating and designing highway drainage systems, such as the examples listed in Section 2.5. It is understood and recommended that adopting agencies and/or consulting firms using the RP will look to automate the repetitive portions of the process and these upfront efforts will reduce the time required to conduct the RP.

6.6.1. **Note** - Achievement of automation is simplified at the agency level because many design and policy decisions, such as the approved pipe system inventory, backfill and installation requirements, headwater criteria, durability criteria, design service life, bid formats, amongst other agency-specific policies and requirements, are standardized at the agency level while they are often not standardized across AASHTO agencies.

6.6.2. **Note** - The widespread implementation of this RP along with other national standard design and evaluation approaches will tend to increase standardization and harmonization, which should increase competition across agency boundaries and allow for greater leveraging of economies of scale through the creation of a more national design and marketplace environment.

7. PHASE 1 – PROJECT DEFINITION

7.1. The purpose of Phase 1 is to define all of the inputs required to implement the RP. This phase is separated into four stages:

Stage 1A – Roadway and Geometrical
Stage 1B – Hydrology and Waterway
Stage 1C – Geotechnical and Environmental
Stage 1D – Inventory of Available Pipe Systems

7.2. Stage 1A - Roadway and Geometrical

7.2.1. The initial phase of use for the RP is to define the project details. The fundamental roadway and geometrical parameters are compiled so that they are available for use in the design evaluations completed in Phases 2 and 3.

7.2.2. The following are the recommended roadway and geometrical design parameters:

- Unique Project, Bid, or Agency-wide identifier
- Type of installation or pipe function (culvert or storm sewer)
- Location
- Road way functional classification
- Design service life
- Culvert length
- Minimum fill height
- Maximum fill height
- Maximum pipe size (considering vertical and lateral conflicts)
- Minimum pipe size (considering maintenance, future rehabilitation, etc.)
- Upstream invert elevation
- Downstream invert elevation
- Design slope
- Skew
- Breaks in slope or alignment
- Installation condition (embankment/trench)

7.3. **Stage 1B – Hydrology and Baseline Hydraulic Design**

7.3.1. The fundamental hydrologic, waterway, and hydraulic parameters are compiled in this stage for use in the design evaluations completed in Phases 2 and 3 of the RP. At least one baseline hydraulic design for the drainage application being evaluated is also required to be undertaken outside of the RP to provide a starting point for the Phase 2 and 3 design evaluations of available alternatives.

7.3.2. The basic hydrologic design parameters are:

- Drainage area
- Design flow rate
- Design storm
- Check storm
- Allowance for future watershed changes

7.3.3. Perform hydrological analyses to define the drainage system flow requirements using procedures outlined in the most recent version of the following documents:

- FHWA Hydraulic Design of Highway Culverts – HD5
- AASHTO Model Drainage Manual

7.4. Define the hydraulic design parameters:

- Allowable Headwater Criteria
- Minimum Allowable Flow Velocity
- Maximum Allowable Flow Velocity
- Joint Rating: Soil Tight, Silt/Fines Tight, or Water Tight
- End Treatments
- Section Variations (e.g., Bends, Junctions, Wyes, Transitions, etc.)
- Aquatic Organism Passage Requirements

7.4.1. Define the baseline pipe roughness categories to be used in evaluating hydraulic adequacy of the various pipe system options. Two default options are defined below, noting that agencies may use alternate default category names and representative minimum Manning's *n* values as preferred.

7.4.1.1. The recommended default pipe roughness categories are:

- Smooth ($n = 0.012$)
- Corrugated ($n = 0.024$)

7.4.1.2. If a more rigorous category classification scheme is desired, the following four categories are recommended:

- Ultra Smooth ($n = 0.009$)
- Smooth ($n = 0.012$)
- Corrugated ($n = 0.024$)
- Structural Plate ($n = 0.036$).

7.4.2. Perform baseline hydraulic design for each of the generic baseline pipe roughness categories through use of the FHWA HY-8 Hydraulic Analysis Program or other means.

7.4.2.1. **Note -** In the absence of minimum flow requirements and other special hydraulic considerations the classification of the drainage application as Inlet or Outlet controlled can be used to streamline the baseline hydraulic evaluations. Starting with analysis of the roughest category first, if the system is found to be inlet controlled, all smoother baseline categories can be set to that same size without requiring independent analysis. If an evaluation results in outlet controlled conditions, the next roughness category evaluation would be completed to determine the potentially smaller baseline pipe size requirements for that roughness condition.

7.5. **Stage 1C – Environmental and Geotechnical**

7.5.1. Collection of site-specific environmental and geotechnical data from the native soil, backfill, flow and groundwater is necessary to estimate the material service life of drainage pipe systems.

7.5.2. Definition of Site Environmental Parameters. Data on the soil, backfill and water should be collected in accordance with the most recent versions of the following standards:

- Soil pH: AASHTO T 289 or ASTM G51
- Water pH: ASTM D1293 or ASTM D5464
- Soil resistivity: AASHTO T 288
- Water resistivity: ASTM D1125
- Chloride concentration: AASHTO T 291 or ASTM D512
- Sulfate concentration: AASHTO T 290 or ASTM D516
- Flow rate: ASTM D3858 or ASTM D5243

7.5.2.1. Relevant standardized test procedures adopted by state transportation agencies may also be used to collect site-specific environmental data. Alternatively, many agencies make use of field kits that are specifically designed for this purpose and are useful in supplementing the data from laboratory testing.

7.5.2.2. **Note -** Data collected at a single location at a specific time may not be representative of conditions that exist at a site over the lifetime of the drainage pipe system. To account for potential seasonal and other variations in water characteristics, collection of environmental data at multiple locations and at multiple times during the year should be considered depending on the scale of the project. Changes in surrounding land use (e.g., fertilizer impacted runoff from nearby agricultural lands, roadway salting efforts in the winter, etc.) and flow characteristics should also be considered.

7.5.2.3. **Note -** Test values can be seasonally affected by such factors as rainfall, flooding, drought, decaying vegetation, and man-made influences (e.g., fertilizer or road salt runoff). Whenever possible, environmental tests should be taken during periods considered representative of average environmental conditions.

7.5.2.4. **Note –** Data collection and analysis should be performed by independent parties that do not have a financial interest in the results of the environmental testing. Specific guidelines for sampling and testing should be adopted to provide consistency between testing parties and between project sites.

7.5.3. In addition to the collection of soil and water environmental data to allow completion of the quantitative durability evaluations in Phase 2, it is strongly recommended that the in-service performance of nearby drainage systems be recorded and used to back calculate estimated environmental parameters for the observed service life conditions through reverse application of the methods discussed in Phase 2.

7.5.3.1. Based on comparison of the field measured and back-calculated environmental parameters the designer would choose the critical value in each category to bring forward through the remainder of the RP.

7.5.4. Geotechnical Information. A geotechnical investigation should be performed in accordance with AASHTO Standard Recommended Practice R13-03 “Conducting Geotechnical Subsurface Investigations” and agency-specific guidance. It is convenient to include the geotechnical data needed for drainage system design in the scope of a pavement rehabilitation investigation.

7.5.4.1. The focus of the investigation for drainage system design should be on:

- Determining the ground conditions that will act in support of the drainage pipe system
- Determining the elevation and fluctuation of groundwater levels
- Determining the suitability of native materials to be used in construction
- Considering the compaction characteristics of construction materials
- Considering the potential for abrasive bedload to be generated from watershed soils
- Collecting samples for the testing listed in Section 7.5.2

7.5.5. One of the outputs from Stage 1C is to assign an abrasion level using the data collected in Stages 1B and 1C.

7.6. Stage 1D - Additional Considerations

7.6.1. Additional design drivers should also be considered at this time and may cause the drainage application to be designed outside of the RP, and/or for additional design constraints to be placed on the technical evaluations.

Examples of such additional considerations include but are not limited to:

- Earthquake hazards including liquefaction, fault crossings, etc.
- Ecological factors upstream, downstream, or within the culvert
- Minimum and Maximum temperatures, and resulting extreme temperature impacts

  - Ground freezing and other cold weather considerations
  - High maximum temperatures can impact the material service life of thermoplastics and other pipe materials and may require special design considerations
- Erosion and scour potential
- Fire risk and consequence
- Roadway chemical spill risk and consequence
- Other geologic, environmental, or man-made conditions

7.7. **Output from Phase 1 - Set the Inventory of Evaluated Pipe Systems**

7.7.1. In Phase 1 the design engineer should refer to the agency inventory of available and approved pipe systems to set the listing of pipe systems to be included in the matrix and to be evaluated as part of the current application of the RP. This RP stage is included to promote recording of the inventory used in the RP for a given project or drainage application as agency inventories will likely change over time.

7.7.2. The range of sizes evaluated in each application of the RP should be sufficient to capture all suitable alternative pipe systems, but be limited to those systems that are practical for a given drainage application. It may be beneficial to evaluate pipe systems within two sizes above the baseline designs during application of the RP so as to increase the bidding options.

7.7.2.1. The evaluation of non-circular shapes (pipe arch, horizontal elliptical, vertical elliptical, etc.) is not required for many standard drainage applications. However, these alternate shapes and/or the use of multiple barrels are common practice and require evaluation when applicable. It is recommended that the potential need for non-circular shapes be identified during Phase 1 through evaluation of the baseline hydraulic design and the roadway and geometrical data, with alternate shapes included in the RP evaluations if it is determined that non-circular shapes are required.

7.7.2.2. **Note –** In line with standard design practice, if the Phase 1 evaluations do not identify a potential need to use non-circular shapes, it is recommended that these shapes not be evaluated to simplify and streamline the implementation of the RP.

7.7.2.3. **Note** - Multiple barrel drainage systems can be evaluated using the RP through analysis of an individual component with the RP process, noting that the chosen option (size and number of barrels) must meet the geometric constraints defined in Phase 1A.

8. PHASE 2 - TECHNICAL EVALUATIONS

8.1. Following the setting of design performance criteria and the baseline drainage design in Phase 1, the RP moves to Phase 2 where technical evaluations are completed across the portion of the pipe system inventory set in Phase 1D.

8.2. Technical evaluations within the RP are split into three categories, each completed independently and in parallel.

Stage 2A – Hydraulic Evaluation – (“H”)
Stage 2B – Structural Evaluation – (“S”)
Stage 2C – Durability Evaluation – (“D”)

8.3. **Stage 2A – Hydraulic Evaluation**

8.3.1. During Stage 2A the user compares each evaluated pipe system's hydraulic capacity to the hydraulic requirements of the drainage application. The RP recommends conducting these evaluations not through detailed hydraulic design of each pipe system, but rather through comparison of pipe size (equivalent circular diameter) and pipe roughness.

8.3.2. **Note –** While independent rigorous hydraulic capacity evaluation for each pipe system is not considered necessary for most applications, verification of equivalency or the adequacy of the defined pipe roughness categories to adequately achieve all hydraulic requirements can be conducted in Stage 3A for critical drainage applications if desired.

8.3.3. Minimum pipe diameters for standard roughness categories were established in Stage 1B. If the range of pipe roughness in the pipe system inventory can be adequately represented through grouping into one of the Manning's *n* categories defined in Phase 1B then no further hydraulic evaluation is required and pipe systems are considered hydraulically acceptable.

8.3.4. If it is desired to hydraulically evaluate each pipe system's specific Manning's *n* value, or to define the pipe size requirements for additional pipe roughness categories not previously set in Stage 1B, these evaluations are recommended to be performed in Stage 2A using hydraulic equivalency charts.

8.3.4.1. Starting from the baseline hydraulic designs completed in Phase 1B, the Manning's equation may be used to determine the equivalent hydraulic capacity of different pipe materials under the drainage system flow conditions.

8.3.5. The completion of the hydraulic evaluation step results in each pipe system option being rated as either hydraulically acceptable or unacceptable. This rating is then carried forward to the reporting and presentation of the results stage.

8.3.6. The systematic matrix approach presented in Section 5 is used for tracking the results of each evaluation phase.

8.3.7. While many of these aspects are accounted for in the evaluation of the baseline hydraulic design, the following design aspects are not incorporated directly into the RP. These design considerations should either be set in Phase 1 or accounted for in the final design and policy checks completed in Phase 3:

- Flow Control and Measurement
- Low Head Installations
- Siphons
- Aquatic Organism Passage
- Scour at Inlets/Outlets
- Sedimentation and Debris Control
- Multiple Barrels
- Perforated Pipes

8.3.8. As with the other technical evaluation steps, the results matrix presents the evaluation results from the hydraulic evaluation stage. The hydraulic matrix is denoted with "H" identifiers within the box for each pipe system type and highlighted green in cases calculated to be suitable, or highlighted red and crossed out for pipe system options that do not meet the design criteria.

8.4. **Stage 2B – Structural Evaluation**

8.4.1. Evaluate the structural capacity of each pipe system in the inventory using the most recent version of the AASHTO LRFD Bridge Design Specifications.

8.4.2. The use of previously prepared minimum and maximum fill height tables is the most practical and efficient means of performing the structural evaluations.

8.4.3. Structural capacity must be checked for each allowable pipe system combination of pipe material type, material class/thickness, bedding and backfill material, bedding and backfill compaction, and installation condition.

8.4.3.1. **Note -** In manual applications of the RP (without the benefit of software automation) it is recommended that users evaluate pipe system options starting with the lowest available structural class, as structural classes above the minimum approved class are typically acceptable (except in the rare case when the additional wall thickness of the higher class pipe results in a geometric conflict).

8.4.4. Structural evaluation methods (e.g., fill height tables) not in accordance with the current AASHTO LRFD Bridge Design Specifications should not be used in this stage of the RP. Such fill height tables should be applied in Phase 3 if agency policy is divergent from current AASHTO standards.

Note - The use of national standards in the technical evaluation stage is one key component of the RP, in that it is intended to clearly rely on AASHTO-approved procedures. The intent of completing initial technical evaluations using the latest national standards is to maintain the integrity of the RP. Where agencies have not adopted national standards, agency-specific evaluations can be implemented as part of Phase 3.

8.4.5. Presentation of Results. As with the other technical evaluation steps, the results matrix is used to present the evaluation results from the structural evaluation stage. The structural matrix is denoted with “S” identifiers within the box for each pipe system type and highlighted green in cases calculated to be suitable, or highlighted red and crossed out for pipe system options that do not meet the design criteria.

