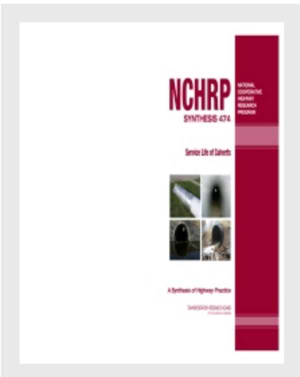

Service Life of Culverts

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Service Life of Culverts

A Synthesis of Highway Practice

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

TRANSPORTATION RESEARCH BOARD 2015 EXECUTIVE COMMITTEE*

* Membership as of February 2015.

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TRANSPORTATION RESEARCH BOARD

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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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Cover figures (clockwise from top left): Section of helical-corrugated metal pipe used as exposed end piece on PVC pipe (*Courtesy*: FDOT); older invert paved corrugated steel culvert in excellent condition (NYSDOT 2011); 36-in. diameter high-density polyethylene drainage pipe (*Courtesy*: Golder Associates); reinforced concrete culvert pipe (*Courtesy*: Thinkstock; used with permission).

FOREWORD

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

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, "Synthesis of Information Related to Highway Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice*.

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

PREFACE

By Jon M. Williams
Program Director
Transportation Research Board

This study showed a diverse range of pipe types in common usage among the states, with concrete, corrugated galvanized steel, and high-density polyethylene (HDPE) pipes as the most common pipe types in use, followed by galvanized structural plate and polyvinyl chloride (PVC). Within the past 15 years there has been significant advancement in understanding the mechanisms of pipe degradation in service. Significant work has been done with respect to corrosion and the main factors that influence its development in concrete and metal pipes; that is, pH, resistivity, chloride, and sulfates. This has led to studies into how to retard or prevent corrosion by the use of thicker walls, better materials, coatings, and liners. Advances have also been made in a better understanding of abrasion and how it enhances the rate of degradation from corrosion, and how its damaging effects can be mitigated. There has also been effective research undertaken in understanding the time-dependent changes in mechanical properties of thermoplastic pipe, particularly slow crack growth and oxidative/chemical failure and how they can be controlled. Little recent advancement has been made in refining pipe service prediction models, even for the more common pipe types. However, with the combination of research on the degradation mechanisms, a better understanding of the progression of deterioration, tied in with greater sources of pipe performance data from agency pipe inventories, in future more rapid progress in improving these models should be possible.

Information was acquired by survey of North American transportation agencies and a literature review.

Michael Maher, Gregory Hebeler, and Andrew Fuggle, Golder Associates, Inc., Whitby, Ontario, Canada, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

CONTENTS

Note: Many of the photographs, figures, and tables in this report 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.

SERVICE LIFE OF CULVERTS

SUMMARY

The objective of this study was to update the 1998 *NCHRP Synthesis 254: Service Life of Drainage Pipe*, which in turn updated the 1978 *NCHRP Synthesis 50: Durability of Drainage Pipe*. In the past 18 years, the culvert pipe industry and research community has made numerous developments in pipe materials, sophisticated analytical soil-structure interaction modeling techniques, greater use of in situ pipe rehabilitation, and the introduction of larger and more diverse structures. As such, the AASHTO subcommittees on culverts determined that a new synthesis study of the service life of culverts was needed. The study approach consisted of two primary thrusts. First, a survey of North American transportation agencies was performed to determine the current state of practice. Second, a literature review was performed to assess both the state of practice and the state of the art with regard to the subject topic.

Forty-one U.S. departments of transportation (DOTs) and seven agencies in Canada responded to the survey. The results showed a diverse range of pipe types in common usage, with concrete, corrugated galvanized steel, and high-density polyethylene (HDPE) pipes as the most common pipe types, followed by galvanized structural plate and polyvinyl chloride (PVC). Almost half of agencies gather site-specific environmental data on drainage projects, indicating a broad appreciation of the importance of selecting the durability of materials to match site conditions. Less than a quarter of respondents indicated that they had developed or improved pipe durability prediction models. Those that have developed prediction models include DOTs that are subject to extremely variable or extreme environmental conditions. There was little consistency in definitions of end of service life, but there appears to be a trend toward using the results of pipe inspection rating systems to set threshold values that trigger maintenance, rehabilitation, or replacement. The majority of respondents indicated that quality of pipe installation has a significant influence on culvert pipe performance. HDPE and PVC were identified as the pipe types where the relationship between pipe performance and installation quality were strongest. Less than 40% of agencies had a formal culvert asset management system in place. In situ pipe rehabilitation is becoming routine, with only two agencies indicating that they have not used it. Sliplining was the most common technology in use. Agencies are developing methods for predicting the service life of culverts, but developments are generally concentrated within a core group of agencies where this topic is regarded as a high research priority.

Within the past 15 years, much advancement has occurred in understanding the mechanisms of pipe degradation in service. Significant work has been done with respect to corrosion and the main factors that influence its development in concrete and metal pipes; that is, pH, resistivity, chloride, and sulfates. This work has led to studies about how to retard or prevent corrosion through the use of thicker walls, better materials, coatings, and liners. Advances have also been made in understanding abrasion and how it enhances the rate of degradation from corrosion and how its damaging effects can be mitigated. Effective research has also been undertaken in understanding time-dependent changes in the

mechanical properties of thermoplastic pipe, particularly slow crack growth and oxidative/chemical failure and how they can be controlled.

Florida DOT and several other select agencies have sponsored significant research in the area of pipe degradation, and this research can form the basis for better service life prediction models in the future. The schematic degradation models for metal-reinforced concrete and thermoplastic pipe materials (Figure 7 in chapter two, Figure 11 in chapter three, and Figure 20 in chapter four) indicate the trend of an initial relatively stable condition followed by a more rapid deterioration.

Little recent advancement has been made in refining pipe service prediction models, even for the more common pipe types. However, with research on degradation mechanisms and a better understanding of the progression of deterioration, combined with greater sources of pipe performance data from agency pipe inventories, more rapid future progress in improving these models should be possible.

Survey results indicate that, in practice, a majority of agencies predict service life using case studies, internal research results, or default estimated service life values holistically or categorized by local environmental conditions, rather than published models.

This study has confirmed rapid growth in the use of in situ pipe rehabilitation or trenchless technologies for extending the life of culverts. This trend will continue as technologies improve and more contractors can offer the service. This trend will increase the demand from agencies for better methods for predicting pipe durability so that a broader range of pipe strategies can be evaluated and best value for money in delivering highway drainage systems can be achieved.

This report provides an overview of the current state of knowledge with respect to deterioration mechanisms of various pipe types under a range of field conditions and applications. The current service prediction models are generally based on a selected end-of-service-life indicator and consider only one distress mode—typically corrosion—to predict expected service life. Where there is combined abrasion and corrosion, the models no longer apply.

The current deterioration models, while providing broad guidance on pipe type suitability, are not sufficiently developed to allow a meaningful comparison of alternatives. A further limitation is the inability to relate a defined end-of-service-life indicator to ultimate failure of the pipe system. Ideally, pipe deterioration models need to be able to model the progressive loss of pipe condition from installation to final failure. With this type of model, it would be possible to evaluate the cost-effectiveness of maintenance activities, rehabilitation options, and full pipe replacement and to assist in establishing when these interventions are needed.

CHAPTER ONE

INTRODUCTION

OBJECTIVE AND BACKGROUND

This study is an update of *NCHRP Synthesis 254: Service Life of Drainage Pipe* (1998), which itself was an update of *NCHRP Synthesis 50: Durability of Drainage Pipe* (1978). In the past 15 years, the culvert pipe industry and research community have made significant developments in plastic pipe, fiber-reinforced concrete pipe, polymeric-coated metal pipe, recycled materials, larger and more diverse structures, and sophisticated analytical soil-structure interaction modeling. As such, there is a growing need for a new study of the service life of culverts.

For the purposes of this study, service life is defined as the time duration during which a culvert is expected to provide the desired function with a specified level of maintenance established at the design or retrofit stage.

SCOPE

The selection of culvert materials for a particular site is based on the materials' ability to satisfy the requirements of five design criteria:

- Structural design
- Hydraulic design
- Environmental and site considerations
- Joint performance
- Service life (durability).

Significant published works provide guidance for the first three criteria, and NCHRP Project 15-38 and AASHTO 20-07 Task 347 address joint performance. Service life criteria are the missing piece. No consensus exists among state DOTs on service life, and predictive models are often parameterized to specific geographic and environmental considerations. Design service lives range from 15 to 100 years based most often on average daily traffic or functional classification of roadway. Material service life models developed for different pipe materials are inconsistent and do not relate to limit state (failure mode) or service distresses adversely affecting both structural and hydraulic performance, including cold-weather-induced distresses.

Specifically, the following topics are addressed in this synthesis:

- Summary of the required service life for culverts in varying conditions.
- Summary of the bases for determining service life.
- Summary of any additional design parameters or maintenance requirements based on service life, including considerations of maintenance.
- Summary of the conditions constituting the end of useful service life for various culvert installations (including pipe materials, soil and backfill properties, hydraulic performance, and appurtenances).
- The time for a particular material to reach the end of its useful service life.
- Information on how material service life and culvert failure limit states are correlated.

STUDY APPROACH

The study approach consisted of two primary thrusts. First, a survey of state transportation agencies was performed to determine the current state of practice. Second, a literature review of state, local, and international practice was performed.

Key results of the state of practice survey are summarized in chapter two, with the full survey results presented in Appendix A. Results of the literature review are included primarily in chapters three and four.

CHAPTER TWO

SYNTHESIS OF THE STATE OF THE PRACTICE

This chapter summarizes the results of the survey of North American transportation agencies regarding the service life of culverts, which was performed from March through July 2014. Summary plots and tables of the results are provided in Appendix A, with select results of interest summarized in this chapter.

Through July 9, 2014, 48 agencies submitted complete survey responses—41 from agencies based in the United States and seven from agencies based in Canada. Figures 1a and 1b show the responding states and provinces/territories through shading for the United States and Canada, respectively.

Bar chart summaries of each survey question are provided in Appendix A, along with summary tables of manually entered additional information. This section provides general summary commentary on the state of the practice based on the survey responses.

PIPE MATERIAL TYPES

The past three decades have seen improvements and innovations in drainage pipe materials and products, resulting in a wide range of pipe material types available and in use as culverts on highway projects. The range of pipe material types in use across North American practice is demonstrated in the survey results shown in Figure 2.

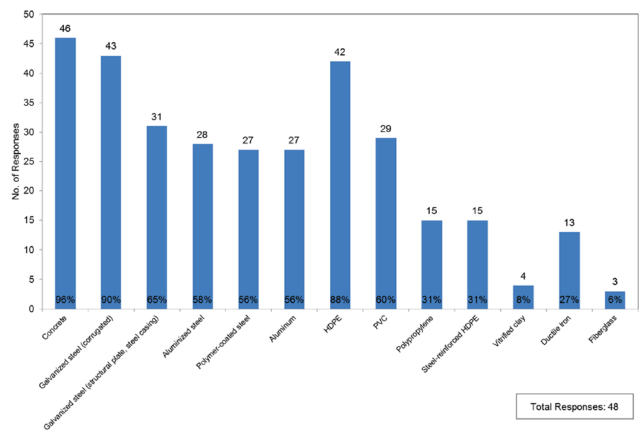

FIGURE 2 Pipe material types in use, or being considered for use.

Results show that concrete, high-density polyethylene (HDPE), and corrugated galvanized steel pipes are the three most commonly used pipe types, with 88% or more of respondents indicating their use. More than half of the respondents are also using galvanized steel (structural plate or steel casing), aluminized steel, polymer-coated steel, aluminum, and

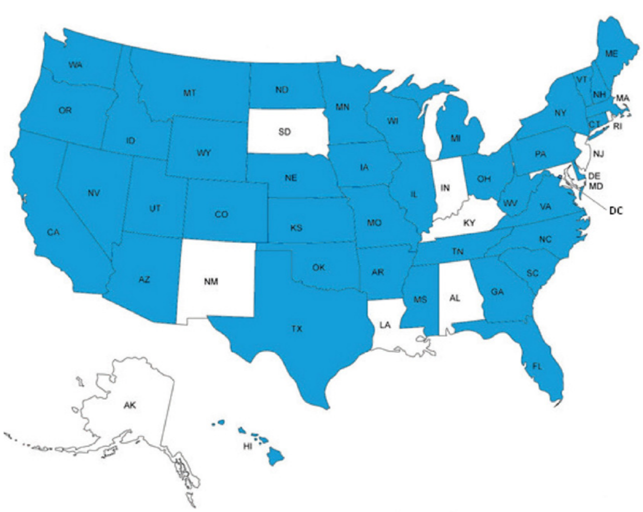

FIGURE 1a U.S. transportation agency responses; shading indicates survey participation.

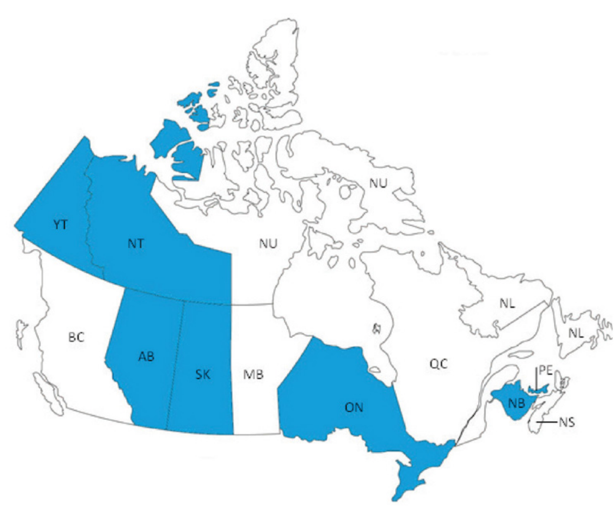

FIGURE 1b Canadian transportation agency responses; shading indicates survey participation.

polyvinyl chloride (PVC), while about a quarter are using steel-reinforced HDPE, polypropylene, and ductile iron.

It is a noteworthy development that the more recently developed pipe materials are being used fairly widely. Less than a quarter of respondents are using vitrified clay or fiberglass pipes. In general, the responding agencies are using a wide range of pipes, but with a definite concentration around three primary pipe material types.

SERVICE LIFE

One focus of the survey was the state of practice regarding service life across the range of available pipe material types, including each of the following main areas:

- The bases and values used for design service life (DSL)
- The factors and methodologies used to estimate or set material service life (MSL)
- The criteria and definitions used to define the end of service life.

Design Service Life

A wide range of criteria are used to set DSL values across North American practice, with the most common approaches considering roadway classification, usage (i.e., average daily traffic), risk of premature failure, and cost to rehabilitate in either combination or as a standalone basis, as seen in Figure 3.

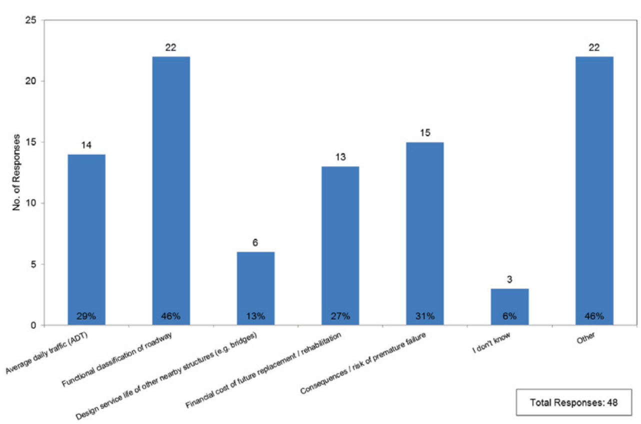

FIGURE 3 Agency bases for determining the design service life of culverts.

The large number of "other" responses to the survey question on DSL indicate variability across North American practice in this area, and that a number of agencies are not using the concepts of design and material service lives to evaluate and select culverts. DSL requirements were reported to generally range from 25 to 100 years, with the highest DSL required at many agencies being 50 or 75 years.

Material Service Life

Assumed agencywide values are still the predominant method for estimating MSL 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 MSL evaluations, corrosion and abrasion were the most common factors considered, followed by settlement and stress cracking.

Forty-six percent of respondents collect site-specific environmental data on all projects. A further 31% allow the engineer to decide whether to collect data, with another 23% collecting site-specific data only in areas of known environmental concerns. The types of environmental parameters collected are widely distributed, as seen in Figure 4.

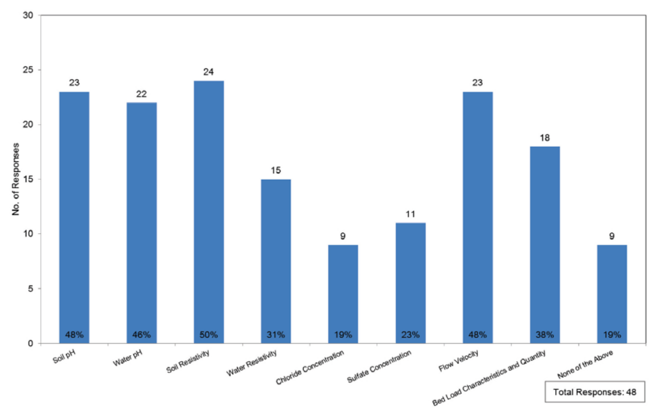

FIGURE 4 Types of environmental parameters collected for MSL evaluations.

One-third of agencies maintain maps that indicate regions of environmentally aggressive conditions, with the types of maps in use depicted in Figure 5.

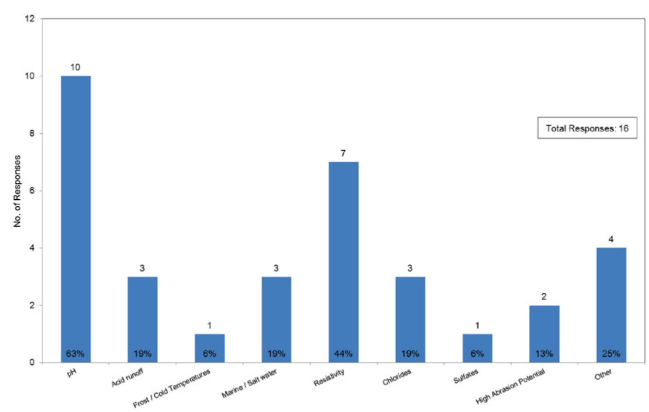

FIGURE 5 Types of environmental condition maps maintained by transportation agencies.

The tools and aids used to complete MSL evaluations typically including some combination of assumed values, agency-specific data, and industry-supplied data. Software programs are still relatively infrequently used to predict MSL values.

Based on the literature review, state transportation agencies are often the leaders in developing or improving MSL methods. Only 22% of responding agencies have developed or improved durability methods, which indicates that a focused core group of agencies are engaging on this topic. The other agencies cited a lack of resources (time, money, etc.) and other priorities as the key reasons for not engaging on this topic. Figure 6 presents which pipe materials were deemed in most need of new or improved methods for estimating MSL.

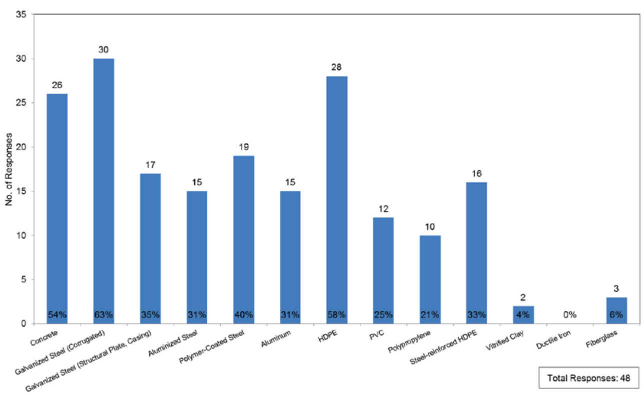

FIGURE 6 Pipe material types deemed most in need of new or improved MSL estimation methods.

The near-universal application of assumed values for all pipes other than concrete and metal may result from the limited methodologies available to complete project-specific evaluations of MSL for thermoplastic and other nonconcrete/metal pipe types. The results of the survey highlight the importance of maintaining complete design, installation, and maintenance records to facilitate service life estimates.

Defining the End of Service Life

Multiple factors are considered by most agencies in defining the end of service life, with the most common being section failure (crushing, buckling, de-bonding), cracking, joint performance, and deflection (flexible pipes only). A number of agencies use inspection rating systems to quantify serviceability, and have threshold values that trigger maintenance, rehabilitation, or replacement.

AGENCY POLICIES, SYSTEMS, AND EXPERIENCES

Several queries about agency policies, systems, and experiences related to culvert service life were included in the state of the practice survey.

Installation Quality and External Factors

Installation quality has significant influence on realized service life for all pipe material types, with the responses for thermoplastic pipes indicating greater installation influence across agency experience than for the other main material pipe types. Agencies were asked which nontypical external factors have impacted culvert performance. Exposure to chemicals and contaminants, exposure to agricultural runoff, fire damage, vehicle impacts, and “other factors” were all identified in more than 35% of responses. Agencies submitted a wide range of responses in the “other” category, including factors related to local soil or climatological conditions, and installation or maintenance concerns.

Culvert Management Systems

More than half (60%) of respondents use no system to manage culvert pipe installation, maintenance, and service life information. This represents a significant potential opportunity to improve the state of practice in managing culvert assets, reinforced by the fact that 82% of survey respondents indicated that such a culvert system would be helpful.

Culvert Rehabilitation

Culvert rehabilitation is becoming a more common practice; only two agencies do not use common rehabilitation methods. Sliplining is the most common rehabilitation approach with 89% of respondents successfully using this method. Jacking and boring, joint repair, invert lining, and cured in-place liners are used by more than half of the agencies. Six additional rehabilitation techniques were identified as having been used successfully; namely, close-fit liner, spiral-wound liner, spray-on liner, concrete liner, micro-tunneling, and pipe bursting.

Life-Cycle Costing

Life-cycle costing analysis (e.g., considering multiple less durable culvert installations, initial oversizing for future relining) is generally not performed for typical projects, with 58% of agencies not conducting this analysis on any projects. Thirteen percent of respondents use this analysis on all projects, whereas another 16% use it on interstate projects only. Eighteen percent of respondents use life-cycle costing analysis on large projects above a certain value.

GENERAL STATE OF THE PRACTICE SURVEY OBSERVATIONS

The following general observations can be made based on the 48 survey responses across U.S. and Canadian transportation agencies:

- A wide range of practices for evaluating pipe service life are currently in use across North American transportation agencies.
- Most agencies are comfortable designing for a range of pipe material types and appreciate the differences in performance each provides.
- The survey data indicate that agencies are increasingly using asset and inventory management and tracking database systems to track their highway drainage networks.
- Agencies are at the forefront of developing methods for predicting the service life of culverts and for managing culvert assets, but developments are generally concentrated within a core group of agencies.
- Joint performance is an important issue to agencies, across all materials.
- Agencies are using material and installation performance specifications more often than prescriptive standards and specifications.

CHAPTER THREE

DEGRADATION MECHANISMS

This chapter summarizes the degradation mechanisms that cause deterioration in the serviceability of culvert pipes over time. The environmental, structural, and hydraulic loading conditions that lead to degradation are also addressed. Corrosion and abrasion are the two primary degradation mechanisms for properly specified and installed culvert pipe systems. These two aspects will be addressed in separate subsections; however, it is important to note that corrosion and abrasion are processes that work in tandem and may cause a combined effect greater (more detrimental) than simply the combined sum of each process applied separately. Discussion on this combined effect is presented in the section on the combined effect of corrosion and abrasion.

The other forms of nonpressure pipe degradation can be described as weathering effects. These include damage as a result of freeze-thaw cycles, slow crack growth, and exposure to ultraviolet (UV) radiation.

Section 12.6.9 of the LRFD [Load and Resistance Factor Design] Bridge Design Specifications (AASHTO 2013) requires that the degradation of structural capacity resulting from 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.

CORROSION

Corrosion is the loss of section or coating by chemical or electrochemical processes (AASHTO 2010). Corrosion most commonly impacts metal culverts or the metal reinforcement in concrete pipe. Figure 7 schematically depicts the mechanisms and life cycle of metal corrosion.

All corrosion processes involve the flow of current from one location to another (a corrosion cell) (AISI 1999). As such, corrosion requires the presence of water or some other liquid to act as an electrolyte, with pipe materials acting as an anode, cathode, or conductor. As electrons move from the anode to the cathode, metal ions are released into solution. This causes characteristic pitting at the anode. In culvert pipe applications, the culvert itself will typically serve as both the anode and the cathode. A summary table and schematic of common corrosion mechanisms after ASM (formerly American Society of Metals) is provided in Figure 8.

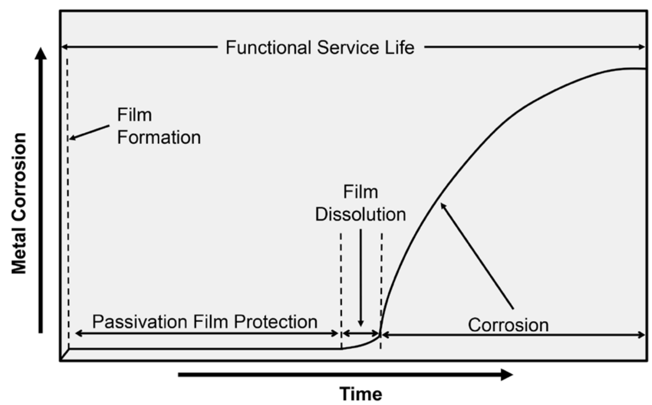

FIGURE 7 Life-cycle schematic of metal corrosion (after M. Paredes, FDOT, personal communication, May 5, 2014).

Corrosion can affect either the inside (water side) or outside (soil side) of a pipe or both. The potential for corrosion to occur, and the rate at which it will progress, is dependent on a variety of factors, including:

- pH
- Resistivity
- Chlorides
- Sulfates
- Other conditions (soil moisture content, dissolved gases, bacterial activity, etc.).

Depending on the particular nature of the corrosive environment, the following mitigation measures may be required:

- Increased wall thickness (metal culverts)
- Additional cover over reinforcing steel (concrete culverts)
- Coatings or protective pavings applied to the culvert (all culvert material types)
- Electrical grounding or cathodic protection, or both
- Placement of the culvert in a nonaggressive (e.g., granular) backfill.

Type of Corrosion	Material System	Driving Force	Control Point	Remark
Uniform/General Corrosion	All Metals in Atmospheric Environment	- Atmospheric -Temperature	- Painting - Hot Dip Galvanizing	- Corrosion Cost of this form about 50% of the total corrosion cost - Seldom lead to failure
Intergranular Corrosion	Al Alloys, Ni-Cr Austenitic Stainless Steel Acids Containing Oxidizing Agents (sulfuric, phosphoric), Hot Organic Acid. High Cl Content Seawater	-Third Phase Precipitate - Temperature	- Heat Treatment in Manufacturing - Welding during Fabrication	- Loss of Strength and Ductility - Severe attack can lead to failure
Galvanic Corrosion	Galvanic Coupling Materials e.g. Fe with Cu, Carbon steel with Stainless Steel	Different Metal in electrolytic solution	- Proper Design; - Rivetting/Joining Materials; - Insulating Coupling Materials	Moderate effect but can be detrimental for a longer period
Crevice Corrosion	Metal to Metal/Non Metal in Electrolyte Metal in two Electrolyte Aluminium and Stainless Steel in Seawater	- Small Gap in electrolyte (<3,18mm) - Stagnant Fluid	- Proper Design - Gasketting Materials -Proper Drainage Practice	Moderate effect but can be detrimental for a longer period
Pitting	Stainless Steel and Aluminium in cloride or bromide environment (water/soils)	- Surface Irregularities - Presence of Cl or Br Ion - Chemical Composition - Temperature	- Surface Quality Control - Proper Welding Practice -Proper Material Handling - PREN (Material Selection) - CPT (Critical Pitting Temperature)	Severe attack can lead to failure (second biggest corrosion failure)
Erosion Corrosion Tribo-Corrosion	Carbon Steel, Stainless Steel in flowing fluid containing abrasives	Synergy effect of passive film breakdown by abrasive and localized corrosion	Corrodent; turbulency Corrodent impingement in elbow and tees	Severe attack can lead to failure
Stress Corrosion Cracking (SCC)/ HE-SCC	Stainless Steel, Carbon Steel in High pH (pH >9,3) - 600 - 750 mV - Temperature Sensitive Near Netral pH (5,5 - 7,5) - Free Potential - Non-Temperature Sensitive	- Microstructure - Temperature Region - Existence of Residual Stress - Suitable pH - Presence of H_2S, Chloride ion -Residual Stress	- Microstructure Control during - H_2S Content & Temperature - Operation Temperature	-Biggest Cause of Corrosion Failure -SCC found in gas and liquid pipelines - In Canada since 1977: recorded 22 catastrophic failure (12 rupture, 10 leaks)
Biological Corrosion/ Microbial Induced Corrosion	All Metals in Environment with: - Sulfate Reducing Bacteria - Sulphur/Sulfate Oxidizing Bacteria - Fe/Mn Oxidizing Bacteria - Organic Acid Producing Bacteria	- Gravitational & Pellicular Water - pH 6 - 8 - Potential -42mV to 820mV - Temperature: 20 °C - 45 °C	Application of Organic Coating Cleaning Practice Use of Biocide	In US, $1.2 billion SPENT annually on biocidal chemicals to fight MIC.

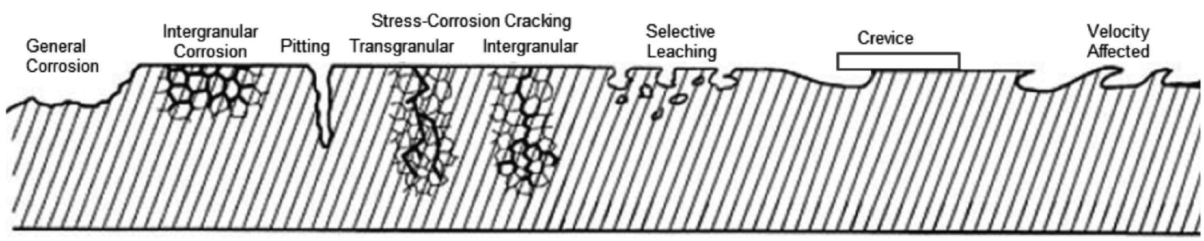

FIGURE 8 Table and schematics of common corrosion mechanisms (after ASM International 2003).

pH

pH is a measure of a solution's acidity or alkalinity. It is a measure of the concentration of hydronium ions in solution, and ranges from 0 to 14. Acidic solutions have pH values less than 7, and alkaline (or basic) solutions have pH values greater than 7. A solution with a pH of 7 is considered neutral.

pH values in natural waters generally fall within the range from 4 to 10. A pH value less than 5.5 is considered to be strongly acidic, while values of 8.5 or greater are considered to be strongly alkaline. pH values that are either highly acidic or highly alkaline are indicative of an increased potential for corrosion. Generally, pH levels between 5.5 and 8.5 are not considered to be severely detrimental to culvert life.

The lowest pH levels in natural soils are typically seen in areas that have received historically high rainfall where the runoff and percolation have leached soluble salts from the soil, resulting in the soil becoming acidic. Other likely sources of potentially acidic runoff are from naturally occurring acid-generating geologic formations, mine sites, and other industrial wastes. Milder acids can be found in runoff from marshy areas, which contain humeric acid, and mountain runoff that may contain carbonic acid. Arid areas are more likely to be alkaline owing to soluble salts contained in groundwater being drawn to the surface through capillary action and then concentrating in the soil after water evaporation occurs through the normal daily and seasonal drying cycles.

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; the temperature, moisture content, and compactness of the soil; and the presence of inert materials such as stones and gravel. The greater the resistivity of the soil and/or the lower the soil moisture content, the less capable the soil is of conducting electricity and the lower the corrosive potential.

Resistivity values in excess of 2,000 to 5,000 ohm-cm (depending on the reference guideline) are generally considered to present limited corrosion potential (Table 1). Resistivity values below the range of 1,000 to 3,000 ohm-cm will usually require some level of pipe protection, depending on the corresponding pH level and pipe material susceptibility to corrosion. In general, the lower the pH, the higher the resistivity at which mitigation measures may be required.

TABLE 1
TYPICAL RESISTIVITY RANGES FOR SOIL AND WATER

	Classification	Resistivity (ohm-cm)
Water	Surface water	$R > 5{,}000$
	Brackish water	$R = 2{,}000$
	Seawater	$R = 25$
Soil	Rock	$R > 50{,}000$
	Sand	$50{,}000 > R > 30{,}000$
	Gravel	$30{,}000 > R > 10{,}000$
	Loam	$10{,}000 > R > 2{,}000$
	Clay	$2{,}000 > R > 750$

Sources: After *NCHRP Synthesis Report 254* and AISI (1999).

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 range from 3,000 to 10,000 ohm-cm. Soils that are of a more granular nature typically exhibit even higher resistivity values and as such present lower risk to resistivity induced corrosion (Tables 2–4).

TABLE 2
TYPICAL SOIL CORROSION POTENTIAL RESISTIVITY VALUES

Soil Corrosion Potential	Resistivity (ohm-cm)
Negligible	$R > 10{,}000$
Very Low	$10{,}000 > R > 6{,}000$
Low	$6{,}000 > R > 4{,}500$
Moderate	$4{,}500 > R > 2{,}000$
Severe	$2{,}000 < R$

Sources: After *NCHRP Synthesis Report 254* [Gabriel and Moran (1998)].

TABLE 3
TYPICAL SOIL CORROSION POTENTIAL RESISTIVITY VALUES

Soil Corrosion Potential	Resistivity (ohm-cm)
Normal	$R > 2{,}000$
Mildly Corrosive	$2{,}000 > R > 1{,}500$
Corrosive	$1{,}500 > R$

Sources: After AISI (1999).

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, near brackish water sources, and at locations that use winter deicing salts.

TABLE 4
TYPICAL CORROSION POTENTIAL OF VARIOUS SOIL CONDITIONS

Soil Type	Description of Soil	Aeration or Drainage	Water Table
1—Lightly Corrosive	• Sands or sandy loams • Light-textured silt loams • Porous loams or clay loams thoroughly oxidized to great depths	Good	Very low
2—Moderately Corrosive	• Sandy loams • Silt loams • Clay loams	Fair	Low
3—Badly Corrosive	• Clay loams • Clays	Poor	2 to 3 ft below surface
4—Unusually Corrosive	• Muck • Peat • Tidal marsh • Clays and organic soils	Very poor	At surface or extreme imperme-ability

Source: After Hurd (1984).

In most instances, corrosive potential increases as the negative chloride ion decreases the resistivity of the soil or water and destroys or degrades protective films 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 the concrete cover is inadequate, cracked, or highly permeable.

Sulfates

Sulfates can occur naturally or may result from human activity, for example, agricultural runoff, mine wastes, illegal dumping effluents, and spills. Sulfates, in the form of hydrogen sulfide, can also be created from biological activity, which is more common in wastewater, sanitary sewers, and some industrial piping applications, and can combine with oxygen and water to form sulfuric acid.

Although high concentrations of sulfates can lower pH, and be of concern to metal culverts, sulfates are typically more damaging to concrete culverts. Typically, sulfates (in various forms) combine with the lime in cement to form calcium sulfate (gypsum), which creates structural weakness in concrete culverts and promotes degradation.

Concrete pipe can normally withstand sulfate concentrations up to 1,000 parts per million without special considerations. For higher concentrations of sulfates, higher-strength concrete, concrete with lower amounts of calcium aluminate, or special coatings may be necessary.

Microbially Induced Corrosion

Corrosion promoted or caused by microorganisms is known by a number of different terms, including; microbially induced corrosion, microbial corrosion, bacterial corrosion, biocorrosion, and microbiologically influenced corrosion. The term microbially induced corrosion (MIC) will be used throughout this report. In this report, the term MIC will also refer to both the direct and indirect effects that microorganisms have on corrosion.

MIC is the deterioration of metals resulting from the metabolic activity of microorganisms, and has been identified as one of the major causes of corrosion failures of buried metal structures. MIC primarily affects metal culverts but can also affect the reinforcing steel in reinforced concrete culverts. Many industries are affected by MIC, primarily those in marine and coastal environments. As part of the environmental characterization of a highway drainage project site, factors relevant for MIC are now being investigated (Sagüés et al. for FDOT 2009). It has been reported (Peng and Park 1994) that almost half of Wisconsin's steel culvert corrosion was related to MIC.

MIC can occur in many metals, including carbon steel, stainless steel, aluminum alloys, and copper alloys. MIC can occur in pH ranges from approximately 4 to 9, and in temperatures ranging from approximately 10°C to 50°C. MIC presents as corroded metal surfaces covered in slime, black iron sulfide deposits, algal growth, and as a rotten-egg odor.

Microorganisms' actions can either inhibit or promote corrosion by changing the corrosion reactions that occur at the metal's surface. Microorganisms also affect the formation of biofilms, which in turn can also inhibit or promote corrosion by changing the pH, acting as a catalyst for corrosion reactions, acting as a barrier to gas diffusion, and harboring other microorganisms that may influence MIC reactions.

Many microorganisms are thought to influence MIC, including iron-oxidizing, sulfur-oxidizing, iron-reducing, and sulfur-reducing microorganisms. Sulfur-reducing bacteria are widely believed to be largely responsible for MIC in anaerobic conditions.

MIC reactions are generally localized and occur at cracks, crevices, and areas where the metal has been welded. Other factors that influence the rate of MIC are the availability of oxygen and organic carbon, with an increase in availability of these two components causing an increased rate of MIC.

Based on a field study by Sagüés et al. (2009) for the Florida DOT (FDOT), the following general observations regarding MIC of metals used for highway drainage pipes can be made:

- Carbon steel, galvanized steel, and aluminized steel are all susceptible to MIC.
- The potential for MIC is reduced where pipe flow is rapid and the pipe is placed above the water table in free-draining soils or engineered backfill.
- Consideration should be given to determining the organic carbon content of the soil and water to assess the potential for MIC.

Other Corrosion Considerations

Industrial Effluent

Industrial effluents can contain compounds that are extremely destructive to pipe materials. Waste streams from most industries are sufficiently regulated to be of limited concern to the highway engineer. However, tailings from historic (i.e., less regulated) mining operations (or natural runoff from minable geologies) can be a source of highly acidic runoff, as can livestock operations or illegal connections from residential or small commercial lots. Potentially corrosive runoff can also be of concern at locations known for a high probability of accidental spills (e.g., runaway truck escape ramps).

An assessment of the presence and concentrations of corrosive constituents in the streamflow needs to be conducted whenever industrial effluents are suspected in the runoff. If the source can be identified, corrective action can usually be taken or culvert protective measures can be implemented.

Stray Electrical Current

Corrosion can be induced by electric current in proximity to the pipe. Although corrosion most often affects metal pipes, the steel in reinforced concrete pipes may also suffer an increased rate of corrosion. Typical sources of stray current are electrified rail lines, high-tension electric transmission lines, and cathodically protected structures (gas transmission mains). Protective coatings are usually applied to the pipe to negate the effects of stray electric currents.

ABRASION

Abrasion is the progressive loss of section or coating of a culvert by the continuous, rapid movement of turbulent water containing a bedload of particulate matter (sands, gravel, transported debris, etc.). Abrasion will almost always manifest itself first in the invert of the culvert. As with corrosion, several factors contribute to abrasive potential, including culvert material, frequency and velocity of flow in the culvert, and bedload composition.

AASHTO (2007) Chapter 14 advises against the use of metal pipe in abrasive environments unless the invert is paved. Ault and Ellor (2000) and NCHRP 10-86 (2015) recommend incorporating the existing Federal Lands Highway Design Guidance abrasion rating system (Levels 1 through 4) into culvert condition assessment and durability prediction practices at a minimum.

Bedload

Bedload is the portion of the total transported sediment that is carried by intermittent contact with the streambed (or culvert invert) by rolling, sliding, and bouncing. Contact between bedload and the culvert pipe is the leading cause of culvert abrasion. Critical factors in evaluating the abrasive potential of bedload are the size, shape, and hardness of the bedload material, and the velocity and frequency of flow in the culvert.

Flow velocities depend on the drainage barrel roughness, the cross-sectional geometry, slope, and the depth of flowing water. Abrasion will increase by a factor of approximately four when the flow velocity is doubled. Theoretically, doubling the velocity of a stream increases its ability to transport solid fragments of a given size by as much as a factor of 32. Abrasion is thus highly sensitive to the flow velocity.

The AASHTO Highway Drainage Guidelines (2007) define bedload by the 2- to 5-year return frequency flow velocity. Generally, flow velocities less than 5 ft/s are not considered to be abrasive, even if bedload material is present. Velocities that exceed 15 ft/s and carry a bedload are considered to be very abrasive.

Tests performed on concrete pipe have generally shown excellent wear characteristics with respect to abrasion resistance. 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 strike with enough force to break away small particles of the concrete pipe 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 concrete's resistance to abrasion.

Manufacturing methods that lead to a denser concrete mix, such as roller-compacted or spun concrete or higher-compressive-strength concrete, can also exhibit increased resistance to abrasion. Where velocities are known to be high, and a bedload is present, many agencies recommend additional concrete cover over the reinforcing steel.

Debris

Debris carried by storm waters can also be a destructive element in culverts. However, this destructive potential is primarily related to clogging of the culvert by the attendant effects of overtopping and erosion or to a single impact from a large piece of debris that causes immediate damage to the culvert. Large volumes of debris can, however, add to the effects of bedload abrasion. The potential for debris to add to abrasion will depend primarily on the relative hardness of the debris and the culvert material.

The most common types of debris that lead to major damage are boulders, trees and shrubs, and ice, although during major storm events, anything movable by storm waters can be transported to culvert locations. Types of areas that have proven troublesome are drainages with unstable hillsides, heavily forested areas subject to fire, streams that support beaver activities, and cold-weather sites where ice accumulation can block or otherwise damage drainage structures.

Whenever debris is likely to pose a problem, appropriate debris-control structures should be considered for installation.

FHWA Definitions of Abrasion Levels

The following abrasion levels are intended as guidance to help the engineer consider the impacts of bedload wear on the invert of pipe materials. Sampling of the streambed materials is not required, but visual examination and documentation of the size of the materials in the streambed and the average slope of the channel will give the designer guidance on the expected level of abrasion. Where existing culverts are in place in the same drainage, the conditions of inverts could also be used as guidance. The expected stream velocity should be based on a typical bank-full design discharge generated by a 2- to 5-year return frequency flood and not a 10- or 50-year design flood.

- Level 1. Nonabrasive conditions exist in areas of no bedload and very low velocities. This is the condition assumed for the soil side of drainage pipes.
- Level 2. Low abrasive conditions exist in areas of minor bedloads of sand and velocities of 5 ft/s or less.
- Level 3. Moderate abrasive conditions exist in areas of moderate bedloads of sand and gravel and velocities between 5 ft/s and 15 ft/s.
- Level 4. Severe abrasive conditions exist in areas of heavy bedloads of sand, gravel, and rock and velocities exceeding 15 ft/s.

Caltrans Definitions of Abrasion Levels

The California DOT (Caltrans) *Highway Design Manual*, Chapter 850 (Caltrans 2011b), provides comprehensive guidance on abrasion levels coupled with material selection guidance and estimates of additional service life provided by various protective coatings. A series of tables provides specific guidance, as outlined in the following list:

- Table 855.2A: Definitions of abrasion levels and corresponding material recommendations.
- Table 855.2B: Bed-material size and estimate of nonscour velocities for different flow depths.
- Table 855.2C: Estimated additional service life as a result of protective coatings.
- Table 855.2D: Estimated wear (mils/year) for corrugated metal pipe under different abrasion levels.
- Table 855.2E: Relative assessment of abrasion-resistant materials.
- Table 855.2F: Guide for minimum material thickness to achieve 50-year maintenance-free service life.

DeCou and Davies (2007)—Caltrans Abrasion Study

DeCou and Davies' (2007) 5-year study on Shady Creek in Nevada County, California, is the most in-depth pipe abrasion study found. Figure 9 shows the variety of pipe material and coating-type test specimens used in the California Abrasion study. Taylor and Marr (2012) provide an excellent summary of this site-specific abrasion study at a highly abrasive site, which is explained in the following text.

FIGURE 9 Caltrans abrasion test panel installation showing various culvert materials and coatings (Caltrans 2013).

This site, with average flow velocities of 12 to 18 ft/s and median grain sizes between 3 and 11 mm, is highly abrasive. The service life estimates developed for this study are site specific because of these conditions. DeCou and Davies found that abrasive wear at the site is event driven and not linear with time. Several material comparisons and observations were made:

- All nonconcrete pipe materials studied have lower abrasive wear rates than concrete; however, concrete pipe walls are much thicker than the nonconcrete pipe materials studied.
- Smooth pipes wear slower than rough-walled pipe.
- PVC pipe wears slower than HDPE; however, the construction of smooth-walled, corrugated HDPE provides a positive characteristic. After the inner wall is perforated, the outer wall remains intact.
- Polyethylene coating for composite steel spiral rib pipe was the only steel coating studied that could provide the desired 50-year service life.

COMBINED EFFECT OF CORROSION AND ABRASION

The abrasive properties of bedload that is traveling at high velocities and is harder than the exposed pipe invert or coating will erode metal, concrete, and thermoplastic pipes. Erosion may begin with the formation of corrosion products of the pipe material. These corrosion products are often more brittle than the parent material from which they were formed and may then be removed by the bedload's abrading action more easily than the parent material. The parent pipe material is then reexposed and not protected against subsequent cycles of corrosion and abrasion. When corrosion and abrasion operate together in this manner, they can produce a larger detrimental effect than either would if applied in isolation. Abrasion accelerates corrosion by removing protective coatings, and corrosion can produce products less resistant to abrasion (Figure 10).

FIGURE 10 Corrosion accelerated by abrasion causing void formation below (Caltrans 2013).

Water flowing at a velocity high enough to create appreciable turbulence can also cause a localized effect known as impingement. Impingement is caused by suspended solid particles (as opposed to abrasion, which is caused by particles transported along the streambed) or gas bubbles striking the surface and can occur at pipe entrances, sharp bends, protrusions (such as rivets and lapped joints), and other abrupt changes in flow patterns. The protective layer of a metal or concrete can thus be locally compromised, facilitating subsequent corrosion of an unprotected material.

Steel culverts are the most susceptible to the dual action of abrasion and corrosion, particularly where thinner-walled pipes are used. Once a steel pipe's thin protective coating—whether it is zinc or another substance—is worn away, exposure to low-resistivity or low-pH environments can dramatically shorten a steel culvert's life. Although aluminum culverts are occasionally specified to combat corrosion, plain aluminum is typically not recommended for abrasive environments since tests indicate that aluminum can abrade as much as three times faster than the rate of steel.

Plastic culvert materials (both PVC and HDPE) exhibit good abrasion resistance. Since plastic is generally 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 is primarily based on tests using small aggregate sizes (gravels and sands) flowing at velocities ranging from 2 to 7 ft/s (AASHTO 2007). The effects of large bedload particles (cobbles and larger) or high-velocity flows are not well defined because of limited data. Additionally, as a result 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 common current strategies (e.g., invert paving) are not effective with plastic pipes because of their smooth surface and inability to achieve a satisfactory bond.

An illustrative case study example of combined corrosion and abrasion is provided by Caltrans (2013). It relates to the back-analysis of a structural steel plate pipe culvert with inlet velocity of 12 ft per sec and outlet velocity of 22 ft per sec. The original steel thickness was 0.140 in. (10 gage). From a back-analysis of the time to perforation, the rate of steel loss was estimated at about 4.6 mils per year. Using the site values for pH and resistivity, the contribution from corrosion alone was estimated at 2.7 mils per year, indicating that the contribution to metal loss from abrasion was about 1.9 mils per year. It was concluded that to provide a 50-year service life for that application with abrasion level 5, three-gage (0.250 in.) steel plate would have been needed. This culvert was replaced with reinforced concrete pipe (RCP) and within 5 years the steel was exposed, indicating that the concrete loss was approximately 200 mils per year. The ultimate solution was to provide 12 in. of concrete paving with a flat bottom to spread the flow concentration.

OTHER DURABILITY FACTORS

Some factors that can potentially impact culvert service life but are less common than the primary mechanisms of corrosion and abrasion are briefly summarized in this section.

Freeze/Thaw

Free-draining bedding requirements and extra care with pipe joint protection are needed when the top of the pipe (crown) is located above the frost-penetration depth; however, the requirements are independent of pipe material type. Particular attention is needed for pipe replacements or extensions during road rehabilitation works to ensure that the frost treatment details are maintained uniformly between old and new construction. Typically, buried pipe is not exposed to freeze-thaw conditions when installed as a storm sewer below the frost-penetration depth. However, culverts are frequently installed within the frost zone and deeper installations are exposed to frost action at the inlets and outlets. Failure to account for freeze-thaw impacts across all pipe materials may lead to differential settlement causing joint separation, longitudinal cracking of the pipe, localized overstressing, and decreased hydraulic performance. It can also lead to differential performance of the road pavement above the pipe. The potential impacts of freeze-thaw are typically alleviated through the use of frost tapers (the incorporation of excess sloped excavations around culvert locations backfilled with free-draining granular backfill).

High-Humidity Conditions

High humidity (100% relative humidity) and high atmospheric temperatures (> 85°F/30°C) are not uncommon within gravity pipes, such as in swamp or marsh areas with partially submerged, stagnant, or low flow conditions. In such an environment, hydrogen sulphide released from stagnant, sewage-like conditions is absorbed by the film of moisture on that portion of the pipe lying above the water. In the presence of aerobic bacteria, the hydrogen sulphide is converted to sulphuric acid. This can lead to deterioration of concrete and steel, although the pipe materials are not directly affected by humidity and temperature.

Time-Dependent Mechanical Properties

Thermoplastic materials (HDPE and PVC) are viscoelastic; that is, their mechanical properties are time-dependent and incur strain and creep deformation under a sustained load, or exhibit stress and load relaxation under a sustained deflection. HDPE and PVC pipes sustain deformations that are controlled by the surrounding soil, so stress relaxation in the pipe can be expected over its lifetime. Slow crack growth and oxidative and chemical failure have been identified as the primary long-term failure mechanisms for corrugated HDPE pipes. No methods based on service histories have yet been developed for serviceable life predictions for these materials; rather, material specifications are used to assign standard service life values based on historic performance or laboratory bench-scale evaluations. Figure 11 schematically illustrates the time-dependent oxidation mechanism for stabilized and unstabilized polyethylene (M. Paredes, FDOT, personal communication, May 5, 2014).

Established practice (AASHTO 2013) is to account for the long-term material response by employing a long-term "effective" modulus of elasticity selected in accordance with the design life of the system (the longer the time period, the lower the modulus). Thermoplastics are relatively resistant to corrosion and abrasion in buried highway drainage applications; therefore, the effective modulus of elasticity may control the long-term stability (this material response over time can be considered one factor dictating the estimated material service life). This "modulus of relaxation" can be obtained experimentally by dividing a residual stress in the pipe wall by the strain at that location, and can be estimated from measurements made using constant deflection tests conducted on the pipe as part of quality assurance processes (Gabriel and Moran 1998).

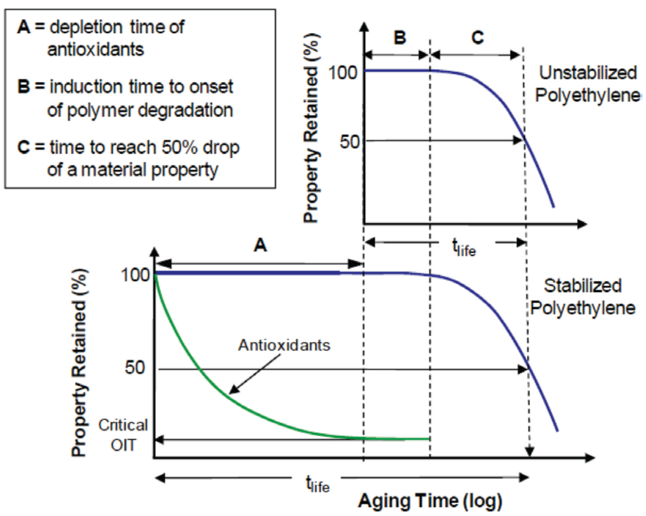

FIGURE 11 Schematic of time-dependent oxidation degradation mechanism for polyethylene (M. Paredes, FDOT, personal communication, May 5, 2014).

Moore and Hu (1996) have examined the time-dependent behavior of various HDPE materials and provide viscoelastic parameters that can be used to estimate "relaxation moduli" at various time intervals. AASHTO (2014) provides short and 50-year values of modulus for both PVC and HDPE materials, and 100-year values have recently been proposed by McGrath and Hsuan (2004), updated in McGrath et al. (2009) (Figure 12).

Slow Crack Growth

Slow crack growth (SCG) occurs because thermoplastics, when subjected over a long time period to tensile stresses substantially lower than those necessary to cause a short-term rupture, can develop crazes and small cracks that grow slowly until eventually rupture occurs (NCHRP 14-19 2010). Crazes are very fine cracks that develop in the direction normal to tensile stress; their surfaces are still bounded together by molecular fibrils, approximately 10 nm in diameter, which continue to support the load (i.e., crazes represent the redistribution of local stresses throughout the thermoplastic matrix). The formation of these crazes and cracks is not caused by any chemical degradation of polymer and is only the result of mechanical or thermal forces (McGrath et al. 2009).

NCHRP 14-19 reports that, in general, the rate of SCG can be accelerated by different factors, for example, stress intensity, cycling of the stress (fatigue), elevated temperature, and exposure to certain environments (referred to as environmental stress cracking). This type of brittle cracking in HDPE pipes generally results from a combination of high tensile stress (resulting from applied loads, residual stresses, or thermal effects) and low-quality resin with poor crack resistance. It may be associated with simple two-dimensional behavior of the pipe (where circumferential tensions develop on the outside surface of the pipe at the springlines, or on the inside surface at the crown or invert). More commonly, the tensile stresses result from three-dimensional behavior caused by complexities of the profile (e.g., Moore and Hu 1995).

A series of studies were conducted for FDOT (FDOT 2008a–d), following which they developed a new specifica-

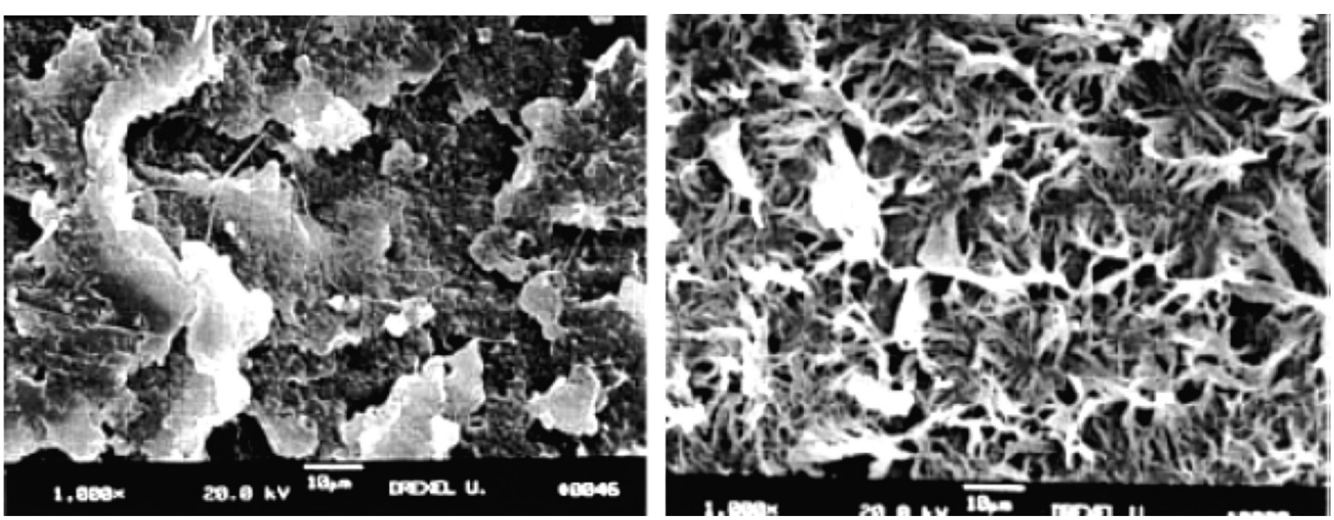

FIGURE 12 Microscope images of HDPE crack surfaces (Hsuan and McGrath 1999): (*left*) flake morphology characteristic of impact-type fracture; (*right*) fibrous morphology characteristic of slow crack growth.

tion incorporating material performance and test requirements to allow HDPE pipe materials to be given a default 100-year service life. The material requirements take into account the higher ambient temperatures present in Florida, but do not consider freeze-thaw issues and as such are somewhat regionally specific in their applicability and acceptance across North American transportation agencies.

Ultraviolet Radiation

No reports indicate that UV radiation degrades concrete or steel. HDPE and PVC pipe may incur surface damage when exposed to long-term UV radiation, typically at the exposed ends of culverts. UV degradation may include color change, a slight increase in tensile strength and elastic modulus, and a decrease in impact strength. FDOT limits exposure of UV-susceptible pipe materials to 2 years (M. Paredes, FDOT, personal communication, May 5, 2014).

With the use of carbon black (a UV stabilizer), HDPE pipe is protected against prolonged exposure to sunlight and the potential for UV degradation of mechanical properties.

UV stabilizers are used in PVC pipe materials to protect against UV degradation, although the longevity of these additives has not been proven. However, it is considered prudent to protect the exposed ends of installed PVC (and to a lesser extent HDPE) pipes that include UV stabilizers. Once buried, except for exposed ends, exposure of plastic pipe to sunlight generally does not occur. Exposure issues often can be overcome if nonsensitive (e.g., concrete or steel) end walls are used. Outdoor storage practices are to be managed by the manufacturers to ensure that the pipes are not subject to prolonged UV exposure prior to site delivery.

Seismically Induced Degradation

For small-span (less than 10 ft) gravity-pipe road applications, seismic loads are generally not considered in design in many areas. However, for high-risk applications with the potential for upstream flooding or for permanent ground displacement, it is recommended that a seismic design be incorporated into the structural analysis.

Seismic loads on installed pipes arise from inertia forces owing to earthquake shaking or from large permanent ground movement generally associated with strength and stiffness loss of loose or sensitive saturated foundation soils. Liquefaction and lateral spreading are the main causes of pipe failures, and these failure modes should be considered in design.

Access/Construction Equipment

Damage to pipes from overloading during construction is a common issue and can significantly reduce the service life of culverts. Most agencies set minimum fill heights above the crown of the pipe before power-operated tractors or rolling equipment can be used for compaction. The specified minimum heights for heavy-equipment crossing may affect gravity-pipe selection and may require the placement of temporary fill protection for pipes during construction. Depending on final grade restrictions, fill-material costs, and construction traffic, these minimum fill heights may influence the initial installation costs and are to be considered in the life-cycle cost analysis.

Thermoplastic pipes are particularly vulnerable to damage during installation, hence the need for rigorous post-installation inspection. Examples of random-type damage to thermoplastic pipe as observed from video inspection are shown in Figures 13–15.

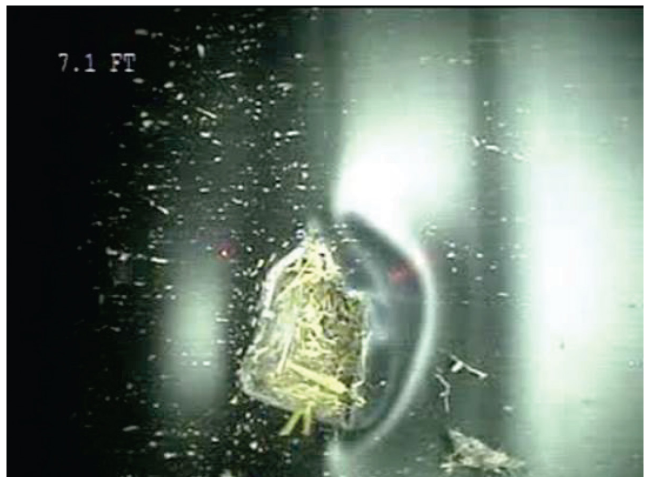

FIGURE 13 Approximately 2-in.-diameter puncture in HDPE pipe.

FIGURE 14 Split in inner pipe wall and local buckling.

Impact Resistance (Brittleness) and Temperature Effects

During construction, pipes are required to withstand forces that are normally expected during shipment, handling, and installation. In addition, rockfill is often used above the pipe cover material, and rock fragments that are used to form the side slopes and embankments will frequently roll onto exposed pipe ends or penetrate the pipe's overlying cover or embedment soil. Temperature affects all pipe materials differently. For normal operating temperatures experienced during highway construction projects in Ontario, the use of concrete, steel, high-density polyethylene, and polyvinyl chloride is considered acceptable. Special provisions should be made when pipe installations are required in rare extreme-temperature conditions (i.e., below -228°F/-308°C) for emergency situations. Table 5 can be used as a guideline for minimum installation temperatures.

FIGURE 15 Wall penetration and puncture from metal spike.

TABLE 5
RECOMMENDED MINIMUM PIPE INSTALLATION TEMPERATURES

Pipe Material	Minimum Installation Temperature[1] (°F)/(°C)
Concrete	-22/-30
HDPE	-22/-30
PVC[2]	0/-18
Steel	-22/-30

Source: MTO (2007).
Notes:
[1]Minimum operating temperature for workplace assumed to be -30°C.
[2]AASHTO (2000) reports PVC as becoming brittle at exposure to temperatures less than 37°F/3°C, and many agencies (e.g., Minnesota DOT) specify that brittle transition temperature as the minimum allowable during installation due to the risk of construction impact–based damages.

The Ministry of Transportation of Ontario (MTO) design guidance (MTO 2007) provides the following additional commentary on temperature impacts. Concrete material compressive and tensile strengths are reported to increase with a reduction in operating temperatures. The effect of temperature on the impact strength of steel material is not considered an issue and the pipe itself can be designed to withstand handling and installation forces according to ASTM A796 (defined as the flexibility factor). HDPE material has an impact resistance that ranges from about 0.27 to 0.80 Nm/mm (Vasile and Seymour 1993); however, this can be reduced significantly by oxidation resulting from sunlight or by overheating during the manufacturing extrusion process. PVC material has an impact resistance much less than that of HDPE, of about 0.026 Nm/mm (Titow 1990), but can be increased to about 1.07 Nm/mm by blending with an impact modifier during the extrusion process. However, impact modifiers may reduce chemical resistance, increase susceptibility to oxidation, and increase permeability.

Fire Damage

Although the risk of damage to storm drainage systems is quite low, under certain circumstances, such as forest fires, damage to culverts can occur. In forest fires, all pipe material types can sustain damage from exposure to extremely high temperatures. While thermoplastic pipes would be the most vulnerable, the National Fire Protection Association (NFPA 2012) has given both polyethylene and polypropylene a rating of 1 (Slow Burning) on a scale of 0 to 4, where higher ratings indicate a greater vulnerability.

Existing "Pipe System" Conditions

Where new pipe is to be installed and incorporated into an existing pipe system, an assessment of the existing pipe material type should be made prior to design. If the existing pipe material is considered to be performing satisfactorily, many agencies prefer to maintain the same pipe material to minimize the risk of construction and performance issues related to connections, joints, geometrics, differential settlement, strain compatibility during temperature variations and loading, and so on.

Scour at Outlet and Channel Degradation

Local scour at the outlet of culverts based on discharge, culvert shape, soil type, duration of flow, culvert slope, culvert height above the bed, and tailwater depth can result in service life issues. These types of failures are avoided through proper design, such as following the guidance provided in FHWA Hydraulic Engineering Circular 14 (Figure 16).

FIGURE 16 Example of outlet scour protection rock (*Source*: Ohio DOT).

Pipe–Headwall Connection Issues (Rotation, Settlement, Scour, etc.)

Other types of drainage pipe system failures are difficult to predict and can include rotation, settlement or foundation failure of headwalls, and scour at inlet and outlet ends (Figures 17 and 18). These types of failure are avoided through adequate subsurface investigation, appropriate headwall and scour protection design, and good workmanship and materials.

FIGURE 17 End treatment and scour failure at culvert outlet.

FIGURE 18 Major culvert pipe system failure behind timber headwall.

Gasket Degradation Within Pipe Joints

Performance requirements for pipe joint gaskets are typically based on short-term criteria; little is known about long-term degradation performance (Figure 19).

FIGURE 19 Damage at joint in RCP revealing joint sealant as detected from video inspection.

CHAPTER FOUR

PIPE MATERIALS

This chapter summarizes the key issues, definitions, and design methods used to evaluate the service life of culvert materials. Each major pipe material type is discussed in a separate section.

CONCRETE PIPE

Material Properties and Specifications

In general, material properties for concrete pipes are defined by ASTM and AASHTO standards as listed in the AASHTO LRFD Bridge Manual (AASHTO 2013), which states in Section 12.4.2 that:

- Concrete shall conform to Article 5.4 of the LRFD Bridge Manual.
- Precast concrete pipe shall comply with the requirements of AASHTO M 170 (ASTM C76) and M 242M/M 242 (ASTM C655M and C655). Design-wall thickness, other than the standard wall dimensions, may be used, provided that the design complies with all applicable requirements of Section 12.4.2.
- Precast concrete arch, elliptical, and box structures shall comply with the requirements of AASHTO M 206M/M 206 (ASTM C506M and C506), M 207M/M 207 (ASTM C507M and C507), M 259 (ASTM C789), and M 273 (ASTM C850).
- Steel reinforcement shall comply with the requirements of Article 5.4.3, and shall conform to one of the following:
  - AASHTO M 31M/M 31 (ASTM A615M/A615),
  - AASHTO M 32M/M 32 (ASTM A82M/A82),
  - AASHTO M 55M/M 55 (ASTM A185M/A185),
  - AASHTO M 221M/M 221 (ASTM A497), or
  - AASHTO M 225M/M 225 (ASTM A496M/A496).

AASHTO (2007) Chapter 14 provides the following recommendations for concrete pipe:

- Sulfate concentration must be less than 1,000 ppm.
- Extra concrete cover over steel reinforcement is recommended when abrasion is severe.
- Extra steel cover or coated steel is also recommended when the pH is less than 5.5.

Definition of Useful Service Life

Durability requirements vary considerably between agencies owing to the very wide range of environments encountered and the agencies' different durability requirements. In practice, the expected service life of concrete pipe is generally 75 to 100 years.

Service life of concrete pipe depends greatly on the class of pipe and the environment in which it is installed. Assuming a single value for the service life of concrete pipe does not reflect the variation in the environments in which the pipes are installed. A number of prediction methods have been developed by various agencies and researchers to determine the expected service life of concrete pipe. Also, agencies have no standard definition of what constitutes a critical failure condition for concrete pipe as a result of corrosion or other deterioration mechanisms. Examples of agencies' estimated expected service lives for concrete pipe use include the following:

- Utah DOT tests soil and water for resistivity, pH, soluble salts, and sulfate content, then uses charts to estimate the expected service life for various types of pipe. The expected service life of Portland cement concrete can be up to approximately 120 years (Molinas and Mommandi 2009).
- Arizona DOT assigns concrete pipe a service life of 100 years for installations where the pH is 5 or greater (Molinas and Mommandi 2009).
- The U.S. Forest Service has defined acceptable conditions for concrete pipe to resist corrosion (Molinas and Mommandi 2009). If the pH of the water or soil surrounding the pipe is between 4.5 and 10 and the resistivity of the soil is greater than 1,500 ohm-cm, then the expected corrosion service life of concrete pipe is 75 years or greater.
- A literature review by the National Research Council of Canada (Zhao 1998) stated, based on various studies in the United States, that the predicted service life of concrete pipe varies from 50 to more than 100 years, depending on the environmental conditions to which the pipe is subjected.
- A survey by the New York State Department of Transportation (Molinas and Mommandi 2009) found the useful life of concrete pipe varied from 20 to 75 years with an average of 56.3 years.

- A study commissioned by Ohio DOT (Mitchell et al. 2005) found from a survey of 40 DOTs that service life of concrete culverts appeared to be limited to 70 to 80 years. The most frequently encountered conditions were deteriorated headwalls, deterioration of concrete in the crown region or top slab and inlet walls, and transverse shear cracks on abutment walls.

Factors Affecting Service Life

Pipe Construction and Concrete Properties

Pipe material properties are critical to resisting potential durability impacts. For reinforced concrete pipe, the predominant pipe material properties impacting durability are (after ACPA 2008):

- Compressive strength
- Density
- Absorption
- Cement content and type
- Aggregate characteristics
- Water cement ratio
- Air entrainment
- Concrete cover of reinforcement
- Steel reinforcement characteristics and coatings.

Corrosion

Corrosion of the reinforcing steel is the primary concern when considering corrosion for concrete pipes. Corrosion of reinforcing steel can lead to spalling, cracking, and further susceptibility to corrosion.

Corrosion of reinforcing steel in concrete pipe occurs when moisture, oxygen, and chlorides reach the steel. Reinforced concrete corrosion is a result of the quality of the concrete, its permeability, the thickness of the cover, and the presence of cracks in the concrete pipe. Its deterioration follows the service life mechanisms detailed in Figure 20.

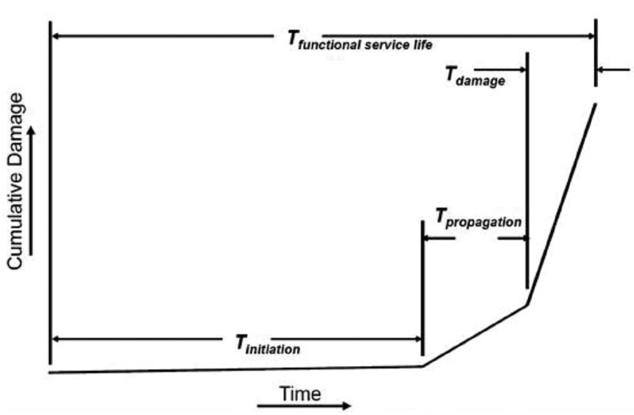

FIGURE 20 Steel-reinforced concrete corrosion service life diagram (FDOT 2014b).

Selecting the proper pipe class and inspecting the pipe before installation can minimize the risk of damage to pipes being installed. Chlorides, which accelerate corrosion, are most often associated with the use of road salt or exposure to seawater in coastal areas. Even in aggressive environments for corrosion, a service life of 100 years is achievable with the proper selection of concrete class and pipe design.

Pipe Cracking and Steel Corrosion

Cracks in reinforced concrete pipes can occur for a number of reasons, including drying shrinkage or impact during shipping, handling, and installation. Concrete cracks are not always a durability risk on their own, but more critically they can allow for corrosion through chloride attack of the reinforcing steel. Increased concrete cover and low-permeability concrete with an absence of voids and cracks will reduce or delay the severity of chloride attack.

The LRFD Bridge Construction Specifications (AASHTO 2010) specifies a maximum in-place width of 0.100 in. for noncorrosive conditions and 0.010 in. for corrosive conditions. The general view was that in the case of very narrow cracks, the process of concrete leachate interacting with atmospheric or waterborne CO_2 would cause calcite and other carbonate deposits that would seal such cracks. This process is referred to as autogenous healing. Larger in-place RCP cracks can degrade pipe performance by decreasing structural strength and dimensional stability, which permits leaks, and by allowing premature corrosion of steel reinforcement (Sagüés et al. 2001). Such corrosion, once initiated, has the potential to lead to concrete spalls, causing increased pipe roughness and leading to reduced pipe-wall-bearing thickness and loss of serviceability.

FDOT initiated a study at South Florida University (Busba et al. 2011) to investigate this phenomenon and develop guidelines for acceptable concrete pipe crack widths during construction. The research found that:

- Significant autogenous healing was not detected in cracks as narrow as 0.020 in. during their experiments;
- Corrosion tests showed that significant reinforcement corrosion took place in a short period of time with 0.100-in.-wide cracks, but that corrosion damage was much slower with cracks 0.020 in. wide; and
- Based on the corrosion testing and model projections, cracks of up to about 0.020 in. on the inner pipe face are acceptable up to moderately aggressive environments. However, allowable crack width limits above 0.100 in. are not acceptable under any circumstances.

Thus as crack widths increase above 0.020 in. and where exposure to environmental chlorides increase above about 500 ppm, significant reduction in predicted RCP service life should be anticipated with the likely deterioration mode

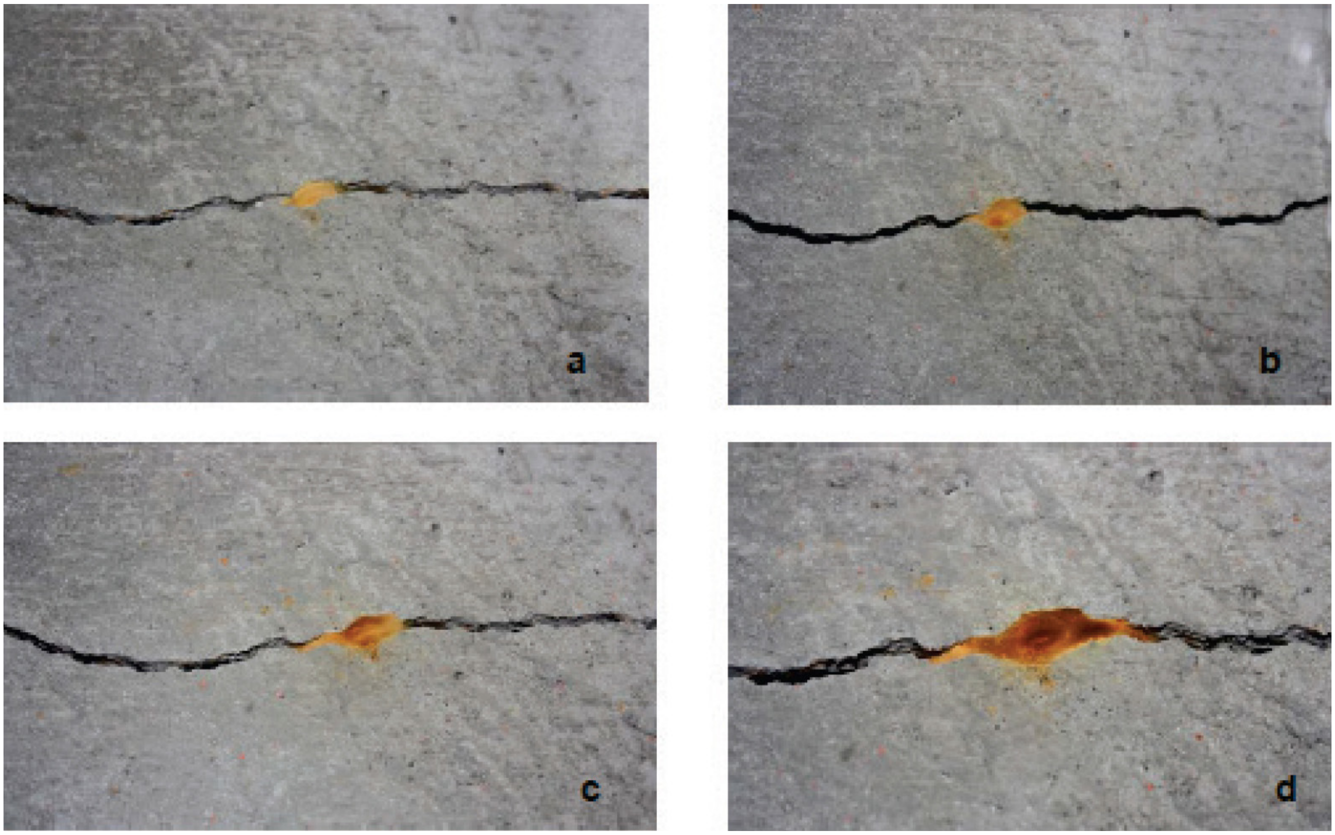

FIGURE 21 Progression of corrosion in RCP with a 0.100-in. crack exposed to chloride solution after (*a*) 6 days, (*b*) 20 days, (*c*) 34 days, and (*d*) 52 days (Busba et al. 2011).

being concrete spalling caused by corrosion of reinforcement (Figure 21).

Sulfate Damage

High sulfates in soil, groundwater, and flow water can cause sulfate-related damage to concrete over time. Various threshold levels for sulfates are used by various agencies. Typically, an upper level is defined for sulfates where no special precautions are needed. Above this threshold, concrete pipe can still be used; however, special mix designs are required. Special mixes typically require either sulfate-resistant cement, higher cement contents, or the use of supplementary cementitious materials such as fly ash, slag, silica fume, and so on, to provide some resistance to sulfate attack. The relationship is the smaller the quantity of tricalcium aluminate (C3A) in the hydrated cement, the lower the vulnerability to sulfate attack. ASTM C 150 limits Type II cement, moderately sulfate resisting, to a maximum of 8% C3A; Type V cement, identified as sulfate resisting, is limited to 5% C3A.

An upper threshold for sulfates can be defined to determine where concrete pipe is not to be used. For example, in Utah (Molinas and Mommandi 2009), if the sulfate content of the surrounding soil is less than 0.5%, Type II cement can be used. If the sulfate content is greater than 0.5%, then Type V cement is used.

Often the guidelines in Chapter 4 of ACI 318, *Building Code Requirements for Structural Concrete*, are used to specify the type of cement to be used, or blended cement is used to address concerns related to potential sulfate attack on concrete (ACI 318 2011).

Acid Attack

Acid will attack the exposed surface of portland cement concrete. Acids are naturally neutralized by the alkalinity of concrete, and so without acid replenishment the adverse impacts of acid are not of concern. According to the ACPA (2008), continuous replenishment of acid with a pH below 5 is an aggressive environment, and a pH below 4 is a highly aggressive environment.

Three common types of acidic attack are (ACPA 2008):

- Biochemical, which occurs in a sanitary sewer. The acid involved is always sulfuric (H_2SO_4) and the attack is confined to the interior, unsubmerged perimeter part of the pipe.
- Effluents that are acidic in nature. Attack is confined to the wetted interior surface of the pipe.
- Exterior acid attack resulting from acidic groundwater, backfill, or natural soils. The most common areas prone to exterior acid attack are areas of acid mine drainage, sanitary, or industrial waste facilities.

If either interior or exterior acidic conditions are estimated or encountered, and cannot be alleviated by other countermeasures, the following special acid protection provisions are recommended by the ACPA (2008):

- Increased total concrete alkalinity
- Increased/sacrificial concrete cover
- Use of protective coatings
- Use of low permeability and/or alkaline (e.g., limestone) backfill.

Abrasion

Abrasion is not a problem typically associated with concrete pipe. Most high-abrasion conditions are short-term events (e.g., spring runoff from storms). Abrasion is usually only considered relevant for the design of concrete pipe in severe abrasive conditions.

The following list includes the general ways agencies provide abrasion resistance for concrete pipes, though some of these methods conflict with FHWA aquatic organism passage guidance:

- Use a paved invert.
- Provide an upstream catchment device to restrict bedload from passing through the culvert.
- Limit the use of concrete pipe to slopes flatter than a certain value (thereby limiting flow velocity).
- Require a mechanical barrier (epoxy liner).
- Select a higher class of pipe (higher concrete strength) or modify the mix design.
- Specify thicker walls (for protection of steel reinforcing).

One parameter that influences the abrasion of concrete pipe is the hardness of the aggregate used in the concrete. Aggregates that are harder than the bedload will provide a greater level of resistance to abrasion than softer aggregates. Based on the literature search, the authors did not find any states that explicitly considered aggregate hardness's effect on abrasion resistance.

Other Factors

Joint performance–related issues frequently cause many types of culvert and storm sewer pipe failures. The relatively short length of concrete pipe sections (generally 8-ft-long sections are manufactured) requires a larger number of joints than flexible types of pipe. If the pipe joint separates or fails, material can enter the pipe from the surrounding backfill, leading to loss of ground and, on some occasions, to the formation of sinkholes in the roadway above. Joints, if not appropriate for the application or if not properly installed, can become the weak link in a buried pipe system and can become the controlling factor in causing the end of useful service life. The AASHTO Subcommittee on Materials PP 6309, "Standard Practice for Pipe Joint Selection for Highway Culverts and Storm Drains" (AASHTO 2009), is the most comprehensive guide on the selection of pipe joints. It provides definitions of soil-tight, silt-tight, leak-resistant, and special joints, depending on project or site requirements.

A recent study for Minnesota DOT (Taylor and Marr 2012) indicates that joint separation is the most common failure mode of concrete pipe in Minnesota DOT experience. This report recommends the longer joint and more favorable joint geometrics provided by gasketed joints to reduce the incidence of failure resulting from joint separation.

Concrete pipes can also undergo damage from progressive deterioration of the concrete. This deterioration can result from the use of poor quality concrete mixes or nondurable aggregates, or from poor-quality construction. This type of damage manifests as efflorescence, honeycombing, and popouts.

Methods to Estimate Concrete Pipe Material Service Life

The most commonly accepted methods for estimating the service life of concrete pipes are listed in Table 6. They are:

TABLE 6
METHODS FOR DETERMINING ESTIMATED MATERIAL SERVICE LIFE FOR REINFORCED CONCRETE PIPE

Durability Method	Reference	Notes
Ohio DOT Model	Potter (1988)	Based on large data set over a wide range of pH and size values. Includes an abrasive component. *Note that this method is not currently used by Ohio DOT, which has generated recommendations based on the Hurd model.*
Hurd Model	Potter (1988)	Method developed for large-diameter pipes in acidic environments.
Hadipriono Model	Potter (1988)	Method includes a wide pH range.
Florida DOT Model	*Drainage Manual-Optional Pipe Handbook* (FDOT, 2012)	Considers corrosion and sulphate attack but not abrasion.

- Hurd model (Hurd 1985)
- Hadipriono model (Hadipriono 1986)
- Florida model (FDOT 2014a)
- Ohio DOT model (Meacham et al. 1982).

The Hurd and Hadipriono models are both based on the same data set from Ohio DOT, but they use different regression models and exclude various subsets of the overall data set. Factors considered in these models include pH, slope, sediment depth, and diameter. The Florida model assumes that corrosion is the critical degradation mechanism and includes such factors as depth of steel cover, chloride and sulfate concentrations, and concrete mix in its equation, which the other models do not explicitly incorporate. Potter (1988) and Gabriel and Moran (1998) provide more detailed discussions and descriptions of these methods.

In addition to the previous quantitative methods, review and comparison to the achieved service life of nearby installations is often used to provide both qualitative and quantitative (through back-calculation of environmental parameters) material service life estimates.

The formulas representing each of these four service life prediction models are provided in detail in Appendix B "Aluminized Steel (Type 2) Pipe) along with supporting charts and tables for the FDOT model.

METAL PIPE

Material Properties and Specifications

Material properties for metal pipes are generally defined by ASTM and AASHTO standards as listed in the AASHTO LRFD Bridge Manual (2013), which states in Section 12.4.2 that:

- Aluminum for corrugated metal pipe and pipe-arches shall comply with the requirements of AASHTO M 196 (ASTM B745). Aluminum for structural plate pipe, pipe-arch, arch, and box structures shall meet the requirements of AASHTO M 219 (ASTM B746).
- Steel for corrugated metal pipe and pipe-arches shall comply with the requirements of AASHTO M 36 (ASTM A760). Steel for structural plate pipe, pipe-arch, arch, and box structures shall meet the requirements of AASHTO M 167M/M 167 (ASTM A761M/A761).
- Steel for deep-corrugated structural plate shall comply with the requirements of AASHTO M 167. Deep-corrugated structural plate may be reinforced (Figure 22).

The current state of practice is summarized in Table 7 in the form of a list of findings from relevant studies grouped by topic.

Definition of Useful Service Life

The most common definitions of useful service life of metal culverts relate to the loss of wall section. Typical service life criteria relate to section loss as a result of the subsequent reduction in structural capacity and the potential for soil erosion through the pipe wall, which can lead to significant softening of the backfill, ground loss, and the potential for significant sudden and dangerous impacts to the overlying roadway.

FIGURE 22 Older invert paved corrugated steel culvert in excellent condition (NYSDOT 2011).

Halem et al. (2008) provides a clear and concise summary of the most common serviceability criteria used for steel culverts. The California method (Caltrans 2001) defines service life as the time to first perforation, while the American Iron and Steel Institute (AISI) method indicates that first perforation typically occurs when there is an average metal loss of 13% in the invert of a pipe (Figure 23). However, AISI defines the end of the useful service life of the pipe as the time when an average metal loss of 25% occurs in the invert. Therefore, AISI predicts the service life to be approximately twice as long as that of the California method. The National Corrugated Steel Pipe Association (NCSPA) has also published a corrugated steel pipe durability guide that uses the AISI chart to predict the service life of corrugated steel pipe and provides a table with additional service life durations for different coatings (NCSPA 2000).

FIGURE 23 Perforated invert of metal culvert (Caltrans 2013).

The state of the practice across transportation agencies appears to vary widely based on the responses to survey questions 3B to 3F related to the definition of end of service life for metal culverts as presented in full in Appendix A.

Factors Affecting Service Life

The extensive research work that agencies have undertaken on the subject of factors affecting the service life of metal

TABLE 7
METAL PIPE DURABILITY AND SERVICE LIFE

Factor	Standards of Practice	Reference
General	Most states have found that pH and resistivity of the contacting soil and water bodies correlate well to culvert durability. Based on combination of pH and resistivity, Montana DOT selects either plain steel, type 2 aluminized steel, aluminum, or concrete.	Wyant (2002)
	Utah DOT has a guideline to select the material for both metal culverts and concrete culverts based on pH, resistivity, and percent-soluble salt.	Wyant (2002)
	Studies from the New York and North Carolina DOTs concluded that no correlation exists between pipe service life and pH, resistivity, or chemical content of the soil. These studies stand in contrast to other studies that indicate that pH and resistivity are important and correlative factors affecting durability. New York DOT developed a method to use galvanized steel pipe (with or without invert paving) based on the culvert location.	Gabriel and Moran (1998)
Corrosion	It is common to specify both upper and lower bounds for pH. Typical ranges for plain galvanized steel: Alabama: 6.5 < pH < 8.5 Montana: 6.0 < pH < 8.5 Washington: 5.0 < pH < 8.5 Idaho: 6 < pH < 9 AASHTO (2007): 5.5 < pH < 8.5 Typical ranges for aluminized steel: Idaho: 5 < pH < 9	Gabriel and Moran (1998)
	Because of problems with rapid corrosion damage, general use of plain steel culverts (excepting steel casing pipe) is prohibited in Colorado, Louisiana, and Ohio.	Gabriel and Moran (1998)
	Resistivity for both the contacting soil and water should be determined; e.g., California Test 643. The minimum resistivity is then used to estimate the culvert service life.	Caltrans (1999)
	Soil resistivity has more of an effect on corrosion than the water resistivity based on data from Alberta, Canada.	Gabriel and Moran (1998)
Soil-side and water-side corrosion	Depending on the environmental conditions, loss of metal due to corrosion can occur on either the water side or the soil side of the culvert. Soil-side corrosion controls the pipe service life when site pH is greater than 7.3.	NCSPA (2008)
	A study from Ohio concluded that water-side corrosion was the main factor leading to metal loss in deteriorated metal culverts in Ohio.	Gabriel and Moran (1998)
Abrasion	Many states have found that abrasion from material being carried in the water flow has a significant effect on the durability of metal culverts. Ohio DOT conducted a field study that involved 1,616 pipes and found that low water pH and abrasive bedloads were the two main factors affecting pipe service life. Its study concluded that resistivity did not have a significant impact on the pipe life.	Meacham et al. (1982)
	A field abrasion study conducted in California between 2001 and 2006 concluded that only the polyethylene coating for steel culverts was suitable for abrasive environments with flow velocity > 12 ft/s, but was not suitable for velocities > 14 ft/s.	Decou and Davies (2007)
Abrasion, Corrosion, and Protection	A combination of corrosion and abrasion accelerates wear in metal culverts and reduces culvert service life. Corrosion products act as a protective layer for bare steel; however, abrasion flow removes the corrosion layer and exposes the bare steel to further corrosion.	
	A study from British Columbia's Ministry of Transportation evaluated 21 structural plate and galvanized drainage structures that were more than 20 years old in 1993. Based on corrosion alone, the service life was expected to exceed 100 years; however, two of the structures had significant loss of metal due to abrasion.	CSPI (2007)
	Additional coatings prolong metal culvert service life by providing protection against corrosion and providing abrasion resistance. For example, bituminous coated steel culverts add an additional 10 years to water-side and 25 years to soil-side service life. If invert paving is added, the entire culvert life can be extended by an additional 25 years.	Gabriel and Moran (1998)
	Conventional plain galvanized coating has very little resistance to abrasion. It can still be used in abrasive conditions if it is protected. A typical option is to install 3 to 6 in. of concrete over the lower one-third of the pipe.	AASHTO (2007)
	The Ohio DOT study concluded that bituminous coated steel culverts without invert paving add little value in terms of service life because the average life (years to poor condition) of the bituminous coating was 3.16 years with 50% and 20% chance of coating lasting over 1.5 years and 5 years or more, respectively. Thus, the coating should be used in conjunction with invert paving where the average service life addition was 18.71 years.	Meacham et al. (1982)

culverts indicates its importance in managing drainage network maintenance and replacement costs. Table 7 provides a summary of this research and relevant findings.

Corrosion

As defined earlier, corrosion is the loss of section or coating of a buried structure by chemical or electrochemical processes. The majority of failures in metal pipes are attributed to corrosion, which can degrade both the inside (flow side) and outside (soil side) of a culvert. Soil-side corrosion is most significant in arid or semi-arid regions where the soils are generally alkaline (high pH) and rainfall is minimal. pH generally controls the potential for corrosion to occur, with resistivity generally controlling the rate at which it occurs.

Corrosion of steel is an electrochemical process in which the metallic iron is oxidized to form iron oxide or ferrous ions, depending on the environment's pH level. The presence of aggressive chemicals (such as chloride ions), inorganic acids, or low-pH environments can accelerate corrosion. It should be noted that while most studies have shown a definite influence of pH and resistivity on corrosion of metal culverts, some studies do not show this trend. Generally, state agencies specify minimum and maximum pH and resistivity ranges for the installation of metal pipes.

In an acidic environment (low pH), steel dissolution occurs, whereas in an alkali environment (high pH), steel forms an oxide film. Steel dissolution is thus more severe in an acidic environment because in an alkaline environment, the oxide film formed on the surface of the steel can stabilize it. This protective film can, however, be broken down in the presence of some ions (such as chloride ions) and when the pH is below approximately 8.

A Caltrans study of metal pipe durability is the basis for most metal pipe service life prediction models (Caltrans 1999) and was based on life to first perforation in culverts that had not received any special maintenance treatment. The results included the combined effects of soil-side and interior corrosion, as well as the average effects of abrasion. For pipes where the pH was greater than 7.3, soil-side corrosion controlled and life could be predicted by resistivity. For pipes where the pH was less than 7.3, the interior invert corrosion generally controlled and both resistivity and pH were important. In the field inspection of 7,000 culverts in California for Caltrans, Richard Stratfull, lead project investigator, states he "has no memory of a corrosion perforation being initially found other than in the invert" (NCSPA 2000).

Because plain steel is vulnerable to corrosion, galvanized zinc coatings for steel pipe are standard practice. When zinc (or aluminized coatings) is applied to steel pipe, corrosion resistance increases. This coating provides a sacrificial metallic layer for acidic environments. Polymer laminates applied to steel pipes also provide a protective barrier against corrosion.

Dissolved salts containing chloride ions can be present in the soil or water surrounding a culvert pipe. Chlorides primarily attack exposed metal and will also be of concern at coastal locations, near brackish water sources, and at locations that use winter deicing salts.

Abrasion

Common practice in estimating the durability of metal culverts is to consider corrosion factors (pH and resistivity) assuming nonabrasive or low-abrasive conditions and then to separately consider abrasion as a supplemental evaluation of durability. With the development of new coatings, ongoing research is needed to update service life prediction models.

The expected material service life (EMSL) of polymer-coated steel pipes is generally calculated by adding on a number of years to the service life obtained from estimates for plain galvanized steel pipe. The protective performance of a coating will vary depending on the composition of the coating, quality of bonding, thickness of the coating, and expected abrasion conditions. Specific assumptions and methodologies used in the research and development of the add-on year values also vary. Various sources provide add-on values for polymer and other coatings:

- National Corrugated Steel Pipe Association
  - *Pipe Selection Guide* (NCSPA 2010) provides a table of service life add-ons for supplemental pavings and coatings.
  - Service life add-ons are dependent on the abrasion level (using FHWA scale from 1 to 4).
  - Service life add-on values range from 10 years to greater than 80 years.
  - Field inspection data on polymer-coated steel pipe installations from across a large range of states over several decades is provided in the NCSPA's 2012 report, "Long-Term Field Investigation of Polymer Coated Corrugated Steel Pipe" (NCSPA 2012).
- *Highway Design Manual* (Section 855) (Caltrans 2011b)
  - Service life add-ons are dependent on flow velocity, channel materials, and type of coating or paving.
  - Service life add-on values range from 0 to 70 years.

The choice of additional service life owing to coatings is generally based on a qualitative assessment of the abrasive conditions. Various definitions of these abrasive levels are available. The most widely adopted definition is that proposed by the Federal Highway Administration (FHWA 2011). Caltrans has also defined levels of abrasion based on a study performed in an area known to have highly abrasive conditions (Decou and Davies 2007). The NCSPA uses the FHWA definitions in providing guidance on the applicability of different coatings in different applications.

Methods to Estimate Service Life

Culvert service life will vary significantly depending on environmental conditions, but the typical expected service life of metal culverts can be 25 years, 50 years, or longer, depending on wall thickness and site environmental conditions. Table 8 summarizes the current approaches to estimating metal pipe service life expectations.

Galvanized Steel Pipe

A number of methods are available for estimating the expected service life of galvanized pipe, as listed in Table 8. The most widely recognized methods are the Califor-

TABLE 8
CURRENT APPROACHES TO ESTIMATION OF THE SERVICE LIFE OF METAL CULVERTS

Service Life Estimation Approach	Reference
Expected service life for metal culverts is reported as 50 years. Restrictions on allowable pH and resistivity levels for each type of metal culvert need to be applied to achieve this service life.	Potter (1988)
A study in Alberta evaluated the performance of 201 zinc-coated culverts in 1988 and showed that 83% of the installations achieved the minimum service life of 50 years and that the average expected service life was 83 years.	CSPI (2007)
A study conducted in Washington, D.C., evaluated the performance of 17 galvanized steel storm water detention systems. Due to the absence of abrasion at invert, these steel culverts performed very well after 25 years of service. The study expected that these culverts would exceed 100 years of service life.	NCSPA (2002d)
Louisiana has developed a table to list design service life for each type of culvert and application. For metal culverts, the design service life ranges from 30 to 50 years.	Wyant (2002)
Caltrans has developed a chart to determine the wall thickness of various metal pipes needed to achieve 50 years of maintenance-free service life. It has also developed a guide to determine the minimum thickness of coating material at the invert to achieve a 50-year service under a range of abrasion levels.	Caltrans (2011b)
Chapter 14 of AASHTO (2007) defers to the Caltrans Test Method 643-C (California method) for estimating service life of galvanized corrugated steel pipe.	AASHTO (2007)
A study from Ontario in 1967 concluded that the predicted service life of culverts under local conditions agreed with the California method, based on pH and resistivity.	CSPI (2007)
A study in Alberta found a poor correlation between its results and the California method. The study also proposed that frost action slowed or stopped the metal corrosion process.	Gabriel and Moran (1998)
Colorado DOT has also developed a corrosion rating system modified from the Caltrans system.	Wyant (2002)
Florida, Louisiana, Idaho, Georgia, Nebraska, and Kansas have investigated the actual service life of culverts and compared them with the California method. They concluded that the California method was too conservative.	Meegoda and Juliano (2009)
A study commissioned by Ohio DOT found from a survey of 40 DOTs that with respect to metal culverts, no serious alignment problems were found at the sites. No stress cracks were detected at the bolt lines inside any of the metal culverts and the service life of a metal culvert appeared to be limited to 60 to 65 years.	Mitchell et al. (2005)
A study focusing on corrugated aluminized type 2 steel pipe found that in the absence of abrasion, aluminized type 2 pipe had a service life 3.5 times greater than the service life estimated for plain galvanized corrugated steel pipe via the California method, noting the reported accuracy of the California method as ±12 years.	Ault and Ellor (2000)

nia method and the AISI modified California method. The deterioration rates are based on the pH and resistivity of the flow and soil. The California method has been developed based on surveying the condition of 7,000 corrugated metal culverts located in California (Beaton and Stratfull, 1962). The most recent version of the California method to estimate the service life of steel culverts is the California Test 643 (Caltrans 2012). The methods differ, however, in the definition of the end of service life. The California method defines service life as the time to first perforation, whereas the modified California method permits a 25% loss of invert. Additional methods have been developed by Ohio and Utah DOTs.