8.5. **Stage 2C – Durability Evaluation**

8.5.1. Highway drainage pipe systems deteriorate with time due to in-service loading and environmental exposure. Processes such as abrasion and corrosion can lead to impairment of structural and hydraulic performance and reduce the service life of drainage pipe systems. A key requirement of a rational process to allow bidding of alternative drainage pipe systems is an ability to predict the service life of a drainage pipe system, referred to as the Estimated Material Service Life (EMSL).

Note – Different methods for estimating EMSL are available in the technical literature and there is no widespread consensus on the most accurate method for any given pipe material type. Different methods will provide different levels of accuracy depending on how similar the conditions are between the pipe systems being evaluated and the pipe systems and conditions included in the development of the method. Additional details regarding application of the recommended EMSL evaluation methods are provided in the final report for NCHRP Project 10-86 (published as *NCHRP Report 801*) and within the originating reference documents.

8.5.2. Highway drainage structures are designed with the goal of providing a minimum design service life (DSL). Different drainage pipe system materials respond to environmental conditions in different ways, and thus have different definitions for when the end of the service life is reached.

8.5.3. For a design to be technically acceptable the EMSL must be greater than or equal to the DSL.

8.5.4. Durability performance of existing drainage structures in the same watershed or under similar environmental conditions may also be used as a guide to anticipated durability performance. An inspection program and data management system would facilitate the use of in-service durability performance results in the durability evaluation of new systems. Such comparative evaluations are to be considered a complementary approach, and should be used in conjunction with the quantitative methods described in this section.

8.5.5. Durability evaluation in the RP is performed in the sequence shown in Figure 4:

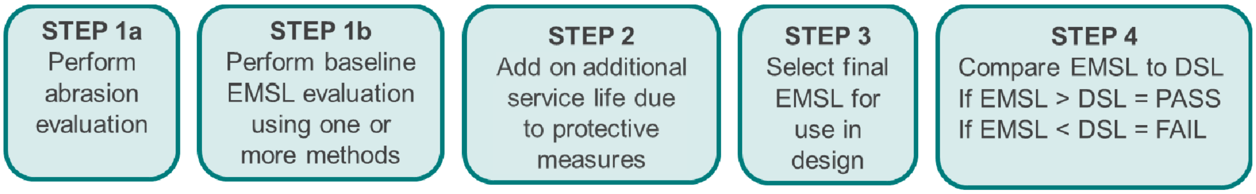

Figure 4 - Durability Evaluation Procedure

8.5.6. **Step 1a**: Use Table 5 to determine what limitations, if any, on pipe material selection are a result of the abrasion level determination made in Phase 1.

8.5.6.1. Abrasion potential is a function of several factors, including pipe material, frequency and velocity of flow in the pipe and composition of the bedload.

8.5.6.2. The most comprehensive abrasion evaluation methodology is the method developed by Caltrans (White and Hurd 2011). Caltrans defines six levels of abrasion for preliminary estimation of abrasion potential based on flow velocities and bedload characteristics.

Note - Only some of the more relevant factors are considered in Table 5 and additional factors may need to be considered when assessing abrasion potential.

Note – It is noted that the Caltrans abrasion evaluation methodology was based on data from a specific site and Caltrans specifications, and the use of this methodology by other agencies in other conditions may require agency- or site-specific correlation.

8.5.6.3. Table 5 provides guidance on how the six Caltrans abrasion levels are related to pipe material selection:

Table 5 - Recommended Abrasion Guidance

Level	Pipe Material Guidance
1	No restrictions on material types due to abrasion.
2	Generally, no abrasive resistant protective coatings needed for steel pipe. Polymeric, polymerized asphalt or bituminous coating or an additional gauge thickness of metal pipe may be specified if existing pipes in the same vicinity have demonstrated susceptibility to abrasion and thickness for structural requirements is inadequate for abrasion potential.
3	Steel pipe may need an abrasive resistant protective coating or additional gauge thickness if existing pipes in the same vicinity have demonstrated susceptibility to abrasion and thickness for structural requirements is inadequate for abrasion potential. Aluminum pipe may require additional gauge thickness for abrasion if thickness for structural requirements is inadequate for abrasion potential.

Level	Pipe Material Guidance
	Aluminized steel (Type 2) not recommended without invert protection or increased gauge thickness (equivalent to galv. steel) where pH < 6.5 and resistivity < 20,000.
4	Steel pipe will typically need an abrasive resistant protective coating or may need additional gauge thickness if thickness for structural requirements is inadequate for abrasion potential. Aluminum pipe not recommended. Aluminized steel (Type 2) not recommended without invert protection or increased gauge thickness (wear rate equivalent to galv. steel) where pH < 6.5 and resistivity < 20,000 if thickness for structural requirements is inadequate for abrasion potential. Increase concrete cover over reinforcing steel for RCB (invert only). RCP generally not recommended. Corrugated HDPE (Type S) limited to > 48" min. diameter. Corrugated HDPE Type C not recommended. Corrugated PVC limited to > 18" min. diameter.
5	Aluminum pipe not recommended. Aluminized steel (Type 2) not recommended without invert protection or increased gauge thickness (wear rate equivalent to galv. steel) where pH < 6.5 and resistivity < 20,000 if thickness for structural requirements is inadequate for abrasion potential. Closed profile and SDR 35 PVC liners are allowed but not recommended for upper range of stone sizes in bedload if freezing conditions are often encountered, otherwise allowed for stone sizes up to 3 in. Most abrasive resistant coatings are not recommended for steel pipe. A concrete invert lining or additional gauge thickness is recommended if thickness for structural requirements is inadequate for abrasion potential. See lining alternatives below. Increase concrete cover over reinforcing steel for RCB (invert only). RCP generally not recommended.
6	Aluminum pipe not recommended. Aluminized steel (Type 2) not recommended without invert protection or increased gauge thickness (wear rate equivalent to galv. steel) where pH < 5.5 and resistivity < 20,000. None of the abrasive resistant protective coatings are recommended for protecting steel pipe. A concrete invert lining and additional gauge thickness is recommended. See lining alternatives below. Corrugated HDPE not recommended. Corrugated and closed profile PVC pipe not recommended. RCP not recommended. Increase concrete cover over reinforcing steel recommended for RCB (invert only) for velocities up to 15 ft/s. RCB not recommended for bedload stone sizes > 3 in. and velocities greater than 15 ft/s unless concrete lining with larger, harder aggregate is placed (see lining alternatives below). SDR 35 PVC liners (> 27 in.) allowed but not recommended for upper range of stone sizes in bedload if freezing conditions are often encountered, otherwise allowed for stone sizes up to 3 in.

Source: Caltrans Highway Design Manual, Table 855.2A

8.5.7. **Step 1b:** Apply the appropriate service life prediction model for the specific pipe material type. While this topic is the subject of on-going research and refinement, the RP relies on a range of prediction models that are currently in use, with the recognition that these will be improved over time as more agencies adopt alternative drainage pipe bidding systems and additional applied research is undertaken. Due to the complexity of different pipe materials' performance and associated deterioration mechanisms, not all current prediction models have the same degree of reliability and so caution must be exercised in their application.

8.5.8. Concrete Pipe. Table 6 lists methods that can be used to determine EMSL values for reinforced concrete pipes. The EMSL values obtained using these different methods can vary widely so the RP selects the lowest EMSL value from the methods used. The limitations and range of parameters for which each method is applicable are described in detail in the NCHRP Project 10-86 final report (*published as NCHRP Report 801*) and are summarized in the Table 6 below:

Table 6 – Methods for Determining EMSLs for Reinforced Concrete Pipe

Durability Method	Reference	Notes
Ohio DOT Model	Potter, 1988	Based on large data set over wide range of pH and size values. Includes an abrasive component.
Hurd Model	Potter, 1988	Method developed for large diameter pipes in acidic environments.
Hadipriono Model	Potter, 1988	Method includes wide pH range.
Florida DOT Model	*Florida DOT, Optional Pipe Materials Handbook, 2012*	Considers corrosion to be the only mechanism of degradation.
Comparison with Actual Service Life of Nearby Installations		Completed qualitatively or quantitatively through back calculation of environmental conditions as described in Section 7.5.3.

8.5.8.1. Plain Galvanized Steel Pipe. A number of methods are available for estimating the EMSL of galvanized steel pipe. The California Method is the most widely accepted and is recommended for use if no state- or location-specific research is available that indicates another method is more suitable. The other methods are modifications of the original California Method. Table 7 lists the methods that can be used to determine EMSL values for plain galvanized steel pipes:

Table 7 - Methods for Determining EMSLs for Plain Galvanized Steel Pipe

Durability Method	Reference	Notes
California Method	*California Test 643, Method for Estimating the Service Life of Steel Culverts, 1999*	Includes combined effects of corrosion and abrasion. Based on soil/water pH and resistivity. Service life of pipe considered to be until time of first perforation.
American Iron and Steel Institute (AISI) Method	*Handbook of Steel Drainage and Highway Construction Products, AISI, 1994*	Modification of California Method. Service life of pipe considered to be until 25% thickness loss in the invert.
Federal Lands Highway Method	*Federal Lands Highway, Project Development and Design Manual, 2008*	Modification of California Method. Increase the EMSL by 25% after first perforation.
Colorado DOT Method	*CDOT-2009-11, Development of New Corrosion/Abrasion Guidelines for Selection of Culvert Pipe Materials, 2009*	Calibration of California Method to state-specific conditions with a limited data set.
Florida DOT Method	*Florida DOT Optional Pipe Materials Handbook, 2012*	Modification of California Method to include a minimum steel thickness of 16 gage.
Comparison with Actual Service Life of Nearby Installations		Completed qualitatively or quantitatively through back calculation of environmental conditions as described in Section 7.5.3.

8.5.8.2. Aluminized Type 2 Steel Pipe. Table 8 lists the methods that can be used to determine EMSL values for aluminized Type 2 steel pipes:

Table 8 - Methods for Determining EMSLs for Aluminized Type 2 Steel Pipe

Durability Method	Reference	Notes
Florida DOT Method	*Florida DOT Optional Pipe Materials Handbook, 2012*	Based on anticipated soil/water pH and resistivity.
Comparison with Actual Service Life of Nearby Installations		Completed qualitatively or quantitatively through back calculation of environmental conditions as described in Section 7.5.3.

8.5.8.3. Aluminum Pipe. Table 9 lists the methods that can be used to determine EMSL values for aluminum pipes:

Table 9 - Methods for Determining EMSLs for Aluminum Pipe

Durability Method	Reference	Notes
Florida DOT Method	*Florida DOT Optional Pipe Materials Handbook, 2012*	Based on estimated corrosion rates due to pH and resistivity.
Comparison with Actual Service Life of Nearby Installations		Completed qualitatively or quantitatively through back calculation of environmental conditions as described in Section 7.5.3.

8.5.9. Thermoplastic Pipe

8.5.9.1. The most commonly used thermoplastics in drainage pipe manufacture are polyvinyl chloride (PVC) and high density polyethylene (HDPE). These materials are largely resistant to the chemical and corrosive elements typically found in soils and flow and ground water.

8.5.9.2. Empirical data regarding the durability of thermoplastic pipes is limited when compared to the data available for pipe material types that have longer histories of service.

8.5.9.3. Slow crack growth and oxidative/chemical failure have been identified as the primary long term failure mechanisms for corrugated HDPE pipes, but no methods based on service histories have yet been developed for serviceable life predictions for these materials.

8.5.9.4. The long term performance of thermoplastic pipes is highly dependent on the quality of the installation. Estimated service lives assume that pipes are installed in compliance with specifications and that such compliance is confirmed by post-installation inspection.

8.5.9.5. Agencies typically assign an estimated service life of between 50 and 100 years for thermoplastic pipes manufactured in accordance with the relevant AASHTO standards and installed in accordance with relevant specifications.

8.5.10. Other pipe material types in current use by agencies or recently incorporated into the AASHTO LRFD Bridge Design Specifications in the 2013 revisions are the following:

- Ductile Iron Pipe
- Fiberglass Pipe
- Metal reinforced HDPE pipe
- Polypropylene Pipe
- Vitrified Clay Pipe

8.5.10.1. The EMSL values for the materials listed in 8.5.10 can be established by past performance history or by application of the above listed methods for pipes with equivalent component materials. In the absence of reliable prediction models, it would be prudent to assign conservative EMSL values, in consultation with the pipe suppliers, until further research and documented case studies are available or until predictive methods become available and widely accepted.

8.5.11. **Step 2** – Incorporation of Add-On Service Life Values

8.5.11.1. Coatings and/or invert protection are often applied to culvert pipes (predominantly to metal pipes) to increase their service life. Many different coatings exist, the main types of which are listed as follows:

- Asphaltic/Bituminous
- Fiber-bonded bituminous
- Asphaltic mastic
- Polymerized asphalt
- Polymeric sheet
- Concrete

8.5.11.2. Guidance on the additional service life due to the application of coatings on corrugated steel pipes can be found in the most recent version of the NCSPA Pipe Selection Guide.

8.5.12. **Step 3:** Selection of EMSL Values for Use in design Evaluations. Where more than one method of estimated EMSL is used, to allow for automation in the process, the RP is to select the lowest of the EMSL values for use in design. Further information and commentary on the available methods is provided in the final report for NCHRP Project 10-86 (published as *NCHRP Report 801*).

8.5.13. **Step 4:** The EMSL design value obtained from the previous step is then compared with the DSL. If the EMSL is greater than the DSL, then the pipe option is determined to be acceptable from a durability standpoint. If the EMSL is less than the DSL, the pipe option does not meet the durability evaluation criteria and is eliminated.

8.5.13.1. Failure of individual pipe systems to meet durability requirements will not disqualify entire pipe classifications, as other similar pipe system options that provide higher EMSL values based on increased wall thickness, additional/different coating, improved concrete mix design, or other factors will be independently assessed against the DSL.

8.5.14. Presentation of Results. As with the other technical evaluation steps, the use of a results matrix is used to present the evaluation results from the durability technical evaluation step. The durability matrix is denoted with "D" identifiers within the box for each pipe system type and highlighted green in cases calculated to be suitable, or highlighted red and crossed out for pipe system options that do not meet the design criteria.