A recent study for Colorado DOT concluded that the California method works well with some adjustments to the metal thickness adjustment factors (Table 9). Montana DOT also recently performed a study and concluded that the method used to determine soil resistivity had a significant effect on the accuracy of the modified method. Neither of these two methods incorporates the effects of abrasion, or the differences between corrugated and structural plate pipe.

In addition to the previous quantitative methods, review and comparison to the achieved service life of nearby installations is often used to provide both qualitative and quantitative (through back-calculation of environmental parameters) material service life estimates.

The NCSPA has also published a corrugated steel pipe durability guide that uses the AISI chart to predict service life of corrugated steel pipe and provides a table with additional service life durations for different coatings (NCSPA 2000).

The Federal Lands Highway Division of FHWA uses a modified version of the California 643 method to estimate the service life of galvanized culverts for nonabrasive and low-abrasive conditions (FHWA 2011). The Federal Lands Highway guidance provides a detailed chart of estimated average service life values for a metallic-coated steel pipe with a thickness of 0.64 in. and assumes that the average service life for metal culverts should be taken as 25% longer than the time to first perforation. Missouri DOT defines the end of useful service life as the time to replacement of the pipe as a result of structural failure or erosion of the roadway bed above the pipe (Gabriel and Moran 1998).

Both the California method and the AISI method use the thickness multiplier to estimate the service life of different gage thickness, and this multiplier was calculated based on the assumption of a linear relationship between corrosion and thickness. However, Colorado DOT recommends a

TABLE 9

METHODS FOR DETERMINING ESTIMATED MATERIAL SERVICE LIFE FOR PLAIN GALVANIZED STEEL PIPE

Durability Method	Reference	Notes
California Method	*California Test 643, Method for Estimating the Service Life of Steel Culverts* (Caltrans 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* (FHWA 2008)	Modification of California method. Increases 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	*Optional Pipe Material Handbook* (FDOT 2012)	Modification of California method to include a minimum steel thickness of 16 gage.
NCSPA Recommendations	*Pipe Selection Guide* (2010)	Includes combined effects of corrosion and abrasion. Based on soil/water pH and resistivity. Service life of pipe considered to be until time of invert perforation.
Utah DOT Method	*UDOT-IMP-76-1, Pipe Selection for Corrosion Resistance* (Leatham and Peterson 1977)	Result of Utah DOT study of 58 installations. The method considers corrosion alone through the following four parameters: minimum soil resistivity, pH, total soluble salts, and sulfate content.

power relationship between corrosion and thickness (Molinas and Mommandi 2009). The California Corrugated Steel Pipe Association found that the AISI method is appropriate for estimating the service life of the upper 270 degrees of the culvert circumference and recommended that the AISI method be used only when the invert is paved (Potter 1988). According to Ault and Ellor (2000), the California method has an accuracy of approximately 12 years.

In 1982, Ohio DOT conducted a study to evaluate the field performance of 1,616 culverts in Ohio (Meacham et al. 1982). This study developed equations and a graph to calculate the expected years to poor condition of bituminous coated culverts and bituminous coated–invert paved culverts. This study also developed equations to predict the metal rating and metal loss based on age, water pH, wall thickness, and abrasion level for both corrugated metal pipe and structural plate pipe. The rating scale ranged from 1 (good) to 4 (critical). Mitchell et al. (2005) indicates that the new Ohio DOT rating scale and proposed rating system ranges from 0 to 9 (9 indicates excellent condition, 1 indicates very poor condition, and 0 indicates failure). The new rating scale (0 to 9) was converted from the old rating scale (1 to 4).

New York DOT has developed a method to deploy galvanized culverts based on a "durability index." The index comprises four criteria: geographical area (rating of 1, 3, 5, 7, or 9), abrasion (rating of 1, 2, or 5), flow condition (rating of 1, 2, or 3), and service rating (1 or 2). If the index value is greater than 13, it is recommended that a paved (bituminous) invert be used. Otherwise, it recommends the use of plain galvanized culverts (Ault and Ellor 2000).

A recent study from Colorado DOT (Molinas and Mommandi 2009) concluded that the California method worked well with some modifications to the metal thickness adjustment factors. Based on the flow velocity and the bedloads, the FHWA defines four levels of abrasion: nonabrasive, low abrasive, moderate abrasive, and severe abrasive (FHWA 2011). The Colorado DOT study recommended applying additional coating at the invert to adjust for the abrasion level. Montana DOT (Hepfner 2001) also performed a study and concluded that the method used to determine soil resistivity had a significant effect on the accuracy of the modified method. The study recommended use of the AASHTO T288 minimum resistivity test to measure soil resistivity instead of the Montana DOT test for durability analysis.

The formulas and design charts for the California, AISI, Federal Lands Highway, FDOT, and Utah DOT methods are provided in Appendix B "Galvanized Steel Pipe."

Aluminum-Coated Corrugated Steel Pipe

White and Hurd (2010) report that type 2 aluminum-coated corrugated steel pipe exhibits a service life 3 to 8 times longer than galvanized corrugated steel pipe. FDOT developed a model, based on the original California method, to estimate the service life (Table 9). This method recognizes that aluminum is affected by both acidic and basic flows.

A New York DOT study (Gabriel and Moran 1998) showed that type 2 aluminized (hot-dip aluminum-coated) culverts had better abrasion resistance than galvanized culverts. However, a more recent study by Caltrans (2011a) stated that type 2 aluminized steel culverts had equivalent abrasion resistance to galvanized steel culverts. Potter (1988) reported that the corrosion rate of aluminized pipes was 6.2 times lower than the California method prediction for galvanized culverts. Aluminized type 2 culverts had service lives 2 times longer than galvanized culverts in the following environment: $5 < pH < 9$ and when minimum soil resistivity was greater than 1,500 ohm-cm (Gabriel and Moran 1998). An investigation of 21 aluminized pipes for the FHWA (Ault and Ellor 2000) concluded that type 2 aluminized pipes in an abrasion-free environment may have a service life up to eight times longer than what the California method predicted for galvanized pipe.

Caltrans (2011a) recommends using aluminized steel culverts (type 2) instead of using other coatings or increasing the steel thickness in nonabrasive conditions with 5.5 < pH < 8.5 and minimum resistivity of at least 1,500 ohm-cm. With 5.5 < pH < 8.5 and resistivity less than 1,500 ohm-cm, Caltrans (2011a) does not recommend the use of aluminized type 2 steel culvert.

The formulas and supporting design charts for the FDOT method are provided in Appendix B "Aluminized Steel (Type 2) Pipe."

Polymer-Coated Corrugated Steel Pipe

Various types of polymers have been tried as coatings for metal culverts because of the excellent corrosive resisting characteristics of polymer compounds. The only polymer coating currently still in production is the Dow "Trenchcoat" polymer coating. The polymer coating is applied to the steel pipe following metallic coating (either zinc, aluminum-zinc alloy, or zinc-aluminum-mischmetal alloy). Polymer coatings are classified by grade corresponding to the thickness on each side of the base pipe material as defined in ASTM A742/A742M. Polymer coatings in drainage pipe applications are typically 12 mils in thickness and laminated to both sides of galvanized sheet metal before forming the corrugated pipe profile.

Industrial trade associations that promote the use of corrugated steel pipe report that polymer coating provides a barrier to both corrosion and abrasion and is reported to provide up to 80 years of add-on service life above the estimated baseline service life of the metal pipe (NCSPA 2000. However, many transportation agencies currently limit the add-on service life assigned to polymer coating to between 30 and 50 years of additional service life.

Ault (2003) developed a service life model to explain why polymer coating provides significant service life extension for metal pipes. It suggested four phases of deterioration: an initiation period, a polymer degradation phase, a zinc corrosion phase, and a steel corrosion phase (Figure 24). It would be expected that the phases would overlap, but one mechanism would dominate a phase of the pipe life.

A Wisconsin DOT study (NCSPA 2002b) that evaluated polymer-coated steel culverts (from 17 to 27 years old) in an aggressive environment concluded that the polymer-coated steel culverts perform as well or better than other coated steel culverts. A New York DOT study (NCSPA 2002a) evaluated 20 polymer-coated steel culverts (from 9 to 13 years old) with asphalt paving. The study concluded that polymer-coated steel pipe with asphalt paving performed well in a severe abrasion environment. Invert abrasion testing was conducted by Corrpro Companies Inc. (NCSPA 2002c). The study concluded that polymer precoat, polymer-modified asphalt, and polymer modified asphalt over precoat at the invert had good performance under moderate-abrasion conditions. Polymer-coated steel culverts with polymer-modified asphalt invert treatment and asphalt paving performed well under severe abrasion conditions (NCSPA 2002d).

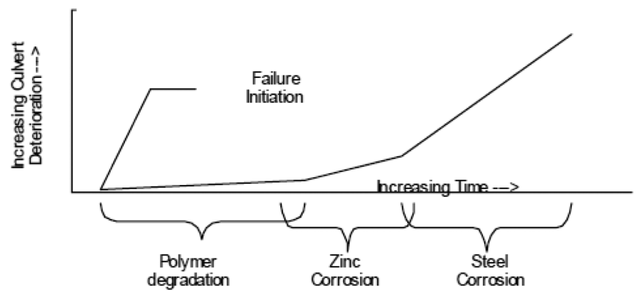

FIGURE 24 Polymer-coated CSP service life model (Ault 2003).

Corrugated Aluminum Pipe

States generally agree that corrugated aluminum pipes will provide the desired service life if the pH is between approximately 5.5 and 8.5 and if the resistivity is above 1,500 ohm-cm. Models to predict the service life of these pipes have been developed by Florida and Utah DOTs (Table 10).

TABLE 10
METHOD FOR DETERMINING ESTIMATED MATERIAL SERVICE LIFE FOR ALUMINUM PIPE

Durability Method	Reference	Notes
Florida DOT Method	*Optional Pipe Material Handbook* (FDOT 2012)	Based on estimated corrosion rates due to pH and resistivity
Utah DOT	*UDOT-IMP-76-1, Pipe Selection for Corrosion Resistance* (Leatham and Peterson 1977)	Result of UDOT study of 58 installations. The method considers corrosion alone through the following four parameters: minimum soil resistivity, pH, total soluble salts, and sulfate content.

A field test was conducted by Colorado DOT to study corrugated metal culvert performance in various Colorado environments (Swanson and Donnelly 1977). The study concluded that corrugated aluminum culverts had better corrosion resistance than galvanized culverts if their exposure was within the manufacturer-specified tolerances. A study from Utah DOT concluded that aluminum culverts had better resistance to corrosion than either concrete or steel culverts when the soluble salt contents approached 10% (Gabriel and Moran 1998). A study from Colorado DOT (Molinas and Mommandi 2009) concluded that the salt content of the surrounding soil was a primary factor that affected the aluminum culvert service life. According to Caltrans (2011b), aluminum pipe has low abrasion resistance and is not recommended for use in an environment with flow velocities greater than 5 ft/s and angular or large bedloads present.

The design chart for estimating the service life of aluminum pipe according to the FDOT method is provided in Appendix B "Aluminum Pipe."

Coatings

Given that corrosion is the main determinant of life expectancy of buried metal pipes in service, a number of factor-applied coatings provide protection to the metal and significant improvements in actual service life. The most common coatings available are discussed in the following sections.

Bituminous and Asphalt Coatings

Several types of bituminous and asphalt-based coatings are currently in use. The most common asphalt coating is the hot-dip application (ASTM A 849) of bituminous material (AASHTO M 190). 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 application provides good protection against soil-side corrosion but very little protection against abrasion, and where flow velocities exceed 6.5 ft/s it will provide almost no additional service life.

Besides limited abrasion resistance, most asphalt coatings sustain damage when 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 coating's bond.

Asphalt coatings can be flammable. Where the risk of fire is high, concrete end walls or other "insulating" end treatments need to be considered. Special care must be taken during shipping and installation to ensure that the coating is not damaged or removed.

Typical service life add-on from the use of asphalt coating is 10 years to the inside of the pipe (NCSPA 2000). Longer-term protection can be anticipated from soil-side corrosion. Where asphalt coating is combined with invert paving, the service life add-on is extended to up to 30 years with low abrasion levels. 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 to improve service life. This type of treatment will typically increase the coating thickness to 0.1 in. and provide longer resistance to abrasion damage. In their metal pipe durability tables, Ohio DOT (Ohio DOT 2014) assumes a 15-year add-on service life for bituminous coating with invert paving for culverts 54 in. and larger and 25-year service life for culverts 48 in. and smaller (Figure 25).

FIGURE 25 Loss of bituminous coat and paving at invert of metal pipe (Ohio DOT 2005).

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

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. The use of fibers improves the reliability of the coating, but the add-on service life expectations would be similar to conventional asphalt coating.

Although still not highly resistive to abrasion, this process does enhance the corrosion resistance of metal pipes in severe conditions. Because it is not subject to corrosion and possesses good erosion resistance, fiber-bonded pipe can be cost-effective in marine environments.

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. It is typically used only as a protective coat on the outside of the pipe. Like bituminous coatings, environmental concerns about its use have been raised and abrasion resistance is minimal.

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 as invert paving to only a 90-degree portion of the pipe.

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.

Polymeric Sheet Coating

Protection for metal culvert pipes can be provided by polymer coatings, which have good corrosion-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 before corrugating. Polymer coatings also typically provide abrasion resistance in excess of bituminous coatings.

Independent studies of the coatings' durability are not available, and guidance on the use of polymeric coatings is given by industry and trade groups representing manufacturers and polymer coating suppliers. 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. The use of polymer coating allows corrugated metal pipes to be used in environments with very low resistivity. 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 to the coating has occurred, the bare metal can be exposed, leading to localized increased rates of corrosion. Corrosion typically will 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 across many agencies.

THERMOPLASTIC PIPE

Generally, plastic pipe is resistant to abrasion by relatively small aggregates and fine sands that are transported by water moving at normal flow rates. The effects of continuous abrasion by larger debris, such as stones and cobbles, at a high velocity are not as clearly defined. The Federal Lands Highway design guide (FHWA 2011) permits HDPE and PVC for nonabrasive and low-abrasive conditions, but requires invert protection for moderate and severe abrasive conditions.

Significant research related to the durability assessment of thermoplastic pipes for nonpressure drainage applications is ongoing. Many state agencies have adopted prescribed service life values for thermoplastic pipe systems (typically between 50 and 100 years), regardless of installation conditions. The approach to apply a standard service life is based on limited direct research of thermoplastic pipe products and extrapolation of durability research and experience from geosynthetic liners, the pressure pipe and fuel gas industries, and other areas with longer experience using thermoplastic products.

The extent of long-term performance and case history for thermoplastic pipes is less than for concrete and steel pipes owing to the shorter time periods with which these pipes have been used extensively in practice. In general, no or very few roadway drainage installations use thermoplastic pipes equal to or longer than the typical EMSL values often used in design. However, it is important to note that thermoplastic pipes have been used successfully in roadway drainage applications for decades and there are no strong indications that the current design EMSL values are grossly out of line with actual performance and continually updated evaluations of field performance.

In general, material properties for thermoplastic pipes are controlled by ASTM and AASHTO standards as listed in the AASHTO LRFD Bridge Manual (2013), which states in Section 12.4.2.8 that:

- Polyethylene (PE) pipe shall comply with the requirements of ASTM F714 for solid wall pipe, AASHTO M 294 for corrugated pipe, and ASTM F894 for profile wall pipe.

- Polyvinyl chloride (PVC) pipe shall comply with the requirements of AASHTO M 278 for solid wall pipe, ASTM F679 for corrugated pipe, and AASHTO M 304 for profile wall pipe.

HDPE Pipes

HDPE pipes are generally regarded as resistant to most naturally occurring chemicals. The major factors affecting durability include:

- Deflection and backfill
- Oxidation
- Slow crack growth
- Rapid crack propagation
- UV light (sunlight) exposure.

No predictive durability models are currently available in the literature reviewed. The example of the use of HDPE liners in landfills is used to support the acceptance of an EMSL value for HDPE pipe, since these applications have been the subject of extensive research. However, the component materials are not identical and the service conditions are quite different. There is a substantial amount of research work and case studies in progress to identify the primary distress modes of HDPE pipe, and to attempt to relate such distresses to environmental or in-service conditions. To date, however, no such predictive methods (equations) are available.

In the absence of reliable predictive models and a means to quantify the influence of unfavorable service conditions or risk factors, most agencies have elected to use one constant value for EMSL for all HDPE pipe products for all applications and environments. The agencies also impose minimum material quality standards as a means to eliminate poorer-quality products; the standards developed by FDOT, which are based on the research by Hsuan, are thought to be the most up to date (Hsuan 2012). Because this base value is not related to risk factors, the EMSL estimate must be conservative. The U.S. Army Corps of Engineers (1998) and FHWA (1996) recommend that an EMSL of 50 years be used for HDPE with no restrictions on pH or resistivity.

FDOT commissioned a study by Drexel University to establish criteria needed to allow corrugated HDPE pipe to last for 100 years. McGrath and Hsuan (2003) defined the following requirements with respect to controlling pipe stresses for long-term durability:

- Minimum pipe tensile strength must be about 3.5 MPa (500 psi) at 2.5% strain;
- Backfill must be limited to well-graded, coarse-grained soils with maximum of 12% fines (i.e., passing the No. 200 sieve according to ASTM D2487-92);
- Increased inspection during construction is recommended;
- Backfill must be compacted to at least 95% of Standard Proctor maximum dry density;
- Pipe must be inspected after installation to verify that the total reduction in vertical diameter is less than 5%;
- Carbon black content must be between 2% and 4%; and
- Minimum cover for applications is subjected to live loads 600 mm (2 ft) or one-half the pipe diameter, whichever is greater.

From *NCHRP Report 429*:

- Pipes investigated were all HDPE, ranging from 300mm (12 in.) to 1,050 mm (42 in.) in diameter.
- Circumferential cracking was the dominant crack type, indicating longitudinal stresses.
- Much of the cracking was associated with installation problems that led to excessive deflection and buckling or longitudinal bending.
- SCR (stress crack resistance) of the pipe resin is an important parameter in preventing cracking in the field.
- Residual stresses (from manufacture) could be a factor leading to circumferential cracking observed in field.

PVC Pipe

The availability of empirical data to assist the designer in predicting EMSL is also limited for PVC pipe when compared with concrete and steel. As for HDPE, no statistical regression equations were found in the technical literature to predict the EMSL for PVC pipe.

In the absence of reliable predictive models and a means to quantify the influence of unfavorable service conditions or risk factors, most agencies have elected to use one constant value for EMSL for all PVC pipe products for all applications and environments. Because this base value is not related to risk factors, the EMSL value must be conservative. The U.S. Army Corps of Engineers (1998) and FHWA (1996a) recommend that an EMSL of 50 years be used for PVC with no restrictions on pH or resistivity values. However, no portion of the pipe (ends) should be exposed to UV light.

Following a 2003 evaluation of available technical information on the performance of PVC pipe up to 910 mm (36 in.) in diameter, FDOT allows a 100-year service life for PVC pipe subject to the following requirements:

- The pipe meets all the requirements of ASTM F 949;
- The pipe will be used only in installations where it is not exposed to direct sunlight (e.g., aboveground applications or installations where mitered end sections are excluded);
- The pipe is manufactured from PVC compound having no less than 1.5 part of titanium dioxide per 100 parts resin, by weight; and

- The pipe shall be installed within 2 years from the date of manufacture (this is to avoid the possibility that the pipe has been stored for long periods with exposure to sunlight before delivery to site).

FDOT has developed a standard for using short corrugated metal pipe sections to protect the exposed ends of PVC culverts (Figure 26).

FIGURE 26 Section of helical-corrugated metal pipe used as exposed end piece on PVC pipe (*Source*: FDOT).

DUCTILE IRON PIPE

Ductile iron pipe is not frequently used for culvert applications across many agencies. The state of the practice and knowledge base regarding the durability of ductile iron has not materially changed from the *NCHRP Synthesis 254* and the summary provided in that document is generally restated in the following paragraphs.

Ductile iron has chemical properties similar to gray iron and mechanical properties similar to those of steel. Both gray and ductile iron contain approximately 3.5% carbon by weight. In gray iron, the carbon exists in the form of flakes; in ductile iron, the carbon exists in the form of discrete spheroids or nodules. The flakes in gray iron give rise to planes of weakness, a phenomenon absent in ductile iron. In the early 1950s, several studies showed that ductile iron pipe had as good as if not better corrosion resistance than the older, more established gray iron pipe. Ductile iron pipe is not generally used by the 50 states for drainage but for sewer and water applications that have high-pressure heads, submerged outfalls, and gravity sewers where tight joints are required. As a result of these applications, literature on this pipe's corrosion is geared toward the soil and not the water in the pipeline. Cast iron pipe is specified by pipe diameter, thickness, strength (class), method of jointing, and type of interior and exterior linings. This type of pipe has a variety of joint connections. In addition to the standard bell and spigot, other connections are mechanically coupled, such as rubber push-on and ball and socket. Ductile iron pipe uses cast iron fittings; most of the same connections are available for both pipe types.

Ductile iron pipes joined at their ends often include rubber gaskets that serve to electrically isolate one section from another. Electrical discontinuity reduces the likelihood of stray current accumulation and long-line corrosion cells. Therefore, joint bonding is discouraged except in cases where cathodic protection requires electrical continuity (Stroud 1989).

Corrosion

Iron pipe, whether cast or ductile, has most of the same characteristics of other metal pipes. Galvanic corrosion often limits correct calculation of the desired service life. Any dissimilar metal nearby or in connection with iron pipe is anodic and likely to start a flow of current away from the iron pipe. Also, electrolytic corrosion or stray direct current from any source will promote corrosion of iron pipe more severely than galvanic corrosion.

Another form of corrosion is graphitic corrosion, or graphitization, a result of electrochemical action between the ferritic and graphitic constituents in the cast iron (Romanoff 1968). Symptoms of graphitic corrosion or graphitization are a dull, black look to the pipe and the lack of a metallic ring when struck by another metallic object. The corrosion products of graphitization adhere to the unattacked substrate and help protect against other forms of corrosion (Sears 1968). Typical methods for protecting iron pipe are bonded coatings, cathodic protection, and polyethylene encasement. Of these methods, the Ductile Iron Pipe Research Association reports that unbonded polyethylene film encasement, which reduces the effectiveness of the electrolyte to support corrosion, is by far the most effective and most economical for cases of corrosive soils (Stroud 1989). The polyethylene is loosely wrapped around the pipe during installation. Groundwater may still find its way through the loose wrap, but since the amount of oxygen is limited, the extent of the corrosion is limited as well.

All corrosion protection methods for ductile iron pipe have disadvantages. Bonded coatings such as coal tar are expensive and may be damaged while handling, shipping, or installing. Also, usual construction procedures may compromise the integrity of a protective polyethylene sleeve.

VITRIFIED CLAY PIPE

Vitrified clay pipe is used by only a very few agencies for new culvert applications, although it remains prevalent on the historic culvert inventory of many agencies. The state of the practice and knowledge base regarding the durability of vitrified clay pipe materials has not materially changed from the *NCHRP Synthesis 254*, and the summary provided in that document is generally restated in the following paragraphs.

Vitrified clay pipe is a well-established pipe that has been used for more than 100 years. Although manufacturing improvements have been made, the material properties of fired clay are essentially unchanged. Clay pipe is available in a variety of sizes starting at 3-in. diameter up to 1,067-mm (42 in.) diameter. Because of its excellent resistance to acid attack, clay pipe is often selected for sanitary sewer applications. Only about 10% of respondents to the 2014 state of the practice survey use vitrified clay for new installations (Survey Question 1). In the manufacture of clay pipe, clays and shales are mined, shaped, and then fired in kilns that reach temperatures as high as 1,100°C (2,000°F). The product is a vitrified dense, hard, and nearly homogeneous material that is highly stable, very resistant to abrasion (Bortz 1985), and capable of resisting the corrosion effects of most acids, including hydrochloric and sulfuric acids.

The usual parameters of concern for corrosion (i.e., resistivity, pH, chlorides, and sulfides) do not apply to this pipe. Clay pipe is vulnerable to corrosive attack by high temperatures. The National Clay Pipe Institute recommends that clay pipe not be used where hydrofluoric or caustics are likely to be present. The institute claims a 150-year useful service life for vitrified clay pipe. A U.S. Army Corps of Engineers study recommends the design service life of vitrified clay pipe be limited to 100 years (Potter 1988).

MATERIAL SERVICE LIFE CALCULATION EXAMPLES

The appendices include a number of examples that show how service life prediction models are used to calculate EMSL. Appendix B presents a summary of the previously listed EMSL methods, including copies of the design charts and tables required to implement the methods. As an introduction to the various standard material service life calculation methods, Appendix C presents a series of example calculations that demonstrate the use of several of the more common material service life prediction models. Three hypothetical scenarios are presented for demonstration, consisting of a neutral environmental condition, a moderately aggressive condition, and a highly aggressive condition.

In addition to summarizing the use of several material models, the following three culvert material service life software applications are also briefly introduced:

- FDOT—Culvert Service Life Estimator (CSLE)
- Ministry of Transportation of Ontario (MTO)—HiDISC (not yet publicly released)
- Caltrans—AltPipe.

HiDISC and CSLE are stand-alone software programs, while AltPipe is an online tool. These software resources provide a quick and efficient means of learning and implementing the key design drivers for material service life of various pipe material types.

CHAPTER FIVE

PIPE PROTECTION, REPAIR, REHABILITATION, AND REPLACEMENT

This chapter summarizes the most common available protection methods and materials, and also discusses rehabilitation, repair, and replacement techniques available to extend or reestablish culvert service life. Many agencies are developing more advanced pipe system inventories and asset management systems to facilitate better drainage infrastructure management and budgeting. For example, New Jersey DOT is researching how to develop a comprehensive plan for inspection, cleaning, condition assessment, and prediction of remaining service life of corrugated steel culvert pipe (Meegoda and Juliano 2009). This process will aid rehabilitation-related decision making about (1) cleaning and painting, (2) invert paving, (3) sliplining, (4) in situ cured liners, and (5) pipe replacement.

COATINGS, LININGS, AND PAVING

Invert Paving (Concrete)

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 varies based on typical flow depth and anticipated abrasive potential. Although the concrete may be placed directly against clean pipe material, steel reinforcing bars, wire fabric, Nelson Studs, or a combination of the three are often welded to the metal pipe before concrete placement (Figure 27).

Although concrete paving is used to rehabilitate corroded and severely deteriorated inverts in corrugated metal pipes, it can also be used in concrete culverts if modifications are made (Figure 28). The method consists of pouring a concrete lining in the culvert invert, which increases surface roughness inside the pipe (and so increases Manning's *n* value) and thus decreases flow velocity. California DOT (Caltrans 2013) use concrete invert paving ranging from 2 in. to 13 in. thick depending on the abrasiveness of the site, up to Abrasion Level 5, to achieve a 50-year maintenance-free service life. Concrete invert paving is not recommended for Abrasion Level 6. The invert paving sections typically vary from 90 to 180 degrees for the internal angle depending on the extent of the deterioration on both sides of the pipe.

Although concrete invert paving is generally regarded as a temporary repair, a survey undertaken by Minnesota DOT identified a case study where invert paving had lasted longer than 25 years (Minnesota DOT 2012). Ohio DOT assumes a 20-year add-on service life for concrete paving. The key performance factors are the use of high-strength concrete with durable aggregate and ensuring that the concrete insert is adequately anchored to the host pipe.

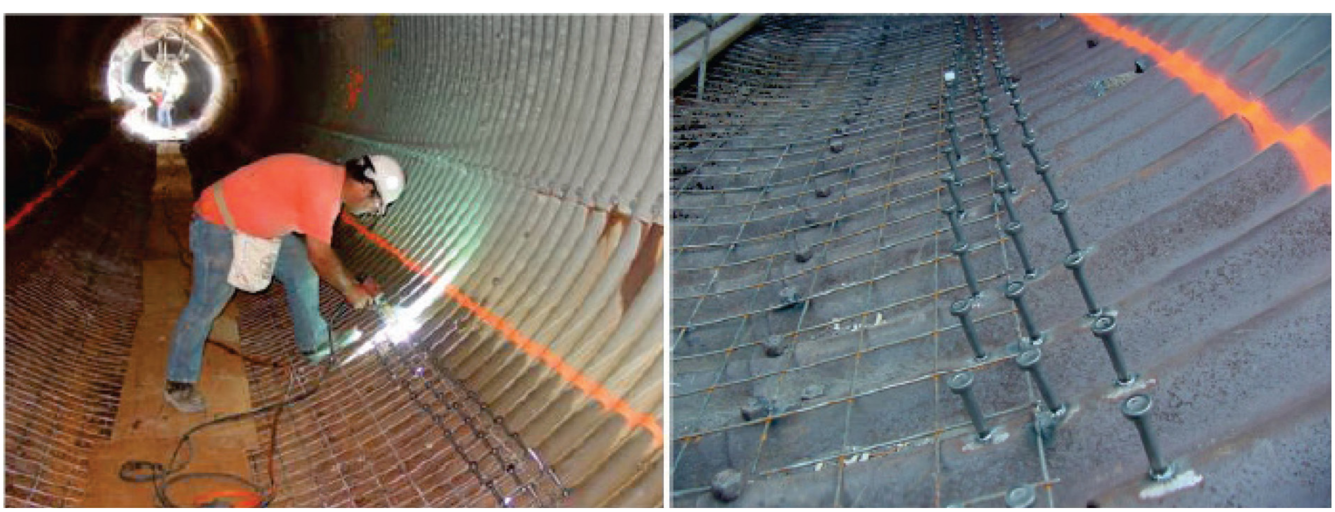

FIGURE 27 Shear connector welding studs (Nelson Studs) and wire fabric being installed prior to concrete invert paving (Caltrans 2013).

In California, an alternative to concrete invert paving is the use of steel armor plating 0.25 to 0.50 in. thick over the bottom third of the pipe. It is mainly suitable only for large-diameter (> 48 in. diameter) corrugated metal pipe in highly abrasive water flows because of the high cost.

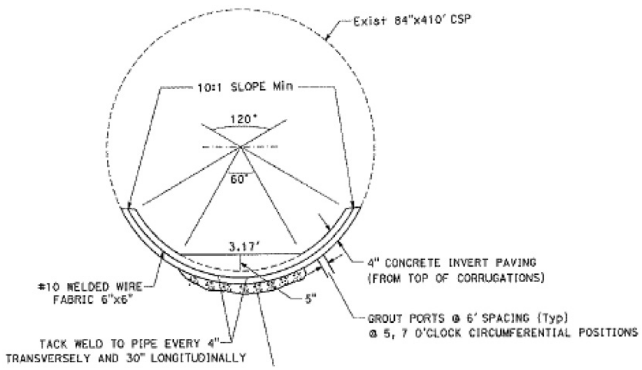

FIGURE 28 Standard detail for concrete invert paving (Caltrans 2013).

Epoxy Coatings for Concrete

A wide range of proprietary epoxy coating treatments can be applied to protect and extend the life of concrete culverts. These coatings, which are usually sprayed on, are suitable for treating minor deterioration in exposed concrete surfaces, such as popouts, minor scaling, and hairline cracks. Epoxy coatings are not appropriate for severely deteriorated concrete or where reinforcing steel is exposed. These coatings can also be effective in protecting concrete from degradation caused by exposure to mildly aggressive flow waters. Epoxy coatings are hard and bond well to concrete if it is properly cleaned and prepared prior to application. These types of coatings should be regarded as maintenance treatments but can help to slow some forms of progressive concrete degradation and can provide add-on service life in appropriate applications.

REHABILITATION AND REPAIR PRACTICES

Pipe rehabilitation and repair technologies are discussed in detail in the literature review of NCHRP 14-19 (2010). NCHRP 14-19 should be consulted for additional detail on these topics.

Lining an Existing Pipe

Sliplining

Sliplining is a method of rehabilitation in which a new pipe of smaller diameter is inserted directly into the deteriorated culvert. The annular space between the host pipe and the newly installed pipe is grouted with a cementitious material.

There are two primary methods of sliplining: segmental sliplining and continuous sliplining. For segmental sliplining, short pipe segments are assembled as a liner at the entry of an existing pipe, and new segments are added as the liner is fed into the pipe. For continuous sliplining, a liner is manufactured as a continuous pipe or assembled in the field prior to insertion, to match the entire length of the existing pipe.

The main advantages of sliplining are simple installation, the ability to rehabilitate a wide range of pipe sizes and shapes, the ability to accommodate large radius bends, the variety of available sliplining pipes, and a reduced need for flow bypassing (Figure 29). Sliplining is often an economical rehabilitation option for culverts. The method does not involve chemical processes and is environmentally safe relative to other procedures.

FIGURE 29 Sliplining 20-year-old corrugated steel pipe culverts with profile wall HDPE pipe. The annular space is filled with cellular foamed grout with specified strength of 210 psi (Doherty and Angelo 2012).

The main limitations of sliplining are the need for pit excavation (although the digging of access pits may be avoided with shorter culvert lengths), and the grouting of the annular space (which is generally required). Other limitations are flow reductions in cross-sectional areas (although the smooth interior surface of slipliner pipe could restore or even increase flow capacity), the potential for increased in-pipe and downstream flow velocities, and the need for sufficient work area.

Properly sliplined culverts should provide the full service life anticipated from the type of pipe used in the sliplining. Thus, it is generally equivalent to full pipe replacement in terms of future service life.

Spirally Wound Liner

Spirally wound liners are fabricated in the field from a continuous thermoplastic strip that has one male and one female edge (Figure 30). During the helical winding process, the male and female edges self-interlock to form a leak-tight joint. Typically, spirally wound liners use nonstructural grout or do not require grouting of the annular space.

FIGURE 30 Expandable-diameter or spirally wound pipe liner being installed (Caltrans 2013).

The main advantages of spirally wound liners are that they remove the need for excavation, on-site pipe storage, and bypass flow (for most applications). Installation is relatively quick, and the liners can accommodate large radius bends as well as diameter changes. The use of spirally wound liners does not involve chemical processes and is more likely to be environmentally safe when compared with liners that require grouts and sealants.

The main limitations of spiral winding are the reduction in flow area (although the smooth interior surface of the liner pipe often restores or even increases flow capacity), and that the ends of the relined pipe require watertight sealing. The method is also only applicable to circular pipes.

Caltrans (2013) use spirally wound liners for both flexible and rigid pipes to provide a corrosion barrier suitable to meet a 50-year design service life for abrasion levels 1 through 3. Spirally wound liners are not recommended for use in high-abrasion applications.

Sprayed-on Liner (Cementitious/shotcrete)

Shotcreting has been used as a lining for pipes since the 1990s. Shotcreting is generally a wet-mix process that uses plain concrete mixes or mixes with synthetic or steel fiber reinforcement. The shotcrete is applied by way of a robotic rig and has been used for pipes of 24-in. diameter and wider. More recently, improved technology called centrifugal sprayed concrete (CSC) has been developed. CSC delivers the new concrete lining by way of a rotating spinner head. Projects have been completed for Colorado and Kansas DOTs. CSC produces a uniform 2-in.-thick concrete liner that achieves a compressive strength of 6,000 psi in 7 days. It has been used extensively for rehabilitating corrugated steel pipe culverts (Figure 31).

If properly installed, shotcrete and CSC liners with durable and high-strength concrete mixes enhance the structural capacity of the pipe and provide serviceable lives that exceed 50 years.

Sprayed-on Liner (Epoxy)

Spray-on epoxy is used mostly for rehabilitation of potable water pipes, although it can also be used to line culverts. It generally applied with manual spraying. Epoxy can be applied as a protective coating against corrosion and to eliminate infiltration and exfiltration. Epoxy coatings are typically 100% solids and solvent-free (i.e., they do not require a solvent to keep the binder and filler parts in a liquid-suspension form). Application thickness is between 0.06 in. and 0.25 in. per application layer and a minimum of two layers is recommended.

The main advantage of polymer-based coatings and liners is the ability to provide protection against corrosion. Some

FIGURE 31 Examples of completed CSC liners (*Source*: Shotcrete Technologies Inc.).

also provide structural enhancement and no excavation is required. The main limitation is that the culvert must be completely free of water and flow bypass may be required. An extensive surface preparation is essential for successful application with some systems. Epoxy lining systems are relatively new and no data are available on life expectancy.

Cured-in-Place Pipe

Cured-in-place (CIP) relining is a method in which a flexible material (typically a tube) saturated with thermosetting resin is inserted into the deteriorated culvert by inversion or winching, expanded by means of air or water pressure, and then the resin is cured at ambient or elevated temperature (by means of steam or hot water) or with UV light. The final product, which is often referred to as cured-in-place pipe (CIPP), has minimal or no annular space, thus eliminating the need for grouting. Typical CIPP liners range in thickness from 0.25 in. to 0.5 in.

The CIP liners can be categorized into conventional CIPP and composite CIPP. Composite CIP liners are high-strength, fiber-reinforced CIP liners (fiber reinforcement provides increased stiffness and strength resulting in thinner liner walls compared with conventional CIP liners) and are used to rehabilitate medium to large sewers, drains, and culverts.

The main advantages of CIP relining are elimination of the need for excavation and grouting, and installation of continuous single-piece (jointless) products that provide structural renewal with an expected 50-year service life. CIPP is a proven technology (it has been in use for 30 years), is often cost-effective, and causes minimal traffic disruption. Small-diameter installations can be completed in as little as 1 day.

The main limitations of this method are that flow bypass is needed (unless the culvert pipe is empty at the time of rehabilitation), custom-made tube is required for each installation, trained personnel are required, prolonged liner cure is needed for large diameters, it can cause thermal pollution (if hot water was used to accelerate resin cure), and it can damage the environment (if styrene-based resins are used).

Winnipeg, Canada, was one of the early adopters of CIPP technology in North America when it began relining its sewer pipes in 1978. Video inspection and sampling of the CIPP liners after 34 years of service has confirmed that the liners' condition are still excellent with no evidence of material degradation or induced stress on the liners (Macey and Zurek 2012) (Figure 33).

Pipe Replacement

A number of trenchless technologies for pipe replacement exist, including jack and bore, tunneling, and horizontal directional drilling. These methods are not discussed in this section, but the pipe bursting/splitting method is discussed because it reuses the same alignment of the existing culvert.

Pipe Bursting/Pipe Splitting

Pipe bursting is a construction method of trenchless pipe replacement in which deteriorated culvert pipes are replaced with new pipes of the same or somewhat larger diameter. The bursting tool is passed through the pipe, breaking it into fragments if the pipe is brittle or slicing through it if the pipe is ductile (also known as pipe splitting), and the new pipe is simultaneously pulled in (Figure 34).

The typical replacement pipe installed by pipe bursting is an HDPE pipe. Since these pipes are chemically inert, they can readily flex to meet changes in loading along the culvert length while maintaining their circular shape. Other pipe types installed using pipe bursting include fusible PVC pipe, retrained joint PVC pipe, ductile iron pipe, and vitrified clay pipe.

FIGURE 32 Cured-in-place pipe liner being installed and after installation in a 20-year-old corrugated steel pipe; 75-year service life assumed in design (Doherty and Angelo 2012).

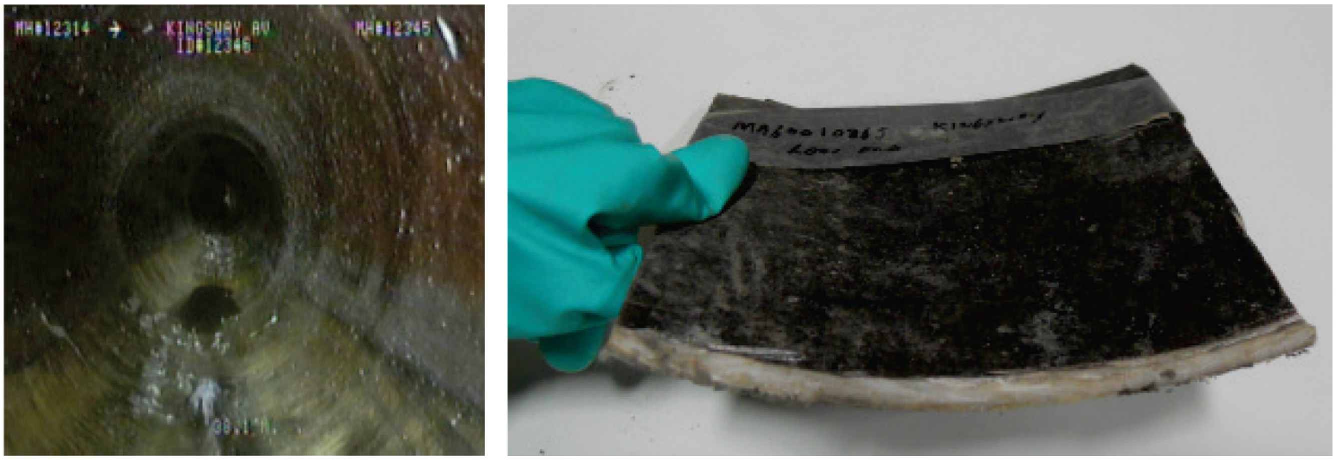

FIGURE 33 Video inspection of CIPP liner after 23 years of service (*left*) and cut section of liner after 34 years of service (*right*) confirming excellent performance and no measurable deterioration (Macey and Zurek 2012).

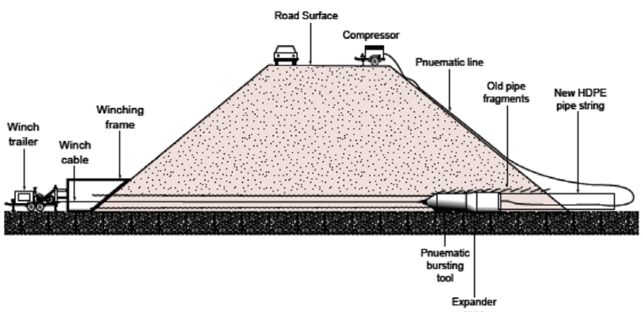

FIGURE 34 Pipe bursting schematic (USDA Forest Service 2005).

Pipe bursting can replace circular pipes up to 54 in. in diameter. The length is typically limited to 750 ft (Sterling et al. 2009). Applicability is not limited by culvert pipe type or condition. Replacement can be performed in live-flow conditions. Most favorable bursting projects involve pipes that were originally installed by trenching or open cut because the fill material surrounding them is usually conducive to pipe bursting. The potential for feasible upsizing through pipe bursting depends on soil conditions, overburden cover, and other factors.

The main advantages of pipe bursting include the installation of a new pipe, ability for pipe upsizing, and reduction of necessary excavation by 85% or more compared with open cut replacement. It is often more cost-effective than open trenching in urban environments.

The main limitations of this method are inapplicability for already collapsed pipes or difficulties that arise when existing pipe composed of brittle material has had point repairs with ductile material. Pipe bursting can cause ground heave or settlement above or at some distance from the culvert, especially in dense sand, when the culvert pipe is shallow and ground displacements are primarily directed upward, and when significant diameter upsizing is performed. In addition, pipe bursting is not applicable when the host pipe has experienced significant sagging or deviation from the original grade.

The service life expectations for pipe replacement by way of pipe bursting is equivalent to that for the replacement pipe type and material.

CHAPTER SIX

INSPECTION

Experience has shown that one of the critical issues affecting the performance (short and long term) of pipe systems is the quality of the installation. Appropriately designed and properly installed drainage systems will generally perform well throughout the pipe system's design life, and it is on this basis that design service lives are assigned.

Post-installation inspection of a buried pipe system is one phase of a comprehensive quality assurance program. Mill certificates for all pipe materials are to 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 are to be performed on the pipe, bedding, and backfill materials before and during installation. The agency's specifications for compaction and general requirements and for workmanship during construction need to be enforced.

Some agencies conduct periodic routine, systemwide inspections for in-service pipe systems as part of an asset management program. While this practice is not considered essential, it can identify potential future serviceability problems that can be addressed by routine maintenance rather than by emergency repairs. Early detection of deterioration may allow a low-cost intervention, such as invert paving, that may defer full pipe replacement for 10 years or longer.

The inspection of drainage system materials before installation and during construction will be summarized briefly in this section, 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 *Culvert Inspection Manual* (1986). As new pipe products (e.g., materials, coatings, and rehabilitative liners) and remote-access inspection technologies have been introduced since the *Culvert Inspection Manual* was developed, a need has arisen 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 due to be released in 2015.

The LRFD Bridge Construction Specifications (AASHTO 2010) provides 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). These recommendations can also be applied to other flexible and rigid pipe material systems.

INSPECTION OF PIPE MATERIALS AT DELIVERY

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

- Qualification of manufacturer and manufacturing facility, and review of mill certificates.
- Inspection of deliveries, which may include inspection of:
  - 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 pipe samples for additional testing (chemical, mechanical, coatings, etc.).

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 or costly-to-repair installations. The timing and frequency of such inspections depends on the structure's significance and the fill depth. In general, inspections would be conducted when materials arrive at the job site, during pipe installation, during backfilling, and before construction of final finishes (e.g., paving).

Inspections during construction may include examination of:

- 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.

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 LRFD Bridge Construction Specifications (AASHTO 2010) recommends that final post-construction inspections for culvert approval be completed no sooner than 30 days after completion of installation and final fill such that defects under initial conditions can have time to present themselves. The AASHTO construction specifications commentary expands on this recommendation by stating, "Soil consolidation continues with time after installation of the pipe. While 30 days will not encompass the time frame for complete consolidation of the soil surrounding the pipe, the period of 30 days is intended to give sufficient time to observe some of the effects that this consolidation will have." However, occasionally pavement is placed over the pipe sooner than 30 days. Although the 30-day time limit needs to be maintained, a brief inspection of the pipe before paving over it, particularly for the first few joints, may be prudent to ensure that good construction practices are being applied. The most frequent distresses identified from comprehensive pipe inspection are leaking joints, joint gaps, deflection, and cracking.

Post-installation inspection can be carried out in a number of ways. The most common methods are (Figure 35):

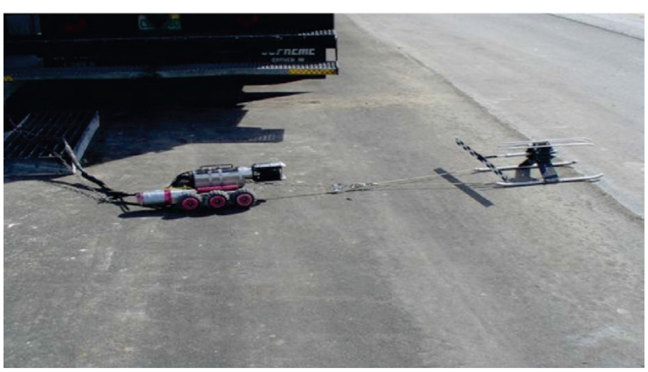

FIGURE 35 Laser profiler and CCTV used in tandem for pipe inspections.

- Visual inspection performed manually (usually for larger-diameter pipes, typically greater than 36 in.)
- Visual inspection performed remotely by video inspection using closed-circuit television (CCTV)
- Mandrel testing
- Laser profiling (forthcoming ASTM F36 method)
- Nondestructive inspection/testing (NDI/NDT) techniques.

Across state agencies, post-installation inspection requirements for pipe systems vary more significantly than practices for the other stages of inspection. 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 help to deliver more consistent and predictable pipe performance and service life.

POST-INSTALLATION INSPECTION TECHNIQUES

Post-installation inspections can be broadly categorized into three main groups: visual inspection, installation deflection testing, and joint inspection.

Visual Inspection

Visual inspections are typically performed using one of the following techniques:

- Manual pipe entry (for larger pipe diameters)
- Video testing (using CCTV)
- Optical scanning (obtaining a full circumferential optical scan of the pipe interior)
- Laser profiling (combined visual and deflection testing technique, available in 2D and 3D).

Installation Deflection Testing

Confirmation that the original shape of the pipe is not distorted beyond an acceptable tolerance level (referred to as "ovalisation" in a circular pipe) is used as a key indicator of post-installation quality. Inspection of post-installation deflection is typically conducted no sooner than 30 days following installation [as per the LRFD Bridge Construction Specifications (AASHTO 2010)] and is typically performed using one of the following techniques:

- Mandrel testing
- Physical survey (manual entry into pipe, measurement of diameter using rod or tape)
- Laser profiling (combined visual and deflection testing technique).

Mandrels are devices that are pulled through the pipe to determine if the deflection is acceptable. They do not provide quantitative information. Installation deflection testing performed by mandrel can typically identify only the first occurrence of excessive deflection, because a test mandrel cannot be pulled past sections failing the deflection criteria.

When possible, either laser profiling or physical surveys (in the case of larger-diameter pipes) are preferred because they provide more quantitative and complete information, potentially allowing any required repairs to be completed more efficiently. Since laser profiling is usually performed in conjunction with video, the engineer can inspect the nature of the nonconformance.

Additional information on the physical survey requirements can be found in the LRFD Bridge Construction Specifications (AASHTO 2010).

Joint Inspection

Joint inspection typically occurs after installation and involves one of the following techniques:

- Manual pipe entry (for larger-diameter pipes)
- Video recording (using CCTV)
- Laser profiling (combined visual and deflection testing technique)
- Joint leak testing (typically not conducted for highway drainage systems, although leaking joints can be identified from video inspection).

NCHRP Web-Only Document 190: Structural Design Requirements for Culvert Joints (Moore et al. 2012) reports that movements during culvert installation are typically significantly larger than movements measured during any of the surface loading tests examined in the field. As such, installation plays an important role in creating permanent deformations in pipes and in causing such potential problems as leakage at the joints. In addition, soil stiffness increases after years of service and this leads to substantial reductions in incremental response under repeated vehicle loads. The main concern with open joints is the potential either for backfill fines to enter the pipe or for water to flow outside the pipe, both of which can lead to the formation of voids along the outside of a pipe and a reduction of structural support for the pipe overall.

AASHTO LRFD BRIDGE CONSTRUCTION SPECIFICATIONS

Standard post-installation inspection recommendations are found in the following sections of the LRFD Bridge Construction Specifications (AASHTO 2010):

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

AASHTO Visual Inspection Recommendations for Flexible Pipe Systems

The recommended inspections for flexible pipe system installations include checks for:

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

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.

OTHER INSPECTION TECHNIQUES

A wide range of other, less commonly used culvert inspection techniques are available, including:

- Destructive core sampling and evaluation
- Ground-penetrating radar (applied from ground surface and from within pipes)
- Impact echo testing
- Infrared thermography
- Mechanical impedance testing
- Microdeflection testing
- Natural frequency measurement
- Pigs (basic mandrels through Instrumented “Smart” Pigs)
- Spectral analysis of surface waves
- Ultrasonic testing
- Ultra-wideband radar.

SUMMARY OF INSPECTION TECHNIQUES

Two ongoing NCHRP projects—14-19, *Culvert Rehabilitation to Maximize Service Life while Minimizing Direct*

TABLE 11
METHODS OF CULVERT INSPECTION

Technique	Culvert Type	Flow in Pipe	The inspection will find:
Visual inspection of man-entry culverts	Any culvert type	No	Visible surface defects and defective joints; also, pipe misalignment, shape, or uniformity of curvature with additional field measurements
Pigs	Any culvert type	Not important	Pipe-shape deformations over allowed tolerances
CCTV	Any culvert type	No	Visible surface cracks, deformation, defective joints, stains from corrosion, shape distortion
Optical scanning	Any culvert type, preferably not corrugated	No	Visible surface cracks, deformation, defective joints, stains from corrosion, shape distortion
Laser profiling	Any culvert type	No	Ovality, alignment, diameter; also, defects such as surface cracks, corrosion of pipe inner surface, deposits
Impact-echo	Concrete culvert	No	Pipe-wall thickness, delamination conditions within reinforced concrete pipe
Spectral analysis of surface waves	Concrete culvert	No	Conditions inside the concrete pipe and soil conditions (density, voids) outside of the pipe
Mechanical impedance	Any culvert type	No	Soil conditions outside of the pipe (voids or over-compaction in the soil around culvert)
Natural frequency		No	Changes in overall pipe condition over time
Microdeflection	Concrete culvert	Yes	Damaged areas in pipe wall
Ultrasonic, pipes empty	Any culvert type	No	
Ultrasonic, pipes full	Any culvert type	Yes	Pipe surface conditions and anomalies, deposits
Infrared	Any culvert type	Not important	Soil conditions outside of the pipe (voids, leakage from pipes)
Ground penetrating radar (GPS) from surface	Any culvert type	Not important	Soil conditions outside of the pipe (location, depth of voids)
GPR, from pipe	Any nonconductive culvert type	No	Defects behind liners

Source: NCHRP 14-19 (2010).

Costs and Traffic Disruption, and 14-26, *Culvert and Storm Drain System Inspection Manual*—are proposed to provide updated summaries of culvert inspection techniques.

The interim draft literature review summary report for NCHRP (2010) Project 14-19 provides an excellent summary (Table 11) of techniques for culvert inspection, outlining their applicability (culvert pipe type and flow) and ability to find defects.

SUMMARY OF CURRENT INSPECTION PRACTICES

The following observations were made based on the results of the NCHRP 10-86 survey completed in 2012:

- 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.

In recent decades, the procedures for conducting and documenting highway culvert condition surveys have benefited tremendously from significant improvements in inspection technologies. Most notably, improvements in CCTV, remote control robotics, laser profiling, optical scanning, and other remote techniques make inline 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 and post-installation, and for long-term monitoring and inventory management.

Inspector training is provided by the National Association of Sewer Service Companies, and a number of DOTs have developed their own training courses, including Florida and Ohio DOTs.

CHAPTER SEVEN

LIFE-CYCLE COST ANALYSIS

Life-cycle cost analysis (LCCA) is an accepted procedure in infrastructure design to compare alternative strategies for providing a specific product over a relatively long period of time. The overall objective of LCCA is to identify the most effective long-term value alternative to the facility owner.

LCCA anticipates all the costs an installation is likely to incur over its lifetime and provides a means for the efficient use of construction and maintenance funds. The comparison of alternative strategies is based on the total cost over the designated analysis period, including initial construction costs, maintenance costs, rehabilitation costs, and disposal costs at the end of the analysis period, if applicable. Indirect costs, such as detour costs to users, accidents, and damage to other areas during the period of repair or replacement, can also be accounted for. Because the analysis periods are usually relatively long and since expenditures can be incurred at any point within the analysis period, all expenditures are adjusted to present-day costs using a discount rate.

The analysis period is frequently estimated as the design service life of a culvert installation, but a different time period could be used. Alternative analysis periods include the expected survival time of the pipe alternative that would need the earliest rehabilitation or replacement, the alternative that would have the longest service life, the period of time for which increased capacity is expected to be needed, or any other period consistent with the physical or economic constraints of the owner agency.

It must also be noted that uncertainty in service life predictions, future event forecasting, appropriate discount rates, and future inflation rates can lead to considerable uncertainty in the estimated present-day costs of alternatives.

The current survey of U.S. states and Canadian provinces shows 21 of 48 responding agencies completing life-cycle costing on some projects, which is a substantial increase of the Perrin and Jhaveri (2004) survey result showing only three of 25 responding agencies applying some sort of LCCA to highway drainage pipes. The Perrin and Jhaveri study developed a methodology to compute the total cost of installing a culvert over a given design life, usually 100 years. The method takes the total cost as the sum of the installation or replacement cost and user-delay cost (resulting from the high frequency of post-failure emergency repairs observed to occur from their surveys). Several culvert failures were reviewed to illustrate various costs (normal and emergency replacement costs, user delay costs, etc.) and demonstrate how longer life would result in significant cost savings in the long run.

New York State DOT is considering the use of a ranking metric—"the performance indicator"—for culvert screening and prioritizing needs. This indicator calculates items directly related to the condition of the culvert as well as elements from the channel rating, thus including a risk element (risks associated with large culverts can be safety risks, for example, structural collapses or sinkholes, or operational risks, for example, roads overtopping during storm events, inundation of upstream facilities resulting from backwater effects). For evaluating the system management performance, tracking of the investment metric with the average condition rating is proposed, so that relative tends over time would indicate the effectiveness of capital investment.

Life-cycle costing may remain limited until reliable data on maintenance costs incurred from traditional and life-cycle cost projects become available. The significant increase in the use of culvert rehabilitation and repair techniques as opposed to culvert replacements will provide an opportunity for these data to be compiled in the coming decade.

CHAPTER EIGHT

CONCLUSIONS

This chapter summarizes the key findings of this study, including the state of the practice for the required service life for culverts in varying conditions, the basis for determining the service life, the range of processes that cause culverts to deteriorate and how they are controlled, the time for a particular material to reach the end of its useful service life, methods to allow the useful service life of culverts to be extended, and information on how the concepts of material service life and culvert failure limit states are correlated.

This chapter also identifies gaps in current knowledge and implementation, and research needs.

SUMMARY OF KEY FINDINGS

Loss of Service Life Mechanisms

Corrosion is the most commonly considered mechanism when predicting the rate of loss of service life of concrete and metal drainage pipes. The mechanisms of corrosion have been extensively studied and the causation factors are reasonably well defined for metal pipes. With reinforced concrete pipes, while the loss of serviceability mechanisms are understood, how and when they lead to a critical loss of pipe serviceability are less well defined. Abrasion is also considered in predicting rates of pipe degradation, but not to the same extent as corrosion as fewer, more geographically localized methods are available. The combined effects of corrosion and abrasion are generally not adequately considered.

Mechanisms relating to the degradation of joints are also not often considered in practice, but research efforts in this area and toward this end are under way, and would be helpful to advance the state of knowledge and practice. The use of various coatings and treatments act to delay the onset of the critical mechanisms leading to the loss of service life of the host pipe product. However, the coatings' deterioration relate not only to the breakdown of the coating itself but also to how well it is bonded to the host pipe. The loss of service life mechanisms of thermoplastic pipes is not as well understood. Deterioration mechanisms such as slow crack growth and ultraviolet light–induced degradation have been studied, but how they may lead to loss of service life in the field is not understood.

In general, loss of serviceability is defined in terms of some degree of physical degradation of the pipe material that can be identified by inspection or testing. However, these definitions are somewhat arbitrary (e.g., time to first perforation) and are not correlated with their effect on structural capacity or when they may lead to total collapse of the pipe system. No methods exist to predict when voids may develop along the outside of a pipe or under a pipe, or under what circumstances that could lead to catastrophic sinkhole formation.

Service Life Prediction Methods and Models

The majority of the available service life prediction models for concrete pipes are largely empirical and not directly related to the physical mechanisms of degradation or when such degradation reaches a critical point. These methods also have not been recently updated or developed, and they focus predominantly on corrosion and do not consider other degradation mechanisms or joint performance. The use of culvert maintenance data to calibrate these methods to agency-specific conditions could be investigated.

A range of methods exist for predicting the service life of metal pipes, and these methods are variations of a single well-established method. The corrosion rates for metal pipes are probably the best defined since there has been a long history of applied research and the prediction models have been correlated with numerous field-performance studies. The service life prediction models have been particularly useful in identifying where certain metal pipe types are unsuitable and where upgraded coatings are needed. Recent research has shown that the basic corrosion models can be calibrated to agency-specific data with minor modifications. Other than for type 2 aluminized coatings, the add-on service life of most coatings and treatments are assigned somewhat arbitrarily.

Predictive models for thermoplastic pipes have not yet been developed; however, research is being performed with these pipe materials. Reliable predictive models for joints, and for rehabilitation and repair methods, are not available.

Correlations Between Service Life Degradation and Pipe Failure Modes

Recent research has addressed some of the links between joint failure and service life degradation, but this area needs additional research. The time to reach a defined level of section loss by corrosion in metal pipes can be predicted, but this definition of loss of serviceability does not explicitly address a critical pipe failure mode. With limited maintenance budgets, it may not be practical to use a very conservative definition of loss of serviceability as the trigger for major pipe rehabilitation intervention.

DOTs have done significant work in developing comprehensive pipe condition rating systems, which take into account a broad range of distress types and severities. It is the combination, severity, and extent of certain distresses that defines the overall pipe system condition. Thus, the challenge is to enhance the current pipe service prediction models to cater for these more realistic definitions of pipe condition and end of service life.

Caution must be applied when evaluating new pipe material types with existing models or failure modes because current failure modes may not apply to newer pipe materials, which can have quite complex modes of failure. For example, it may be inadequate to consider only existing knowledge of HDPE pipe failure modes for steel reinforced high-density polyethylene pipes, given the differences in the structural performance and deflection mechanisms.

A further limitation on the current models for predicting service life is their inability to account for variations in pipe material quality, installation quality, and the degree to which post-installation verification will be carried out.

Effect of Regional Initiatives and Federal Policies

Research efforts encompassing multiple agencies and a wide variety of conditions would assist in the development of service life prediction models with broad applicability and acceptance. State-specific research understandably tends to address the needs of the sponsoring state agency, but can limit the extent to which the research is applied outside of that state. Broader collaboration between agencies, initially between those with similar concerns or environmental conditions, is suggested in order to accelerate the improvement of service life estimates.

MAP-21, Moving Ahead for Progress in the 21st Century, encourages state DOTs to extend their asset management efforts beyond pavement and bridges to include ancillary structures through the use of risk-based asset management plans. A recent FHWA study (FHWA 2014) presents a series of culvert management case studies. In the case of Ohio DOT, the collapse of a culvert on Interstate 480 in 2001 (Figure 36) facilitated the launch of a statewide culvert management program. Fortunately, a district staff member noted a small dip in the pavement, which on investigation revealed that the traffic was being supported solely by the concrete pavement spanning the large void.

FIGURE 36 Failed culvert under I-480 in 2001 (FHWA 2014).

As part of the questionnaire responses for this synthesis, another agency reported the collapse of a 30-in.-diameter RCP under 18 ft of fill near an urban intersection (Figure 37). It caused a sinkhole about 20 ft in diameter in a major roadway. The pipe was believed to be 30 years old.

FIGURE 37 Emergency repairs following collapse of 30-in.-diameter culvert near busy intersection.

These and similar pipe failures highlight the need for both better pipe system service life prediction methods and better understanding of failure mechanisms (Figure 38). They also demonstrate the need for pipe asset inventory systems that can provide early warning of potential problems and feed into improvements in service life prediction models. In conjunction with a pro-active, ongoing inspection program, Ohio DOT now has in its inventory about 79,000 culverts and storm drains less than 10 ft in diameter.

Case studies of seven culvert failures were presented at the 2004 Transportation Research Board Meeting (Perrin and Jhaveri 2004). The pipes were reported to be from 25 to 60 years old at the time of failure. One of the recommendations from that paper was to set up a national database where culvert failures are documented using a "culvert accident

FIGURE 38 Failure of road embankment slope above a 12-ft-diameter structural plate corrugated steel culvert that had been extended at both ends. Perforation along bolt lines and 18-in. deflection at obvert of pipe.

report" form. In one of the case studies, it was noted that whereas the actual cost of emergency repair was more than $4 million, when user-delay costs were factored in, the cost exceeded $8 million.

SUMMARY OF KNOWLEDGE GAPS

Knowledge gaps constitute areas where the state of knowledge has not reached maturity or where consensus has not been reached about the appropriate approach to a given design problem or an evaluation of a particular aspect of performance. To date, the following critical knowledge gaps that affect evaluation of culvert system service life have been identified:

- Fundamental Pipe Failure Models—Although culvert research is an active area and progress has been made in understanding pipe deterioration mechanisms, still no comprehensive deterioration models have been developed that consider the combined effects of all critical parameters for the major pipe types and define when end of service life occurs or when total failure will occur.
- Design Service Life—Standard (universal) and objective guidelines for defining service life requirements for various drainage pipe system applications are not defined by AASHTO.
- 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., LRFD Bridge Design Specifications, Chapter 12 (AASHTO 2013)] are well accepted as appropriate. However, the methodologies and procedures to estimate durability and service life of culverts are not as mature and do not cover all of the material types in use.

Fundamental Pipe Failure Models

This report provides an overview of the current state of knowledge with respect to deterioration mechanisms of various pipe types under a range of field conditions and applications. The current service prediction models are generally based on a selected end-of-service-life indicator and only consider one distress mode, typically corrosion, to predict expected service life. Where combined abrasion and corrosion are present, the model no longer applies. Thus, to prolong service life resulting from corrosion, coatings can be considered; however, at what stage is invert paving required and what are the economics of selecting various invert paving options? The current deterioration models, while providing broad guidance on pipe type suitability, are not sufficiently developed to allow a meaningful comparison of alternatives.

A further limitation is the inability to relate a defined end-of-service-life indicator to the ultimate failure of the pipe system. For example, how much time is available between the first perforation of a metal pipe and the risk of complete pipe failure? This type of information would allow agency engineers to decide whether a deteriorated pipe can be left in place for a further 5 years until road rehabilitation is required. Clearly, deferral of pipe rehabilitation to coincide with road rehabilitation can be cost-effective, provided the risk can be managed.

Ideally, pipe deterioration models need to be able to model the progressive loss of pipe condition from installation to final failure. With this type of model, it would be possible to evaluate the cost-effectiveness of maintenance activities, rehabilitation options, and full pipe replacement, and assist in establishing when these interventions are needed.

Such a deterioration model would have to consider the potential for changes in system material properties (pipes and surrounding materials) over time (durability) because these changes affect all aspects of drainage system performance. The process is further complicated in practice because most prediction models assume the pipe system is correctly installed and are invalidated if this is not the case. Ideally, a deterioration model could have some optional risk factors defined related to installation quality. One reason most pipe protective coatings are given very conservative add-on lives is the concern about damage to the coating during installation. If this risk could be properly quantified, then the cost-effectiveness of protective coatings would be better demonstrated.

The knowledge gaps related to pipe durability are well known and reported in a wide range of reference documents including MTO (2007) and *NCHRP Synthesis 254* (1998), and significant ongoing research being conducted at universities, within state DOTs, and by pipe manufacturers and trade associations aims to improve understanding of this subject. To date, the significant research progress that has been made over the past 15 years in understanding the various deterioration mechanisms for a range of pipe types has yet to be incorporated into improving the overall pipe deterioration models. Although this research has improved pipe material selection methods and refined pipe material specifications, it is yet to be integrated into a more comprehensive model of pipe failure mechanisms. A lack of comprehensive failure models exists for all pipe types, although metal and concrete pipes have initial limited working models. However, with the continuing growth of new pipe products, especially those involving composite materials, and the rapid increase in the use of trenchless technologies for pipe rehabilitation, significant research and development work still needs to be done.

Design Service Life

Establishing the life expectancy at a minimum required level of service for a pipe system is a basic necessity to allow a comparison of alternative pipe systems at the design stage. Although some DOTs and industry have guidelines on defining design service life for various highway applications, a standard approach for this process does not exist. On a simple level, most agencies relate design service life 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 highway detour, the design service life may need to be increased irrespective of the road classification. The authors are not aware that any comprehensive life-cycle costing studies have been done on the differential between a 25-year pipe design and a 75-year pipe design. The study by Perrin and Jhaveri (2004) provides the most thorough analysis; it indicates that longer design service life requirements will likely result in overall savings.

With in situ rehabilitation technologies becoming almost routine for many DOTs, the notion of initial pipe design service life becomes less rigid and enhanced life-cycle costing tools could play a bigger part in helping agencies get the best value for money in terms of drainage infrastructure investments.

Time-Dependent Performance Data

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

For newer pipe products and systems, the lack of both evaluation and unbiased compilation of performance data leads to the exclusion of newer pipe products in some jurisdictions. The need for continued and additional studies to collect and analyze drainage system performance data is well established. As more DOTs adopt comprehensive drainage pipe inventory and condition rating systems, the source data for a greater understanding of pipe performance through its life cycle becomes available.

Pipe Joints

The performance of many joint systems is strongly dependent on the quality of installation (i.e., proper versus improper installation), and the performance of improperly installed joints is in general not well documented or quantifiable. Instances where joint performance data 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) related to pipe joints. Joints can affect the pipe system's hydraulic and structural performance through leaks that can degrade or erode bedding and embedment materials. Infiltration of soil particles into pipes can also increase abrasion. Objective data are needed on the relative merits of alternative joint types and how they impact overall pipe performance and service life.

RESEARCH NEEDS

Based on the literature reviews, additional research into durability and the development of additional durability evaluation models would benefit the practice. Future research on durability evaluation models would benefit from the following:

- Develop a more global fundamental understanding of overall pipe deterioration and failure mechanisms that includes all contributions to deterioration as well as combined and consequential effects.
  - Develop models that account for the combined and coupled effects of corrosion and abrasion (not simply additive).
  - Develop models that account for the combined and coupled effects of structural loading–induced pipe stress with respect to corrosion.
- Investigate the relative importance of soil-side corrosion compared with water-side corrosion in predicting pipe failure owing to corrosion.
- Use recognized and measurable engineering parameters in the development of future models.
- Develop statistical and probabilistic models and include variations in construction quality.
- Estimate the accuracy of the existing models and work toward defining the accuracy of new models.
- Use predictive models to back-analyze pipe failures and suggest modifications to the regression equations.
- Use the results of actual pipe condition survey data to improve understanding of deterioration throughout the complete pipe life cycle.
- Conduct a cost-benefit study that quantifies the effect of increasing the frequency and extent of performing post-installation inspections.
- Conduct additional research on developing structural and durability design methods for in situ pipe rehabilitation technologies.
- Analyze the costs associated with waiting until failure to replace a pipe, rather than replacing a pipe at the end of a defined service life, prior to the risk of emergency replacement.
- Develop material abrasion prediction models based on the physical mechanisms of abrasion on different materials.
- Develop best-practice guidelines for environmental sampling of soil and water to obtain representative values for use in culvert durability assessment. In particular, the timing (summer, winter, etc.), number, and location of sampling should be addressed.
- Investigate the use of, and augmentation of, existing maps of environmental parameters (from the Natural Resources Conservation Service or similar organizations) in culvert durability assessments.
- Investigate the mechanisms of joint separation in concrete pipes, especially how the freeze-thaw process affects joints.

In addition to the development of more and improved durability evaluation methods and models, the continued collection and evaluation of field performance data and case histories will provide significant benefits to the accurate prediction and evaluation of durability during design. Increasing the database of available field performance data will be especially critical for new products and those with shorter service life histories than for more established pipe products.

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APPENDIX A

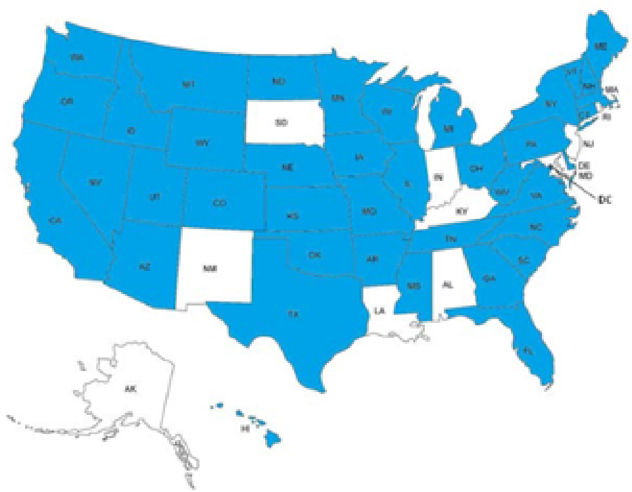
State of the Practice Survey Results

APPENDIX A

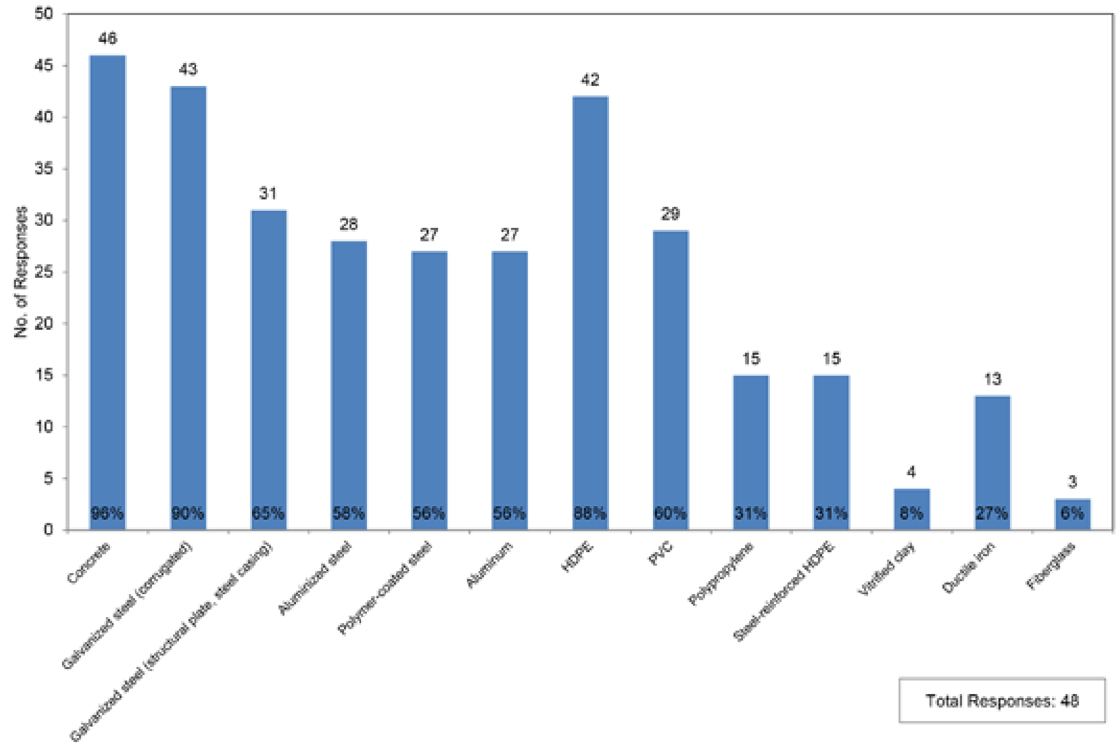
SERVICE LIFE OF CULVERTS STATE OF THE PRACTICE SURVEY

1.0 SYNTHESIS OF THE STATE OF THE PRACTICE

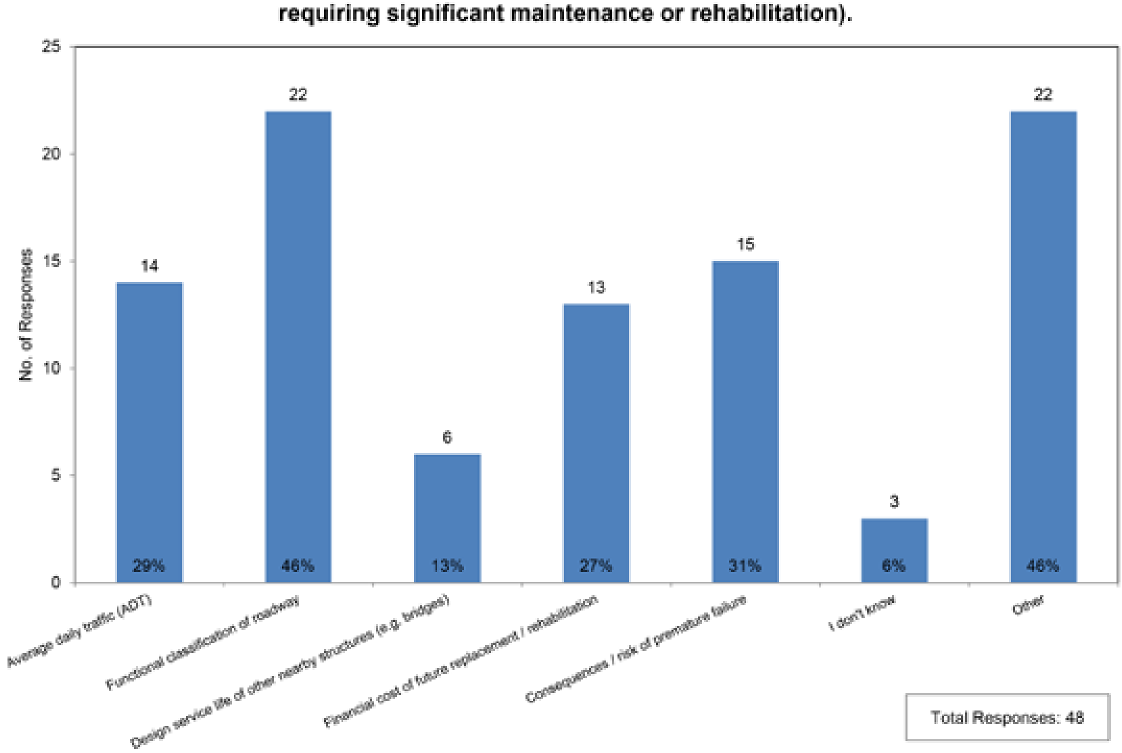
This Appendix provides the results of the survey of North American transportation agencies regarding the service life of culverts, performed from March through July 2014. The survey results are presented in bar charts followed by summary tables of manually entered additional information. Through 09 July 2014, 48 complete survey responses were received, with 41 from agencies based in the United States, and 7 from agencies based in Canada as shown in the shading of the following maps.



Q1: Which of the following pipe material types does your agency currently use, or is considering for use?



Q2: What basis does your agency use to determine the design service life of a culvert? (i.e. the desired number of years a culvert must be in service prior to requiring significant maintenance or rehabilitation).



Q2: What basis does your agency use to determine the design service life of a culvert? (i.e. the desired number of years a culvert must be in service prior to requiring significant maintenance or rehabilitation).

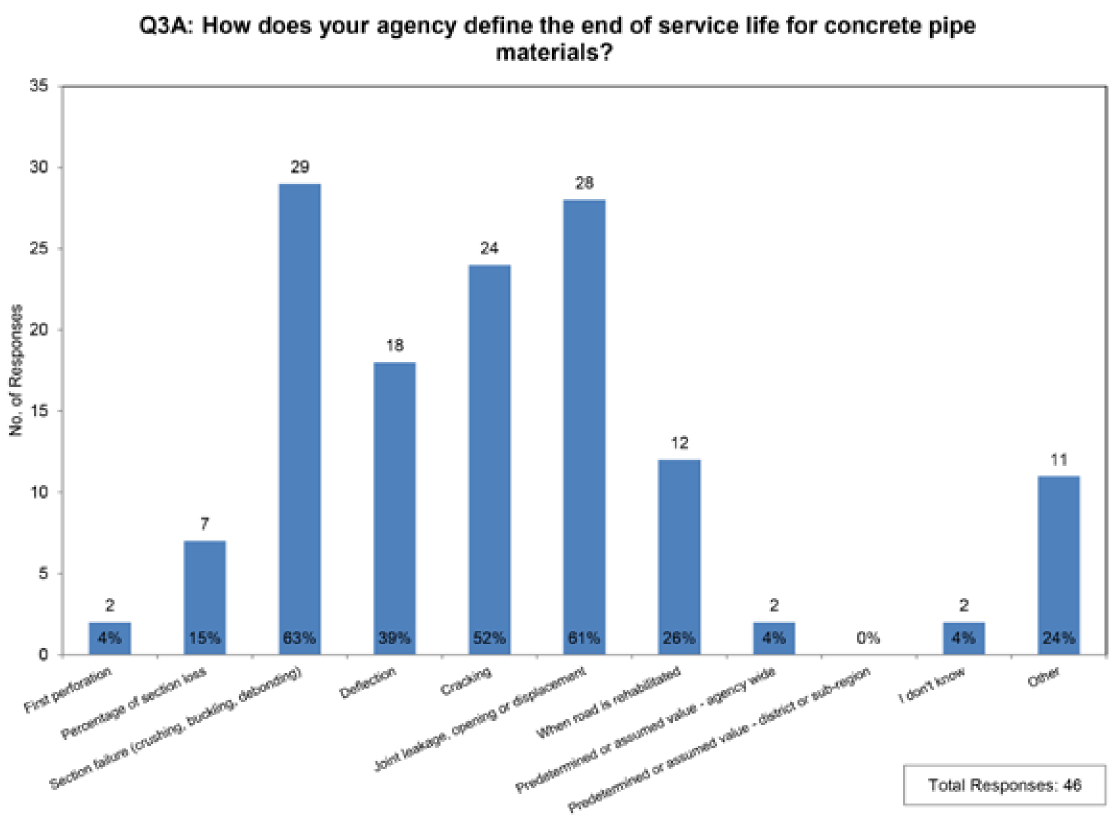
Responding Agency	Additional Information Provided by the Responder
Arkansas	The higher the classification of roadway, the longer the anticipated service life of the pipe culver material. Concrete is used on Interstates, corrugated metal is only used on secondary roads.
California	Predetermined number.
Colorado	Other: 50 year design life
Delaware	For more information: http://www.deldot.gov/information/pubs_forms/manuals/dgm/pdf/1-20_revised_pipe_materials.pdf
District of Columbia	For culverts under local roadways, a culvert is replaced only a major collapse has occurred and most are over 40 years old. For Federal Road, the culverts are replaced based on the Reconstruction of that roadway or the hydraulic capacity and safety.
Florida	Other: water and soil environmental parameters. See our optional pipe handbook. (FDOT)
Idaho	Other: Pipe Manufacturer Data
Illinois	Other: AASHTO
Kansas	Other: KDOT Pipe Policy
Maine	Other: roadway cross pipes are 50 year design life, entrance way pipes are 25 years. We just developed a policy that mandates RCP only on Interstate and other high priority roadways.
Michigan	Other: Input from industry reports, historical data and experience.
Minnesota	Other: Drainage Manual and Experience. MnDOT Drainage Manual Guidance : Pipe for culverts shall be selected on the basis of the type which best fulfills all of the engineering requirements for a specific installation. Factors to be considered in fulfilling the engineering requirements should be hydraulic performance, structural stability, serviceability, and economy.
Missouri	We have some guidance related to AADT and functional class, but a primary consideration is fill height, which relates to consequences of failure.
Montana	Other: detour length, evacuation routes.
New Brunswick	Other: Canadian Highway Bridge Design Code. Principally, long service is considered. Capacity for rare large discharges and debris are equally important.
New Hampshire	Class of roadway may dictate service life but cost plays a role.
New York	Design life is assigned by location, Initial cost, cost to rehab or replace, disruption to traffic during rehab. Or replace.

Q2: What basis does your agency use to determine the design service life of a culvert? (i.e. the desired number of years a culvert must be in service prior to requiring significant maintenance or rehabilitation).

Responding Agency	Additional Information Provided by the Responder
North Carolina	Other: Agency does not estimate service life of culverts.
Ohio	Other: Height of Cover. We use a minimum service life of 50 years for all culverts. We use a service life of 75 years if the fill height is 16 feet or greater or if the conduit is on a freeway.
Ontario	Other: Site specific considerations. Lower DSL may be suitable for sites that would have easy non-disruptive replacement characteristics (i.e. entrance culverts may have minimal disruption to traffic flow) selected DSL to coincide with future capital construction projects (i.e. assign DSL of 30 years if major reconstruction of highway is to occur in 25 years or so).
Prince Edward Island	Other: Code requirements. Canadian Highway Bridge Design Code (CHBDC) requires a design life of 75 years.
Saskatchewan	The Ministry does not have a standard for this. We have used the above criteria on an adhoc project basis. We are currently looking at establishing a standard. We do not have any responsiblilty within urban areas so we just deal with rural highway culverts.
South Carolina	Other: Design Life not evaluated. Pipe is not assumed to have a fixed expiration date. Inspection, rehab, and repair options may be considered on a case by case basis prior to replacement.
Tennessee	Other: No guidelines at this time
Utah	Other: We do not proactively predict service life. Our current replacement strategy is based on observed failure of installations. It fails, we repair or replace. We are currently going through a culvert inventory and condition assessment process to move to risk of failure/service life model. Our biggest impediment is lack of accurate installation dates. We have some wooden culverts 60 years old that are in excellent condition and other culverts that have failed in ten years.
Vermont	Other: Capitol Projects. The Agency depends less on design service life for culvert replacement and more on coincidental capital projects to limit the effect of culvert replacement on high quality pavement highway sections and capitalize on mobilization.
Virginia	We have a Standard that shows what pipe types are allowed under basically all VDOT roads, ADT >4000; subdivision and smaller roads allow more pipe types. The assumption is >4000 ADT is 75 yr life, <4000 ADT is 50 yr life.

Q2: What basis does your agency use to determine the design service life of a culvert? (i.e. the desired number of years a culvert must be in service prior to requiring significant maintenance or rehabilitation).

Responding Agency	Additional Information Provided by the Responder
Washington	Other: We require a 50 service life for all our culverts and have many tool to help achieve this. Fill height tables, corrosion zone restrictions, flowcharts to aid designers in knowing when treatments are needed on steel pipes, or when alternate pipe materials should be used.
Wisconsin	Other: Durability of material at site conditions. ADT is a factor on low-fill culverts - we require a stronger culvert, but inspection of the culvert determines maintenance or rehab. Standards are based on expected service life of material, location (durability when subjected to corrosive or abrasive site conditions.)
Wyoming	Other: CR analysis. Soil and water samples taken at pipe locations are tested for resistivity, pH, and sulfates. Based on the test results, a CR (corrosion rating) is determined for the culvert location. A CR table was developed to choose the correct type of pipe, coating, bedding, and backfill material for a given CR. The table was based on selecting the appropriate culvert type for a 30 year design life. The table is a summation of multiple sources of historic culvert design/performance information (e.g, CalTrans, Rocky Mountain region, etc.)



Q3A: How does your agency define the end of service life for concrete pipe materials?

Responding Agency	Additional Information Provided by the Responder
Colorado	Predetermined or assumed value - agency wide, Assumed 50 yr service life
Delaware	Condition of pipe is most important. Otherwise, if a capital project is in design, the age of the existing pipe would be considered as well.
Florida	Other: chloride penetration to the reinforcing steel.
Georgia	Other: Inspection results by Area Engineer.
Iowa	Other: unable to maintain road/shoulder/drainage.
Maine	It is generally in some type of failure mode before replaced. Excessive cracking, deterioration, etc.
Michigan	Service life is a case by case basis. MDOT is currently locating and compiling our culvert/sewer assets. During ARRA work drainage was sometimes over looked: out of sight, out of mind. Then the surface was improved but the drainage was not upgraded. With an asset list each proposed upgrade will then be prompted to check all assets at the design phase, including drainage, to determine if that upgrade is needed. Each of these list anomolies above can prompt an upgrade or repair - depending on the severity of the issue and/or the number of differing issues in a pipe run. MDOT is seeking assistance items (apps, documents, brochures) that will assist our inspectors and maintenance personnel in making determinations between upgrade or repairs. The Florida Matrix helps. The Ohio Maintenance Manual has helped. The old 1986 FHWA Culvert Inspection manual has helped; but MDOT needs its own source for our unique soil and water table condidtions. Currently, industry is lobbying for MDOT to change our 'no crack is acceptable in new pipe' policy. MDOT will soon publish a research document on concrete, metal and plastic pipe that has been insitu for up to 20 years. Severity of cracking can determine need for rehabilitation or replacement.

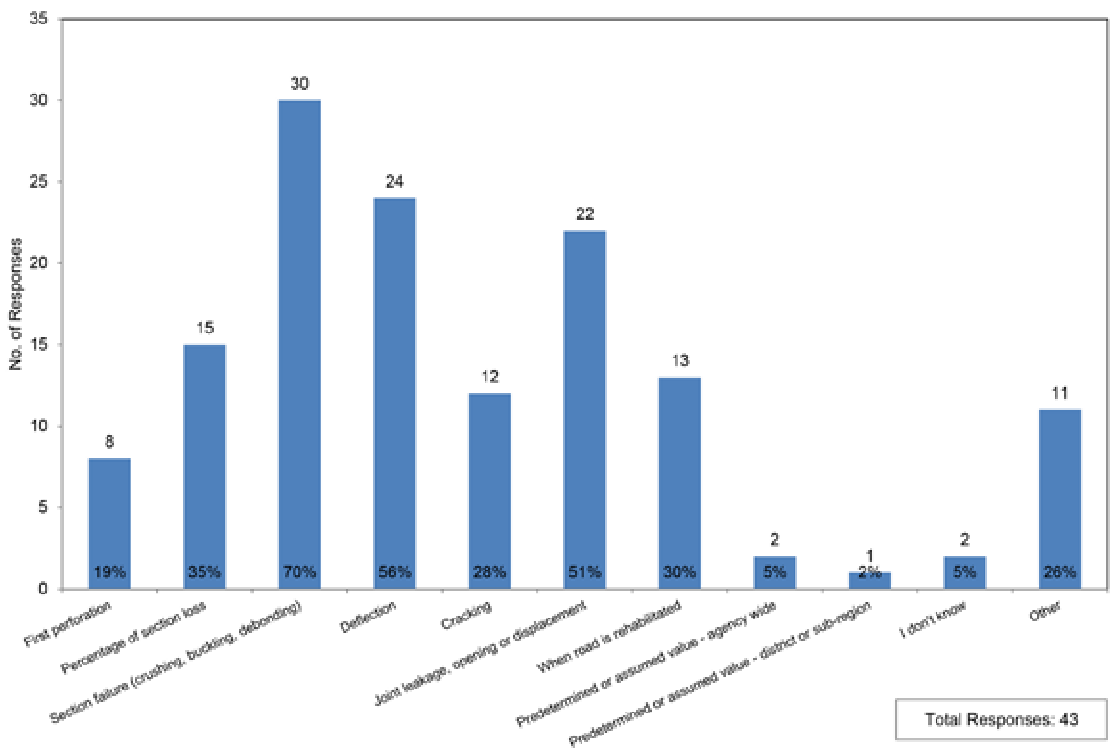
Q3A: How does your agency define the end of service life for concrete pipe materials?

Responding Agency	Additional Information Provided by the Responder
Minnesota	MnDOT has an inspection and inventory database. Pipes rated as very poor are a priority for repair. When a road is rehabilitated poor and very poor pipes are a priority for repair. http://www.dot.state.mn.us/bridge/pdf/hydraulics/HYDINFRA_Culvert_and_Storm_Drainage_System_Inspectio n_Manual.pdf Joint separations are the most common problem with RCP.
Missouri	Multiiple failure components are considered.
Montana	Depending on the scope of work and age of the material when roads are re-built we may extend or use RCP or other materials in place if the condition is adequate. Example: If we are overlaying or doing minor widening we expect and additional service life of 20 years. Generally for project that are 50+ years old we replace all pipes.
New Brunswick	Other: Road Surface Distress. All of the above are used to estimate a condition index for each asset.
New Hampshire	If current failure mode is threatening roadway traffic.
New York	Culverts that no longer function as designed due to deteriorations above can still be repaired. Further deterioration leading to roadway settlement, severe structural deformations, embankement failures, constriction of opening (among other forms of deterioration not mentioned) require replacement.
Ohio	Other: General Appraisal Rating of 2 or less. We use a General Appraisal rating that evaluates the different aspects of the culvert as found in our CR-86 Inspection form. Items that have bold boxes may control the GA value. Action is required when the GA value reaches a value of 4 or less. In many cases, this value may be improved with maintenance activities. We would consider the Service Life to be at end of life when this value is 2 or less. A value of 2 cooresponds to a "critical" issue. If the question relates to the service life for the specific material, then this would be the General rating that evaluates only the material. This value will control the GA value if it is lower than the other controlling items found on the CR-86 form.
Ontario	Other: failure to service future drainage and site needs. Poor pipe condition, insufficent capacity, changing catchment parameters, highway geometric changes are but a few of the considerations used to determine if a concrete pipe has reached the end of its useful service life.

Q3A: How does your agency define the end of service life for concrete pipe materials?

Responding Agency	Additional Information Provided by the Responder
Oregon	Other: ODOT Rating System. Oregon DOT has developed a statewide rating system for culverts that uses groups and individual ratings fields to determine the condition of a culvert.
Prince Edward Island	A structure may not immediately require work; however, if we are reconstructing the road bed above, we will look closely at replacing the structure at that time if it makes sense economically and structurally.
Saskatchewan	The joint criteria is applied in relation to void development due to joints opening due to differential pipe settlement. Pipes are sometimes replacement on road regrading projects based on a need to increase performance or to address pipe alignment issues which would faciltate void development in the embankment.
Utah	When flow stops or sinkholes develop we know the pipe has failed.
Vermont	Section separation often leads to replacement before other deterioration factors
Virginia	Really, it would just be when inspection rating puts the structure rating at 4 or below.
Washington	Other: we are currently establishing a major drainage program to aid our designers in inspection, prioritization and scoping of culverts. We also have a fish passage program to remove culverts that are fish barriers. culverts are also assessed when a roadway project is scheduled for the section of roadway containing the culvert(s).
Wisconsin	We also evaluate pipes when for aquatic organism passage and floodplain issues.
Wyoming	Other: Culverts are periodically reviewed and also analysed on upcoming projects to determine if culverts should be replaced, lined, or extended. These decisions are based on condition, age, and depth of culvert along with current hydrologic needs. The current CR numbers for soils are also considered.

Q3B: How does your agency define the end of service life for corrugated galvanized steel pipe materials?



Q3B: How does your agency define the end of service life for corrugated galvanized steel pipe materials?

Responding Agency	Additional Information Provided by the Responder
Colorado	Predetermined or assumed value - agency wide, Assumed 50 yr service life
Georgia	Other: Inspection results by Area Engineer.
Iowa	Other: unable to maintain road/shoulder/drainage.
Maine	This is primarily a judgement call. Some are easier: invert corrosion through the pipe, crushing or buckling that hinders pipe hydraulically.
Michigan	Please see answer for concrete. Additionally, corrosion of steel pipe will prompt replacement or repairs. MDOT's pipe research covers the aging of metal pipe a bit. For our research MDOT discovered that the metal pipe was, in the installations from 1994, more likely to have been removed due to expansion of business and urban sprawl. This could be due merely to the locations initially studied being closer to populations and rapidly expanding businesses at that time. This experience is not statewide, but was unfortunately a factor for our research.
Minnesota	MnDOT has an inspection and inventory database. Pipes rated as very poor are a priority for repair. When a road is rehabilitated poor and very poor pipes are a priority for repair. http://www.dot.state.mn.us/bridge/pdf/hydraulics/HYDINFRA_Culvert_and_Storm_Drainage_System_Inspectio n_Manual.pdf Joint separations are the most common problem with RCP.
Missouri	Multiple failure components considered, and additional review is typically conducted in advance of road rehab projects in order to effect repairs prior to new pavement.
Montana	Perforation is also considered depending on severity. Also, Depending on the scope of work and age of the material when roads are re-built we may extend or use RCP or other materials in place if the condition is adequate. Example: If we are overlaying or doing minor widening we expect and additional service life of 20 years. Generally for project that are 50+ years old we replace all pipes.
Nevada	In regards to teh roadway rehabilitation: CMP is not installed under mainline facilities, and if the roadway is being rehabilitated, the CMP will be replaced if feasible.