9. PHASE 3 – FINAL CHECK AND POLICY APPLICATION

9.1. Final Design Checks

9.1.1. Phase 3 of the RP is to perform final design checks on the output from Phase 2, and to compare the results of the RP against existing agency policies. It is anticipated that only pipe system options meeting the requirements of all three technical evaluation stages will be carried forward into Phase 3 for completion of final design and policy checks.

9.1.2. Output from Phase 2 should be reviewed by the engineer to

- Identify possible errors and inconsistencies.
- Develop alternative designs that are outside the scope of the standard RP (e.g., multiple barrels, aquatic organism passage, etc.).
- If desired, hydraulic design checks can be considered during this final check phase if generalized Manning's *n* equivalency charts or other generalizations were applied for efficiency in the initial technical evaluations.

9.1.3. The engineer should record why any options considered technically valid through the technical evaluations are not being forwarded into Phase 4.

9.1.4. The engineer should record why any options not proposed by the RP are being added for inclusion in Phase 4.

9.2. **Agency Policy Checks**

9.2.1. The engineer should compare the output from Phase 2 and any adjustments made during final design checks to the drainage pipe system options allowed by the agency for the given application. Policy may dictate or restrict pipe size, pipe class, pipe material, backfill type, minimum or maximum fill height, etc. Those systems evaluated to meet the technical design criteria but not meet policy guidelines will be eliminated from further consideration in this phase.

If AASHTO or FHWA standards have not been implemented as agency policy for hydraulic, structural, and/or durability evaluations, the previous evaluations should be checked against current agency policy in this stage. The intent of separating agency-specific policy evaluations from the initial technical evaluations is to promote greater standardization and adoption of national standards, and/or to identify areas for refinement of national standards to meet the range of needs expressed by all AASHTO agencies.

Note - If agency policy is more restrictive without technical basis, the RP provides the rationale to extend pipe material alternatives beyond the agency policy to explore the possibility of expanding competition, even on a trial basis.

9.2.2. The reason for elimination of a pipe drainage system in the final policy check phase should be recorded to provide full transparency in the design process. It is recommended that adopting agencies regularly review the list of final check eliminations to allow for evaluation and optimization of agency policies.

9.2.3. Presentation of Results. As with the technical evaluation steps, a results matrix is used to present the evaluation results from the final design and policy check stage. The final check matrix is denoted with "F" identifiers within the box for each pipe system type and highlighted green in cases calculated to be suitable for inclusion in bid documents, or highlighted red and crossed out for pipe system options that do not meet all of the design and policy criteria.

10. PHASE 4A - SUMMARY AND REPORTING OF EVALUATION RESULTS

10.1. One of the defining principles of the RP is to promote transparency in the design and selection of drainage pipe systems. Transparency in the process is achieved by presentation of technical and policy evaluations in a systematic and clear manner across the full range of available pipe systems.

10.2. The output from the evaluations performed as part of the RP consists of a large amount of data and the summary and reporting of this information is best managed through a systematic process. The pipe system evaluation results are proposed to be presented via a graphically coded matrix to allow the design engineer, technical reviewers, and other users of the RP (bidders, contract managers, estimators, agency engineers, construction inspectors, etc.) to conduct a visual review of the results.

10.2.1. Transparency and data organization are achieved in the RP through the use of the results matrix presentation which provides a clear and systematic process for recording the adequacy of each pipe system considered versus the various technical and policy criteria. The matrix approach provides a means to conduct a rapid evaluation and check of results through visual recognition and review of patterns within the matrix results. Adjacent rows contain similar pipe systems, and adjacent columns contain similar sizes such that continuous zones of pass and fail for the various technical and final criteria should be apparent in the final results matrices.

10.2.2. The final results from the application of the RP can be converted into a streamlined tender code for bidding purposes, as detailed in Section 11.

10.3. In addition to the results matrices which depict the end result of the three technical evaluations and overall final and policy evaluation, it is important that calculations and other back-up design and decision information relied on are recorded and stored for future reference in line with other document control standards for engineering designs. The RP does not specifically recommend the level or manner in which back-up information is stored, but rather recommends storage and record keeping in line with existing agency standards and protocols.

10.3.1. The main purpose of providing good documentation is to define the design procedure that was used and to show how the final design and decisions were determined. Documentation should be viewed as the record of reasonable and prudent design analysis based on the best available proven technology.

11. PHASES 4B and 4C - INCORPORATION OF ALTERNATIVES INTO BID DOCUMENTS

11.1. Each agency typically has a detailed and multi-faceted system for bidding highway projects that involves cooperation and coordination amongst multiple agency departments and often coordination with multiple national review and funding agencies. As such, the RP is intended to maintain flexibility for each adopting agency to develop the optimum manner for integration of results from the RP into bid and tender documents.

11.2. The result of the RP is a complete list of technically acceptable pipe system alternatives for a specific drainage application. This information is summarized into a concise alphanumeric code format suitable for use by designers, consultants, estimators, contractors, pipe suppliers, and project managers. This code is termed the tender code.

11.3. The tender code is divided into three main parts; a minimum pipe diameter for smooth pipe (generic Manning's *n* of 0.012), a minimum pipe diameter for corrugated pipe (generic Manning's *n* of 0.024), and a material code. The use of these generic Manning's *n* numbers is recommended; however, other Manning's *n* values could also be used. An example tender code is shown in Figure 5:

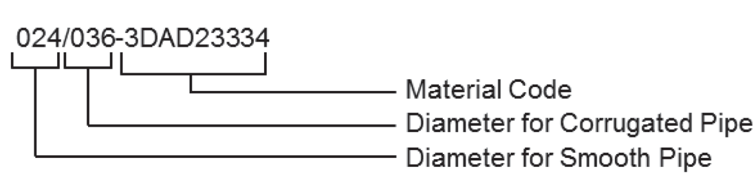

Figure 5 - Format of Tender Code

11.3.1. **Diameter for Baseline Smooth Pipe**
The first element of the code is a three digit number specifying the minimum equivalent circular diameter for the baseline smooth circular pipe case using a Manning's *n* of 0.012.

11.3.2. **Diameter for Baseline Corrugated Pipe**
The second element of the code is a three digit number specifying the minimum equivalent circular diameter for the baseline corrugated circular pipe case using a Manning's *n* of 0.024.

11.3.3. **Material Code**
The material code is a nine digit code that specifies what materials are allowed. Each digit position represents a different pipe material. The value in each position specifies a particular class of pipe, wall thickness, or stiffness rating. Figure 6 shows all the options for the material code portion of the tender code.

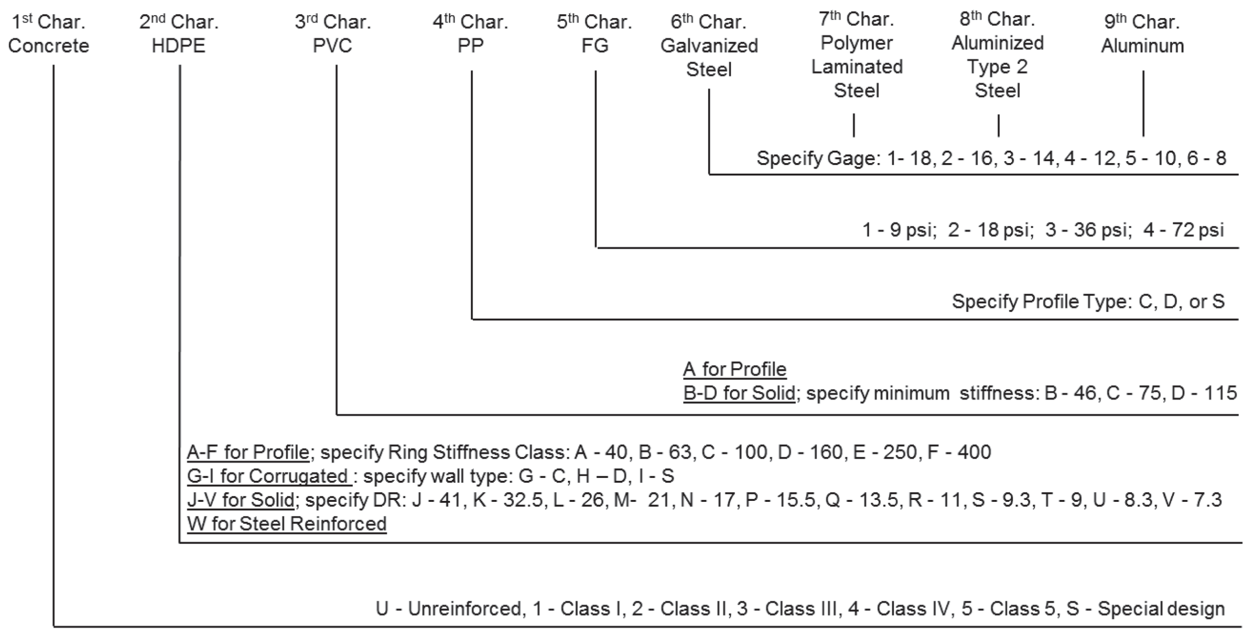

Figure 6 – Material Code Summary

11.4. The material code is interpreted in the following way:

11.4.1. A zero in any position indicates that a particular pipe material is not technically suitable or allowed across all pipe system combinations evaluated for that pipe material type.

11.4.2. An "X" in any position indicates that that pipe material type was not evaluated during the performance of the RP.

11.4.3. The minimum class technically suitable across the range of installation conditions is always specified, with higher classes being allowed. For example, if a Class II concrete pipe is specified as the minimum, a Class III pipe would also be deemed acceptable.

11.4.4. In order to streamline the tender code into a manageable length, only the minimum pipe class is listed for each pipe material type. Because of this presentational efficiency, bidders will need to confirm the installation requirements to use the minimum listed pipe class, and may want to bid the system with a higher class pipe that may have less stringent installation requirements.

11.4.5. The 1st digit represents concrete pipe. Five classes of reinforced concrete pipe can be specified with the numbers 1 through 5. Unreinforced concrete can be specified using the letter "U" and the need for a special design is indicated with the letter "S."

11.4.6. The 2nd digit represents HDPE pipe. Three different wall profiles are allowed: profile, corrugated, and solid wall. Profile wall pipe is specified using one of six ring stiffness constants (RSC). Corrugated wall pipe is specified using one of three profile shapes, defined in AASHTO M294 as Type C, Type D, and Type S. Solid wall pipe is specified using one of twelve dimension ratios (DR). A minimum DR is specified. A letter is used to represent each pipe option as shown in Figure 6. For example, a "D" would indicate that a profile wall pipe with a minimum RSC of 160 was being specified. A "W" indicates that steel reinforced polyethylene is being specified. Note that the letter "O" is not included in the code so as not to be confused with the number zero.

Note - Three different systems are used for specifying the dimensions of solid wall HDPE pipe. Any of these systems can be used with this code system.

11.4.7. The 3rd digit represents PVC pipe. Profile wall pipe can be specified using the letter "A" and solid wall pipe can be specified using the letters "B" through "D" corresponding to three different pipe stiffness classes.

11.4.8. The 4th digit represents polypropylene (PP) pipe. This pipe is specified using one of three profile shapes, defined in AASHTO MP-21 as Type C, Type D, and Type S.

Note – Polypropylene pipe is currently not listed as an available pipe type in the AASHTO LRFD Bridge Design Specifications.

11.4.9. The 5th digit represents glass fiber reinforced pipe and can be specified in one of four pipe stiffness classes; 9, 18, 36, and 72 psi.

11.4.9.1. The 6th, 7th, 8th, and 9th digits represent galvanized steel, polymer laminated steel, aluminized Type 2 steel, and aluminum pipe, respectively. Each of these material options is specified by the minimum gage thickness of the pipe wall.

11.4.10. It is noted that in order to provide a code of realistic length for incorporation and use in bid documents some details regarding the suitability of particular pipe system options such as installation class, installation type, pipe lining, pipe roughness values other than baseline smooth and corrugated, etc. are not uniquely identified in the code. Bidders will be required to refer to the final results matrix (or conduct independent evaluations) to determine which combinations of those factors are suitable for the given performance criteria.

11.4.11. **Note** - A review of existing alternative and optional bidding approaches is provided in the final report for NCHRP Project 10-86 (*published as NCHRP Report 801*), and agencies looking to develop a new system different from that described here are referred to that review for a listing of bid approaches that may be useful in helping to guide the development of new agency protocols.

11.4.12. **Note -** If bidders wish to use larger pipe systems than the minimum specified in the tender documents, it is recommended that a submittal process be used to evaluate these cases.

11.5. Tracking of Bid Results. The RP strongly recommends that agencies record and database bid results such that regular and systematic evaluations of bid results can be made that allow for evaluation of the impact of RP implementation, and also to provide insight into bid trends to direct and guide policy updates as appropriate.

12. DRAINAGE PIPE SYSTEM INSPECTION

One of the main objectives of the RP is to encourage highway agencies to allow contractors to bid on a wider range of alternative pipe products and systems. Without an associated appropriate and adequate post-installation inspection protocol, the risk of premature failure of pipe systems will increase. In this context, post-installation inspection is not an optional extra for the RP and must be seen as an essential component of implementation. All the pipe system evaluation components within the RP are based on the assumption that the pipe system has been installed in compliance with agency specifications.

Phase 5 of the RP describes the recommended steps for overall quality control, inspection and tracking. The five main steps in this phase are described in separate sections below.

12.1. Material Quality Control

12.1.1. All material used for construction should be checked for conformance with the relevant AASHTO standards

12.1.2. Qualification of manufacturer and manufacturing facility should be performed, together with review of certificates

12.1.3. Inspection of deliveries, which may include inspection of identification markings, date of manufacture, shipping papers, diameter, net length, evidence of poor workmanship, damage during shipping or handling, and measurement of surface cracks

12.1.4. Taking samples of pipe for additional testing

12.2. Construction Quality Control

12.2.1. All construction should be performed in accordance with AASHTO standards, in particular the AASHTO LRFD Bridge Construction Specifications.