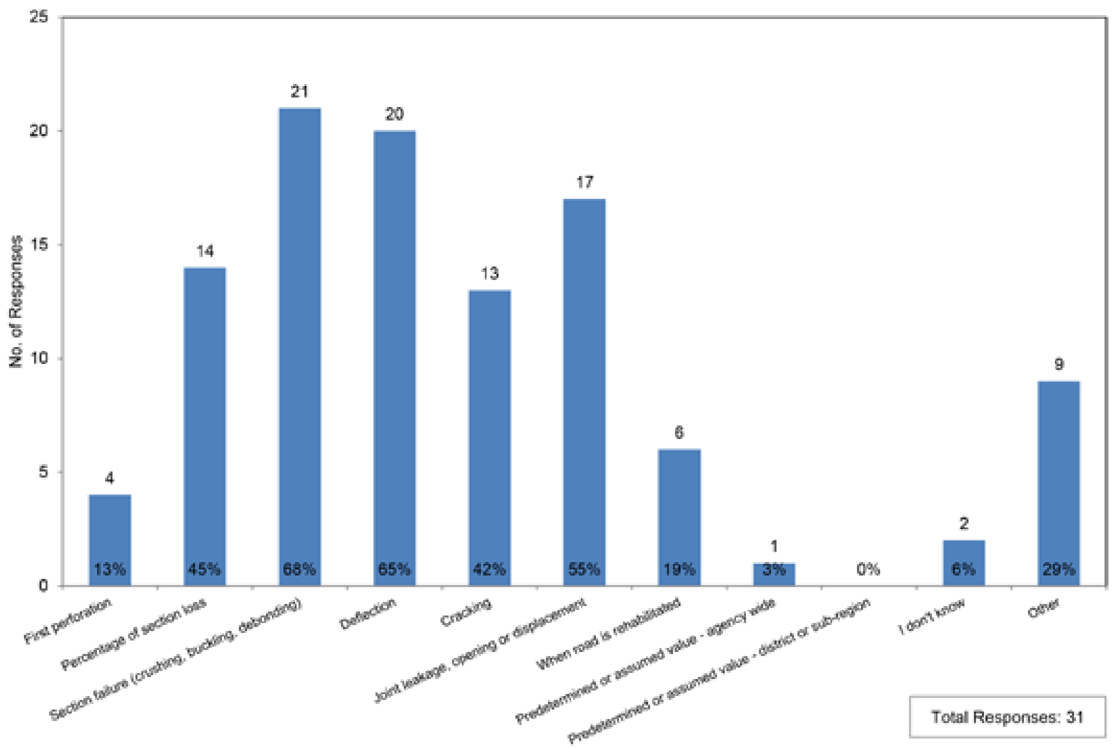
Q3B: How does your agency define the end of service life for corrugated galvanized steel pipe materials?

Responding Agency	Additional Information Provided by the Responder
New Brunswick	Other: Road Surface Distress. All of the above are used to estimate a condition index for each asset.
New York	Steel pipe deterioration of 2-4 mils/year usually leads to invert section loss enough to rehabilitate (invert pave, slipline). 10-18 ga galv steel culverts can last around 30 years depending on location in state.
Ohio	Other: General Appraisal Rating of 2 or less. We use a General Appraisal rating that evaluates the different aspects of the culvert as found in our CR-86 Inspection form. Items that have bold boxes may control the GA value. Action is required when the GA value reaches a value of 4 or less. In many cases, this value may be improved with maintenance activities. We would consider the Service Life to be at end of life when this value is 2 or less. A value of 2 cooresponds to a "critical" issue. If the question relates to the service life for the specific material, then this would be the General rating that evaluates only the material. This value will control the GA value if it is lower than the other controlling items found on the CR-86 form.
Oklahoma	We have areas in the state where the soil aicidity is corrosive to the steel pipe. In those areas, we first find out through survey whether those pipes have parts that have been rusted all the way through the wall (mostly by visual inspection). Then, we replace them with concrete pipes.
Ontario	Other: failure to service future drainage and site needs. Poor pipe condition, insufficent capacity, changing catchment parameters, highway geometric changes are but a few of the considerations used to determine if a concrete pipe has reached the end of its useful service life.
Oregon	Other: ODOT statewide rating system. Oregon DOT has developed a statewide rating system for culverts that uses groups and individual ratings fields to determine the condition of a culvert.
Prince Edward Island	A structure may not immediately require work; however, if we are reconstructing the road bed above, we will look closely at replacing the structure at that time if it makes sense economically and structurally.
Utah	Other: Complete erosion of rusted invert.
Virginia	Really, it would just be when inspection rating puts the structure rating at 4 or below.

Q3B: How does your agency define the end of service life for corrugated galvanized steel pipe materials?

Responding Agency	Additional Information Provided by the Responder
Washington	Other: Culverts will be evaluated using the methodology in the FHWA 'Culvert assessment and decision making procedures manual'. Photo guidance of culvert conditions will aid hydraulic personnel in assessing culvert conditions for rehabilitation or replacement.
Wisconsin	We also evaluate pipes when for aquatic organism passage and floodplain issues.
Wyoming	Other: Culverts are periodically reviewed and also analysed on upcoming projects to determine if culverts should be replaced, lined, or extended. These decisions are based on condition, age, and depth of culvert along with current hydrologic needs. The current CR numbers for soils are also considered.

Q3C: How does your agency define the end of service life for structural plate or steel casing pipe materials made from galvanized steel?

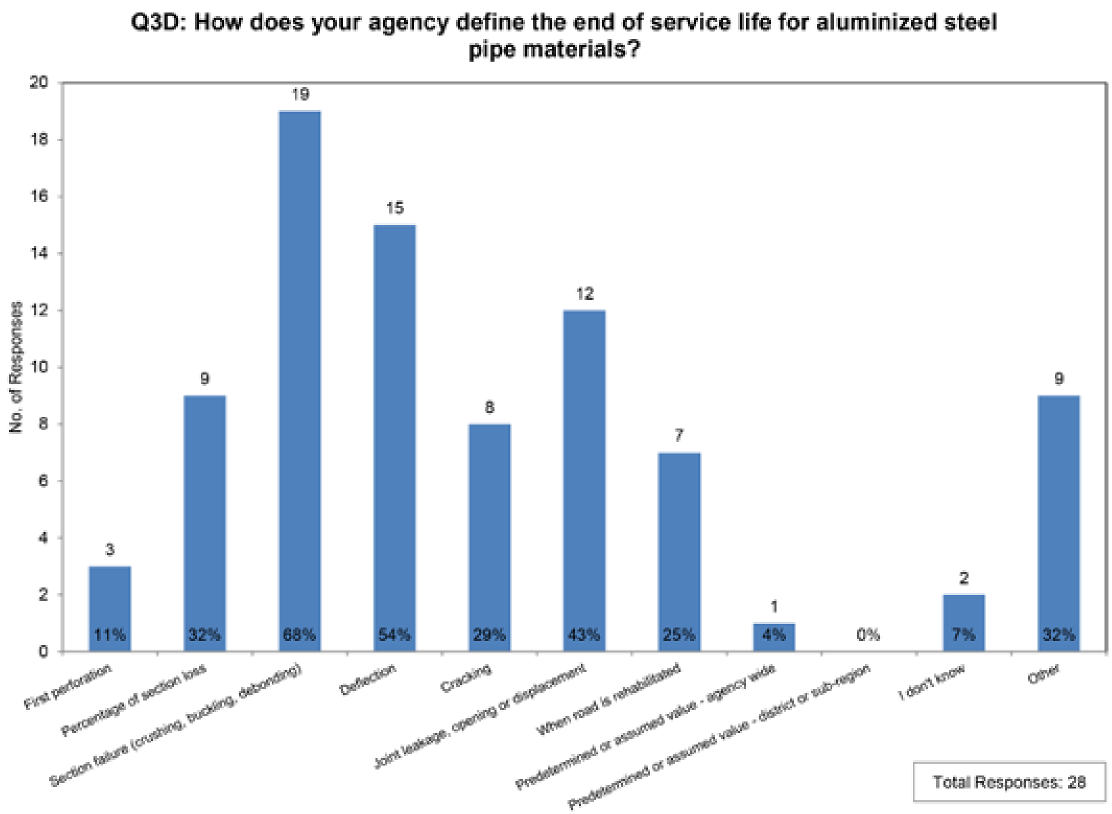


Q3C: How does your agency define the end of service life for structural plate or steel casing pipe materials made from galvanized steel?

Responding Agency	Additional Information Provided by the Responder
Colorado	Predetermined or assumed value - agency wide, Assumed 50 yr service life
Iowa	Other: unable to maintain road/shoulder/drainage.
Maine	This is primarily a judgement call. Some are easier: invert corrosion through the pipe, crushing or buckling that hinders pipe hydraulically.
Michigan	Please see concrete. Each of these items or a combination of the items listed could prompt an upgrade to plate or casing material. Determining need for upgrades is a case by case basis.
Missouri	Similar to others - multiple failure components considered
Montana	Perforation is also considered depending on severity. Also, Depending on the scope of work and age of the material when roads are re-built we may extend or use RCP or other materials in place if the condition is adequate. Example: If we are overlaying or doing minor widening we expect and additional service life of 20 years. Generally for project that are 50+ years old we replace all pipes.
New Brunswick	Other: Road Surface Distress. All of the above are used to estimate a condition index for each asset.
New Hampshire	If current failure mode is threatening roadway traffic.
New York	Again, when the condition of a culvert is reduced to where it no longer functions as designed it should be repaired or replaced.
Ohio	Other: General Appraisal Rating of 2 or less. We use a General Appraisal rating that evaluates the different aspects of the culvert as found in our CR-86 Inspection form. Items that have bold boxes may control the GA value. Action is required when the GA value reaches a value of 4 or less. In many cases, this value may be improved with maintenance activities. We would consider the Service Life to be at end of life when this value is 2 or less. A value of 2 cooresponds to a "critical" issue. If the question relates to the service life for the specific material, then this would be the General rating that evaluates only the material. This value will control the GA value if it is lower than the other controlling items found on the CR-86 form.
Ontario	Other: failure to service future drainage and site needs. Poor pipe condition, insufficent capacity, changing catchment parameters, highway geometric changes are but a few of the considerations used to determine if a concrete pipe has reached the end of its useful service life.

Q3C: How does your agency define the end of service life for structural plate or steel casing pipe materials made from galvanized steel?

Responding Agency	Additional Information Provided by the Responder
Oregon	Other: ODOT statewide rating system. Oregon DOT has developed a statewide rating system for culverts that uses groups and individual ratings fields to determine the condition of a culvert.
Prince Edward Island	A structure may not immediately require work; however, if we are reconstructing the road bed above, we will look closely at replacing the structure at that time if it makes sense economically and structurally.
Saskatchewan	Based on an inspection and review by our Bridge Preservation Engineers.
Utah	Other: Complete erosion of corroded pipe invert.
Virginia	Really, it would just be when inspection rating puts the structure rating at 4 or below.
Washington	Other: Culverts will be evaluated using the methodology in the FHWA 'Culvert assessment and decision making procedures manual'. Photo guidance of culvert conditions will aid hydraulic personnel in assessing culvert conditions for rehabilitation or replacement.
Wisconsin	We also evaluate pipes when for aquatic organism passage and floodplain issues.
Wyoming	Other: Culverts are periodically reviewed and also analysed on upcoming projects to determine if culverts should be replaced, lined, or extended. These decisions are based on condition, age, and depth of culvert along with current hydrologic needs. The current CR numbers for soils are also considered.



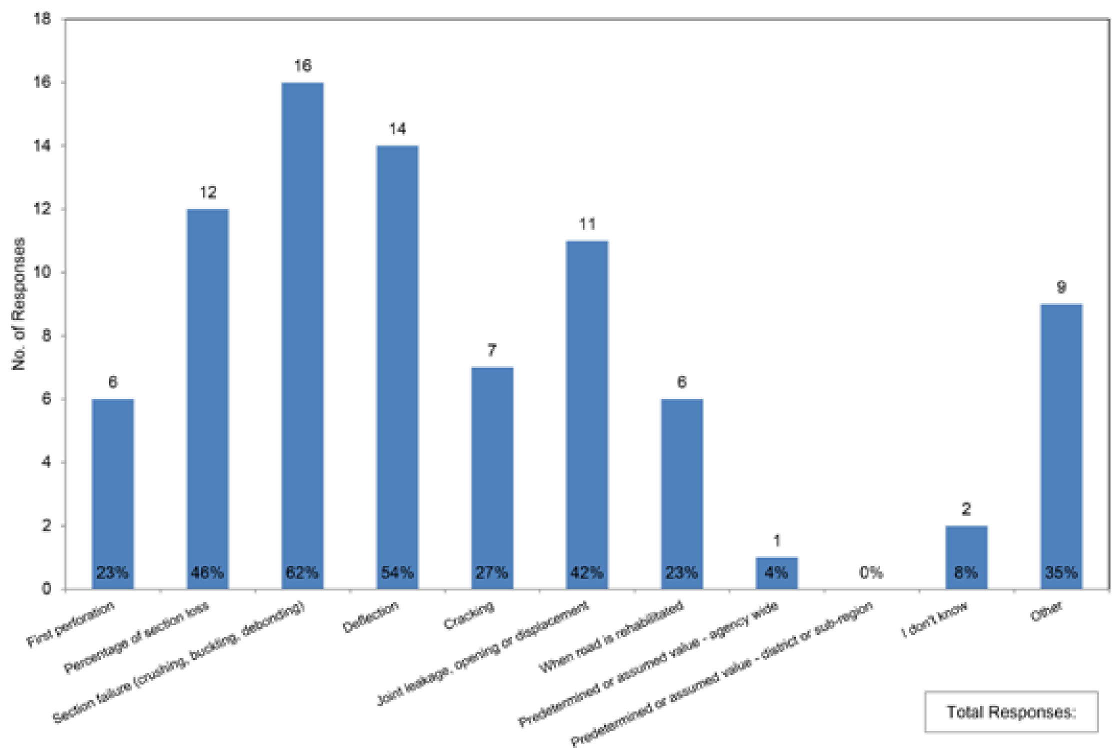
Q3D: How does your agency define the end of service life for aluminized steel pipe materials?

Responding Agency	Additional Information Provided by the Responder
Georgia	Other: Inspection results by Area Engineer.
Iowa	Other: unable to maintain road/shoulder/drainage.
Maine	This is primarily a judgement call. Some are easier: invert corrosion through the pipe, crushing or buckling that hinders pipe hydraulically.
Michigan	Please see concrete. Each of these items or a combination of the items listed could prompt an upgrade to plate or casing material. Determining need for upgrades is a case by case basis.
Minnesota	MnDOT has an inspection and inventory database. Pipes rated as very poor are a priority for repair. When a road is rehabilitated poor and very poor pipes are a priority for repair. http://www.dot.state.mn.us/bridge/pdf/hydraulics/HYDINFRA_Culvert_and_Storm_Drainage_System_Inspectio n_Manual.pdf Joint separations are the most common problem with RCP.
Montana	Perforation is also considered depending on severity. Also, Depending on the scope of work and age of the material when roads are re-built we may extend or use RCP or other materials in place if the condition is adequate. Example: If we are overlaying or doing minor widening we expect and additional service life of 20 years. Generally for project that are 50+ years old we replace all pipes.
New Brunswick	Other: Road Surface Distress. All of the above are used to estimate a condition index for each asset.
Ohio	Other: General Appraisal Rating of 2 or less. We use a General Appraisal rating that evaluates the different aspects of the culvert as found in our CR-86 Inspection form. Items that have bold boxes may control the GA value. Action is required when the GA value reaches a value of 4 or less. In many cases, this value may be improved with maintenance activities. We would consider the Service Life to be at end of life when this value is 2 or less. A value of 2 cooresponds to a "critical" issue. If the question relates to the service life for the specific material, then this would be the General rating that evaluates only the material. This value will control the GA value if it is lower than the other controlling items found on the CR-86 form.
Ontario	Other: failure to service future drainage and site needs. Poor pipe condition, insufficent capacity, changing catchment parameters, highway geometric changes are but a few of the considerations used to determine if a concrete pipe has reached the end of its useful service life.
Oregon	Other: ODOT statewide rating system. Oregon DOT has developed a statewide rating system for culverts that uses groups and individual ratings fields to determine the condition of a culvert.

Q3D: How does your agency define the end of service life for aluminized steel pipe materials?

Responding Agency	Additional Information Provided by the Responder
Prince Edward Island	A structure may not immediately require work; however, if we are reconstructing the road bed above, we will look closely at replacing the structure at that time if it makes sense economically and structurally.
Virginia	Really, it would just be when inspection rating puts the structure rating at 4 or below.
Washington	Other: Culverts will be evaluated using the methodology in the FHWA 'Culvert assessment and decision making procedures manual'. Photo guidance of culvert conditions will aid hydraulic personnel in assessing culvert conditions for rehabilitation or replacement.
Wisconsin	We do very little with this type of material. We also evaluate pipes when for aquatic organism passage and floodplain issues.
Wyoming	Other: Culverts are periodically reviewed and also analysed on upcoming projects to determine if culverts should be replaced, lined, or extended. These decisions are based on condition, age, and depth of culvert along with current hydrologic needs. The current CR numbers for soils are also considered.

Q3E: How does your agency define the end of service life for polymer-coated steel pipe materials?

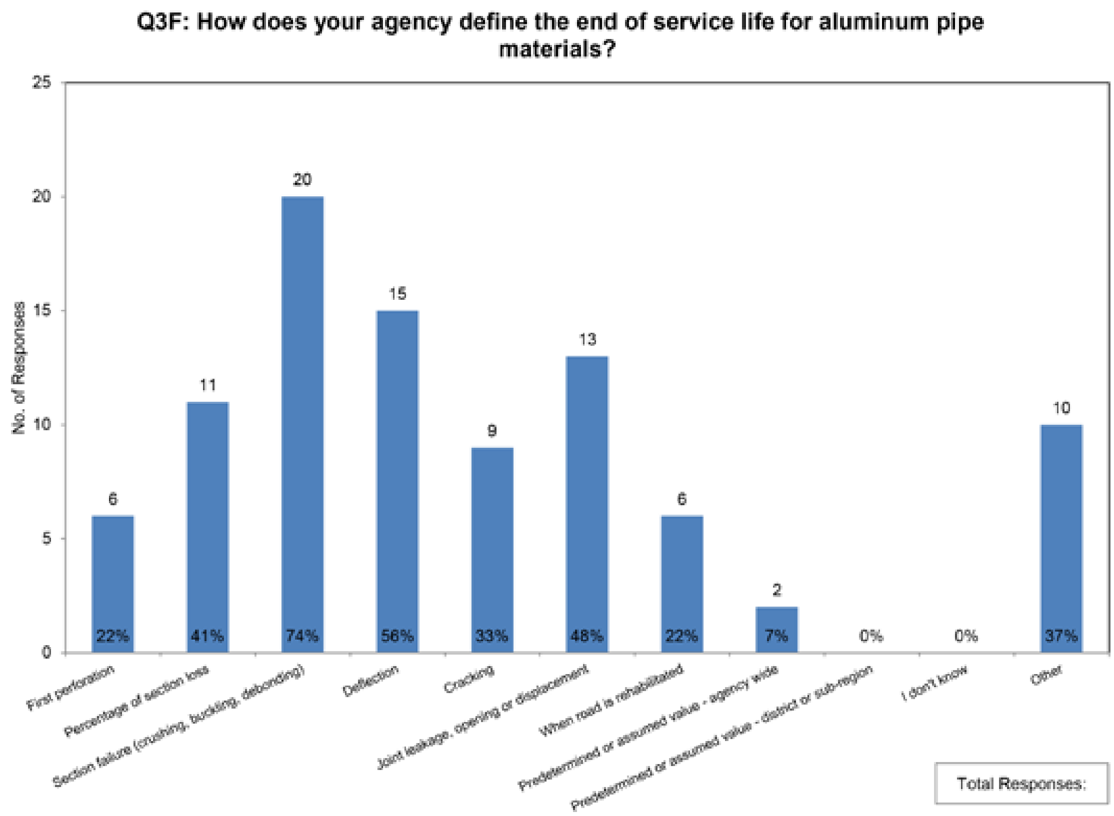


Q3E: How does your agency define the end of service life for polymer-coated steel pipe materials?

Responding Agency	Additional Information Provided by the Responder
Connecticut	At this time there is no information of the Department's use of this product.
Iowa	Other: unable to maintain road/shoulder/drainage.
Maine	This is primarily a judgement call. Some are easier: invert corrosion through the pipe, crushing or buckling that hinders pipe hydraulically.
Michigan	Other: Scour of coating, Case by case basis
Minnesota	Other: Major delamination plugging pipe, Limited quantity installed
Montana	Perforation is also considered depending on severity. Also, Depending on the scope of work and age of the material when roads are re-built we may extend or use RCP or other materials in place if the condition is adequate. Example: If we are overlaying or doing minor widening we expect and additional service life of 20 years. Generally for project that are 50+ years old we replace all pipes.
New Brunswick	Other: Delamination, Road Surface Distress. All of the above are used to estimate a condition index for each asset.
Ohio	Other: General Appraisal Rating of 2 or less. We use a General Appraisal rating that evaluates the different aspects of the culvert as found in our CR-86 Inspection form. Items that have bold boxes may control the GA value. Action is required when the GA value reaches a value of 4 or less. In many cases, this value may be improved with maintenance activities. We would consider the Service Life to be at end of life when this value is 2 or less. A value of 2 corresponds to a "critical" issue. If the question relates to the service life for the specific material, then this would be the General rating that evaluates only the material. This value will control the GA value if it is lower than the other controlling items found on the CR-86 form.
Ontario	Other: failure to service future drainage and site needs. Poor pipe condition, insufficient capacity, changing catchment parameters, highway geometric changes are but a few of the considerations used to determine if a concrete pipe has reached the end of its useful service life.
Saskatchewan	This is not a currently approved culvert material.
Virginia	Really, it would just be when inspection rating puts the structure rating at 4 or below.

Q3E: How does your agency define the end of service life for polymer-coated steel pipe materials?

Responding Agency	Additional Information Provided by the Responder
Washington	Other: Culverts will be evaluated using the methodology in the FHWA 'Culvert assessment and decision making procedures manual'. Photo guidance of culvert conditions will aid hydraulic personnel in assessing culvert conditions for rehabilitation or replacement.
Wisconsin	We do very little with this type of material. We also evaluate pipes when for aquatic organism passage and floodplain issues.
Wyoming	Other: Culverts are periodically reviewed and also analysed on upcoming projects to determine if culverts should be replaced, lined, or extended. These decisions are based on condition, age, and depth of culvert along with current hydrologic needs. The current CR numbers for soils are also considered.

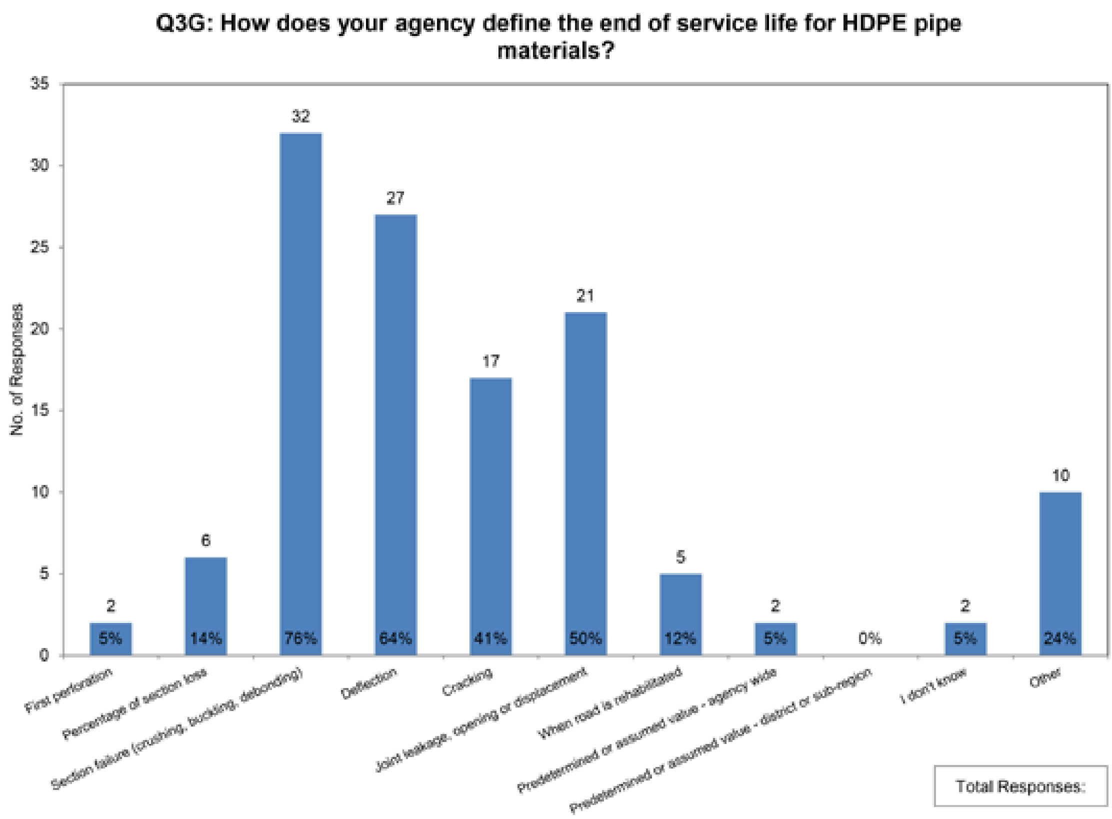


Q3F: How does your agency define the end of service life for aluminum pipe materials?

Responding Agency	Additional Information Provided by the Responder
Colorado	Predetermined or assumed value - agency wide, Assumed 50 yr service life
Georgia	Other: Inspection results by Area Engineer.
Kansas	Other: Have not installed aluminum pipe for several years.
Maine	The issues we've had with aluminum are more related to buckling or deflection. Although I'm not aware of any being replaced to this date.
Michigan	Case by case basis
Minnesota	Limited quantity installed
Montana	Perforation is also considered depending on severity. Also, Depending on the scope of work and age of the material when roads are re-built we may extend or use RCP or other materials in place if the condition is adequate. Example: If we are overlaying or doing minor widening we expect and additional service life of 20 years. Generally for project that are 50+ years old we replace all pipes.
New Brunswick	Other: Anodic/Bacterial, If an aluminum multiplate has steel bolts, the anodic behavior at the bolt holes is monitored. If marine mud contacts the pipe, bacterial attack is monitored.
Ohio	Other: General Appraisal Rating of 2 or less. We use a General Appraisal rating that evaluates the different aspects of the culvert as found in our CR-86 Inspection form. Items that have bold boxes may control the GA value. Action is required when the GA value reaches a value of 4 or less. In many cases, this value may be improved with maintenance activities. We would consider the Service Life to be at end of life when this value is 2 or less. A value of 2 corresponds to a "critical" issue. If the question relates to the service life for the specific material, then this would be the General rating that evaluates only the material. This value will control the GA value if it is lower than the other controlling items found on the CR-86 form.
Ontario	Other: failure to service future drainage and site needs. Poor pipe condition, insufficient capacity, changing catchment parameters, highway geometric changes are but a few of the considerations used to determine if a concrete pipe has reached the end of its useful service life.
Oregon	Other: ODOT statewide rating system. Oregon DOT has developed a statewide rating system for culverts that uses groups and individual ratings fields to determine the condition of a culvert.

Q3F: How does your agency define the end of service life for aluminum pipe materials?

Responding Agency	Additional Information Provided by the Responder
Prince Edward Island	A structure may not immediately require work; however, if we are reconstructing the road bed above, we will look closely at replacing the structure at that time if it makes sense economically and structurally.
South Carolina	Other: Damage to pavement or embankment, Complete, routine maintenance inspections are difficult & expensive. Retained pipe are inspection prior to reconstruction projects & damaged pipe are repaired or replaced. Damage to pavement or embankment due to pipe system generally results in pipe replacement. Routine inspections for 48" dia and larger pipe is underway.
Virginia	Really, it would just be when inspection rating puts the structure rating at 4 or below.
Washington	Culverts will be evaluated using the methodology in the FHWA 'Culvert assessment and decision making procedures manual'. Photo guidance of culvert conditions will aid hydraulic personnel in assessing culvert conditions for rehabilitation or replacement.
Wisconsin	We also evaluate pipes when for aquatic organism passage and floodplain issues.
Wyoming	Other: Culverts are periodically reviewed and also analysed on upcoming projects to determine if culverts should be replaced, lined, or extended. These decisions are based on condition, age, and depth of culvert along with current hydrologic needs. The current CR numbers for soils are also considered.

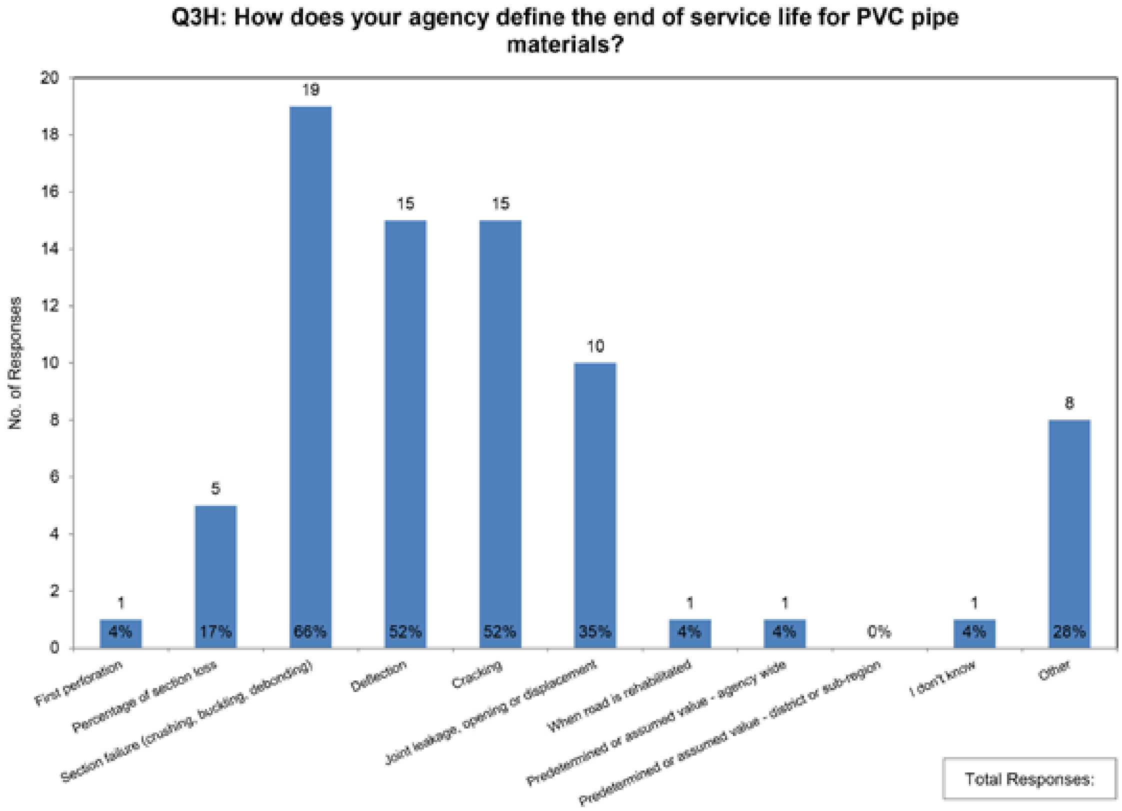


Q3G: How does your agency define the end of service life for HDPE pipe materials?

Responding Agency	Additional Information Provided by the Responder
Colorado	Predetermined or assumed value - agency wide, Assumed 50 yr service life
Delaware	Condition
Florida	Service life is predicted based on Florida test methods to predict slow crack growth and 50% loss of mechanical properties from oxidation of the polymer.
Maine	Issues are buckling, deflection. We haven't replaced many because have used for less than 25 years.
Michigan	Case by case basis
Minnesota	MnDOT has an inspection and inventory database. Pipes rated as very poor are a priority for repair. When a road is rehabilitated poor and very poor pipes are a priority for repair.
Montana	Perforation is also considered depending on severity. Also, Depending on the scope of work and age of the material when roads are re-built we may extend or use RCP or other materials in place if the condition is adequate. Example: If we are overlaying or doing minor widening we expect and additional service life of 20 years. Generally for project that are 50+ years old we replace all pipes.
New Brunswick	Other: Only one HDPE pipe in service. One steel-reinforced pipe is less than one year in service and planned as temporary.
Ohio	Other: General Appraisal Rating of 2 or less. We use a General Appraisal rating that evaluates the different aspects of the culvert as found in our CR-86 Inspection form. Items that have bold boxes may control the GA value. Action is required when the GA value reaches a value of 4 or less. In many cases, this value may be improved with maintenance activities. We would consider the Service Life to be at end of life when this value is 2 or less. A value of 2 corresponds to a "critical" issue. If the question relates to the service life for the specific material, then this would be the General rating that evaluates only the material. This value will control the GA value if it is lower than the other controlling items found on the CR-86 form.
Ontario	Other: failure to service future drainage and site needs. Poor pipe condition, insufficient capacity, changing catchment parameters, highway geometric changes are but a few of the considerations used to determine if a concrete pipe has reached the end of its useful service life.

Q3G: How does your agency define the end of service life for HDPE pipe materials?

Responding Agency	Additional Information Provided by the Responder
Oregon	Other: ODOT statewide rating system. Oregon DOT has developed a statewide rating system for culverts that uses groups and individual ratings fields to determine the condition of a culvert.
Prince Edward Island	A structure may not immediately require work; however, if we are reconstructing the road bed above, we will look closely at replacing the structure at that time if it makes sense economically and structurally.
Saskatchewan	This is a recently introduced culvert material type for the Ministry and we expect our criteria to evolve as we gain more experience with it.
South Carolina	Other: Damage to pavement or embankment, Complete, routine maintenance inspections are difficult & expensive. Retained pipe are inspection prior to reconstruction projects & damaged pipe are repaired or replaced. Damage to pavement or embankment due to pipe system generally results in pipe replacement. Routine inspections for 48" dia and larger pipe is underway.
Virginia	Really, it would just be when inspection rating puts the structure rating at 4 or below.
Washington	Culverts will be evaluated using the methodology in the FHWA 'Culvert assessment and decision making procedures manual'. Photo guidance of culvert conditions will aid hydraulic personnel in assessing culvert conditions for rehabilitation or replacement.
Wisconsin	We also evaluate pipes when for aquatic organism passage and floodplain issues.
Wyoming	Other: Culverts are periodically reviewed and also analysed on upcoming projects to determine if culverts should be replaced, lined, or extended. These decisions are based on condition, age, and depth of culvert along with current hydrologic needs. The current CR numbers for soils are also considered.

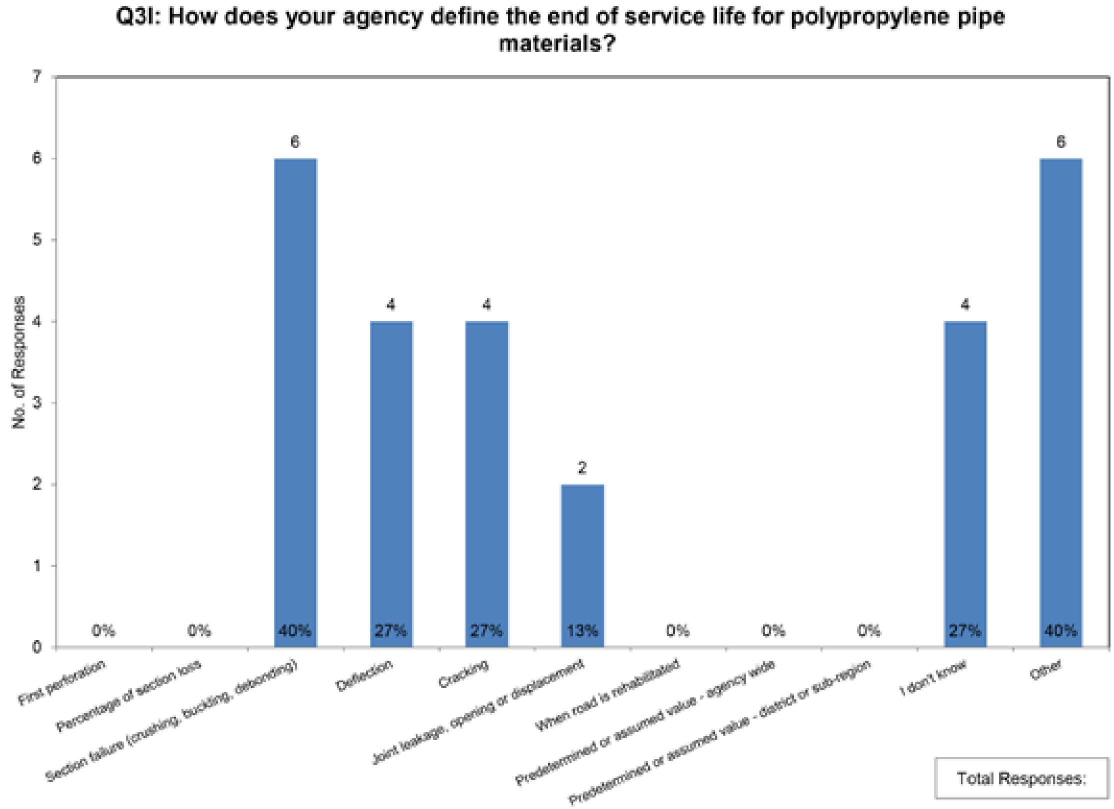


Q3H: How does your agency define the end of service life for PVC pipe materials?

Responding Agency	Additional Information Provided by the Responder
Colorado	Predetermined or assumed value - agency wide, Assumed 50 yr service life
Georgia	Other: Inspection results by Area Engineer.
Iowa	Other: unable to maintain road/shoulder/drainage.
Maine	we don't use much PVC and it is mostly in closed drainage systems in urban areas
Michigan	Case by case basis.
Minnesota	MnDOT has an inspection and inventory database. Pipes rated as very poor are a priority for repair. When a road is rehabilitated poor and very poor pipes are a priority for repair. Limited quantity installed.
Montana	Perforation is also considered depending on severity. Also, Depending on the scope of work and age of the material when roads are re-built we may extend or use RCP or other materials in place if the condition is adequate. Example: If we are overlaying or doing minor widening we expect and additional service life of 20 years. Generally for project that are 50+ years old we replace all pipes.
Ohio	Other: General Appraisal Rating of 2 or less. We use a General Appraisal rating that evaluates the different aspects of the culvert as found in our CR-86 Inspection form. Items that have bold boxes may control the GA value. Action is required when the GA value reaches a value of 4 or less. In many cases, this value may be improved with maintenance activities. We would consider the Service Life to be at end of life when this value is 2 or less. A value of 2 corresponds to a "critical" issue. If the question relates to the service life for the specific material, then this would be the General rating that evaluates only the material. This value will control the GA value if it is lower than the other controlling items found on the CR-86 form.
Ontario	Other: failure to service future drainage and site needs. Poor pipe condition, insufficient capacity, changing catchment parameters, highway geometric changes are but a few of the considerations used to determine if a concrete pipe has reached the end of its useful service life.
Oregon	Other: ODOT statewide rating system. Oregon DOT has developed a statewide rating system for culverts that uses groups and individual ratings fields to determine the condition of a culvert.

Q3H: How does your agency define the end of service life for PVC pipe materials?

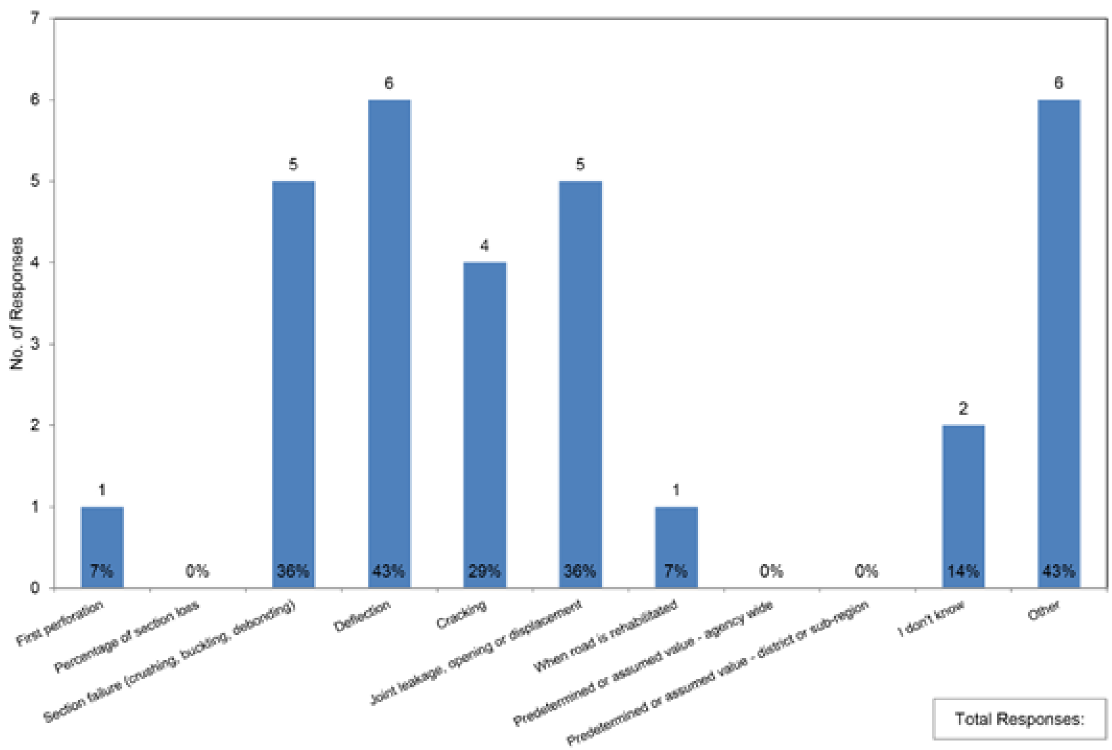
Responding Agency	Additional Information Provided by the Responder
Virginia	Really, it would just be when inspection rating puts the structure rating at 4 or below.
Washington	Culverts will be evaluated using the methodology in the FHWA 'Culvert assessment and decision making procedures manual'. Photo guidance of culvert conditions will aid hydraulic personnel in assessing culvert conditions for rehabilitation or replacement.
Wisconsin	We use very few PVC materials for pipes. We also evaluate pipes when for aquatic organism passage and floodplain issues.
Wyoming	Other: Culverts are periodically reviewed and also analysed on upcoming projects to determine if culverts should be replaced, lined, or extended. These decisions are based on condition, age, and depth of culvert along with current hydrologic needs. The current CR numbers for soils are also considered.



Q3I: How does your agency define the end of service life for polypropylene pipe materials?

Responding Agency	Additional Information Provided by the Responder
Connecticut	At this time there is no information of the Department's use of this product.
Florida	Service life is predicted based on Florida test methods to predict slow crack growth and 50% loss of mechanical properties from oxidation of the polymer.
Maine	We just started allowing PP this year and have only a handful of experimental installations. Performance concerns are with deflection and cracking.
Michigan	Other: In the process of pipe approval for this product. Undetermined. MDOT would first check calculations against AASHTO LRFD Bridge Design Guide Section 12, test joints for water tightness, and then crush test. Once approved this pipe would be tested in use. It can be assumed that anomalies and issues will be those listed above, and then it would be a case by case basis.
Ohio	Other: General Appraisal Rating of 2 or less. We use a General Appraisal rating that evaluates the different aspects of the culvert as found in our CR-86 Inspection form. Items that have bold boxes may control the GA value. Action is required when the GA value reaches a value of 4 or less. In many cases, this value may be improved with maintenance activities. We would consider the Service Life to be at end of life when this value is 2 or less. A value of 2 corresponds to a "critical" issue. If the question relates to the service life for the specific material, then this would be the General rating that evaluates only the material. This value will control the GA value if it is lower than the other controlling items found on the CR-86 form.
Oklahoma	We have just started experimenting with this type of pipe. The first several sections will be installed in a project that was just let.
Ontario	Other: failure to service future drainage and site needs. Poor pipe condition, insufficient capacity, changing catchment parameters, highway geometric changes are but a few of the considerations used to determine if a concrete pipe has reached the end of its useful service life.
Virginia	Really, it would just be when inspection rating puts the structure rating at 4 or below.
Washington	These products are so new, we have very little history of use.

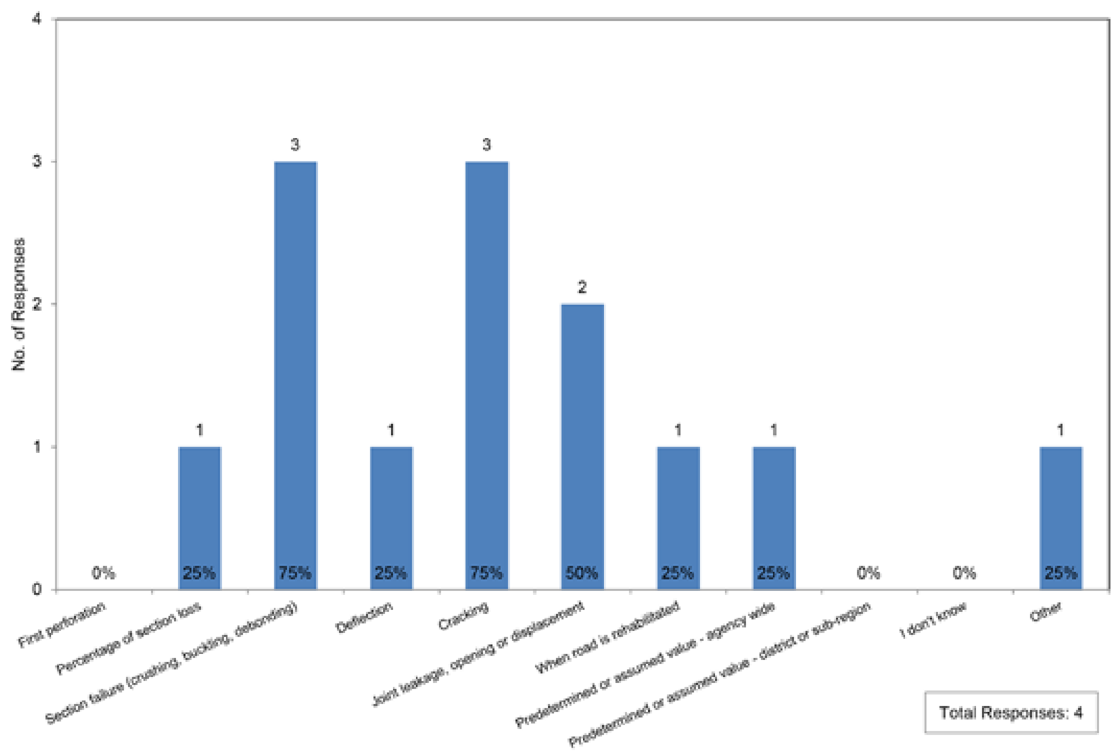
Q3J: How does your agency define the end of service life for steel-reinforced HDPE pipe materials?



Q3J: How does your agency define the end of service life for steel-reinforced HDPE pipe materials?

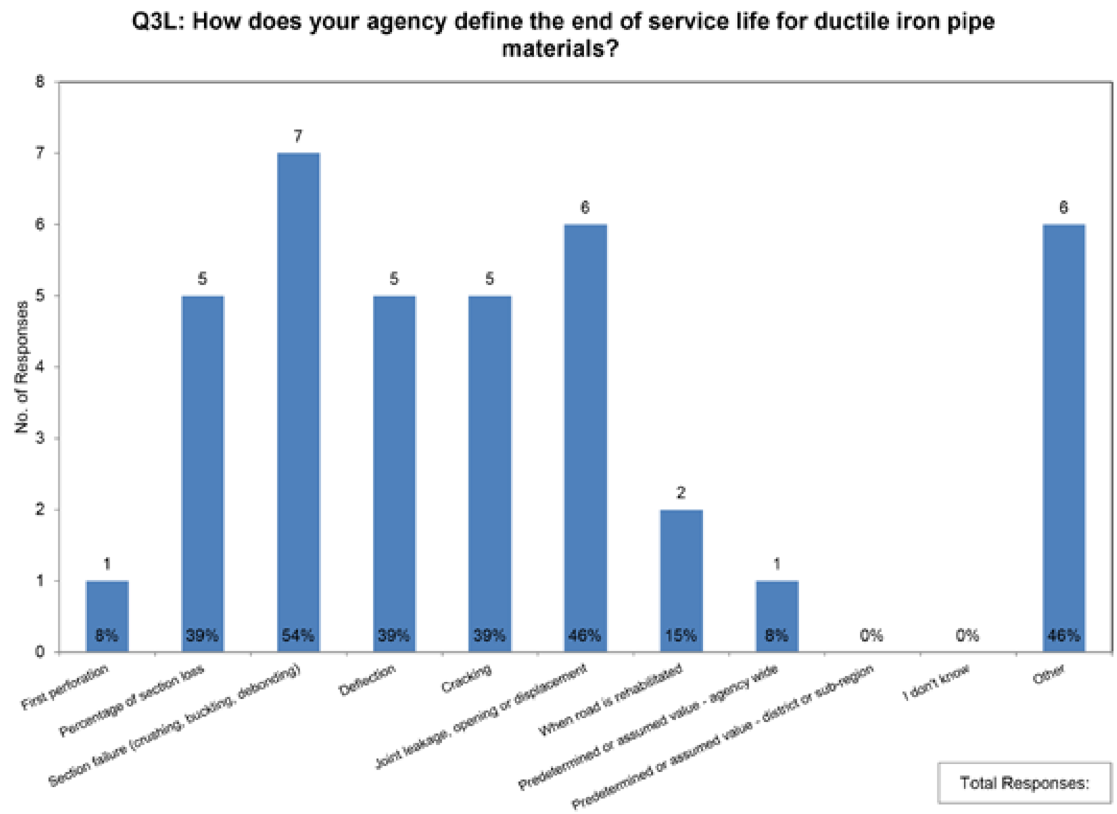
Responding Agency	Additional Information Provided by the Responder
Connecticut	At this time there is no information of the Department's use of this product.
Delaware	Condition
Florida	Service life is predicted based on Florida test methods to predict slow crack growth and 50% loss of mechanical properties from oxidation of the polymer.
Michigan	Other: MDOT is in the approval process for this product. Watertight joint testing, checking AASHTO LRFD Bridge Design Section 12 calculations and crush testing will be performed and hopefully a test installation as well. It is assumed that all of these anomalies will apply for determination of service life of the SRHDPE pipe.
Ohio	Other: General Appraisal Rating of 2 or less. We use a General Appraisal rating that evaluates the different aspects of the culvert as found in our CR-86 Inspection form. Items that have bold boxes may control the GA value. Action is required when the GA value reaches a value of 4 or less. In many cases, this value may be improved with maintenance activities. We would consider the Service Life to be at end of life when this value is 2 or less. A value of 2 corresponds to a "critical" issue. If the question relates to the service life for the specific material, then this would be the General rating that evaluates only the material. This value will control the GA value if it is lower than the other controlling items found on the CR-86 form.
Ontario	Other: failure to service future drainage and site needs. We are considering use of the steel reinforced HDPE pipe and poor pipe condition, insufficient capacity, changing catchment parameters, highway geometric changes would be but a few of the considerations used to determine if a steel reinforced HDPE pipe has reached the end of its useful service life.
Oregon	Other: ODOT statewide rating system. Oregon DOT has developed a statewide rating system for culverts that uses groups and individual ratings fields to determine the condition of a culvert.
Saskatchewan	This is not a currently approved culvert material.
Virginia	Really, it would just be when inspection rating puts the structure rating at 4 or below.
Washington	This type of culvert is very new to the market, we have 1 installation to date

Q3K: How does your agency define the end of service life for vitrified clay pipe materials?



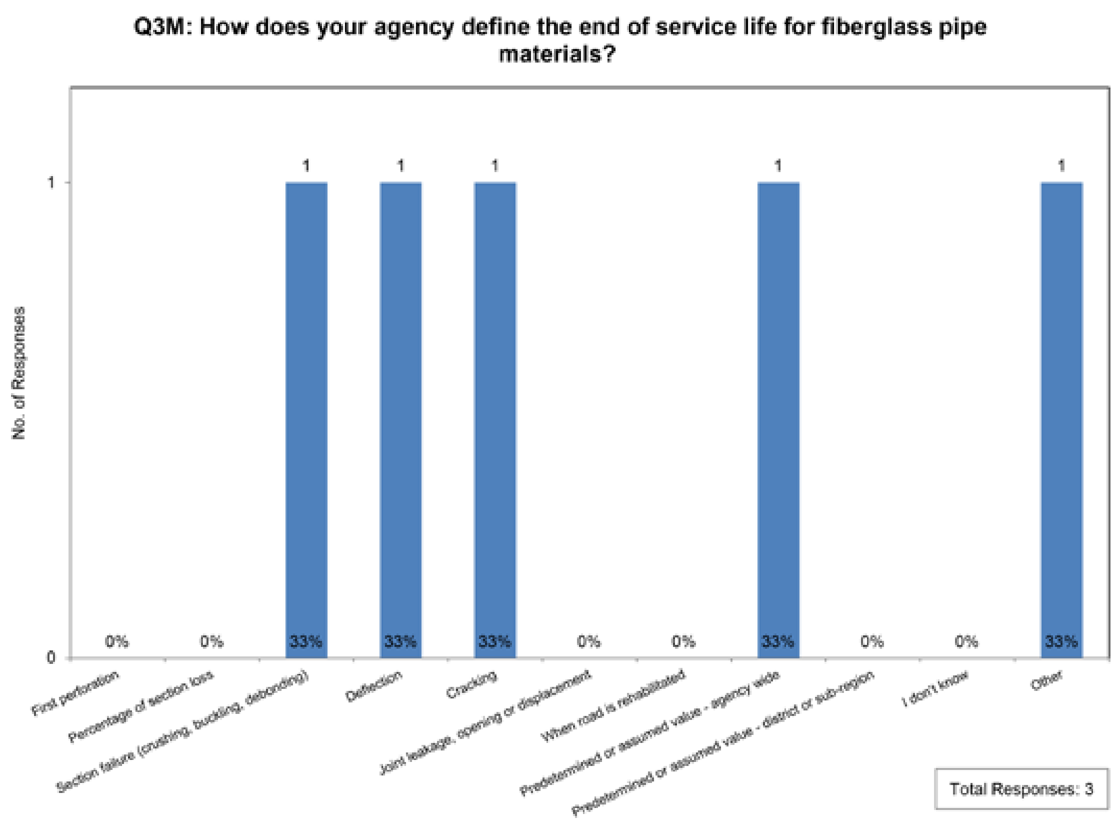
Q3K: How does your agency define the end of service life for vitrified clay pipe materials?

Responding Agency	Additional Information Provided by the Responder
Colorado	Predetermined or assumed value - agency wide, Assumed 50 yr service life
Michigan	Case by case basis.
Ohio	Other: General Appraisal Rating of 2 or less. We use a General Appraisal rating that evaluates the different aspects of the culvert as found in our CR-86 Inspection form. Items that have bold boxes may control the GA value. Action is required when the GA value reaches a value of 4 or less. In many cases, this value may be improved with maintenance activities. We would consider the Service Life to be at end of life when this value is 2 or less. A value of 2 corresponds to a "critical" issue. If the question relates to the service life for the specific material, then this would be the General rating that evaluates only the material. This value will control the GA value if it is lower than the other controlling items found on the CR-86 form.



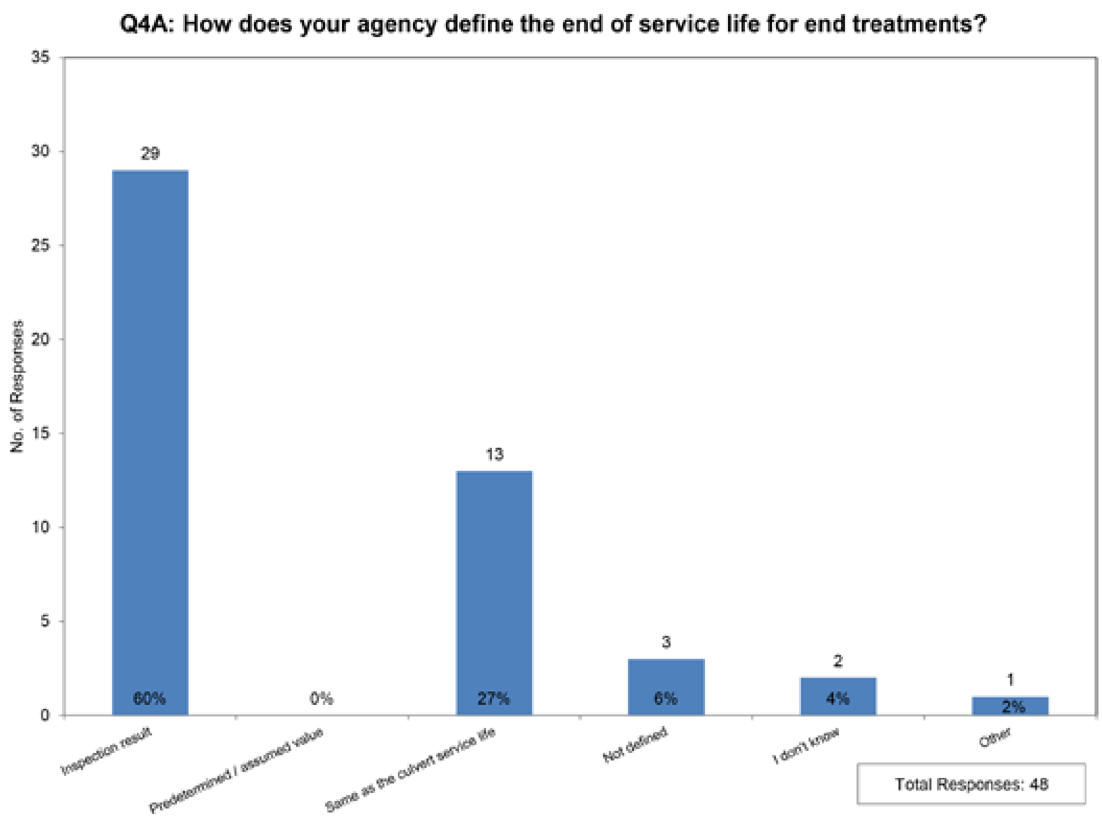
Q3L: How does your agency define the end of service life for ductile iron pipe materials?

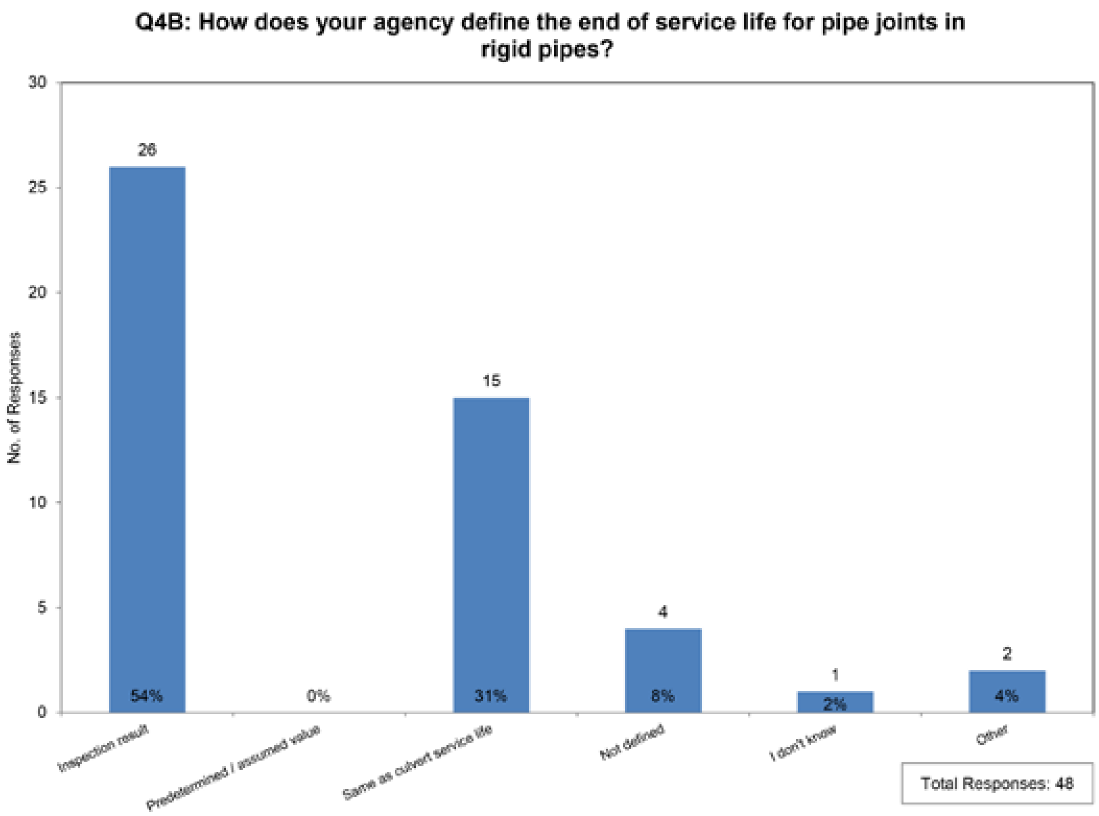
Responding Agency	Additional Information Provided by the Responder
Colorado	Predetermined or assumed value - agency wide, Assumed 50 yr service life
Michigan	Case by case basis.
Ohio	Other: General Appraisal Rating of 2 or less. We use a General Appraisal rating that evaluates the different aspects of the culvert as found in our CR-86 Inspection form. Items that have bold boxes may control the GA value. Action is required when the GA value reaches a value of 4 or less. In many cases, this value may be improved with maintenance activities. We would consider the Service Life to be at end of life when this value is 2 or less. A value of 2 corresponds to a "critical" issue. If the question relates to the service life for the specific material, then this would be the General rating that evaluates only the material. This value will control the GA value if it is lower than the other controlling items found on the CR-86 form.
Oregon	Other: ODOT statewide rating system. Oregon DOT has developed a statewide rating system for culverts that uses groups and individual ratings fields to determine the condition of a culvert.
Pennsylvania	Other: No criteria for ductile iron pipe materials.
Washington	Culverts will be evaluated using the methodology in the FHWA 'Culvert assessment and decision making procedures manual'. Photo guidance of culvert conditions will aid hydraulic personnel in assessing culvert conditions for rehabilitation or replacement.
Wyoming	Other: Culverts are periodically reviewed and also analysed on upcoming projects to determine if culverts should be replaced, lined, or extended. These decisions are based on condition, age, and depth of culvert along with current hydrologic needs. The current CR numbers for soils are also considered.



Q3M: How does your agency define the end of service life for fiberglass pipe materials?

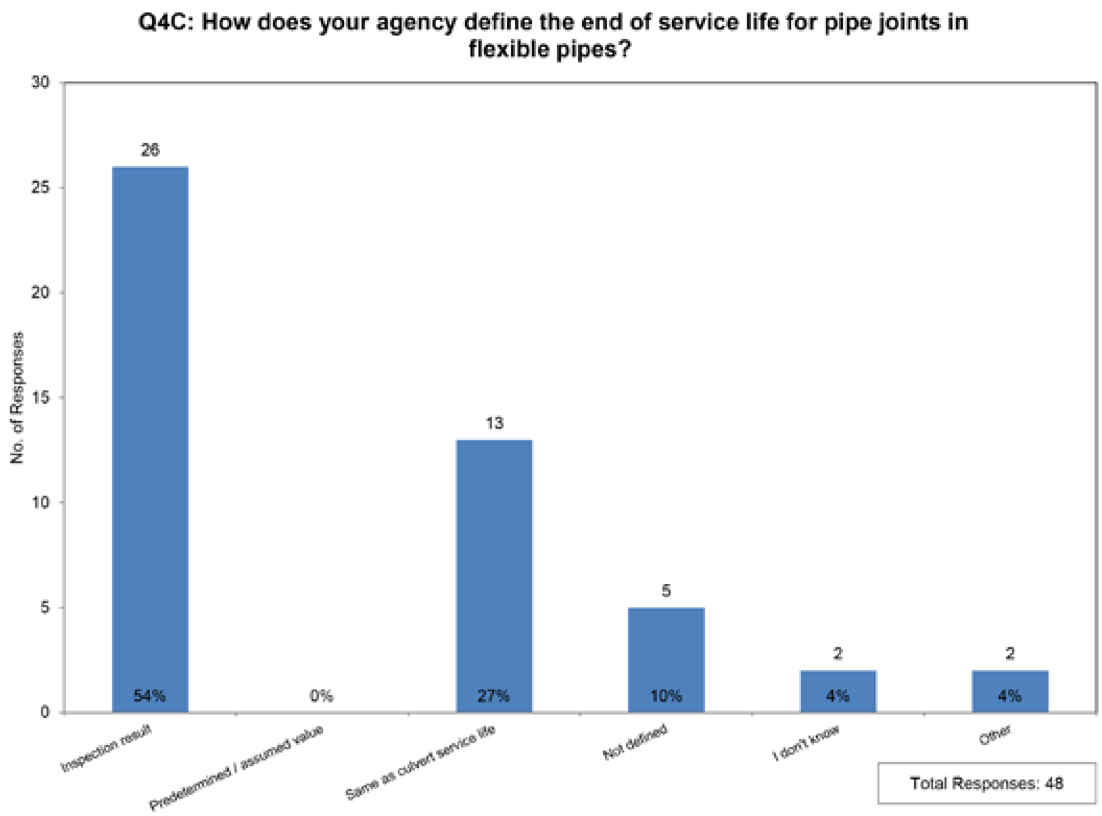
Responding Agency	Additional Information Provided by the Responder
Florida	Only used for bridge collection systems.
Virginia	I am not aware of past use of fiberglass, though we are using it in a jacking job now. End of service life would be same as previous answers.





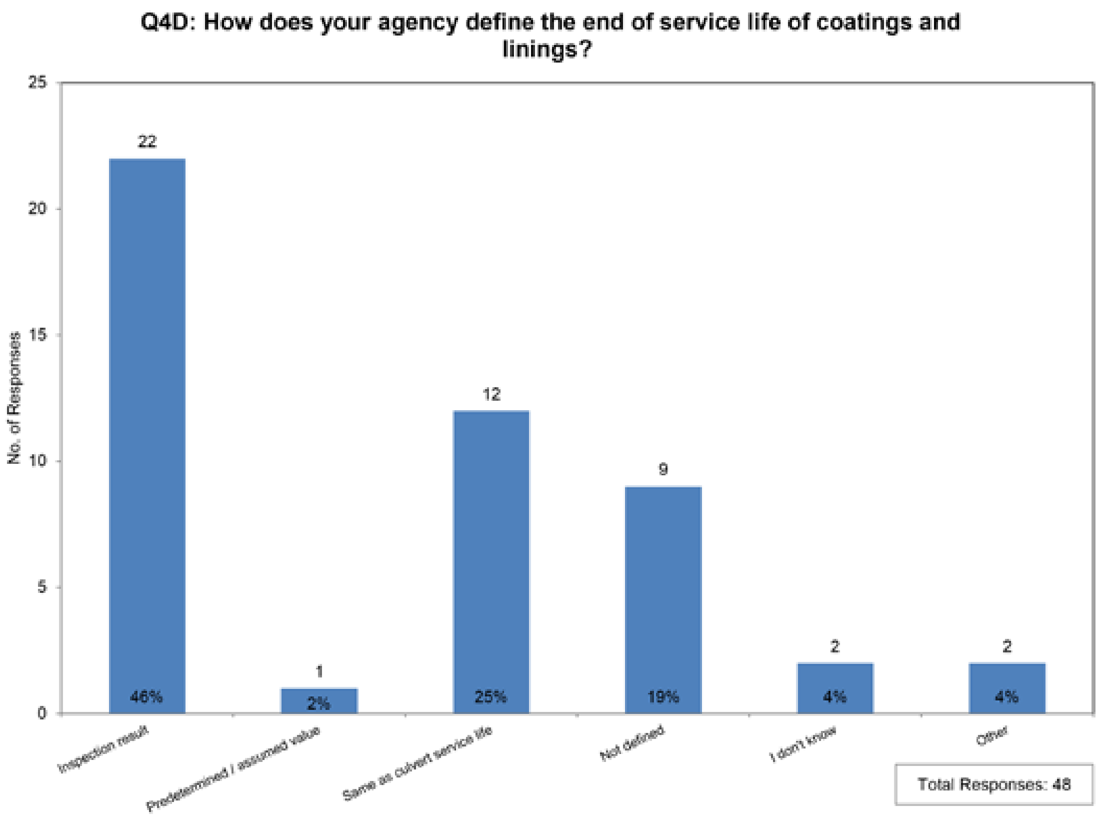
Q4B: How does your agency define the end of service life for pipe joints in rigid pipes?

Responding Agency	Additional Information Provided by the Responder
Idaho	Other: Roadway surface shows moisture
Pennsylvania	Other: When an obstruction occurs or is identified.



Q4C: How does your agency define the end of service life for pipe joints in flexible pipes?

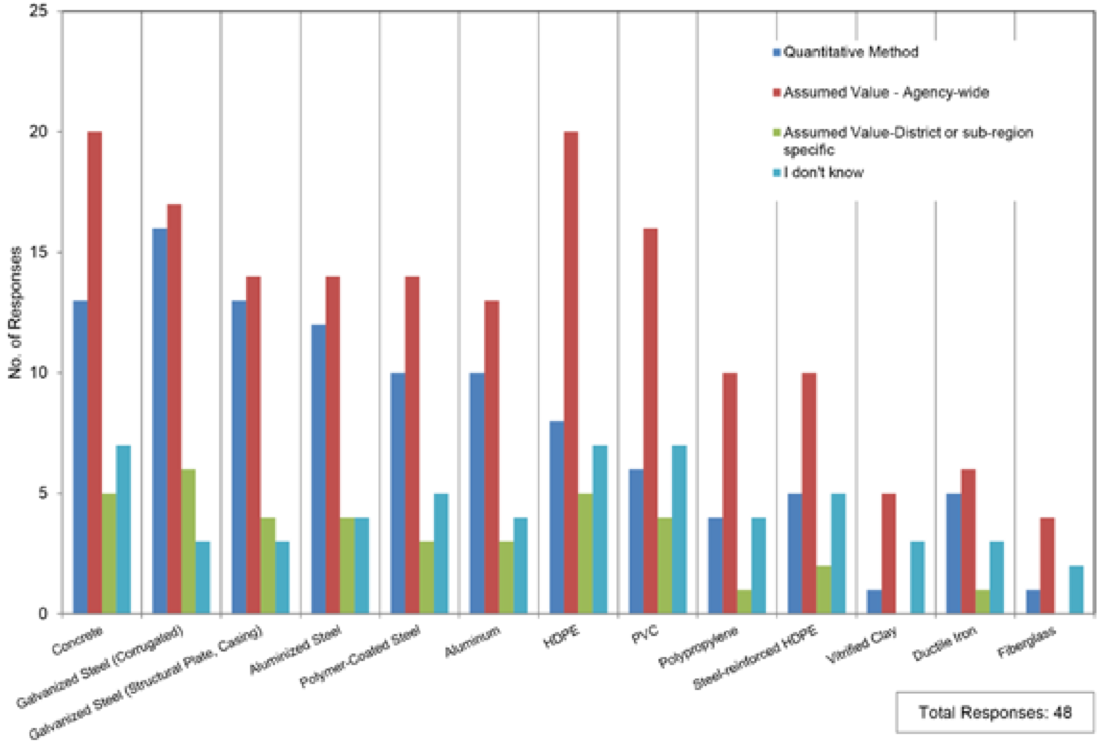
Responding Agency	Additional Information Provided by the Responder
Idaho	Other: Roadway surface shows moisture
Pennsylvania	Other: When an obstruction occurs or is identified.



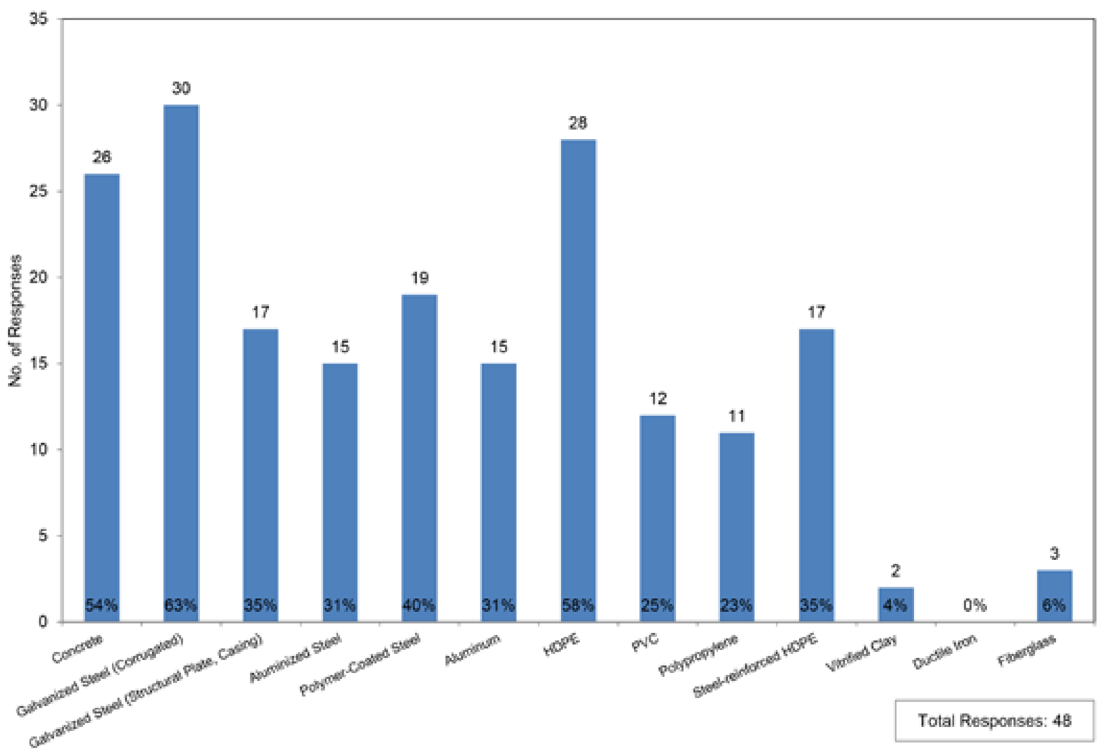
Q4D: How does your agency define the end of service life of coatings and linings?

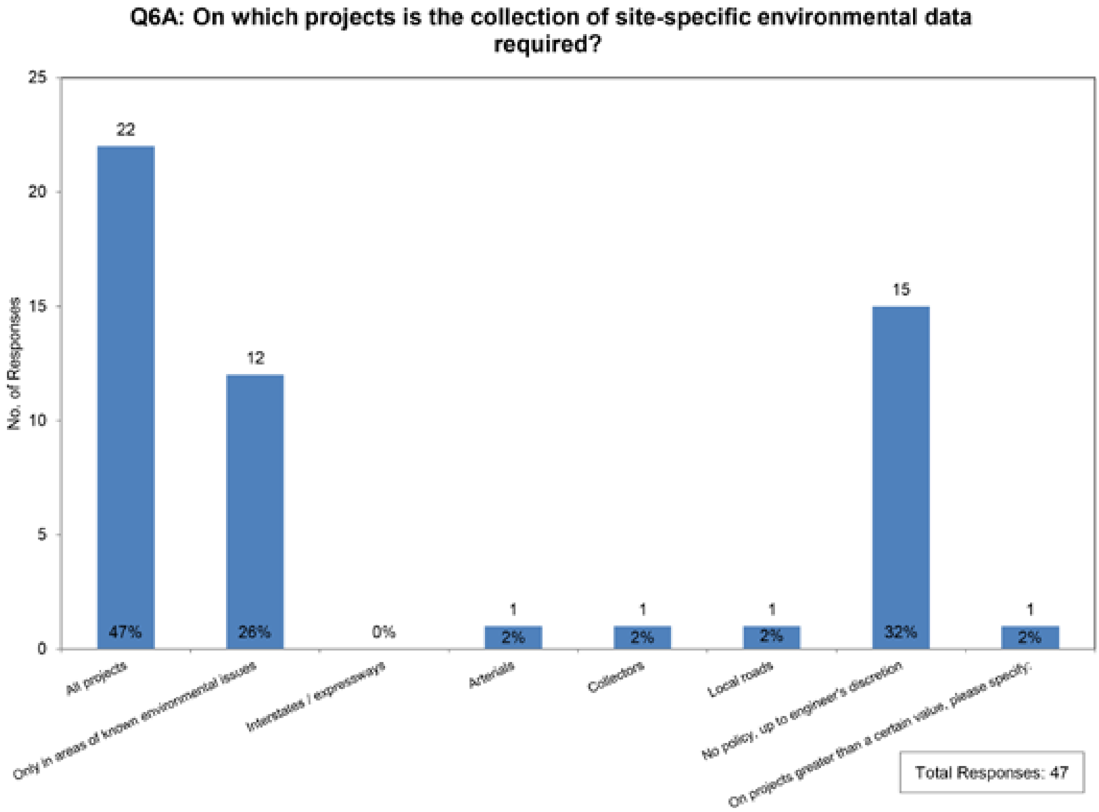
Responding Agency	Additional Information Provided by the Responder
Idaho	Coatings-perforation development in CMP
Ohio	We use research by Hurd to predict the service life and the coatings are rated during the inspection.

Q5A: Please indicate how your agency estimates material service life for each of the following pipe types.



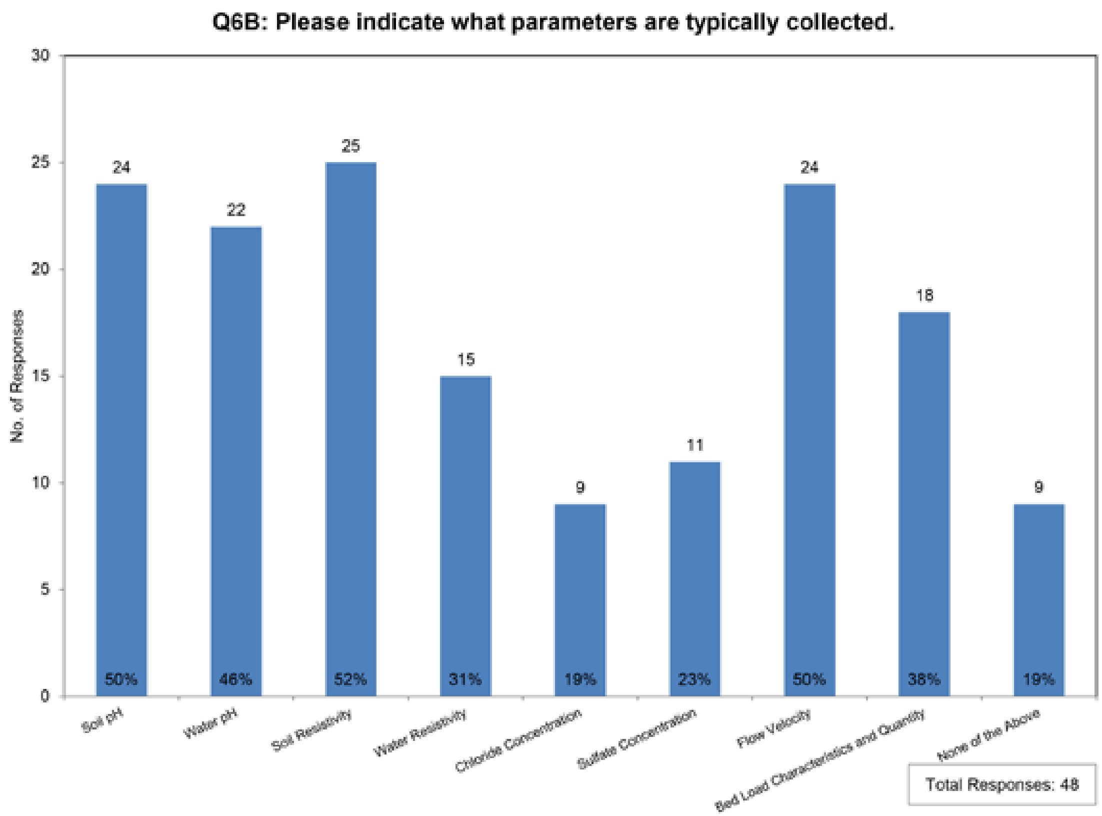
Q5B: Please select up to 5 pipe types that are most in need of new or improved methods for estimating service life.





Q6A: On which projects is the collection of site-specific environmental data required?

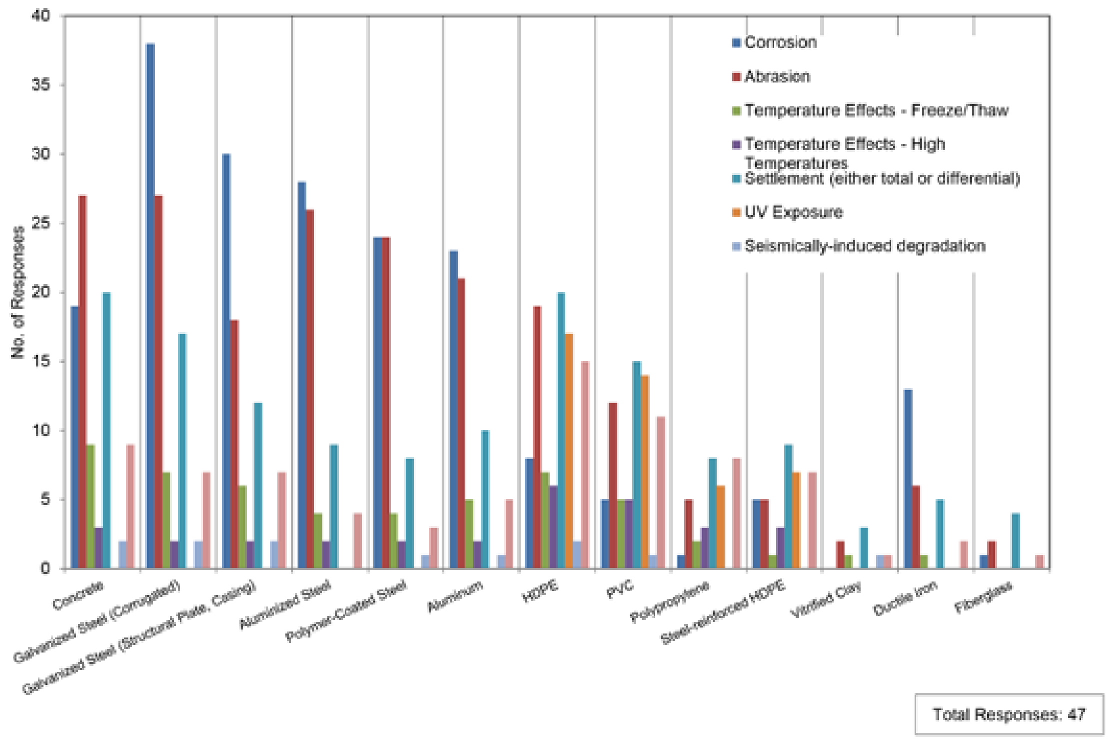
Responding Agency	Additional Information Provided by the Responder
South Carolina	*On projects greater than a certain value, please specify:* Only Chemically resistant or inert pipe materials are specified for natural soil conditions. Extreme sites in harsh environments such as mines or manufacturing must evaluate materials.



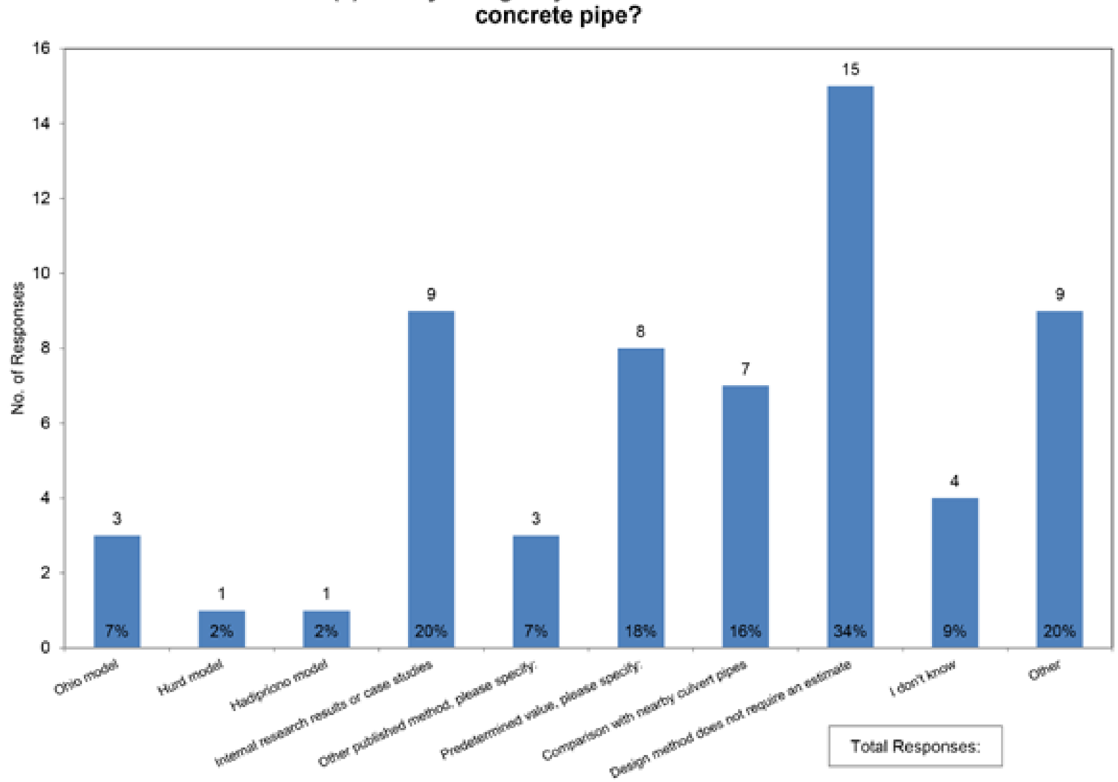
Q6C: Please Indicate if any other parameters are typically collected.

Responding Agency	Additional Information Provided by the Responder
Michigan	OTHER: Fisheries issues/aquatic organism passage (AOP). On SOME projects: Soil pH/Water pH in areas that have been problematic for those issues. Same with soil resistivity - tested for in areas where it has been problematic.
New Brunswick	Aquatic organisms presence, wetland extent, archaeologic potential, historic high water indice levels.
Ohio	Presence of abrasive material. This is somewhat of a subjective call. We are trying to address this with our current research.
Ontario	We will be moving forward to determining water hardness
Prince Edward Island	Flow restrictions, aquatic environment, fish habitat, fauna, flora, stream bed profiles, meander locations.
South Carolina	None of these are "typically" collected due to pipe materials specified. Sites with known pH, resistivity, chlorides, or high concentrations of abrasive materials should be addressed on a case by case basis.
Wisconsin	When aquatic organism passages issues exist, we collect upstream and down stream cross sections, and collect approximate stream profile through the culvert from 300' up to 300' downstream.

Q7. Please indicate what factors are considered when your agency estimates material service life.



Q8A: What method(s) does your agency use to estimate material service life of concrete pipe?

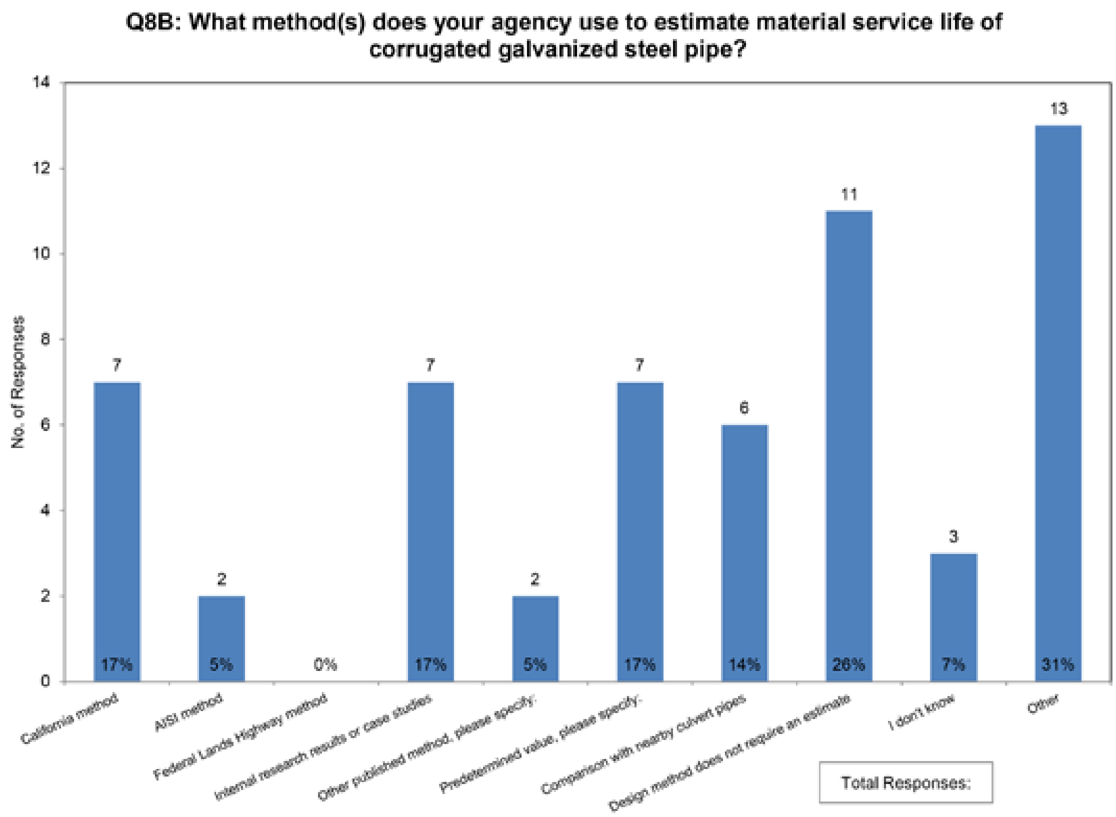


Q8A: What method(s) does your agency use to estimate material service life of concrete pipe?

Responding Agency	Additional Information Provided by the Responder
Arizona	Predetermined value: 50 year minimum
Arkansas	Predetermined value: 50 year +
Colorado	Predetermined value: 50 year
Connecticut	Other: Inspection / manufacture information.
Delaware	Predetermined value: 100 years per AASHTO
Georgia	Predetermined value: Values determine from in-house research.
Idaho	Other: Structural Loading
Maine	Predetermined value: 50 year design life.
Massachusetts	Other: Inspection results.
Michigan	Other published method, please specify: 1986 FHWA Culvert Inspection and Bridge Inspection Manuals, Case by case basis.
Minnesota	http://www.cts.umn.edu/Publications/ResearchReports/reportdetail.html?id=2184, A Research Plan and Report on Factors Affecting Culvert Pipe Service Life in Minnesota, Craig A. Taylor, Jeff Marr, 9/1/2012, Report no. MnDOT 2012-27
Missouri	Other: Historical Experience
Nevada	Predetermined value: 100 year
New Brunswick	Other: Internal expertise. NBDTI has expert staff who continuously advise om manufacturing standards. inspection results confirm or correct for improved durability.
Ontario	Other published method, please specify: Florida Model. Methods presented as options for designer to choose the method most appropriate to their site conditions. More detail available in our MTO Gravity Pipe Design Guidelines.
Oregon	Predetermined value: Manufacture
Prince Edward Island	Other: Visual Inspections. We don't estimate service life per se. based on our available budget and out inventory, we take a 'worst first' approach. We visually inspect each structure on a triennial basis.

Q8A: What method(s) does your agency use to estimate material service life of concrete pipe?

Responding Agency	Additional Information Provided by the Responder
Virginia	Its assumed to be 75 year life
Wyoming	Other: Soil and water samples taken at pipe locations are tested for resistivity, pH, and sulfates. Based on the test results, a CR (corrosion rating) is determined for the culvert location. A CR table was developed to choose the correct type of pipe, coating, bedding, and backfill material for a given CR. The table was based on selecting the appropriate culvert type for a 30 year design life.
Yukon	Other published method, please specify: CSA

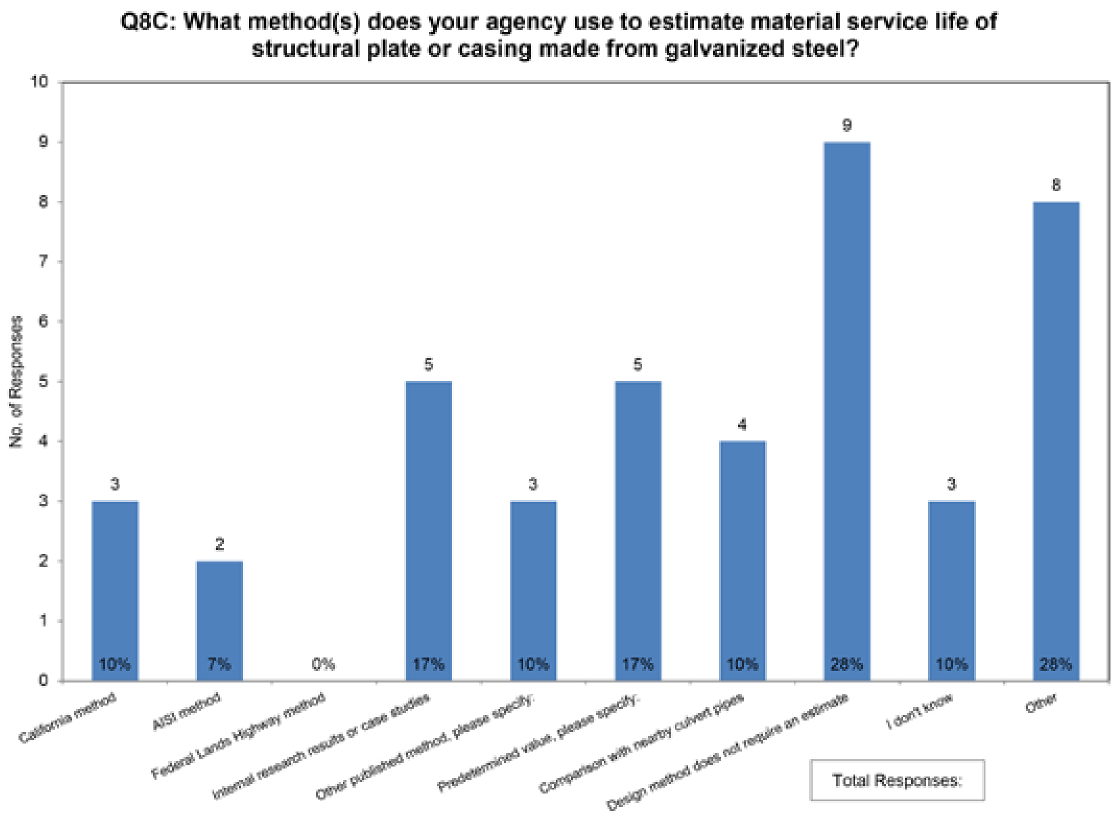


Q8B: What method(s) does your agency use to estimate material service life of corrugated galvanized steel pipe?