12.2.2. Inspection of the pipe system materials and workmanship during construction allows corrections to be made in assembly and backfill practices before construction is complete, and is of particular importance for deeply buried and high traffic installations. The timing and frequency of such inspections should depend on the significance of the structure and depth of fill. In general, inspections should be conducted when materials arrive at the job site, during pipe installation, during backfilling, and prior to construction of final finishes. Inspections during construction may include examination of the following:

- Foundation material
- Trench geometry and dimensions
- Groundwater conditions
- Bedding material
- Line and grade
- Assembly techniques
- Structure backfill and compaction methods
- Joint assembly and materials
- Pipe deflection (during construction)
- Damage to pipe coatings
- Head walls and end treatments

12.3. **Post-Installation Inspection and Approval**

12.3.1. Different pipe materials should be subjected to different post-installation inspection and approval procedures due to the inherent differences in the modes of material behavior. Pipe materials are recommended to be inspected in accordance with the appropriate chapter of the AASHTO LRFD Bridge Construction Specifications:

- Metal Pipe – Chapter 26
- Concrete Pipe – Chapter 27
- Thermoplastic Pipe – Chapter 30

12.4. **Long Term Inspection and Maintenance**

12.4.1. Inspection of drainage pipe systems should be performed in accordance with the FHWA Culvert Inspection Manual (1986).

12.4.2. **Note -** Two ongoing projects: NCHRP Project 14-19, Culvert Rehabilitation to Maximize Service Life While Minimizing Direct Costs and Traffic Disruption, and NCHRP Project 14-26, Culvert and Storm Drain System Inspection Manual, will provide updated summaries of culvert inspection techniques.

12.5. **Tracking of Actual Performance**

12.5.1. Collection of performance data will assist designers, researchers, and policy makers to refine durability evaluation models and pipe selection criteria. Collection of this data should be performed using guidance from the Asset Management Data Collection Guide (2006).

12.5.2. At a minimum, the following information on each culvert should be recorded during each major inspection:

- Environmental parameters of surface water flow in the system
- Condition assessment
- Deflection (for flexible pipe) or joint (for rigid pipe) inspection

13. PRECISION AND BIAS

13.1. The intent of the RP is to eliminate potential biases in the selection of pipe system alternatives approved for bidding through implementation of a systematic, thorough, and transparent evaluation and selection process.

13.2. This standard provides qualitative data only; hence, precision and bias are not specifically applicable.

14. KEYWORDS

14.1. Culvert; highway drainage; Manning's *n*; corrugated metal pipe; galvanized steel pipe; aluminized Type 2 steel pipe; aluminum pipe; reinforced concrete pipe; concrete pipe; thermoplastic pipe; HDPE pipe; PVC pipe; polypropylene pipe; backfill; bedding; embedment; durability; culvert joint; storm drain; alternative bidding.

15. REFERENCE MATERIALS

There is a vast and evolving literature on highway drainage pipe systems, and the following list is a sample of the technical literature on the topic.

AASHTO LRFD Bridge Construction Specifications. American Association of State Highway and Transportation Officials, Washington DC, 2011.

AASHTO Asset Management Data Collection Guide, Task Force 45 Report. American Association of State Highway and Transportation Officials, Washington, DC, 2006.

AASHTO Highway Drainage Guidelines. American Association of State Highway and Transportation Officials, Washington, DC, 2007.

AASHTO LRFD Bridge Design Specifications. American Association of State Highway and Transportation Officials, Washington, DC, 2013.

AASHTO Model Drainage Manual. American Association of State Highway and Transportation Officials, Washington, DC, 2005.

American Iron and Steel Institute (AISI). Handbook of Steel Drainage and Highway Construction Products, Fifth Ed., Washington, DC, 1994.

California Department of Transportation (Caltrans). Highway Design Manual. Sacramento, CA, 2012.

FHWA. Culvert Inspection Manual, Supplement to the Bridge Inspector's Training Manual. FHWA-IP-86-2, U.S. Department of Transportation, Washington, DC, 1986.

FHWA. Durability Analysis of Aluminized Type 2 Corrugated Metal Pipe. FHWA-RD-97-140, U.S. Department of Transportation, Washington, DC, 2000.

FHWA. Federal Lands Highway, Project Development and Design Manual. U.S. Department of Transportation, Washington, DC, 2008.

FHWA. Hydraulic Design of Highway Culverts, Third Ed. Hydraulic Design Series Number 5, FHWA-HIF-12-026, U.S. Department of Transportation, Washington, DC, 2012.

Florida DOT. Drainage Handbook, Optional Pipe Materials Handbook, Tallahassee, 2012.

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Moore, I.D., D.B. Garcia, H. Sezen, and T. Sheldon T. *NCHRP Web-Only Document 190: Structural Design of Culvert Joints.* Transportation Research Board of the National Academies, Washington, DC, 2012.

Potter, J.C. Life Cycle Cost for Drainage Structures. Technical Report GL-88-2, Department of the Army, Waterways Experiment Station, Vicksburg, MS, 1988.

White, K., and J.O. Hurd. Guidance for Design and Selection of Pipes. Report for NCHRP Project 20-07 (Task 264) submitted to AASHTO, Washington, DC, 2011.

APPENDIX B

Worked Example of the Recommended Practice

Appendix B is unpublished herein but can be found on the NCHRP Project 10-86 webpage at www.trb.org.

APPENDIX C

Summary of Durability Evaluation Methods

1.0 Introduction

This appendix summarizes the most commonly accepted independent (i.e., not published by a pipe trade organization) quantitative service life calculation methods for concrete and metal pipes. No known methods are in use to calculate the estimated material service life (EMSL) of thermoplastic pipes. The EMSL of thermoplastic pipes is based on the material performance specifications and details of the resins used in the pipe manufacturing process. The materials are thus generally assigned a fixed EMSL regardless of the environmental parameters at the site. Thermoplastic culvert pipes for highway drainage applications are usually assigned EMSL values between 50 and 100 years.

2.0 Reinforced Concrete Pipe Methods

Concrete culverts are constructed in a large variety of round, elliptical, arch, and rectangular box sizes and have the ability to withstand a wide range of loading and environmental conditions. There are no definitive design methods for estimating concrete culvert service life. As a result, the designer is required to make judgments about the severity of the environmental conditions and the offsetting nature of a variety of design accommodations.

One method of accommodating a harsh environment is the addition of extra sacrificial concrete cover over the reinforcing steel. Typically, where severe abrasion is anticipated, at least 2 in. of additional concrete cover is recommended. Sulfate-resisting concrete or high density concrete should be used where acids, chlorides, or sulfate concentrations in the surrounding soil or water are detrimental. Generally, if soil and/or water have a pH of 5.5 or less, concrete pipe should be required to have extra cover over the reinforcing steel or a protective coating.

Table 1 lists methods that can be used to determine EMSL values for reinforced concrete pipes. The EMSL values obtained using these different methods can vary widely so the RP selects the lowest EMSL value from the methods used. The limitations and range of parameters for which each method is applicable are described in detail for each method below.

2.1 Hurd Model

The Hurd model was developed for use at sites with pH values of 7 or lower, and is given by the following equation:

$$EMSL = \left(\frac{123.5 \times pH^{5.55}}{Slope^{0.42} \times Rise^{1.94}}\right)\left(\frac{1 - Sediment}{Rise}\right)^{-2.64}$$

where:

EMSL = estimated material service life (years)
pH = pH of the water
Slope = pipe invert slope (%)
Sediment = sediment depth in pipe invert (inches)
Rise = vertical pipe diameter (inches)

The Hurd model was developed for conditions where the pH is less than 7.0. For conditions where the pH is greater than 7.0, the primary degradation mechanism that forms the basis of the Hurd model was assumed not to occur. As such, for pH values greater than 7.0, the EMSL is reported to be conservatively estimated as a value less than the EMSL with a pH value of 7.0 (Potter 1988).

2.2 Hadipriono Model

The Hadipriono model is applicable to sites with pH values between 2.5 and 9, and is given by the following equation:

$$EMSL = -33.23 + 160.92 \times \log pH - 4.16 \times Slope^{0.5} - 0.28 \times Rise$$

Table 1. Methods for determining EMSLs for reinforced concrete pipe.

Durability Method	Reference	Notes
Ohio DOT Model	Potter, 1988	Based on large data set over wide range of pH and size values. Includes an abrasive component.
Hurd Model	Potter, 1988	Method developed for large diameter pipes in acidic environments.
Hadipriono Model	Potter, 1988	Method includes wide pH range.
Florida DOT Model	*Florida DOT, Optional Pipe Materials Handbook, 2012*	Considers corrosion to be the only mechanism of degradation.

where:

EMSL = estimated material service life (years)
pH = pH of the water
Slope = pipe invert slope (%)
Rise = vertical pipe diameter (inches)

2.3 Ohio DOT (ODOT) Model

The ODOT model comprises two separate equations, depending on the pH level.

For pH values between 2.5 and 7:

$$EMSL = \left(\frac{[0.349 \times pH^{1.204}]^{7.758}}{Slope^{0.834}}\right)\left(1 - \frac{Sediment}{Rise}\right)^{-5.912}$$

For pH values greater than or equal to 7:

$$EMSL = \left(\frac{3.5}{K}\right)^{5.9}\left(\frac{Flow^{0.52}}{Slope^{0.31}}\right)$$

where:

EMSL = estimated material service life (years)
pH = pH of the water
Slope = pipe invert slope (%)
Sediment = sediment depth in pipe invert (inches)
Rise = vertical pipe diameter (inches)
Flow = velocity rating number (1–rapid, 2–moderate, 3–slow, 4–negligible, 5–none)
K = abrasive constant (0.9–without abrasive flow, 1.19–with abrasive flow)

2.4 Florida DOT (FDOT) Model

The FDOT model includes a number of parameters such as the concrete cover depth and specifications of the concrete mix design. The equation is given as follows:

$$EMSL = 1000(1.107^{C} C^{0.717} D^{1.22} K^{-0.37} W^{-0.631}) - 4.22 \times 10^{10}(pH^{-14.1}) - 2.94 \times 10^{-3}(S) + 4.41$$

where:

EMSL = estimated material service life (years)
C = Sacks of cement per cubic yard
D = Depth of concrete cover over reinforcing steel (inches)
K = Chloride concentration (ppm)
W = Total water percentage in the concrete mix (%)
S = Sulfate content (ppm)

This equation was developed for a 60-in. diameter pipe. The adjustment factors given in Table 2 must be applied depending on the actual pipe size:

Figures 6-4 and Table 6-5 of the FDOT Optional Pipe Material Handbook (February 2012) illustrate the use of this equation and provide a chart showing the relationship between service life, chloride concentration, and pH.

Table 2. Florida DOT conversion factors for different size culverts.

Pipe Diameter (inches)	Factor	Pipe Diameter (inches)	Factor
12	0.36	48	0.76
18	0.36	60	1.00
24	0.41	72	1.25
30	0.48	84	1.51
36	0.54	96	1.77
42	0.65	108	2.04

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FIGURE 6-4

Estimated Service Life vs. pH and Resistivity
for 60" Dia. Concrete Culverts, S = 1500 ppm

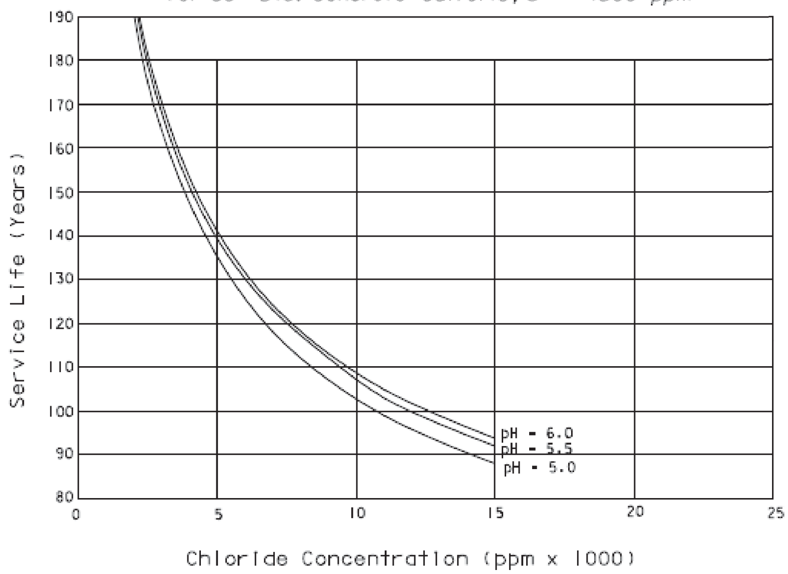

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TABLE 6.5

Estimated Service Life vs. pH and Chlorides for 60" Dia. **REINFORCED CONCRETE** Culverts at 1500 ppm Sulfate Concentration

	Chlorides											
pH	15000	13000	11000	9000	7000	5000	3000	2000	1000	750	500	250
5.0	88	93	99	107	118	135	164	192	250	278	324	360
5.1	89	94	101	109	119	136	165	193	251	279	325	360
5.2	90	95	102	110	121	137	167	194	252	281	327	360
5.3	91	96	102	111	122	138	167	195	253	282	327	360
5.4	92	97	103	111	122	139	168	196	253	282	328	360
5.5	92	97	103	112	123	139	168	196	254	282	328	360
5.6	93	98	104	112	123	140	169	196	254	283	329	360
5.7	93	98	104	112	123	140	169	197	254	283	329	360
5.8	93	98	104	113	124	140	169	197	255	283	329	360
5.9	93	98	105	113	124	140	170	197	255	284	330	360
≥6.0	94	99	105	113	124	141	170	197	255	284	330	360

Conversion Factors for Different Size Culverts			
Pipe Dia.	Mult. By	Pipe Dia.	Mult. By
12"	0.36	48"	0.76
18"	0.36	60"	1.00
24"	0.41	72"	1.25
30"	0.48	84"	1.51
36"	0.54	96"	1.77
42"	0.65	108"	2.04

SL Reduction Factors for Sulfates

Sulfate Content	Subtract from SL
1500	0
3200	5
4900	10
6600	15
8300	20
10000	25

Note: Sulfate derating not applicable When Type V cement is used.

$$\text{Service Life (SL)} = 1000(1.107^{C}C^{0.717}D^{1.22}K^{-0.37}W^{-0.631}) - 4.22\times10^{10}(pH^{-14.1}) - 2.94\times10^{-3}(S) + 4.41$$

Where: C = Sacks of cement per cubic yard D = Steel depth in concrete K = Environmental chloride concentration in ppm
W = Total percentage of water in the mix S = Environmental sulfate content in ppm

3.0 Metal Pipe Methods

The design service life of corrugated metal pipes will normally be the period in years from installation until deterioration reaches the point of either perforation of any point on the culvert or some specified percent of metal loss. Different methods used to estimate service life use different definitions of service life.