Responding Agency	Additional Information Provided by the Responder
Arizona	Predetermined value, please specify: 25 to 50-year.
Arkansas	Predetermined value: 25 year +
Colorado	Predetermined value: 50 year
Georgia	Predetermined value: Values determine from in-house research.
Idaho	Other: Structural Loading
Kansas	Other: KDOT Pipe Policy.
Maine	Other: Based on internal studies, gauge thickness is increased to get 50 year life. Gauge thicknesses are adjusted in order to get 50 year service life. Contractors have the option to select material for 25 or 50 year life.
Massachusetts	Other: Inspection results.
Michigan	Other published method, please specify: 1986 FHWA Culvert Inspection and Bridge Inspection Manuals, Case by case basis.
Minnesota	Other: Drainage Manual
Missouri	Other: Historical Experience
Montana	Other: Modified AISI.
Nevada	Predetermined value, please specify: 50 year.
New Brunswick	Other: CSPI Guidelines. NBDTI research studies and CSPI Durability Guidelines plus site data on environmental parameters are used.
Ohio	Other: Ohio Model. Research that was performed by John Hurd in the 1980's.
Ontario	More detail available in our MTO Gravity Pipe Design Guidelines
Oregon	Predetermined value: Manufacture
Pennsylvania	Other: We use AASHTO Criteria.
Prince Edward Island	Other: Visual Inspections. We don't estimate service life per se. based on our available budget and out inventory, we take a 'worst first' approach. We visually inspect each structure on a triennial basis.

Q8B: What method(s) does your agency use to estimate material service life of corrugated galvanized steel pipe?

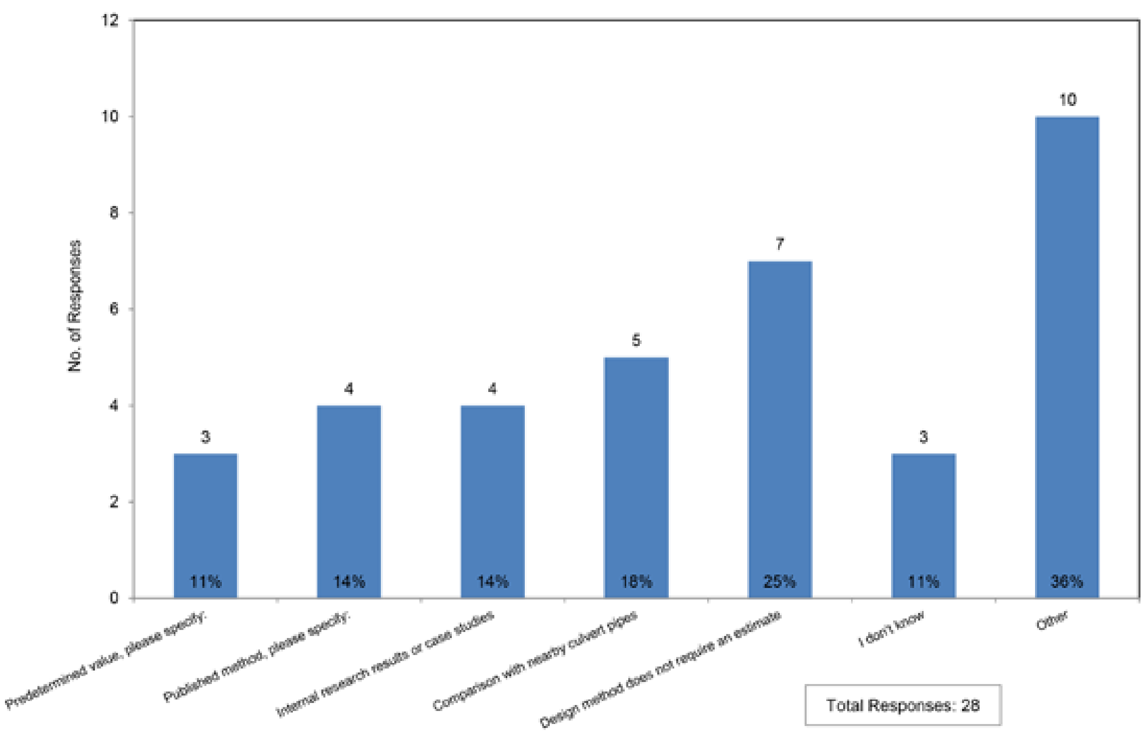
Responding Agency	Additional Information Provided by the Responder
Virginia	Assumed 75-yr life if pH and resistivity within medium limits and flow, otherwise not allowed.
Wisconsin	In addition to ADT, bacterial corrosion is of significant concern in parts of Wisconsin. This type of corrosion has significantly influenced the selection of any steel pipes, which were used for years.
Wyoming	Other: Soil and water samples taken at pipe locations are tested for resistivity, pH, and sulfates. Based on the test results, a CR (corrosion rating) is determined for the culvert location. A CR table was developed to choose the correct type of pipe, coating, bedding, and backfill material for a given CR. The table was based on selecting the appropriate culvert type for a 30 year design life.
Yukon	Other published method, please specify: CSA.



Q8C: What method(s) does your agency use to estimate material service life of structural plate or casing made from galvanized steel?

Responding Agency	Additional Information Provided by the Responder
Arkansas	Predetermined value: 25 year +
Colorado	Predetermined value: 50 year
Idaho	Other: Structural Loading
Maine	Plate thicknesses adjusted.
Michigan	Other published method, please specify: 1986 FHWA Culvert Inspection and Bridge Inspection Manuals, Case by case basis.
Montana	Other: Modified AISI.
Nevada	Predetermined value, please specify: 50 year.
New Brunswick	Other: CSPI Guidelines. NBDTI research studies and CSPI Durability Guidelines plus site data on environmental parameters are used.
Ohio	Other: Ohio Model
Ontario	More detail available in our MTO Gravity Pipe Design Guidelines
Prince Edward Island	Other: Visual Inspections. We don't estimate service life per se. based on our available budget and out inventory, we take a 'worst first' approach. We visually inspect each structure on a triennial basis.
Virginia	Assumed 75-yr life if pH and resistivity within medium limits and flow, otherwise not allowed.
Wyoming	Other: Soil and water samples taken at pipe locations are tested for resistivity, pH, and sulfates. Based on the test results, a CR (corrosion rating) is determined for the culvert location. A CR table was developed to choose the correct type of pipe, coating, bedding, and backfill material for a given CR. The table was based on selecting the appropriate culvert type for a 30 year design life.
Yukon	Other published method, please specify: CSA.

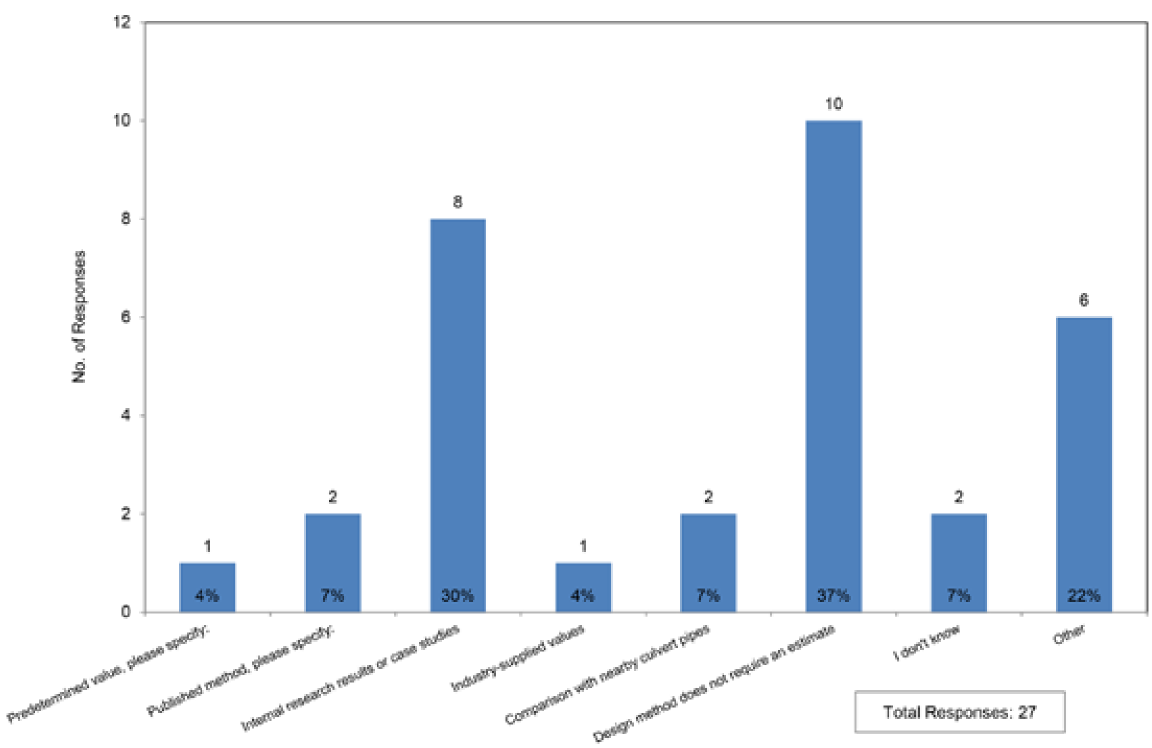
Q8D: What method(s) does your agency use to estimate material service life of aluminized steel?



Q8D: What method(s) does your agency use to estimate material service life of aluminized steel?

Responding Agency	Additional Information Provided by the Responder
Arkansas	Predetermined value: 25 year +
Connecticut	Other: Inspection / manufacture information.
Georgia	Predetermined value: Values determine from in-house research.
Kansas	Other: KDOT Pipe Policy.
Maine	We found aluminized coating had problems with abrasion from bed load. Alum type 2 is allowed for 50 year service life applications when in a closed drainage system.
Michigan	Other published method, please specify: 1986 FHWA Culvert Inspection and Bridge Inspection Manuals, Case by case basis.
Minnesota	Other: Drainage Manual
Montana	Other: Modified AISI.
New Brunswick	Other: CSPI Guidelines. NBDTI research studies and CSPI Durability Guidelines plus site data on environmental parameters are used.
Ohio	Other: Ohio Model
Ontario	Other published method, please specify: CSPI Bulletin 1. More detail available in our MTO Gravity Pipe Design Guidelines.
Oregon	Predetermined value: Manufacture
Pennsylvania	Other: We use AASHTO Criteria.
Prince Edward Island	Other: Visual Inspections. We don't estimate service life per se. based on our available budget and out inventory, we take a 'worst first' approach. We visually inspect each structure on a triennial basis.
Virginia	Assumed 75-yr life if pH and resistivity within medium limits and flow, otherwise not allowed.
Wyoming	Other: Soil and water samples taken at pipe locations are tested for resistivity, pH, and sulfates. Based on the test results, a CR (corrosion rating) is determined for the culvert location. A CR table was developed to choose the correct type of pipe, coating, bedding, and backfill material for a given CR. The table was based on selecting the appropriate culvert type for a 30 year design life.

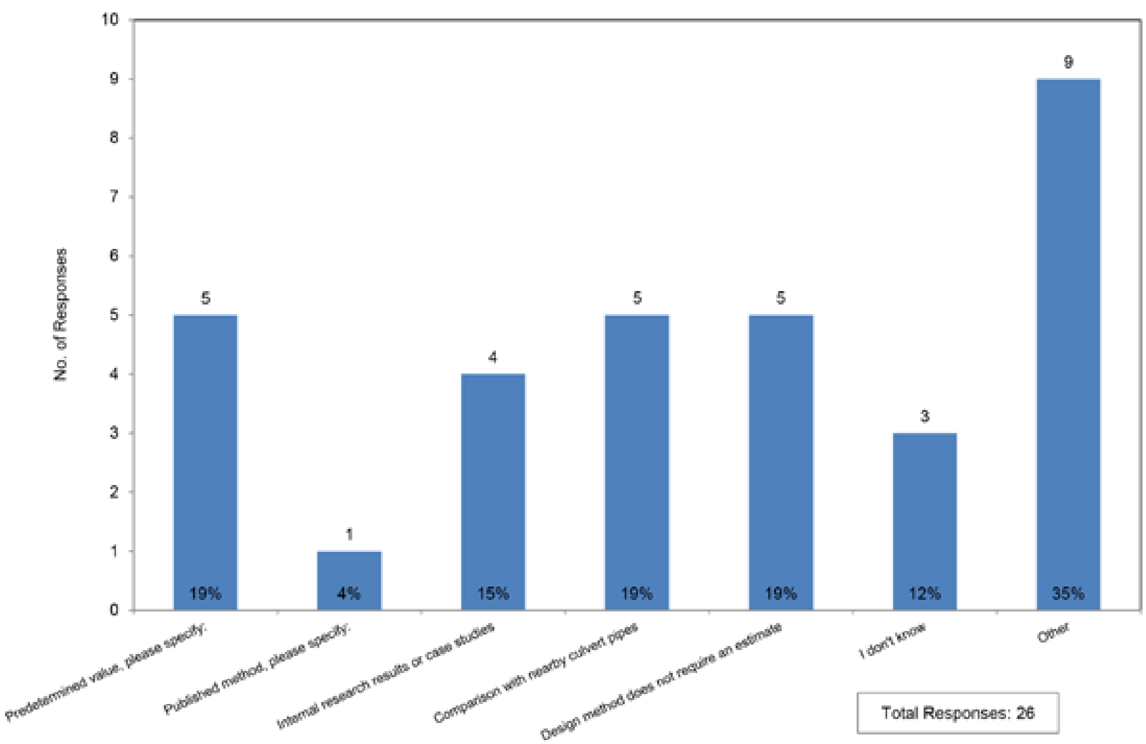
Q8E: What method(s) does your agency use to estimate material service life of polymer-coated steel?



Q8E: What method(s) does your agency use to estimate material service life of polymer-coated steel?

Responding Agency	Additional Information Provided by the Responder
Arkansas	Predetermined value: 25 year +
Connecticut	Other: Inspection / manufacture information.
Maine	We found polymer coating was a 50 year service life pipe
Michigan	Other published method, please specify: 1986 FHWA Culvert Inspection and Bridge Inspection Manuals, Case by case basis.
Minnesota	http://www.cts.umn.edu/Publications/ResearchReports/reportdetail.html?id=2184, A Research Plan and Report on Factors Affecting Culvert Pipe Service Life in Minnesota, Craig A. Taylor, Jeff Marr, 9/1/2012, Report no. MnDOT 2012-27
Missouri	Other: Regional Experience
Montana	Other: Modified AISI.
Ohio	Other: Ohio Model
Ontario	Other published method, please specify: CSPI Bulletin 1. More detail available in our MTO Gravity Pipe Design Guidelines.
Virginia	Assumed 75-yr life if pH and resistivity within medium limits and flow, otherwise not allowed.
Wyoming	Other: Soil and water samples taken at pipe locations are tested for resistivity, pH, and sulfates. Based on the test results, a CR (corrosion rating) is determined for the culvert location. A CR table was developed to choose the correct type of pipe, coating, bedding, and backfill material for a given CR. The table was based on selecting the appropriate culvert type for a 30 year design life.

Q8F: What method(s) does your agency use to estimate material service life of aluminum pipe?

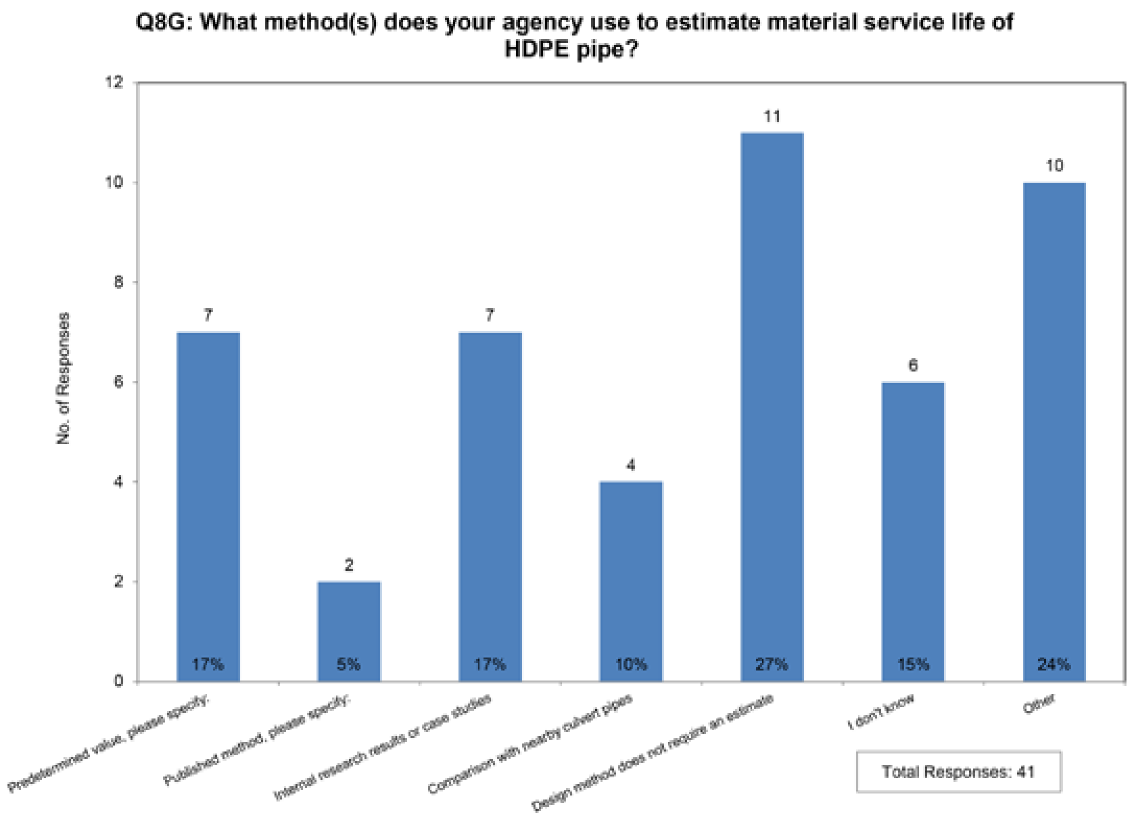


Q8F: What method(s) does your agency use to estimate material service life of aluminum pipe?

Responding Agency	Additional Information Provided by the Responder
Arkansas	Predetermined value: 25 year +
Colorado	Predetermined value: 50 year
Connecticut	Other: Inspection / manufacture information.
Georgia	Predetermined value: Values determine from in-house research.
Kansas	Other: KDOT Pipe Policy.
Maine	Predetermined value: 50 plus year design life.
Michigan	Other published method, please specify: 1986 FHWA Culvert Inspection and Bridge Inspection Manuals, Case by case basis.
Minnesota	http://www.cts.umn.edu/Publications/ResearchReports/reportdetail.html?id=2184, A Research Plan and Report on Factors Affecting Culvert Pipe Service Life in Minnesota, Craig A. Taylor, Jeff Marr, 9/1/2012, Report no. MnDOT 2012-27
Montana	Other: Modified AISI.
New Brunswick	Inspection results, published literature, materials literature and our own field observations.
Ohio	Other: Ohio Model
Ontario	Other: MTO Interim Gravity Pipe Design Guidelines August 2013. More detail available in our MTO Gravity Pipe Design Guidelines.
Oregon	Predetermined value: Manufacture
Prince Edward Island	Other: Visual Inspections. We don't estimate service life per se. based on our available budget and out inventory, we take a 'worst first' approach. We visually inspect each structure on a triennial basis.
South Carolina	Other: Again, a fixed value for Service Life is not estimated. The best practice would be inspection, forensics, and case studies of real world installations to determine an approximate value. Installation method, loading, environmental conditions, embankment properties, and even manufacturing practices will all play a roll in how long an individual pipe will last.
Virginia	Assumed 75-yr life if pH and resistivity within medium limits and flow, otherwise not allowed.

Q8F: What method(s) does your agency use to estimate material service life of aluminum pipe?

Responding Agency	Additional Information Provided by the Responder
Wisconsin	Corrosion from winter road salt has influenced the selection and service life of aluminum pipes.
Wyoming	Other: Soil and water samples taken at pipe locations are tested for resistivity, pH, and sulfates. Based on the test results, a CR (corrosion rating) is determined for the culvert location. A CR table was developed to choose the correct type of pipe, coating, bedding, and backfill material for a given CR. The table was based on selecting the appropriate culvert type for a 30 year design life.

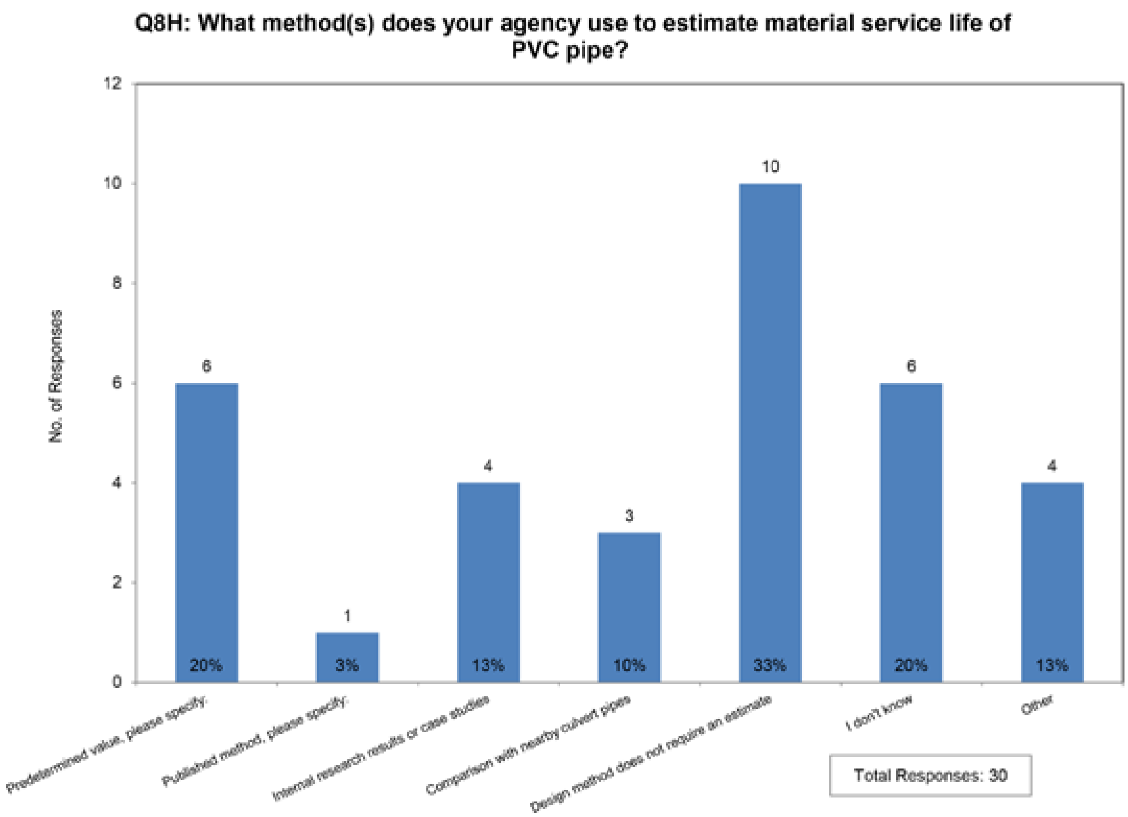


Q8G: What method(s) does your agency use to estimate material service life of HDPE pipe?

Responding Agency	Additional Information Provided by the Responder
Arizona	Other: Not in widespread use
Arkansas	Predetermined value: 25 year +
Colorado	Predetermined value: 50 year
Connecticut	Other: Inspection / manufacture information.
Delaware	Predetermined value: 100 years per AASHTO
Florida	Published method, please specify: FM 5-572, FM 5-573, FM 5-574
Georgia	Predetermined value: Values determine from in-house research.
Idaho	Other: Manufacturer Data
Maine	Predetermined value: 50 year design life. We are finding HDPE performs at a 50 year life when installed properly.
Massachusetts	Other: Inspection results.
Michigan	Published method, please specify: Ohio Culvert Inspection Manual, Case by case basis.
Minnesota	http://www.cts.umn.edu/Publications/ResearchReports/reportdetail.html?id=2184, A Research Plan and Report on Factors Affecting Culvert Pipe Service Life in Minnesota, Craig A. Taylor, Jeff Marr, 9/1/2012, Report no. MnDOT 2012-27
Nevada	Predetermined value, please specify: 75 years.
New Brunswick	Other: Inspection results
New York	Other: Industry Supplied
Ontario	Predetermined value, please specify: MTO Interim Gravity Pipe Design Guidelines. More detail available in our MTO Gravity Pipe Design Guidelines.
Pennsylvania	Other: We are using FDOT criteria for thermoplastic pipes.
Prince Edward Island	Other: Visual Inspections. We don't estimate service life per se. based on our available budget and out inventory, we take a 'worst first' approach. We visually inspect each structure on a triennial basis.

Q8G: What method(s) does your agency use to estimate material service life of HDPE pipe?

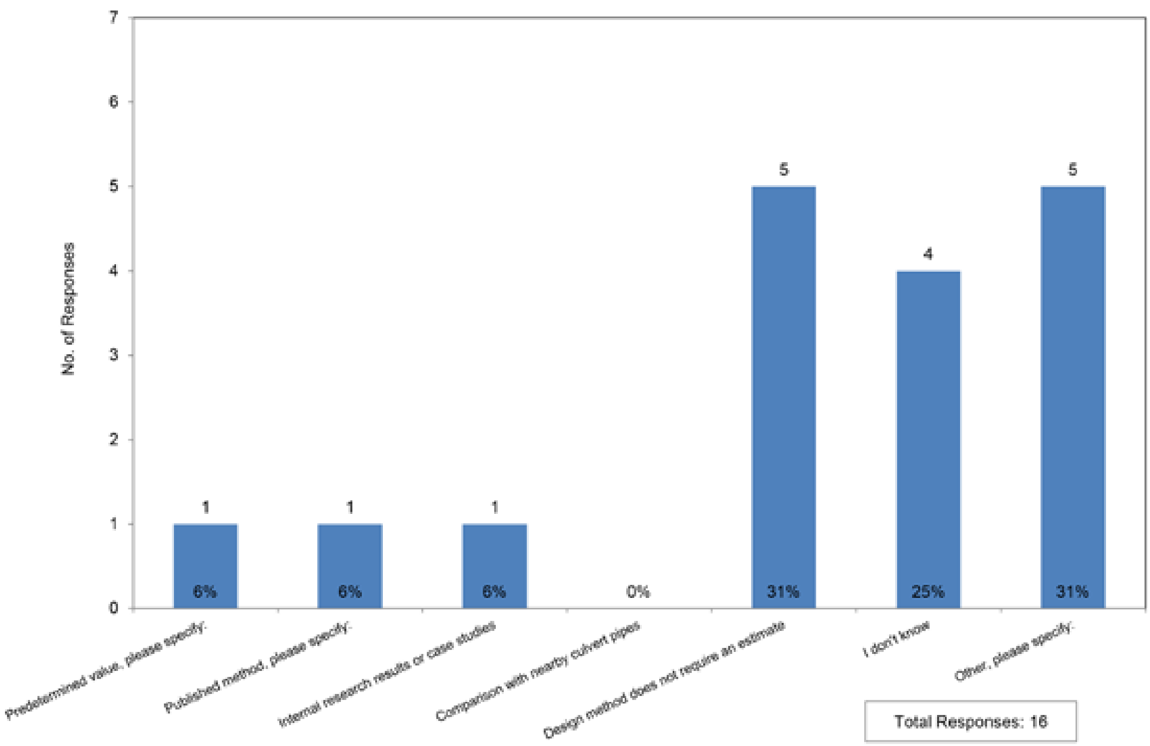
Responding Agency	Additional Information Provided by the Responder
South Carolina	Other: Again, a fixed value for Service Life is not estimated. The best practice would be inspection, forensics, and case studies of real world installations to determine an approximate value. Installation method, loading, environmental conditions, embankment properties, and even manufacturing practices will all play a roll in how long an individual pipe will last.
Virginia	Assumed 75-yr service life.
Wyoming	The main restrictions we currently place on these culverts are fill height limitations. Still developing service life process for this material type.



Q8H: What method(s) does your agency use to estimate material service life of PVC pipe?

Responding Agency	Additional Information Provided by the Responder
Colorado	Predetermined value: 50 year
Connecticut	Other: Inspection / manufacture information.
Florida	Breakdown for Predetermined value, please specify: >100 years
Georgia	Predetermined value: Values determine from in-house research.
Idaho	Other: Manufacturer Data
Maine	Predetermined value: 50 years based on field performance.
Minnesota	http://www.cts.umn.edu/Publications/ResearchReports/reportdetail.html?id=2184, A Research Plan and Report on Factors Affecting Culvert Pipe Service Life in Minnesota, Craig A. Taylor, Jeff Marr, 9/1/2012, Report no. MnDOT 2012-27
Ontario	Predetermined value, please specify: MTO Interim Gravity Pipe Design Guidelines. More detail available in our MTO Gravity Pipe Design Guidelines.
Oregon	Predetermined value: Manufacture
Pennsylvania	Other: We are using FDOT criteria for thermoplastic pipes.
Virginia	Assumed 75-yr service life.
Wyoming	The main restrictions we currently place on these culverts are fill height limitations. Still developing service life process for this material type.

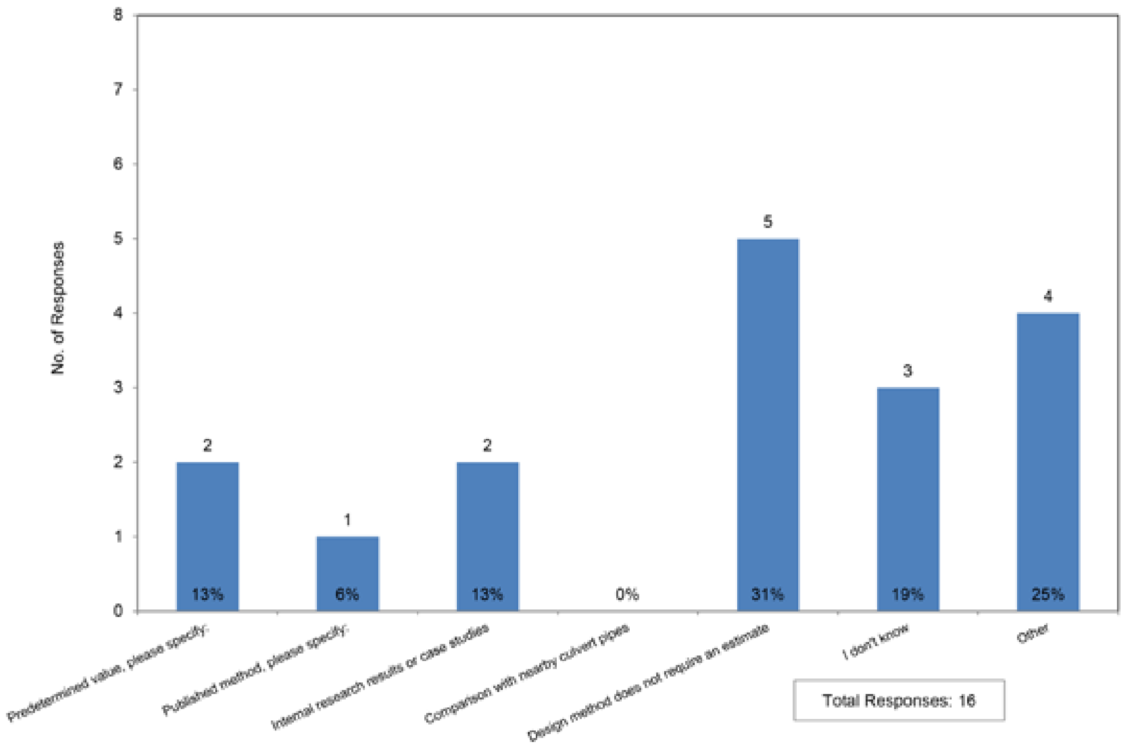
Q8I: What method(s) does your agency use to estimate material service life of polypropylene pipe?



Q8I: What method(s) does your agency use to estimate material service life of polypropylene pipe?

Responding Agency	Additional Information Provided by the Responder
Connecticut	Other: Inspection / manufacture information.
Florida	Published method, please specify: FM 5-572, FM 5-573, FM 5-574
Michigan	Other: MDOT is currently in the process of product approval. MDOT does not have experience with this product. Currently in the approval process.
Ontario	Predetermined value, please specify: MTO Interim Gravity Pipe Design Guidelines. More detail available in our MTO Gravity Pipe Design Guidelines.
Pennsylvania	Other: We are using FDOT criteria for thermoplastic pipes.
Maine	Pipe is only experimental so far.
Virginia	Assumed 75-yr service life.

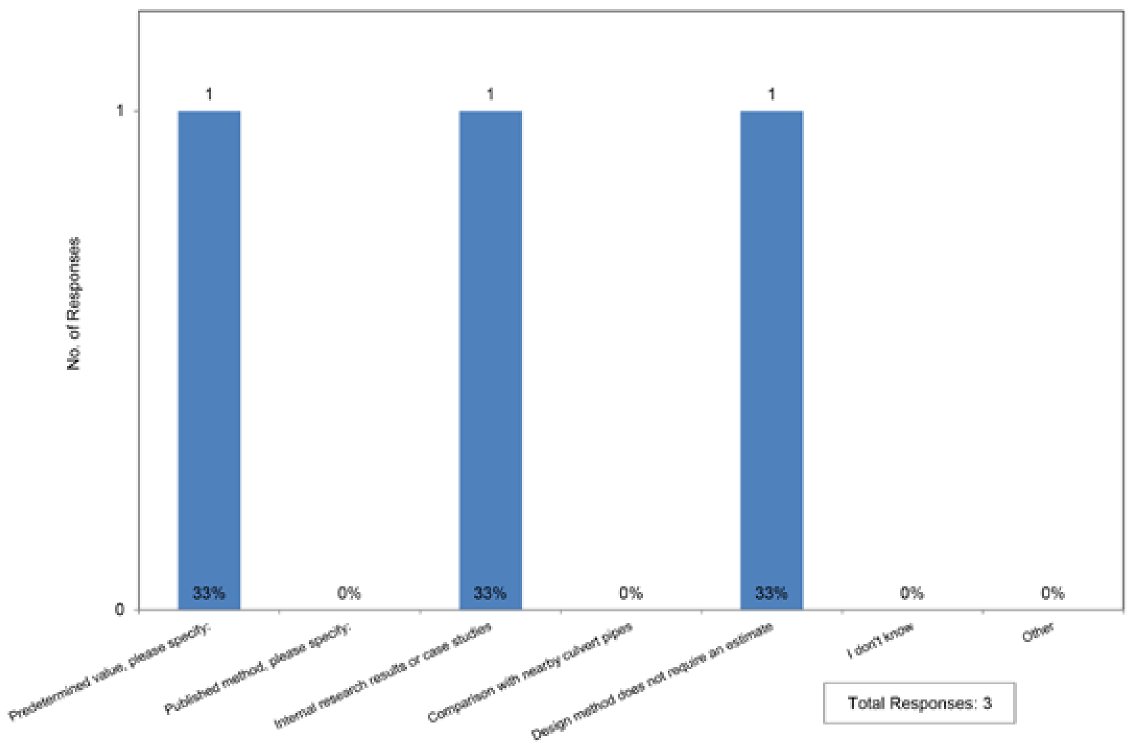
Q8J: What method(s) does your agency use to estimate material service life of steel-reinforced HDPE pipe?



Q8J: What method(s) does your agency use to estimate material service life of steel-reinforced HDPE pipe?

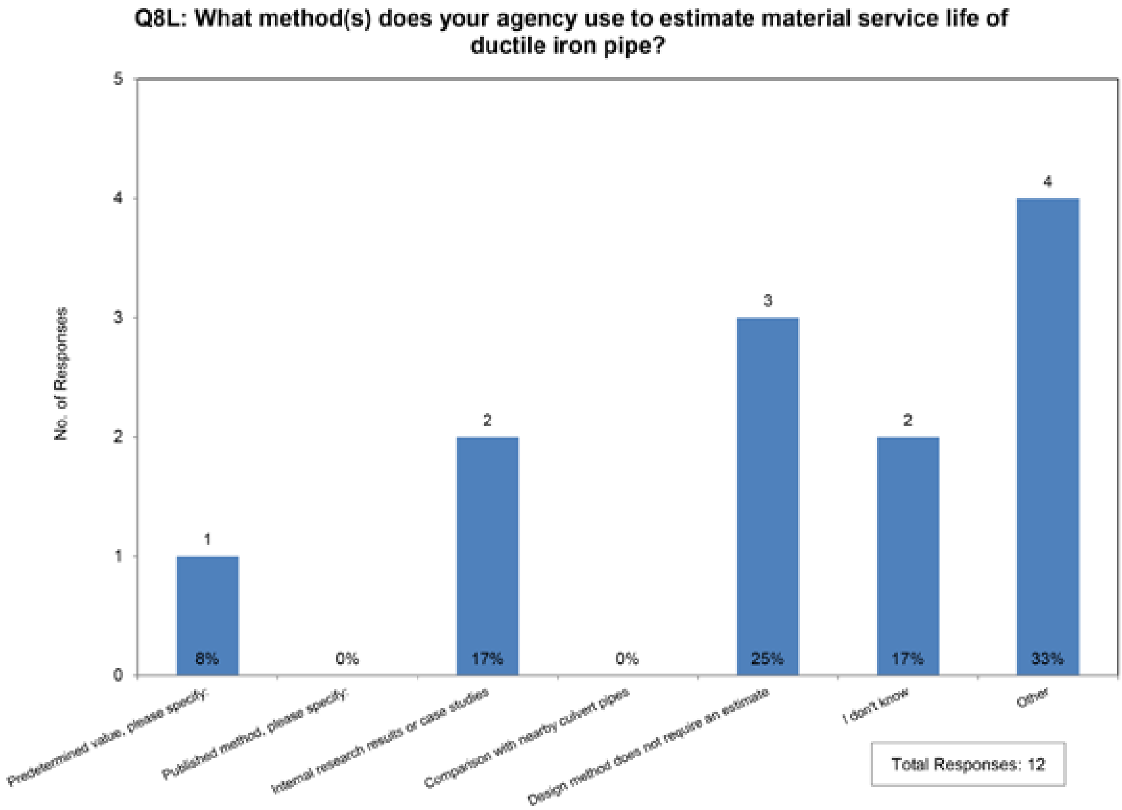
Responding Agency	Additional Information Provided by the Responder
Connecticut	Other: Inspection / manufacture information.
Delaware	Predetermined value: 100 years per AASHTO
Florida	Published method, please specify: FM 5-572, FM 5-573, FM 5-574.
Michigan	Other: MDOT does not have experience with this product. Currently in the approval process.
Nevada	Predetermined value, please specify: 75 years.
Ontario	Other: At this stage we have only started to consider use of this pipe material.
Virginia	Not yet used, may be trialed soon.

Q8K: What method(s) does your agency use to estimate material service life of vitrified clay pipe?



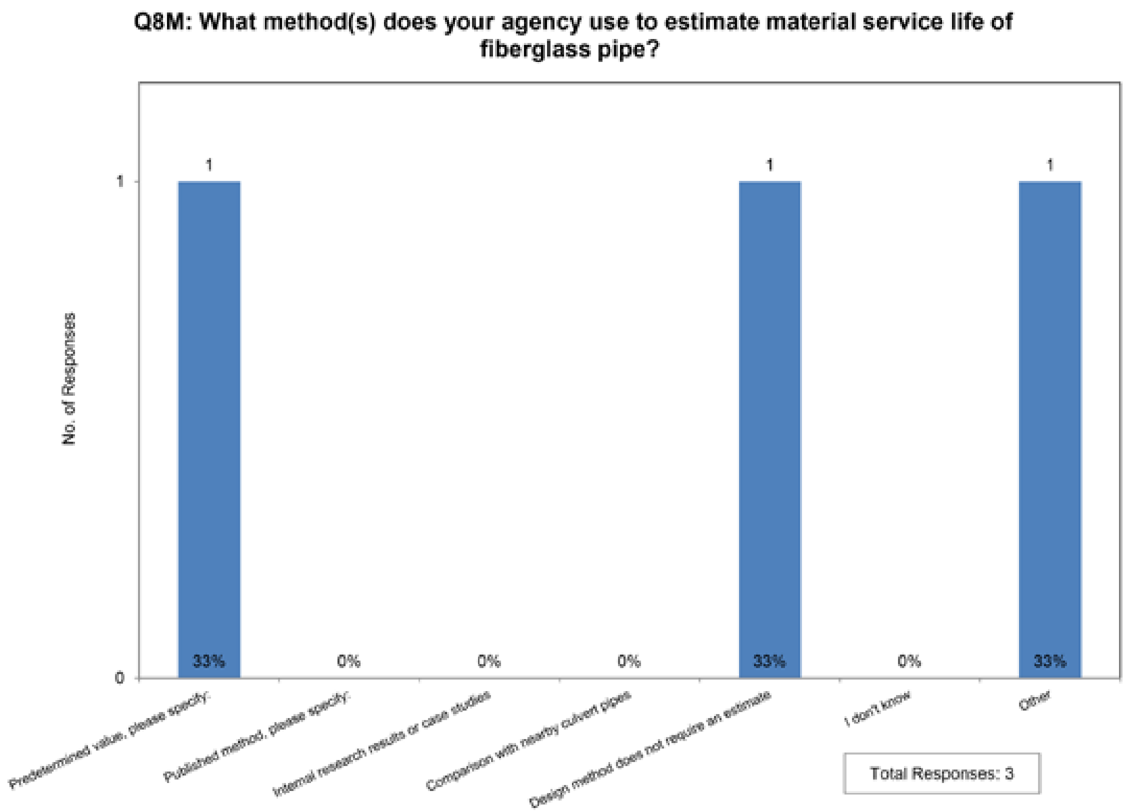
Q8K: What method(s) does your agency use to estimate material service life of vitrified clay pipe?

Responding Agency	Additional Information Provided by the Responder
Colorado	Predetermined value: 50 year



Q8L: What method(s) does your agency use to estimate material service life of ductile iron pipe?

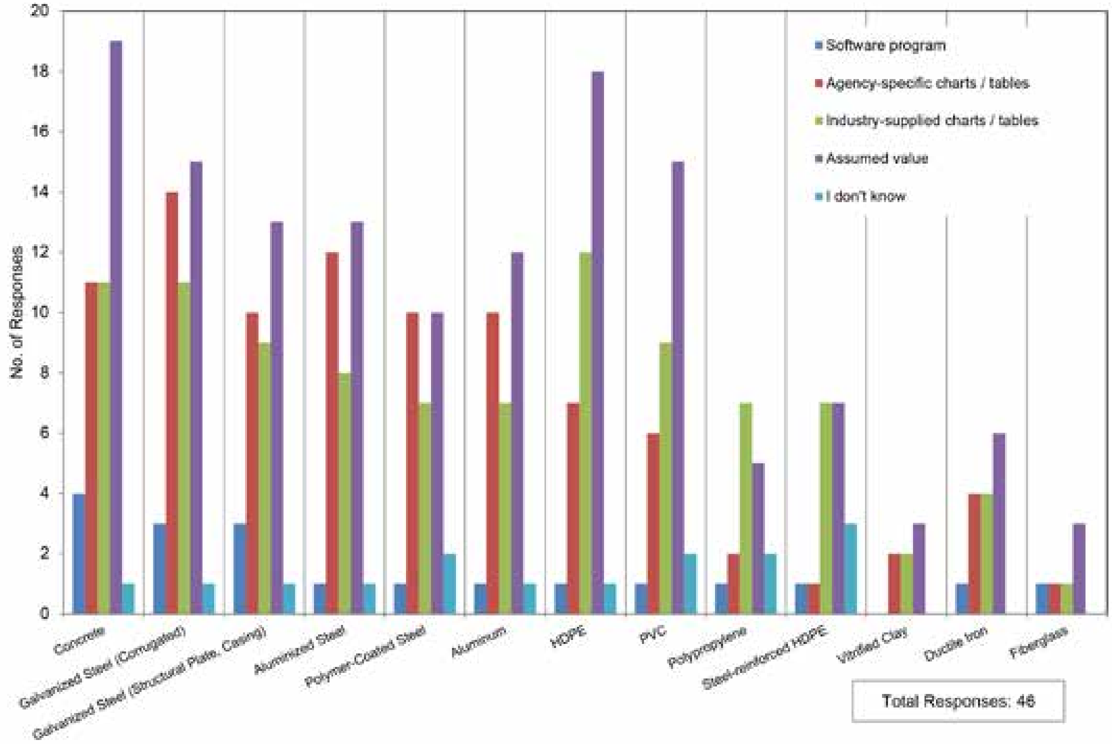
Responding Agency	Additional Information Provided by the Responder
Colorado	Predetermined value: 50 year
Massachusetts	Other: Inspection results.
Michigan	Case by case basis.
Pennsylvania	Other: We use manufacturers guide
Virginia	Assumed 75-yr life.
Wyoming	Other: Soil and water samples taken at pipe locations are tested for resistivity, pH, and sulfates. Based on the test results, a CR (corrosion rating) is determined for the culvert location. A CR table was developed to choose the correct type of pipe, coating, bedding, and backfill material for a given CR. The table was based on selecting the appropriate culvert type for a 30 year design life.



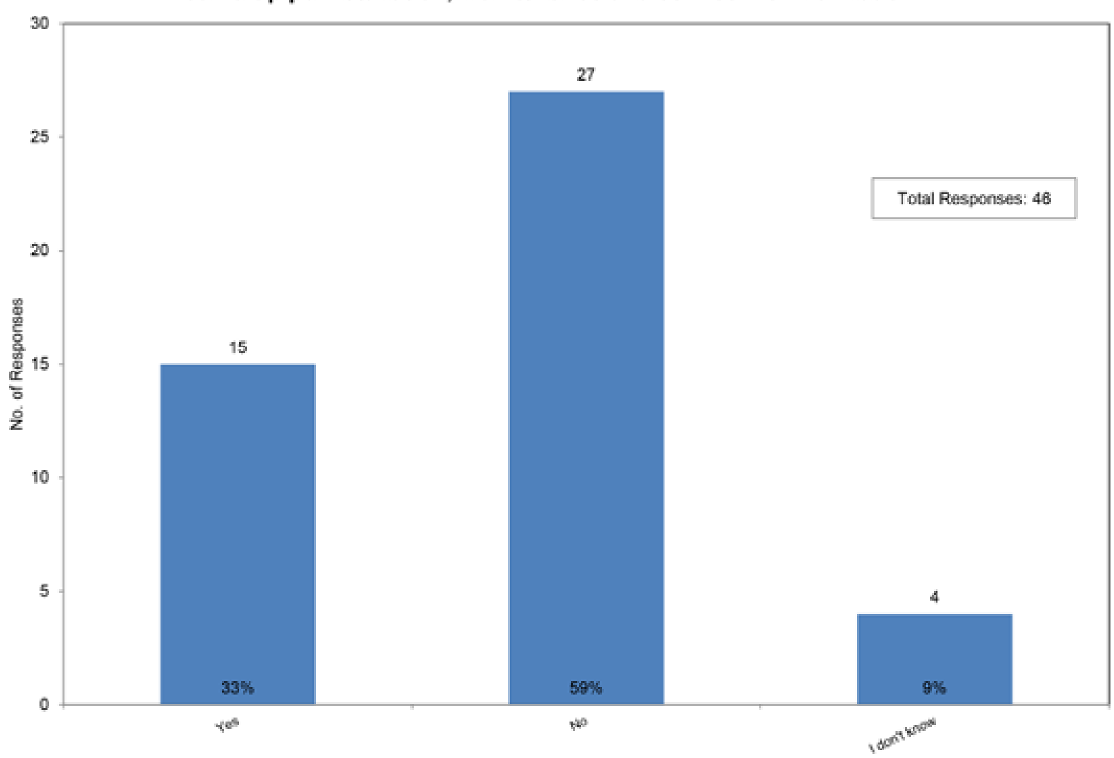
Q8M: What method(s) does your agency use to estimate material service life of fiberglass pipe?