3.1 Galvanized Steel Pipe

A number of methods are available for estimating the EMSL of galvanized steel pipe. The California Method is the most widely accepted and is recommended for use if no state- or location-specific research is available that indicates another method is more suitable. The other methods are modifications of the original California Method. Table 3 lists the methods that can be used to determine EMSL values for plain galvanized steel pipes:

The basic assumptions used to determine service life for standard metal pipes may also be extended to metal structural plate pipes (AASHTO M 167/M 167M). One advantage of metal plate is the ability to specify thicker plates for installation in the invert of the structure while keeping the rest of the plates thinner (meeting structural loading requirements only) for economy. This provides greater protection where corrosion and abrasion will typically be most severe.

3.1.1 California Method

A chart useful for application of the California Method is presented in Figure 1. The following equations can also be used:

For pH values greater than 7.3:

$$EMSL = 1.47 \times R^{0.41}$$

For pH values less than 7.3:

$$EMSL = 13.79\left(\log R - \log\left[2160 - 2490 \times \log pH\right]\right)$$

Where R is the minimum resistivity (ohm-cm).

The resulting EMSL value must be multiplied by a factor depending on the gage thickness (see Table 4):

3.1.2 AISI Method

The AISI is very similar to the California Method, with a different definition of the conditions that occur at the end of the useful service life. The chart titled “Chart for estimating average invert life using AISI Method (AISI 1994)” is useful for application of the AISI Method. The following equations can also be used:

For pH values greater than 7.3:

$$EMSL = 2.94 \times R^{0.41}$$

Table 3. Methods for determining EMSLs for plain galvanized steel pipe.

Durability Method	Reference	Notes
California Method	*California Test 643, Method for Estimating the Service Life of Steel Culverts, 1999*	Includes combined effects of corrosion and abrasion. Based on soil/water pH and resistivity. Service life of pipe considered to be until time of first perforation.
American Iron and Steel Institute (AISI) Method	*Handbook of Steel Drainage and Highway Construction Products, AISI, 1994*	Modification of California Method. Service life of pipe considered to be until 25% thickness loss in the invert.
Federal Lands Highway Method	*Federal Lands Highway, Project Development and Design Manual, 2008*	Modification of California Method. Increase the EMSL by 25% after first perforation.
Colorado DOT Method	*CDOT-2009-11, Development of New Corrosion/Abrasion Guidelines for Selection of Culvert Pipe Materials, 2009*	Calibration of California Method to state-specific conditions with a limited data set.
Florida DOT Method	*Florida DOT Optional Pipe Materials Handbook, 2012*	Modification of California Method to include a minimum steel thickness of 16 gage.

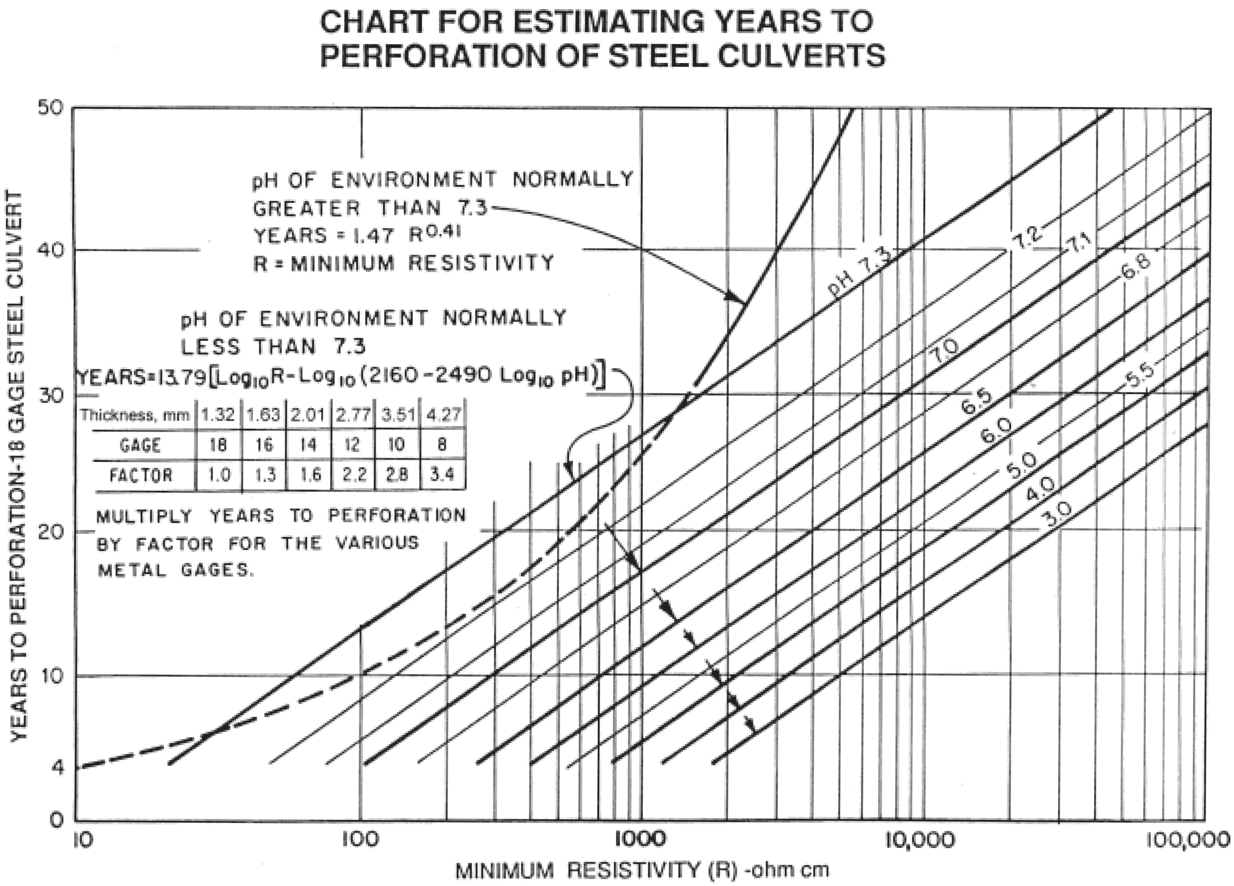


FIGURE 1

For pH values less than 7.3:

$$EMSL = 27.58(\log R - \log[2160 - 2490 \times \log pH])$$

Where R is the minimum resistivity (ohm-cm).

The resulting EMSL value must be multiplied by a factor depending on the gage thickness (see Table 5):

3.1.3 Federal Lands Highway Method

The Federal Lands Highway (FLH) Method is also a modification of the California Method. A chart useful for application of the FLH Method is presented as Exhibit 7.3-B. The following equations can also be used:

For pH values greater than 7.3:

$$EMSL = 2.39 \times R^{0.41}$$

For pH values less than 7.3:

$$EMSL = 22.41(\log R - \log[2160 - 2490 \times \log pH])$$

Where R is the minimum resistivity (ohm-cm).

The resulting EMSL value must be multiplied by a factor depending on the gage thickness (see Table 6):

3.1.4 FDOT Method

The FDOT Method is also a modification of the California Method. A chart and table useful for application of the FDOT Method are presented in Figure 6.1 and Table 6.2, respectively. The following equations can also be used:

For pH values between 7.3 and 9.0:

$$EMSL = 1.84 \times R^{0.41}$$

Table 4. Galvanized steel pipe gage thickness factors—California method.

Gage	18	16	14	12	10	8
Factor	1.0	1.3	1.6	2.2	2.8	3.4

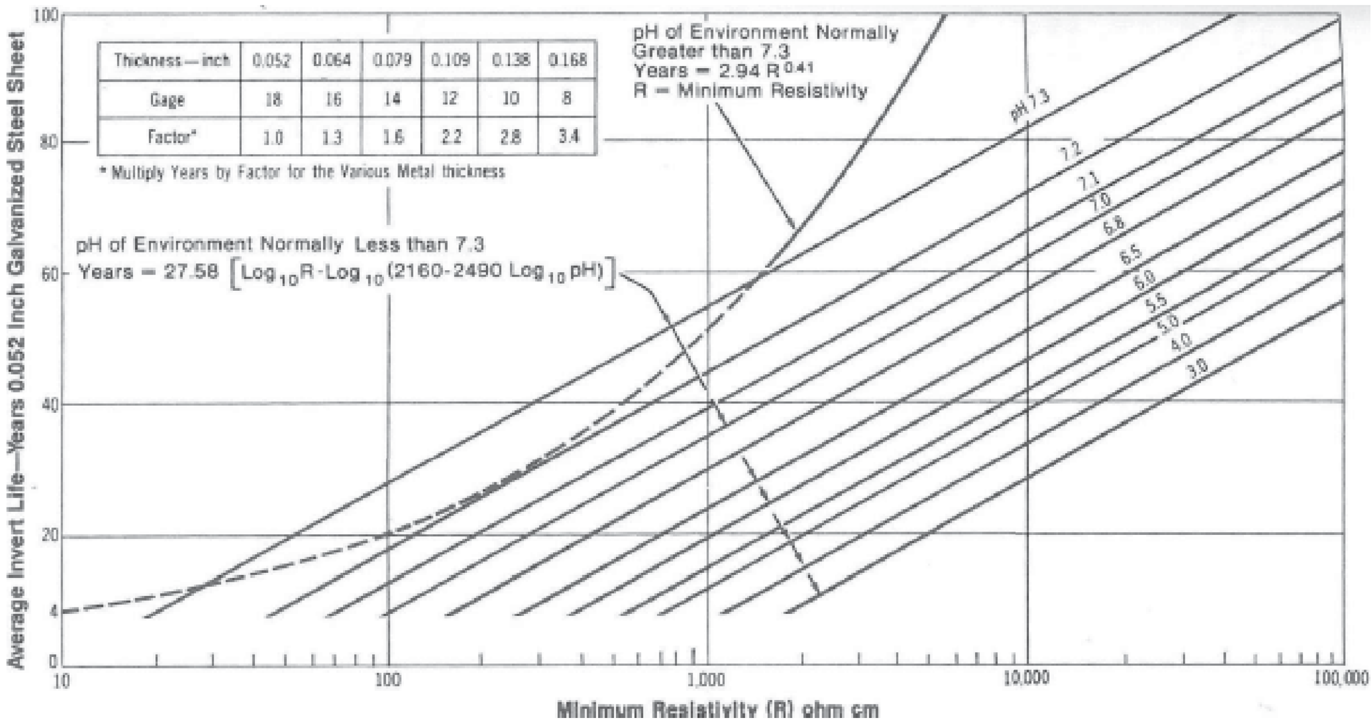


Chart for estimating average invert life using AISI Method (AISI 1994).

For pH values between 5.0 and 7.3:

$$EMSL = 17.24(\log R - \log[2160 - 2490 \times \log pH])$$

Where R is the minimum resistivity (ohm-cm).

The resulting EMSL value must be multiplied by a factor depending on the gage thickness (see Table 7):

3.1.5 Additional Service Life Due to Coatings

Additional service life due to protection by coatings is generally included by adding on a predetermined number of years to the calculated service life using one of the aforementioned methods. Predetermined service life add-on values depend on the abrasion characteristics and type of coating. Add-on service life year values can range from 10 to 80 years. Table C9.0 from the MTO (2007) provides an example of the allowable additional service life values used for various coatings for that agency.

3.2 Aluminized Steel (Type 2) Pipe

3.2.1 FDOT Method

The FDOT Method for estimating material service life of aluminized (Type 2) steel can be applied using a chart presented as Figure 6.2 or by using the table presented as Table 6.3. The following equations can also be used:

For pH between 5.0 and 7.0:

$$EMSL = 50(\log R - \log[2160 - 2490 \times \log pH])$$

For pH between 7.0 and 8.5:

$$EMSL = 50(\log R - 1.746)$$

For pH between 8.5 and 9.0:

$$EMSL = 50(\log R - \log[2160 - 2490 \times \log(7 - 4(pH - 8.5))])$$

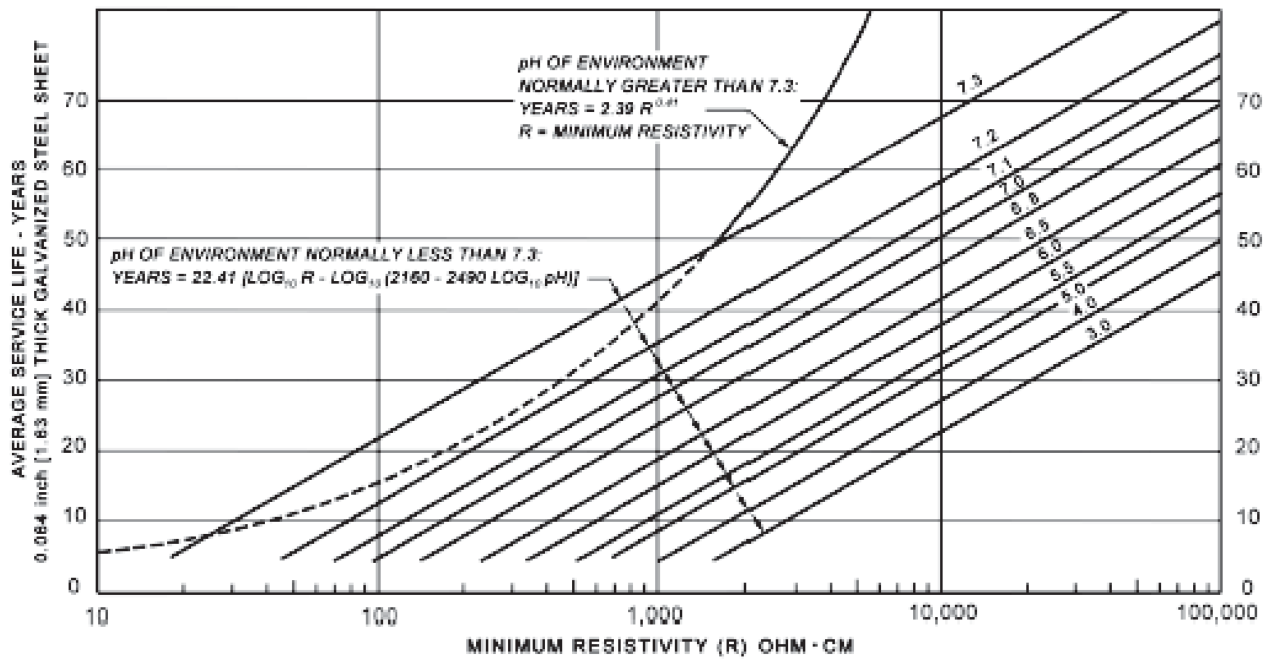
Where R is the minimum resistivity (ohm-cm).

Table 5. Galvanized steel pipe gage thickness factors—AISI method.

Gage	18	16	14	12	10	8
Factor	1.0	1.3	1.6	2.2	2.8	3.4

Exhibit 7.3–B ESTIMATING STEEL PIPE SERVICES LIFE

FEDERAL LANDS HIGHWAY MODIFIED CALIFORNIA METHOD CHART FOR ESTIMATING SERVICE LIFE OF PLAIN GALVANIZED STEEL CULVERTS



Service Life Estimation Chart for Average Service Life of Plain Galvanized Culverts

THICKNESS FACTORS

THICKNESS, inch	0.052	0.064	0.079	0.109	0.138	0.168
GAGE	18	16	14	12	10	8
THICKNESS, mm	1.32	1.63	2.01	2.77	3.51	4.27
FACTOR	0.8	1.0	1.2	1.7	2.2	2.6

Note: Multiply the average Service Life by the Thickness Factor

NOTES:

1. The curves in this Chart are based on the data in FHWA-FLP-91-006 which uses the factors in California Test 643, "Method for Estimating the Service Life of Steel Culverts". These factors increased the estimated service life by 25% after first perforation.
2. The Chart has also been modified to reflect a minimum metal thickness of 0.064 inch or 16 gage [1.63 mm]
3. Under conditions with pH between 5 and 9, and above R ≥ 1500, the average service life determined for plain galvanized culverts should be multiplied by 2.0 for Aluminum coated steel, (Type 2).

Table 6. Galvanized steel pipe gage thickness factors—FLH method.

Gage	18	16	14	12	10	8
Factor	0.8	1.0	1.2	1.7	2.2	2.6

The resulting EMSL value must be multiplied by a factor depending on the gage thickness (see Table 8):

3.3 Aluminum Pipe

Estimates of service life for aluminum pipe can be made based on an FDOT Method, applied through the use of Figure 6.3 or Table 6.4. The EMSL value depends on the minimum resistivity, pH, and gage thickness. The end of useful service life is defined as the time to first perforation. No explicit equation was found for these relationships.

When installed within acceptable pH and soil resistivity ranges (typically 4.0 to 9.0 and > 500 ohm-cm, respectively) aluminum pipe (AASHTO M 196/M 196M) can provide a significant advantage over plain, galvanized steel pipe from a corrosion standpoint. It is therefore possible to use aluminum pipe in lieu of a thicker walled or coated (and thus more expensive) steel pipe.

Because aluminum is softer than steel, it is more susceptible to the effects of abrasion. This is particularly true for higher velocity flows that produce a scraping action, as opposed to lower velocity flows that allow the bedload to roll over the culvert surface. Where high velocity flows (15 ft/s or greater) carrying a bedload are prevalent, use of aluminum should be carefully evaluated. As with all metal pipes, invert loss is caused by a combination of abrasion and corrosion and, thus, the severity of both conditions must be considered.

4.0 Example Material Service Life Calculations

The use of various quantitative methods for estimating material service life is demonstrated in this appendix. The use of a number of available software programs to assist in the estimating of service life is also demonstrated.

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FIGURE 6-1

Estimated Service Life vs. pH and Resistivity
for 16 ga. Galvanized Steel

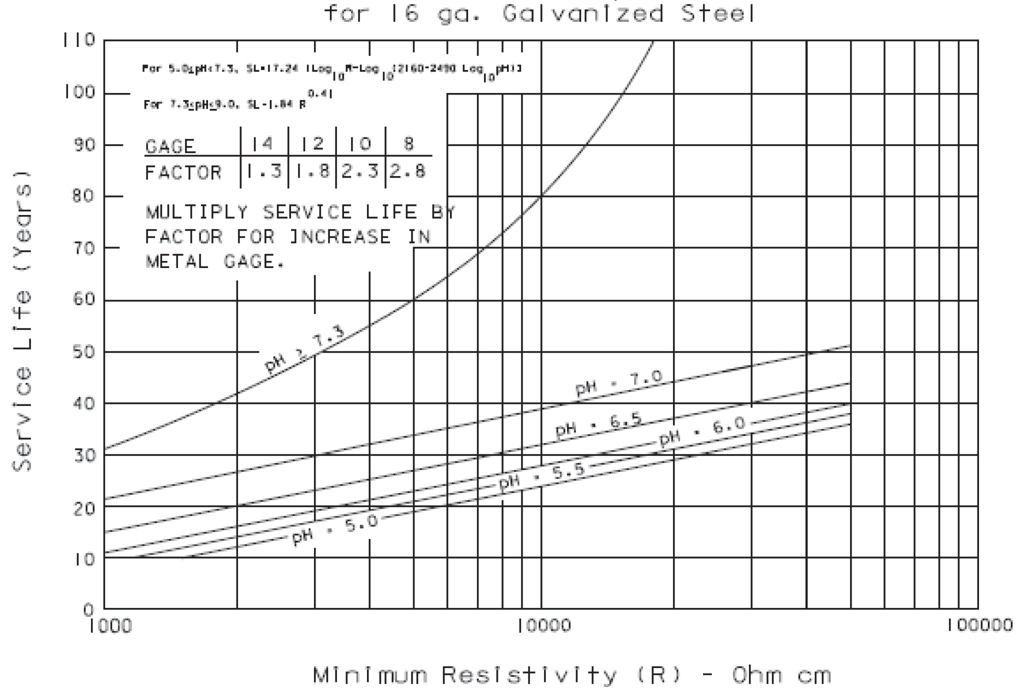

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TABLE 6.2

Design Service Life vs. pH and Resistivity for 16 ga. **GALVANIZED STEEL** Culvert Pipe

pH	Resistivity												
	1000	1500	2000	3000	4000	5000	7000	10000	15000	20000	30000	40000	≤50000
5.0	7	10	12	15	17	19	21	24	27	29	32	34	36
5.1	7	10	12	15	17	19	21	24	27	29	32	34	36
5.2	8	10	13	16	18	19	22	25	28	30	33	35	37
5.3	8	11	13	16	18	20	22	25	28	30	33	35	37
5.4	8	11	13	16	19	20	23	25	28	31	34	36	37
5.5	9	12	14	17	19	21	23	26	29	31	34	36	38
5.6	9	12	14	17	19	21	24	26	29	32	35	37	38
5.7	10	13	15	18	20	22	24	27	30	32	35	37	39
5.8	10	13	15	18	21	22	25	27	30	32	36	38	39
5.9	11	14	16	19	21	23	25	28	31	33	36	38	40
6.0	11	14	16	20	22	23	26	28	32	34	37	39	41
6.1	12	15	17	20	22	24	26	29	32	34	37	40	41
6.2	13	16	18	21	23	25	27	30	33	35	38	40	42
6.3	13	16	19	22	24	25	28	31	34	36	39	41	43
6.4	14	17	19	22	24	26	29	31	34	36	40	42	43
6.5	15	18	20	23	25	27	30	32	35	37	40	43	44
6.6	16	19	21	24	26	28	31	33	36	38	41	44	45
6.7	17	20	22	25	27	29	32	34	37	39	42	45	46
6.8	18	21	23	26	29	30	33	36	39	41	44	46	48
6.9	20	23	25	28	30	32	34	37	40	42	45	47	49
7.0	22	25	27	30	32	34	36	39	42	44	47	49	51
7.1	24	27	29	32	34	36	39	41	44	46	50	52	53
7.2	28	31	33	36	38	40	42	45	48	50	53	55	57
7.3	34	37	39	42	45	46	49	52	54	57	60	61	64
7.4 - 9.0	34	37	42	49	55	60	69	80	95	107	126	142	155

Estimated Service Life: $(SL) = 17.24\{Log_{10}R - Log_{10}[2160\text{-}2490(Log_{10}pH)]\}$ for $5 \leq pH \leq 7.3$

$(SL) = 1.84\ R^{0.41}$ for $7.3 \leq pH \leq 9$

Table 7. Galvanized steel pipe gage thickness factors—Florida DOT method.

Gage	**18**	**16**	**14**	**12**	**10**	**8**
Factor	**--**	**1.0**	**1.3**	**1.8**	**2.3**	**2.8**

Table C9.0
EMSL for Steel Pipe Coatings / Laminations

Coating[3]	Water Side: EMSL	Water Side: Max. Abrasion Level[2] (See Table C8)	Soil Side Add-On Years
Aluminized Type 2 (Sizes 1.3 to 3.5 mm)	Refer to Figure B5	3	-
Lamination[3]	**Add-On Years to Plain Galvanized EMSL**		
Polymer Coated[1] (sizes 1.3 to 3.5 mm)	10 – 40 (Ref.erence 1) 20 – 70 (Reference 2) 50 (Reference 3) 30 (Reference 4)	3 3 - 3	- 50 -75 - -

Notes:

1. Polymeric sheet coating provides adequate abrasion resistance to meet or exceed 50 year design service life for Abrasion Level 2 or below (see Reference 1)
2. No abrasive resistant protective coatings are recommended above Abrasion Level 3 (see Reference 1.)
3. Specific add-on values should be selected based on environmental conditions (abrasion, pH, resistivity, and low soil moisture content) and experience in comparable environments. Upper limits should be considered for the most favourable environmental conditions, (non-abrasive, high pH and resistivity) while low limits should be considered for the maximum abrasion level and most corrosive environments. (See reference 2).

References:

1. California Highway Design Manual, 2002, pg 850-18
2. CSPI, 2002, pg 353
3. Ohio DOT
4. FHWA, 2000

FIGURE 6-2

Estimated Service Life vs. pH and Resistivity for 16 ga. Aluminized Steel Type II

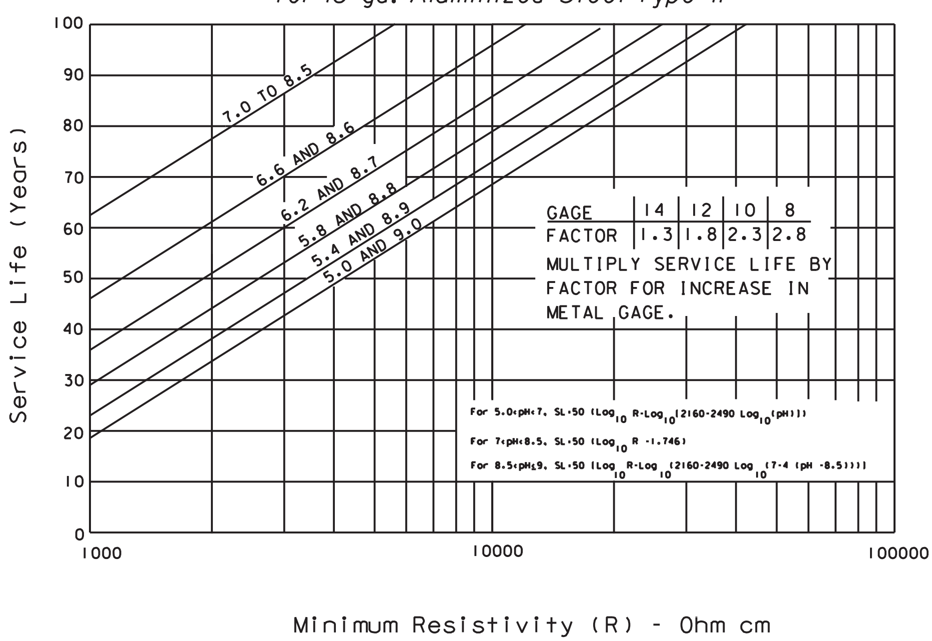

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TABLE 6.3

Estimated Service Life vs. pH and Resistivity for 16 ga. **ALUMINIZED STEEL** Culvert Pipe

pH	Resistivity 1000	1500	2000	3000	4000	5000	7000	10000	15000	20000	30000	40000	≤50000
5.0	19	28	34	43	49	54	61	69	78	84	93	99	104
5.1	20	29	35	44	50	55	62	70	79	85	94	100	105
5.2	21	30	36	45	51	56	63	71	80	86	95	101	106
5.3	22	31	37	46	52	57	65	72	81	87	96	102	107
5.4	24	32	39	48	54	59	66	74	82	89	98	104	109
5.5	25	34	40	49	55	60	67	75	84	90	99	105	110
5.6	26	35	41	50	56	61	69	76	85	91	100	106	111
5.7	28	37	43	52	58	63	70	78	87	93	102	108	113
5.8	29	38	44	53	59	64	72	79	88	94	103	109	114
5.9	31	40	46	55	61	66	73	81	90	96	105	111	116
6.0	33	41	48	56	63	68	75	83	91	98	106	113	118
6.1	34	43	50	58	65	69	77	84	93	100	108	115	119
6.2	36	45	51	60	67	71	79	86	95	101	110	116	121
6.3	38	47	54	62	69	73	81	88	97	104	112	119	123
6.4	41	50	56	65	71	76	83	91	100	106	115	121	126
6.5	43	52	58	67	73	78	86	93	102	108	117	123	128
6.6	46	55	61	70	76	81	88	96	105	111	120	126	131
6.7	49	58	64	73	79	84	92	99	108	114	123	129	134
6.8	53	62	68	77	83	88	95	103	112	118	127	133	138
6.9	57	66	72	81	87	92	100	107	116	122	131	137	142
7.0 to 8.5	63	72	78	87	93	98	105	113	122	128	137	143	148
8.6	46	55	61	70	76	81	88	96	105	111	120	126	131
8.7	36	45	51	60	67	71	79	86	95	101	110	116	121
8.8	29	38	44	53	59	64	72	79	88	94	103	109	114
8.9	24	32	39	48	54	59	66	74	82	89	98	104	109
9.0	19	28	34	43	49	54	61	69	78	84	93	99	104

Estimated Service Life

$(SL) = 50\{Log_{10}R - Log_{10}[2160 - 2490(Log_{10}pH)]\}$ for $5.0 \leq pH < 7.0$

$(SL) = 50(Log_{10}R - 1.746)$ for $7.0 \leq pH \leq 8.5$

$(SL) = 50\{Log_{10}R - Log_{10}\{2160 - 2490\ Log_{10}[7 - 4(pH - 8.5)]\}\}$ for $8.5 < pH \leq 9.0$

Table 8. Aluminized steel (Type 2) gage thickness factors—Florida DOT method.