Responding Agency	Additional Information Provided by the Responder
Florida	Predetermined value, please specify: > 100 years.
Virginia	Assumed 75-yr life.

Q9: Please indicate what tools your agency uses to estimate material service life.



Q10A: Does your agency use an information management system to manage culvert pipe installation, maintenance and service life information?

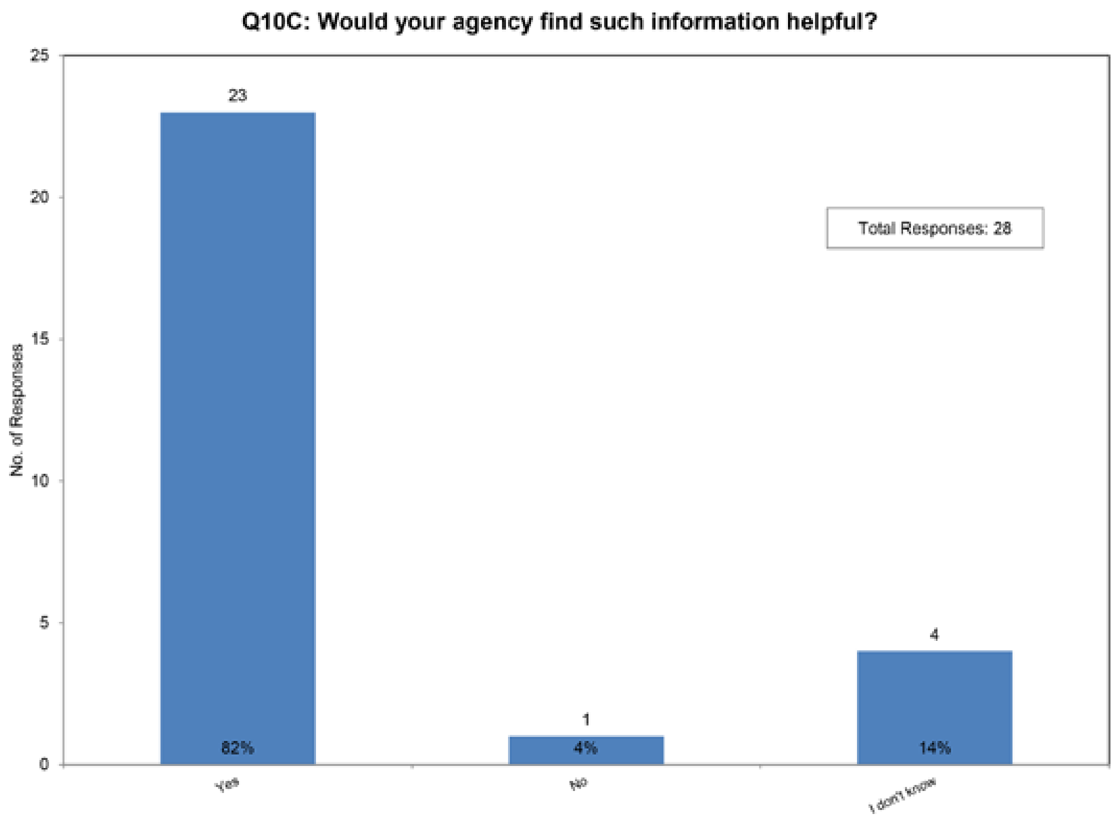


Q10B: Please describe how this data is used.

Responding Agency	Information Provided by the Responder
Delaware	For culvert systems with an opening over 20 sf, we consider them bridges and follow the NBIS procedures. For culvert systems with an opening smaller than 20 sf, we have just developed a database which will be used going forward.
District of Columbia	The data will be used to schedule and estimate future maintenance and replacement costs
Georgia	Information is used by Area Engineers to help manage pipe rehabilitation and replacement program.
Maine	We use a database for location and type of pipe. It has a general assessment of condition. This is used to assist Maintenance & operations and the Capital Program in decisions on replacements and rehab.
Michigan	We are just starting our ArcGIS program. MDOT needs to place all culvert assets in a database which we are working on. Inspector and maintenance will be able to access the information on their iPhone or iPad. There will be prompts for time to inspect, last inspection dates, culvert material information, photos. Used to determine previous culvert condition and current culvert conditions and need for repairs and/or upgrades.
Minnesota	MnDOT has an inventory and inspection database. We also collect some data on highway culvert repairs and rehabilitation. Currently we are working towards collecting data on repair costs for use in moving towards an asset management system. http://www.dot.state.mn.us/bridge/pdf/hydraulics/HYDINFRA_Culvert_and_Storm_Drainage_System_Inspection_Manual.pdf , http://www.dot.state.mn.us/bridge/hydraulics/hydinfra.html.
New Brunswick	Inspection results and asset condition ratings.
New York	Large Culvert Inventory and inspection system. Culvert condition and GPS location is gathered in field and uploaded to a database that can be accessed by regional personnel.
Oregon	ODOT has a Drainage Facility Management System database that is used to track ands rate culverts along the State's highways.
Prince Edward Island	We are in the process of inputting our culvert data into our Bridge Management software. This will be used to track detailed condition state data on each element of the culvert and better prepare ourselves for capital investments on culvert repair/rehabilitation/replacement in the future.
Saskatchewan	The Ministry has an inventorydatabase of all of its culverts and a condition database for all of the culverts greater than 3 meters in diameter. The information is used manually in the development of the annual culvert replacement program.

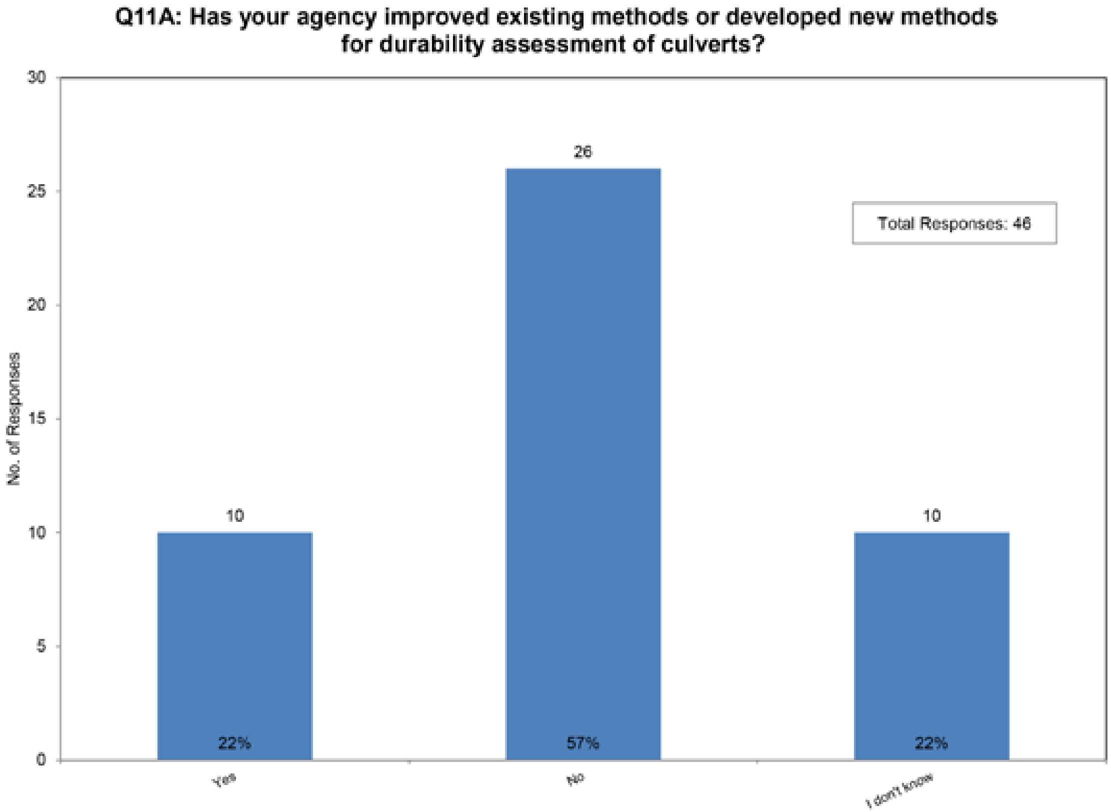
Q10B: Please describe how this data is used.

Responding Agency	Information Provided by the Responder
South Carolina	Pipe material, diameter, strength, location, & fill conditions are collected. Ultimately, this will facilitate tracking trends if specific pipe types/sizes/install depths are more susceptible to damage/failure to address the design of these conditions.
Utah	A GIS map of culverts in Utah is used to locate culverts statewide and obtain basic information on the condition of each cross culvert. This GIS map link: http://uplan.maps.arcgis.com/home/webmap/viewer.html?webmap=a371199ec2db4371a6cb71ded4da6616
Washington	Our maintenance personnel keep an inventory of all roadway features including culverts, storm sewers, signs, guardrail, etc. The data is now used mostly for maintenance but is being phased into use by designers scoping culvert rehab and replacement projects.
Yukon	Each culvert is inspected every 2nd year. Collected structured data is entered into database software to find different performance parameters for design making.



Q10D: Please identify possible barriers to implementing such a system at your agency.

Responding Agency	Information Provided by the Responder
California	In progress
Colorado	Time and money
Connecticut	Data entry and maintenance of the system.
Florida	Cost, initial information uploading effort.
Idaho	Cost
Missouri	We are currently evaluating this type of system, and are constrained by budget priorities.
Ohio	We are in the beginnings of developing this system. We have an inventory of our conduits that id developing. The management of the system based on the data is an ongoing process.
Oklahoma	Man power, Time
Ontario	Currently we are developing such a system, however, it is not complete or functional at this time.
Vermont	We currently do not have a complete inventory of culverts so generating service life specific to our state and regions would be challenging. We are currently developing the database and procedures to support culvert and drainage data management to support this kind of analysis in the future.
Virginia	Funding and manpower
Washington	NDOT is assembling an asset management database. We can search by contract and pipe type, which will help us determine which pipes need inspection and possible replacement.
Massachusetts	MassDOT is currently implementing an asset management program. With additional resources, this information could be included as the program develops.
Wisconsin	Information management system is being considered at this time.
Wyoming	Manpower requirements to collect initial data and potentially cost of this type of system.



Q11B: Please could you provide the final reports, specifications, test methods or other results of the research.
Alternatively, please provide publically-accessible links to the research results.

Responding Agency	Information Provided by the Responder
Alberta	http://www.transportation.alberta.ca/Content/docType253/Production/bstprculvtyp.pdf
District of Columbia	DDOT is in the process of devevloping a database, it should be complete by November, 2014.
Florida	http://www.dot.state.fl.us/statematerialsoffice/laboratory/corrosion/hdpe/index.shtm
Michigan	This is not public yet, I can't share yet. MDOT is seeking to compile further information, as well.
Minnesota	http://www.cts.umn.edu/Publications/ResearchReports/reportdetail.html?id=2184, A Research Plan and Report on Factors Affecting Culvert Pipe Service Life in Minnesota, Craig A. Taylor, Jeff Marr, 9/1/2012, Report no. MnDOT 2012-27. HydInfra inventory and inspection information can be found at http://www.dot.state.mn.us/bridge/hydraulics/hydinfra.html.
New Brunswick	Not available in publically accessible form.
Ohio	We have current ongoing research to address this need.
Ontario	http://www.mto.gov.on.ca/english/engineering/drainage/index.shtml

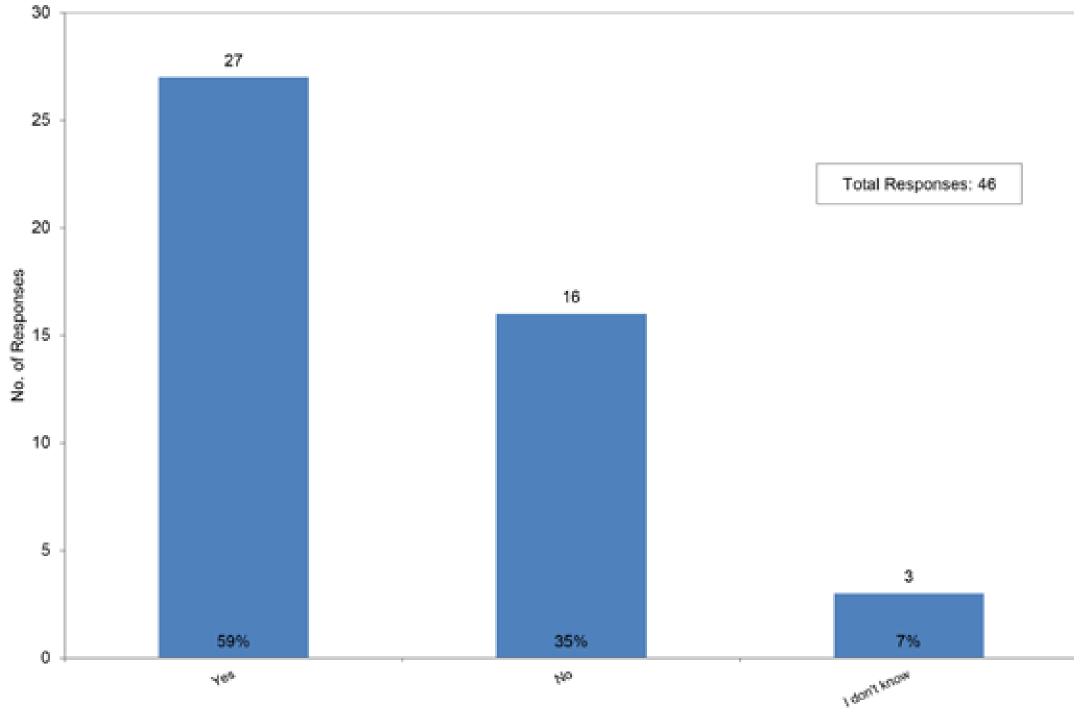
Q11C: Please indicate the main reasons why no research has been undertaken.

Responding Agency	Information Provided by the Responder
Arizona	Limited research budget. We'd rather let other, larger DOT's or FHWA do this type of research and we'll consider results afterward.
Arkansas	Lack of interest. No formal policy. Some pipe culvert installations last 60+ years, while others rust away in 30 years or less. Very site specific. Chemical and soil PH big factors.
Colorado	Time and money
Delaware	Small state with limited funding. Money goes toward more critical needs.
Georgia	Not a top priority.
Idaho	Standard Design Procedure
Iowa	The department has not had significant problems with culvert failures.
Maine	We have done durability assessments on galv, alum type 2, polymer coating. We have HDPE and PP experimental locations where performance is evaluated. But no new or advanced methods are used.
Massachusetts	At present, structures with spans 8' or greater are inspected periodically.
Missouri	Budget priorities
New Hampshire	Awaiting research that other states or venders complete.
Oklahoma	Lack of Man power and Time
Prince Edward Island	Small, underfunded agency. No budget for R&D.
Saskatchewan	Not a priority area for research.
South Carolina	Cost. Improved specifications, design requirements, installation requirements, and inspection practices have been implemented, but usable durability research has not.
Virginia	We have a set of standards, specs, inspection requirements, and material approvals that take care of ensuring good product with proper selection and installation.
Washington	Lack of need, personnel, time and budget
West Virginia	Manpower/priority

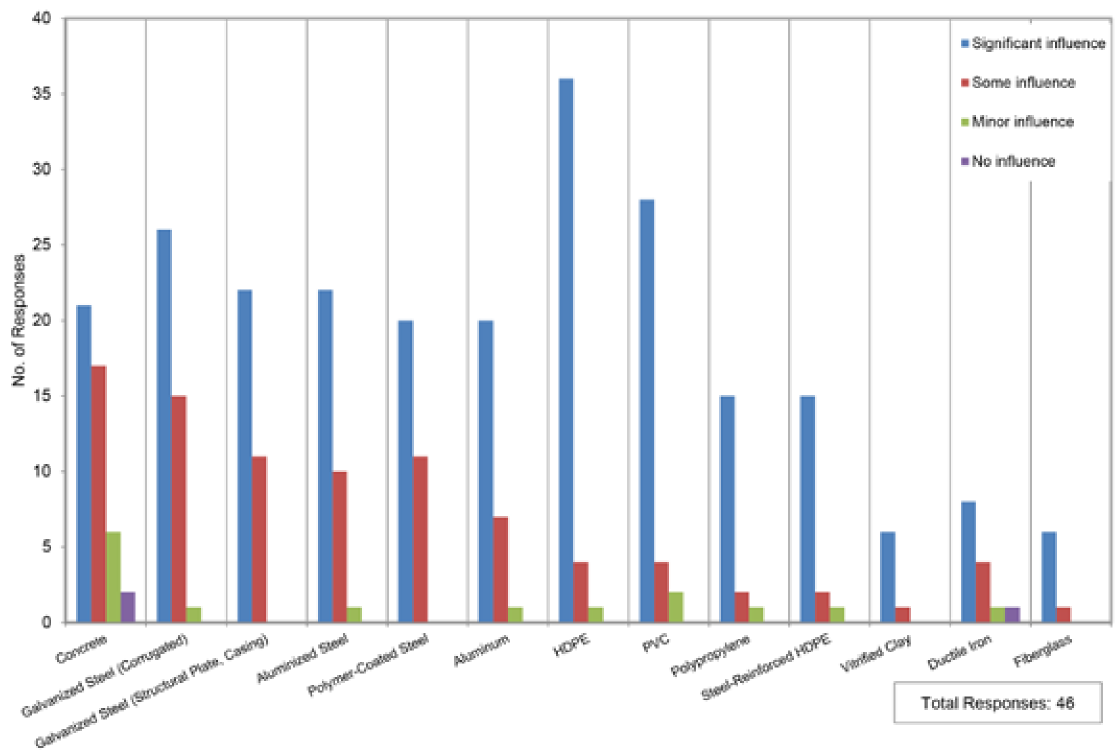
Q11C: Please indicate the main reasons why no research has been undertaken.

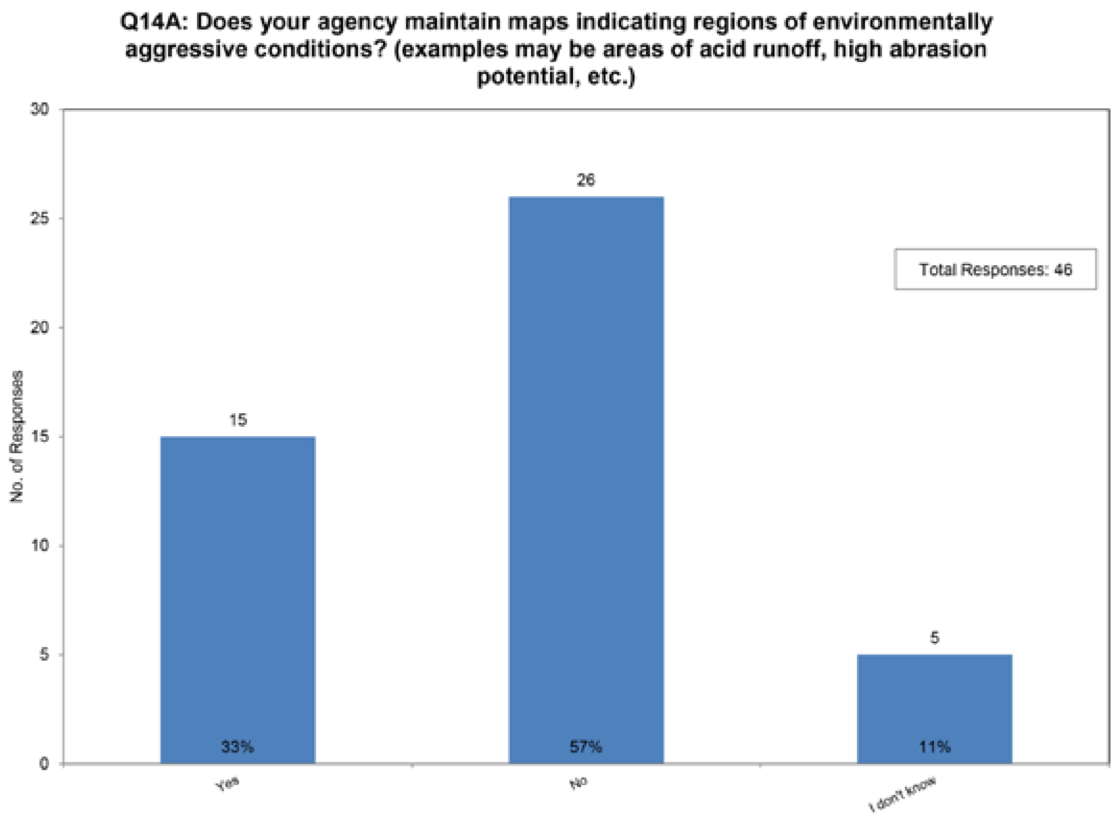
Responding Agency	Information Provided by the Responder
Wisconsin	Not required by the FHWA like bridges are. It has not been a priority.
Wyoming	Our current procedures seem to be working well and was thoroughly researched during initial development. They are currently looking at ways to better assess abrasion characteristics in determining culvert life.

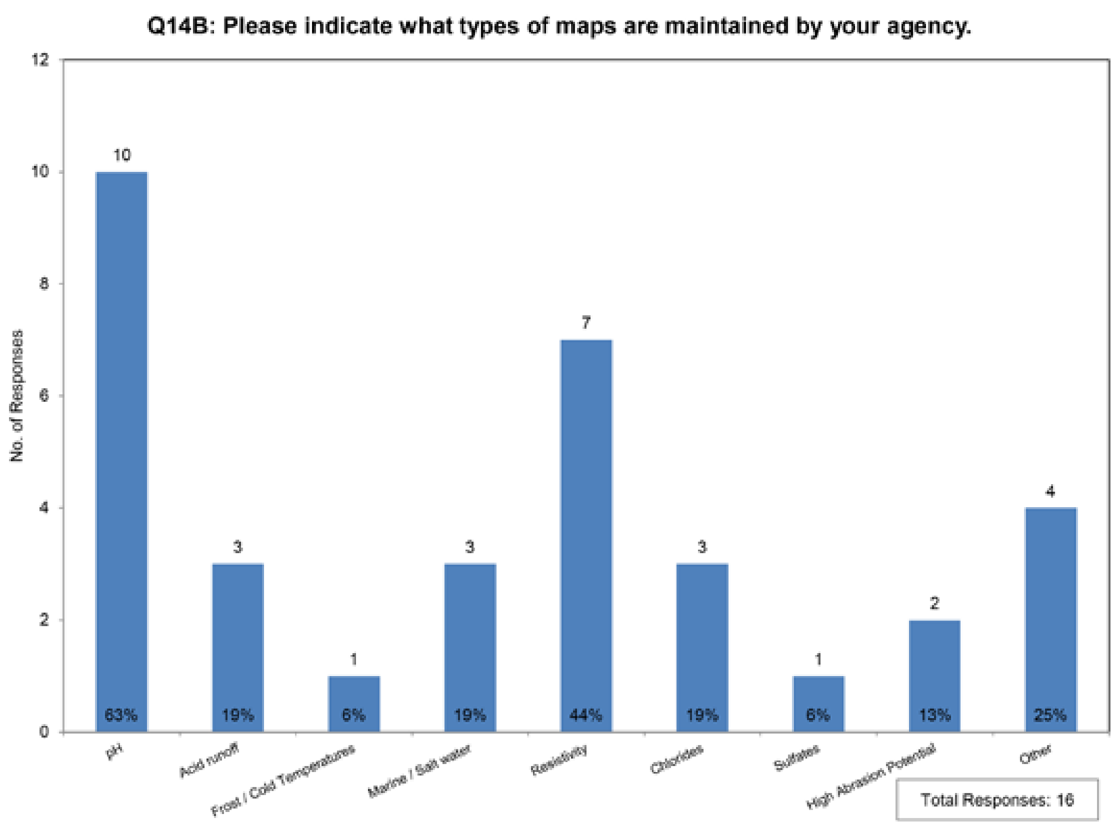
Q12: Does you agency have a formal inspection policy to monitor culvert conditions over time?



Q13: Please rate your agency's experience on how installation quality affects culvert pipe performance (hydraulic, structural or durability).

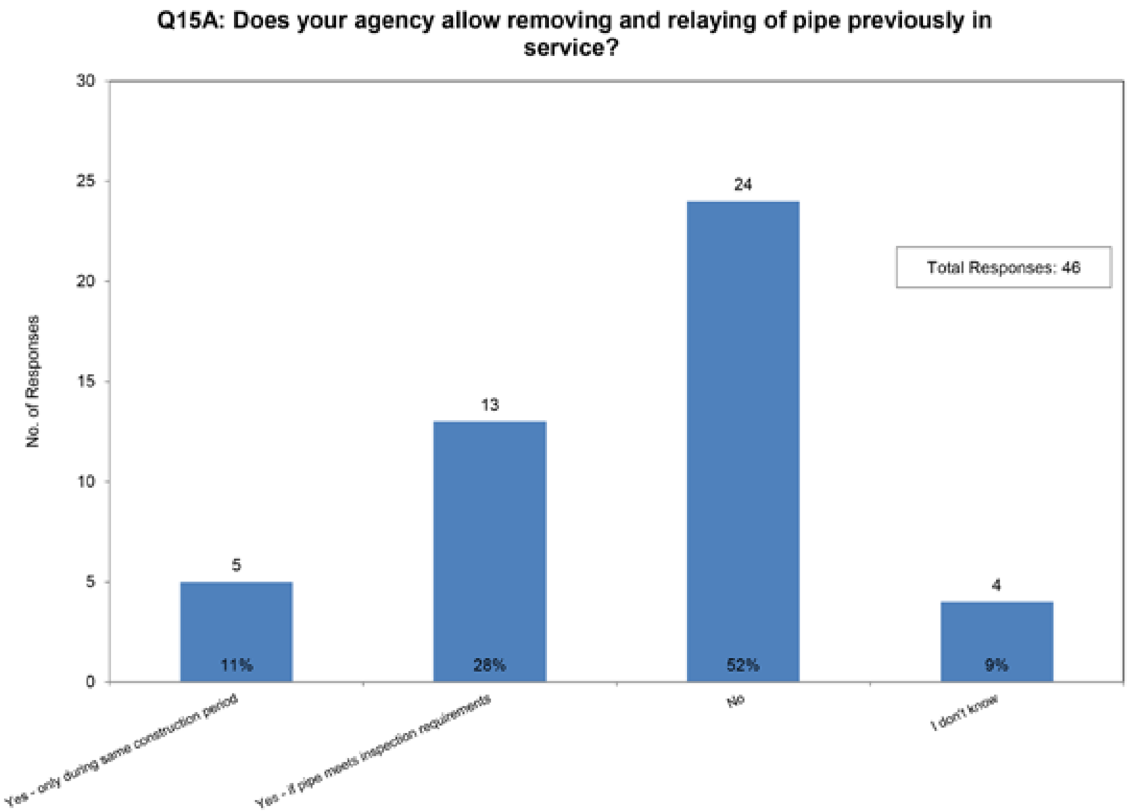


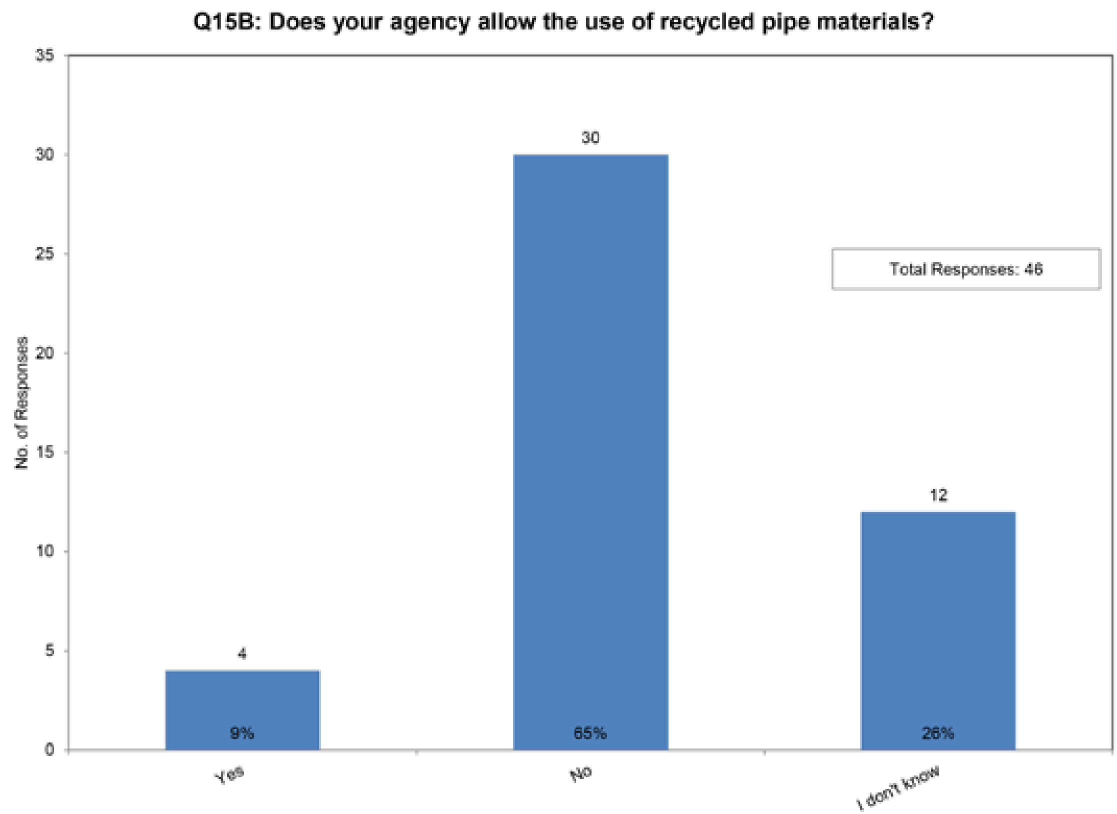

Q14A: Does your agency maintain maps indicating regions of environmentally aggressive conditions? (examples may be areas of acid runoff, high abrasion potential, etc.)
No. of Responses
30
25
20
15
10
5
0
26
15
5
33%
57%
11%
Total Responses: 46
Yes
No
I don't know

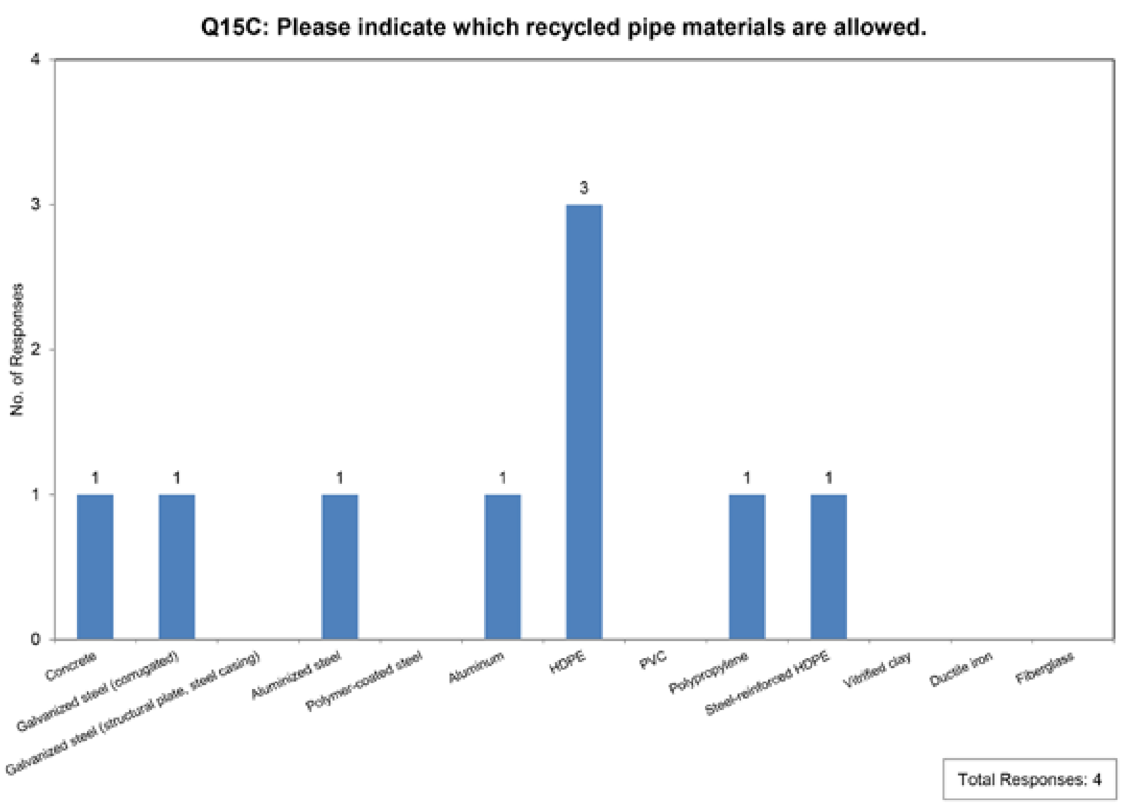

Q14B: Please indicate what types of maps are maintained by your agency.
No. of Responses
12
10
8
6
4
2
0
10
3
1
3
7
3
1
2
4
63%
19%
6%
19%
44%
19%
6%
13%
25%
pH
Acid runoff
Frost / Cold Temperatures
Marine / Salt water
Resistivity
Chlorides
Sulfates
High Abrasion Potential
Other
Total Responses: 16

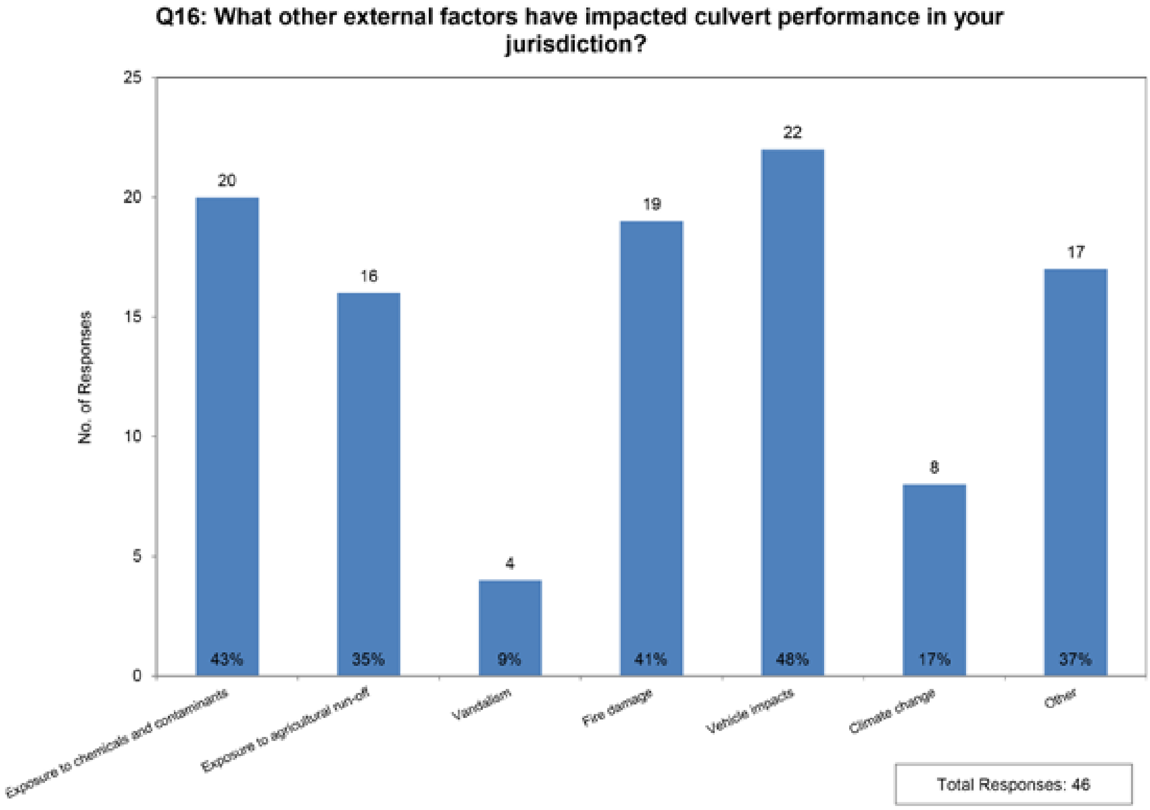
Q14B: Please indicate what types of maps are maintained by your agency.

Responding Agency	Additional Information Provided by the Responder
Michigan	Tidal flows (water runs both ways in pipes)



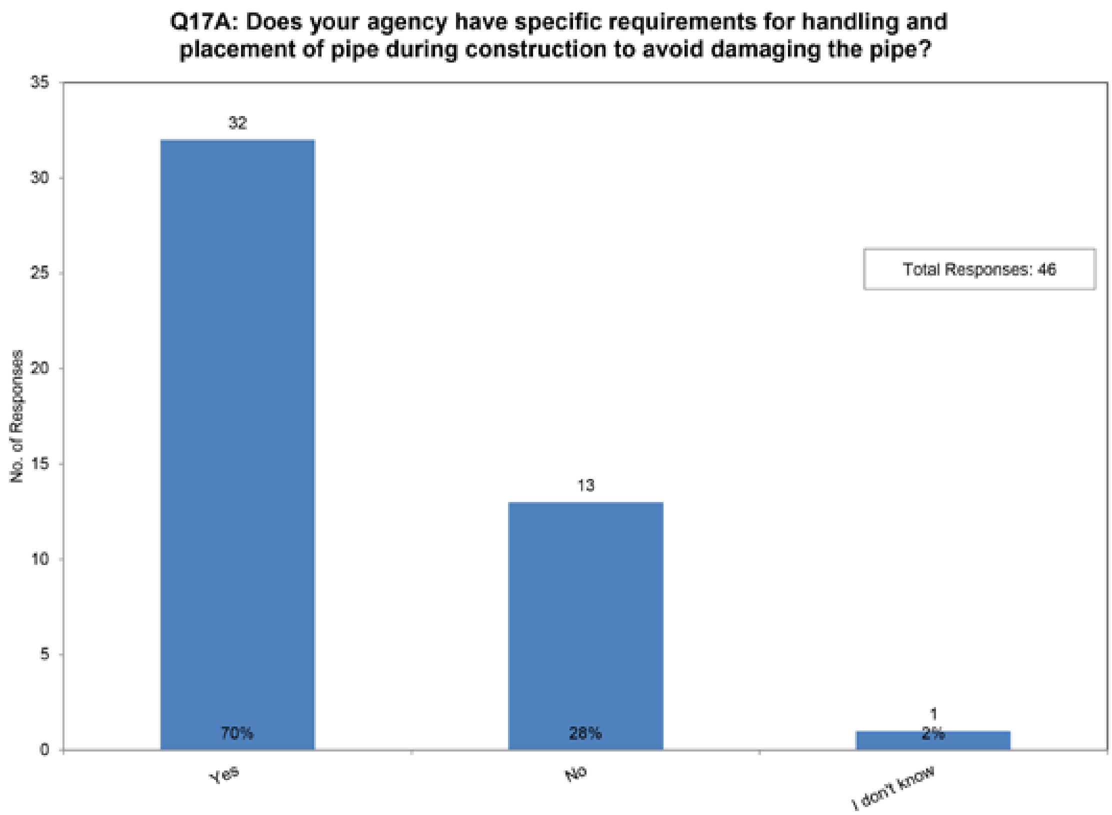

Q15B: Does your agency allow the use of recycled pipe materials?
No. of Responses
35
30
25
20
15
10
5
0
30
12
4
9%
65%
26%
Total Responses: 46
Yes
No
I don't know

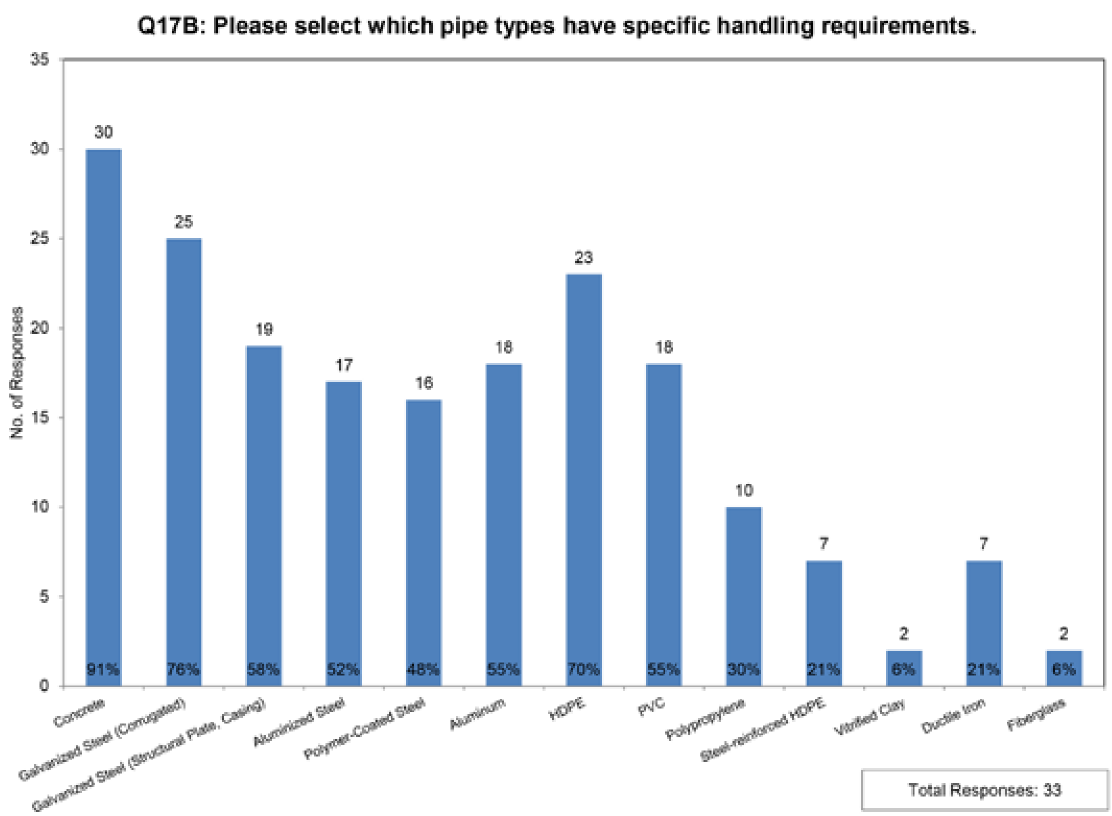

Q15C: Please indicate which recycled pipe materials are allowed.
No. of Responses
4
3
2
1
0
1
1
1
1
3
1
1
Concrete
Galvanized steel (corrugated)
Galvanized steel (structural plate, steel casing)
Aluminized steel
Polymer-coated steel
Aluminum
HDPE
PVC
Polypropylene
Steel-reinforced HDPE
Vitrified clay
Ductile iron
Fiberglass
Total Responses: 4

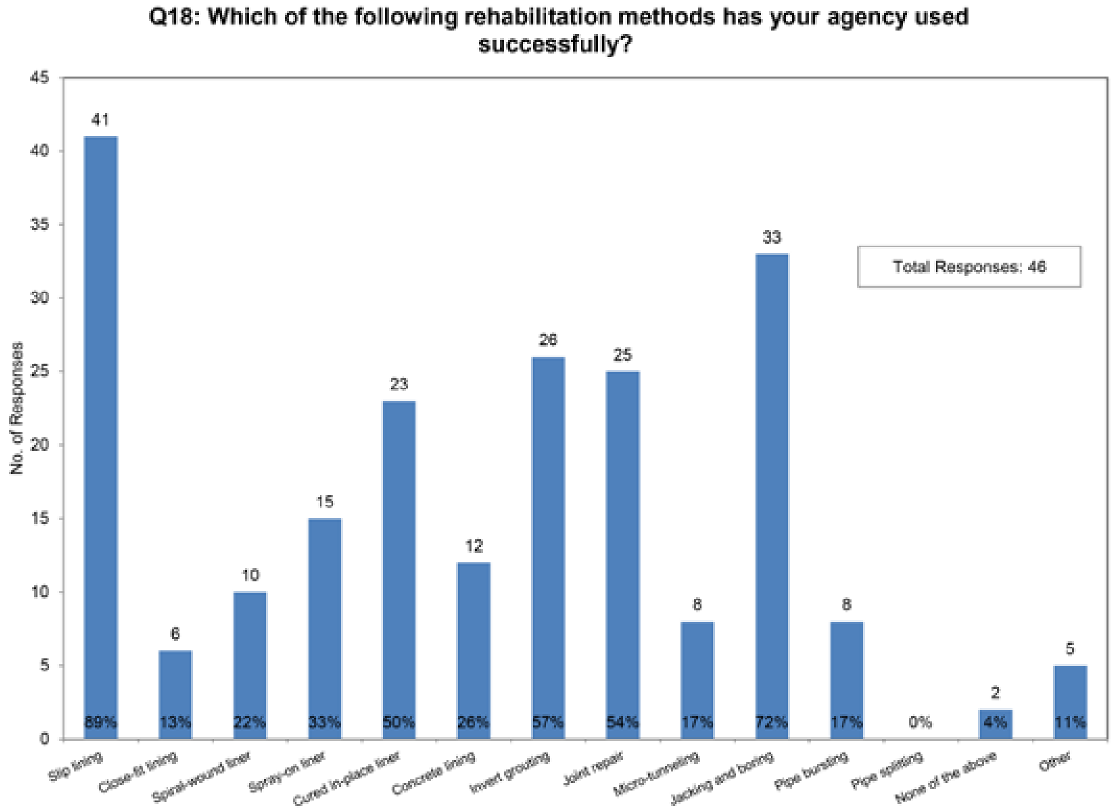


Q16: What other external factors have impacted culvert performance in your jurisdiction?

Responding Agency	Additional Information Provided by the Responder
Minnesota	Other: bogs, wetlands acidic water, frost heave, bad soils, utility hits.
Nevada	Other: aggradation/degradation
New Brunswick	Other: Ice Impact, Debris Clogging
Ohio	Other: Lack of Maintenance Activities
South Carolina	Other: Installation issues, Structural Loading (particularly construction loading), handling damage, field cuts, improper jointing & homing or pulling of joints, differential settlement.
Tennessee	Other: acidic soils
Vermont	Other: proper ditching procedures
Virginia	Other: Local experience.
Washington	Other: Climate
Wyoming	Other: high alkali water discharged during methane well development.
Yukon	Other: Flooding, Washout, Drift accumulation