Gage	18	16	14	12	10	8
Factor	--	1.0	1.3	1.8	2.3	2.8

FIGURE 6-3

Estimated Service Life vs. pH and Resistivity for Aluminum

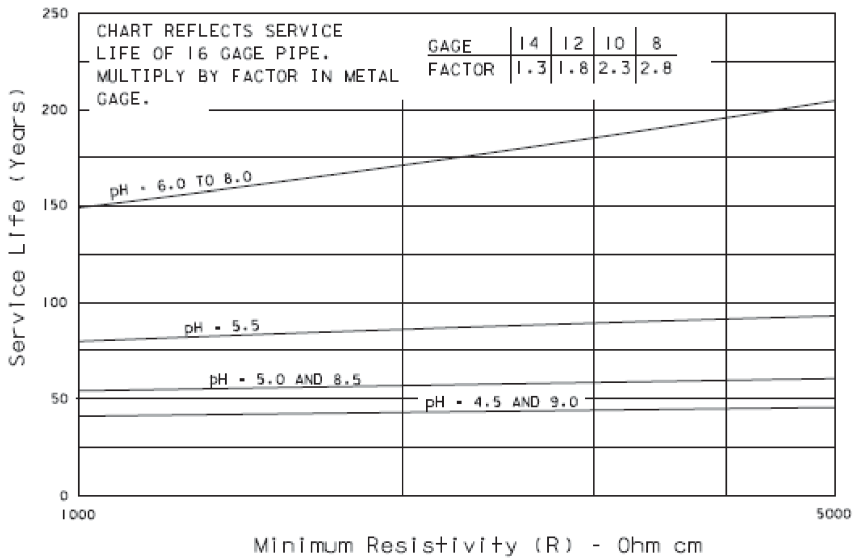

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TABLE 6.4

Estimated Service Life vs. pH and Resistivity for 16 ga. **ALUMINUM** Culvert Pipe

	Resistivity															
pH	≥200	400	600	800	1000	1200	1400	1600	1800	2000	2300	2700	3200	3800	4500	≤5000
4.5 & 9.0	36	39	40	41	41	42	42	42	43	43	43	43	44	44	44	45
4.6 & 8.9	38	41	42	43	43	44	44	45	45	45	45	46	46	47	47	48
4.7 & 8.8	40	43	44	45	46	46	47	47	47	48	48	48	49	49	50	51
4.8 & 8.7	42	45	46	48	48	49	49	50	50	50	51	51	52	52	53	54
4.9 & 8.6	44	48	49	50	51	52	52	53	53	54	54	55	55	56	56	57
5.0 & 8.5	46	50	52	53	54	55	56	56	57	57	58	58	59	59	60	61
5.1	49	53	56	57	58	59	60	60	61	61	62	62	63	64	65	66
5.2 & 8.4	52	57	59	61	62	63	64	65	65	66	67	67	68	69	70	71
5.3	55	61	64	66	67	68	69	70	71	71	72	73	74	75	76	77
5.4 & 8.3	59	66	69	71	73	74	75	76	77	78	79	80	81	82	83	84
5.5	63	71	75	78	80	81	83	84	85	86	87	88	90	91	92	93
5.6 & 8.2	68	78	82	85	88	90	91	93	94	95	97	98	100	102	104	105
5.7	74	85	91	95	98	100	102	104	106	107	109	111	113	116	118	119
5.8 & 8.1	81	95	102	107	110	114	116	119	121	122	125	128	131	134	137	138
5.9	89	107	115	122	127	131	134	138	140	143	146	150	154	158	163	165
≥6.0 & ≤8.0	100	122	133	142	149	154	159	164	168	171	176	182	188	194	200	204

Service Life (SL) = $T_p / (R_{pH} + R_r)$

Where:
SL = Years to first perforation
T_p = Thickness of pipe (inches)
R_{pH} = Corrosion rate for pH (inches/year)
R_r = Corrosion rate for resistivity (inches/year)

Table 9. Assumed environmental parameters for EMSL example calculations.

Case	pH	Resistivity (Ω-cm)	Sulfates (ppm)	Chlorides (ppm)
Non-aggressive	7.5	2000	250	25
Moderate	6.5	1000	500	50
Aggressive	4.5	500	1000	100

Table 10. Additional parameters required for example durability assessments.

Parameter	Value
Invert slope	1%
Pipe length	50 ft
Inside pipe diameter	36 inches
Abrasion level	Low, mildly abrasive, K = 1.19 (with abrasive flow)
Sacks of cement per cubic yard (concrete pipe)	6 sacks
Total percentage of water in aggregate mix (concrete pipe)	9%
Steel depth in concrete (concrete pipe)	0.5 inches
Sediment depth (concrete pipe)	1/8 inch
Gage (metal pipe)	16

Each material type with a quantitative estimation method will be analyzed for three different example cases; namely, an aggressive case, a moderate case, and a non-aggressive case. The three different cases differ in the assumed environmental parameters, as indicated below in Table 9. The assumed environmental values represent the worst case for either the soil-side or water-side of the culvert.

Additional parameters that have been taken as constant regardless of the material type being analyzed are summarized in Table 10.

4.1 Non-Aggressive Case

Table 11 contains results obtained by using the aforementioned equations and charts to estimate material service life for the non-aggressive case.

4.2 Moderately Aggressive Case

Table 12 contains results obtained by using the aforementioned equations and charts to estimate material service life for the moderate case.

Table 11. Example EMSL calculation results—non aggressive case.

Pipe Material	Approach	EMSL (years)
Concrete	Hurd Model	< 6025 Note 1
	Hadipriono Model	94
	ODOT Model	833
	FDOT Method	116
Galvanized Steel	California Method	43
	AISI Method	86
	FLH Method	54
	FDOT Method	42
Aluminized (Type 2)	FDOT Method	78
Aluminum	FDOT Method	171

Note 1 – For pH values greater than 7.0, the Hurd model is not explicitly applicable, with the commentary on the method indicating a conservative estimate of EMSL can be taken as less than the calculated value for the pH 7.0 condition holding other parameters constant.

Table 12. Example EMSL calculation results—moderately aggressive case.

Pipe Material	Approach	EMSL (years)
Concrete	Hurd Model	3993
	Hadipriono Model	84
	ODOT Model	11348
	FDOT Method	90
Galvanized Steel	California Method	16
	AISI Method	31
	FLH Method	19
	FDOT Method	15
Aluminized (Type 2)	FDOT Method	63
Aluminum	FDOT Method	149

4.3 Aggressive Case

Table 13 contains results obtained by using the aforementioned equations and charts to estimate material service life for the aggressive case.

4.4 Discussion of Results

A number of observations can be made based on these results:

- There is a wide variety in the EMSL values for different pipe types.
- There is a wide range of values obtained for a single pipe type depending on the method used.
- Taking an average value of multiple methods is not recommended given the potentially very wide range in values.
- As seen from the results of the Ohio DOT concrete EMSL calculations, many of the current methods do not produce stable and realistic results across the range of feasible values. Careful consideration of the limitations of each method and review of results is recommended.

4.5 Use of Software for EMSL Calculations

Three software programs are demonstrated to show how EMSL calculations can be implemented in an efficient and reliable manner:

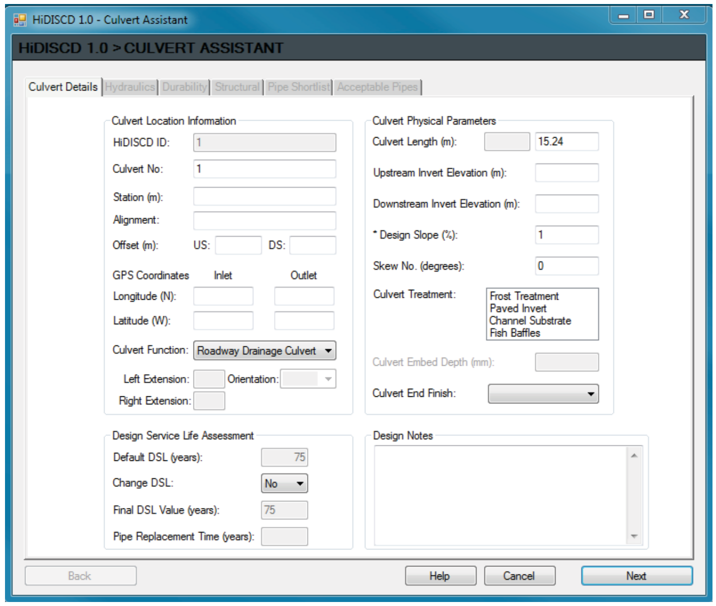
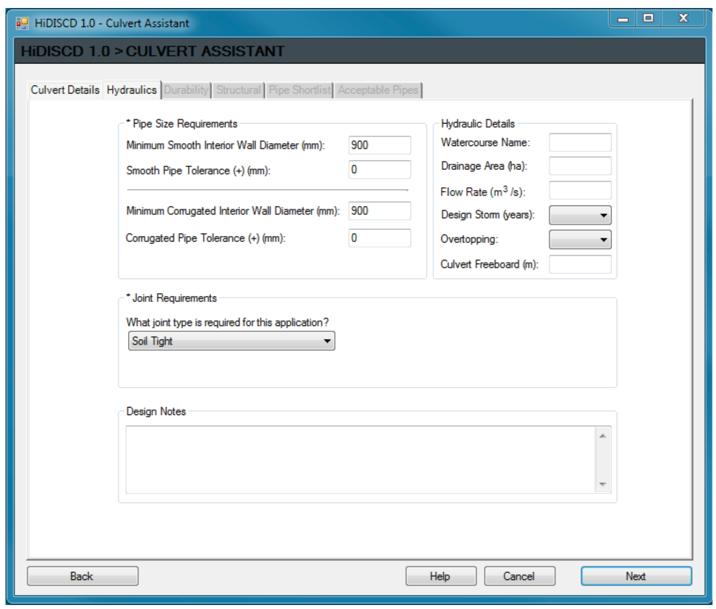
- HiDISC 1.0 developed for the MTO (not yet publicly released)
- CSLE (Culvert Service Life Estimator) 2013 developed by FDOT
- AltPipe v 6.08 developed by Caltrans

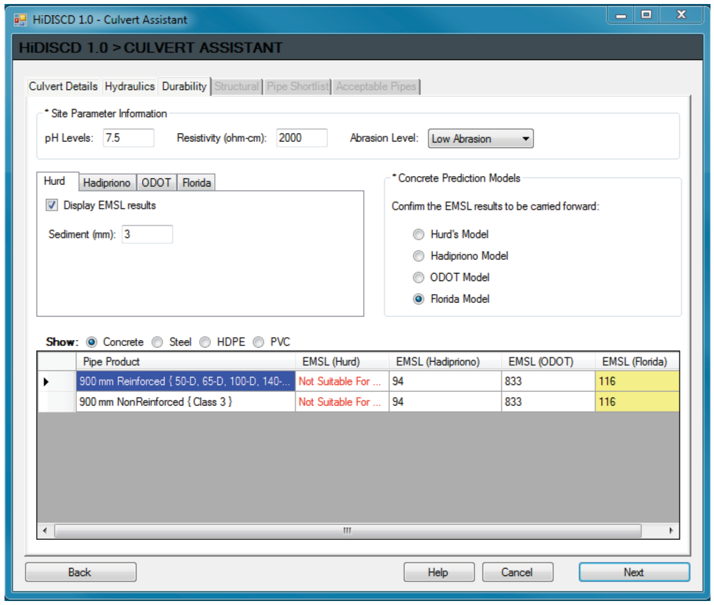
HiDISC and CSLE are stand-alone software programs while AltPipe is an online tool. The following screenshots show the use of these programs for the non-aggressive case.

Table 13. Example EMSL calculation results—aggressive case.

Pipe Material	Approach	EMSL (years)
Concrete	Hurd Model	519
	Hadipriono Model	58
	ODOT Model	366
	FDOT Method	54
Galvanized Steel	California Method	0 (Not Allowed)
	AISI Method	0 (Not Allowed)
	FLH Method	0 (Not Allowed)
	FDOT Method	0 (Not Allowed)
Aluminized (Type 2)	FDOT Method	0 (Not Allowed)
Aluminum	FDOT Method	39

4.5.1 MTO HiDISC 1.0 Example Screen Captures

Data Input – Culvert Details	
Data Input – Hydraulics	

<table>
<tr>
<td>Data Input – Durability</td>
<td>
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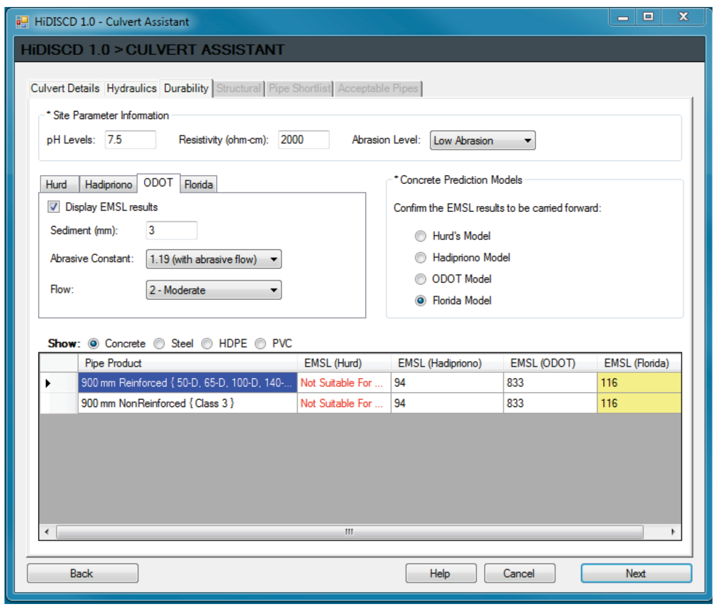
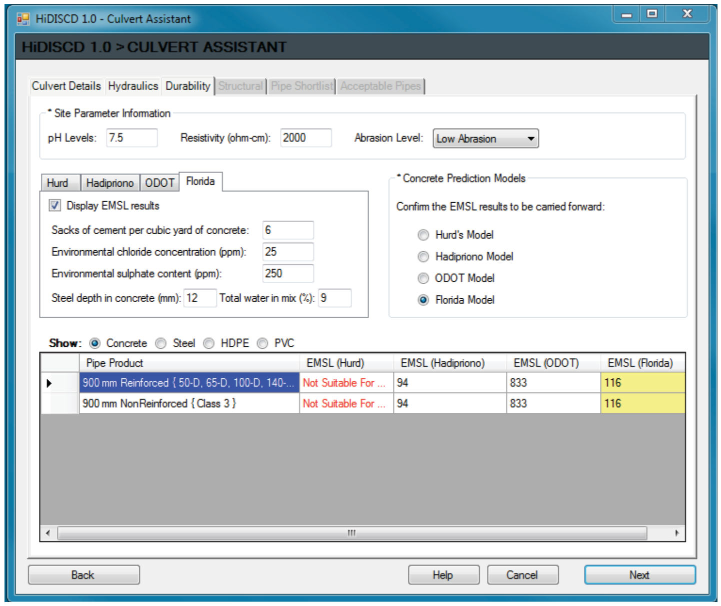
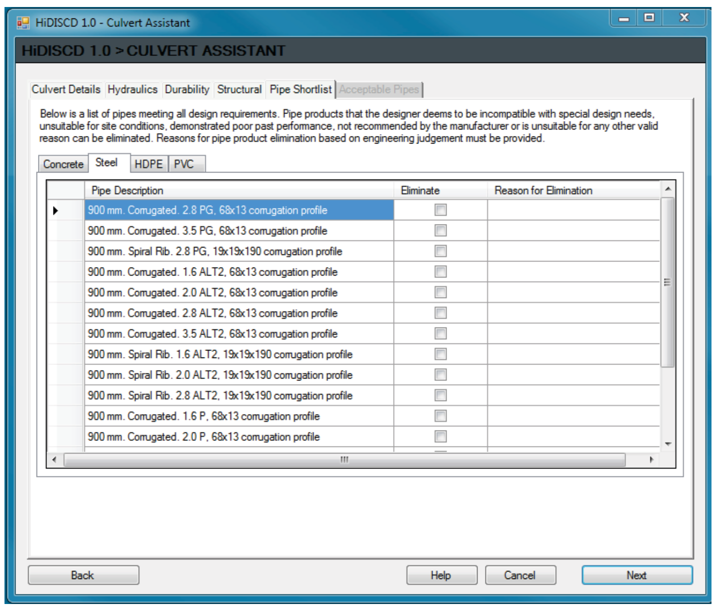
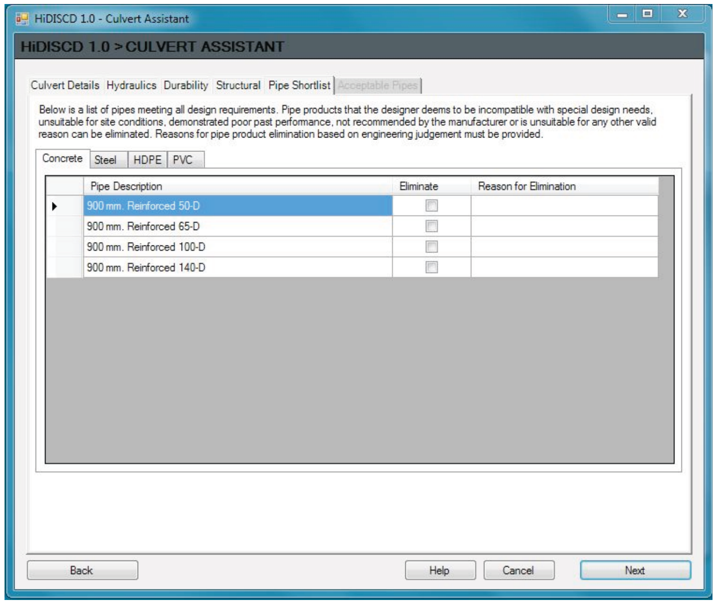
</tr>
<tr>
<td>Data Input – Durability</td>
<td>
</td>
</tr>
</table>

Data Input – Durability

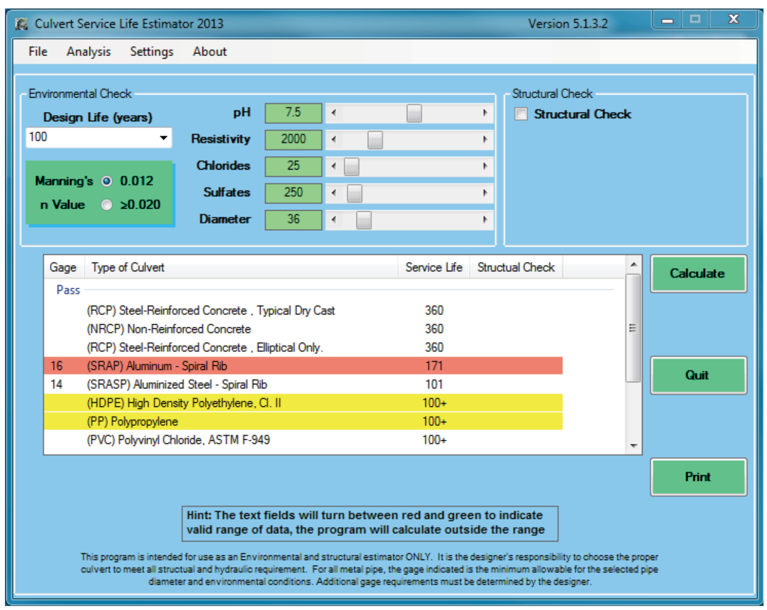


Output - Steel

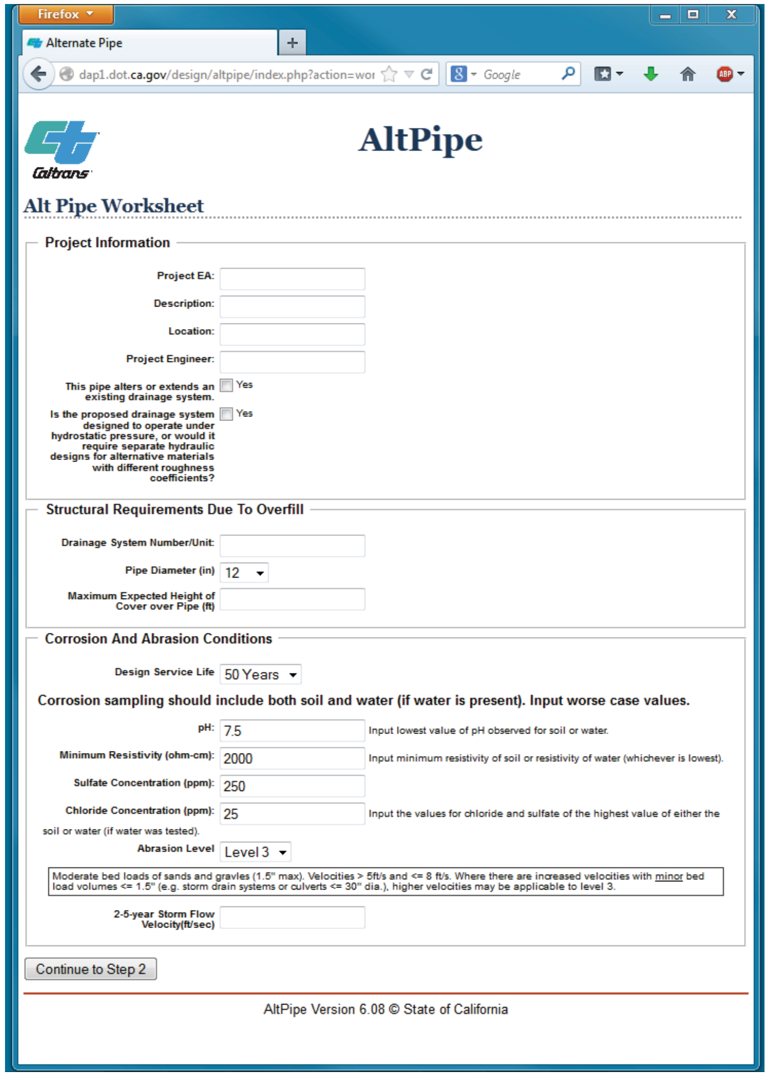


Output - Concrete	

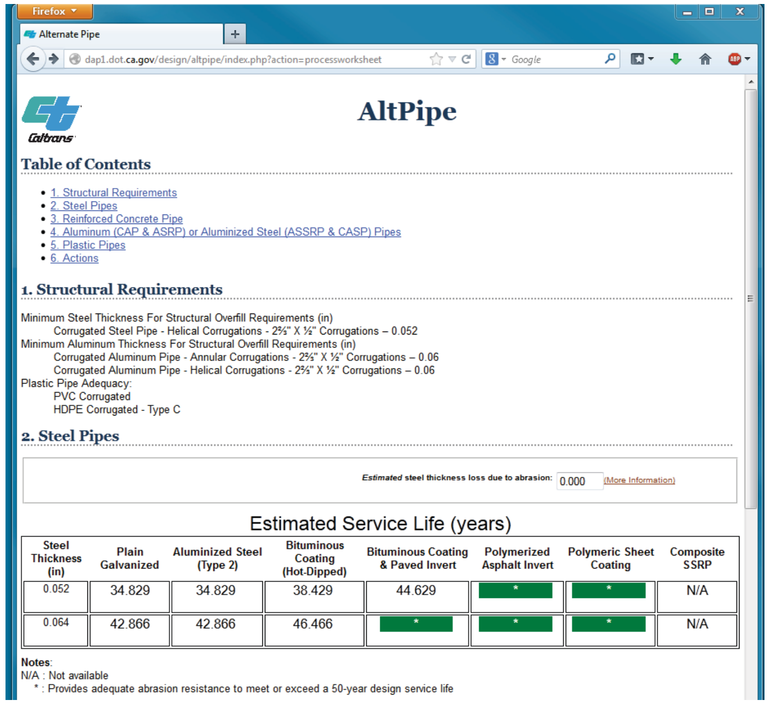
4.5.2 FDOT CSLE 2013 (version 5.1.3.2) Example Screen Captures

Data Output	

4.5.3 Caltrans AltPipe (version 6.08) Example Screen Captures

Data Input	

Output - Steel



Firefox

Alternate Pipe

dap1.dot.ca.gov/design/altpipe/index.php?action=processworksheet

AltPipe

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Corrugated Aluminum Pipe - Annular Corrugations - 2⅔" X ½" Corrugations – 0.06
Corrugated Aluminum Pipe - Helical Corrugations - 2⅔" X ½" Corrugations – 0.06
Plastic Pipe Adequacy:
PVC Corrugated
HDPE Corrugated - Type C

2. Steel Pipes

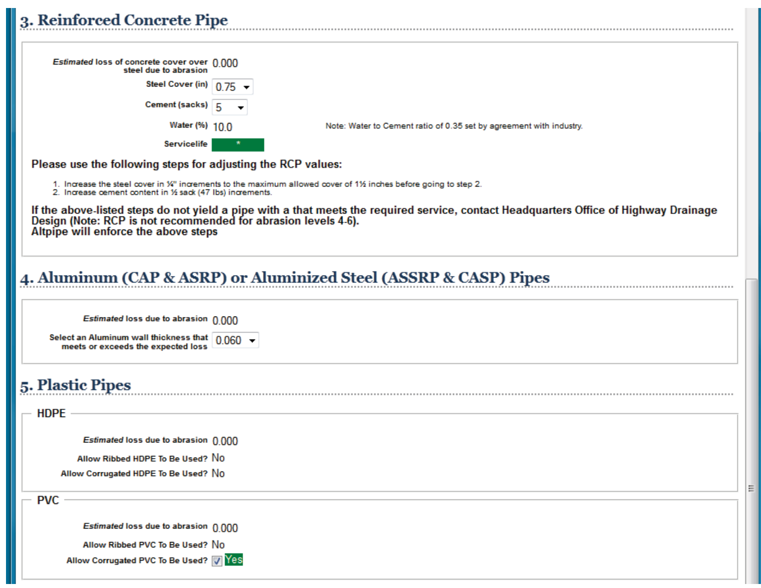
Estimated steel thickness loss due to abrasion: 0.000 (More Information)

Estimated Service Life (years)

Steel Thickness (in)	Plain Galvanized	Aluminized Steel (Type 2)	Bituminous Coating (Hot-Dipped)	Bituminous Coating & Paved Invert	Polymerized Asphalt Invert	Polymeric Sheet Coating	Composite SSRP
0.052	34.829	34.829	38.429	44.629	*	*	N/A
0.064	42.866	42.866	46.466	*	*	*	N/A

Notes:
N/A : Not available
* : Provides adequate abrasion resistance to meet or exceed a 50-year design service life

Output – Concrete, Aluminum, and Plastic



3. Reinforced Concrete Pipe

Estimated loss of concrete cover over steel due to abrasion 0.000
Steel Cover (in) 0.75
Cement (sacks) 5
Water (%) 10.0 Note: Water to Cement ratio of 0.35 set by agreement with industry.
Servicelife *

Please use the following steps for adjusting the RCP values:

1. Increase the steel cover in ¼" increments to the maximum allowed cover of 1½ inches before going to step 2.
2. Increase cement content in ½ sack (47 lbs) increments.

**If the above-listed steps do not yield a pipe with a that meets the required service, contact Headquarters Office of Highway Drainage Design (Note: RCP is not recommended for abrasion levels 4-6).
Altpipe will enforce the above steps**

4. Aluminum (CAP & ASRP) or Aluminized Steel (ASSRP & CASP) Pipes

Estimated loss due to abrasion 0.000
Select an Aluminum wall thickness that meets or exceeds the expected loss 0.060

5. Plastic Pipes

HDPE

Estimated loss due to abrasion 0.000
Allow Ribbed HDPE To Be Used? No
Allow Corrugated HDPE To Be Used? No

PVC

Estimated loss due to abrasion 0.000
Allow Ribbed PVC To Be Used? No
Allow Corrugated PVC To Be Used? Yes

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
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	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation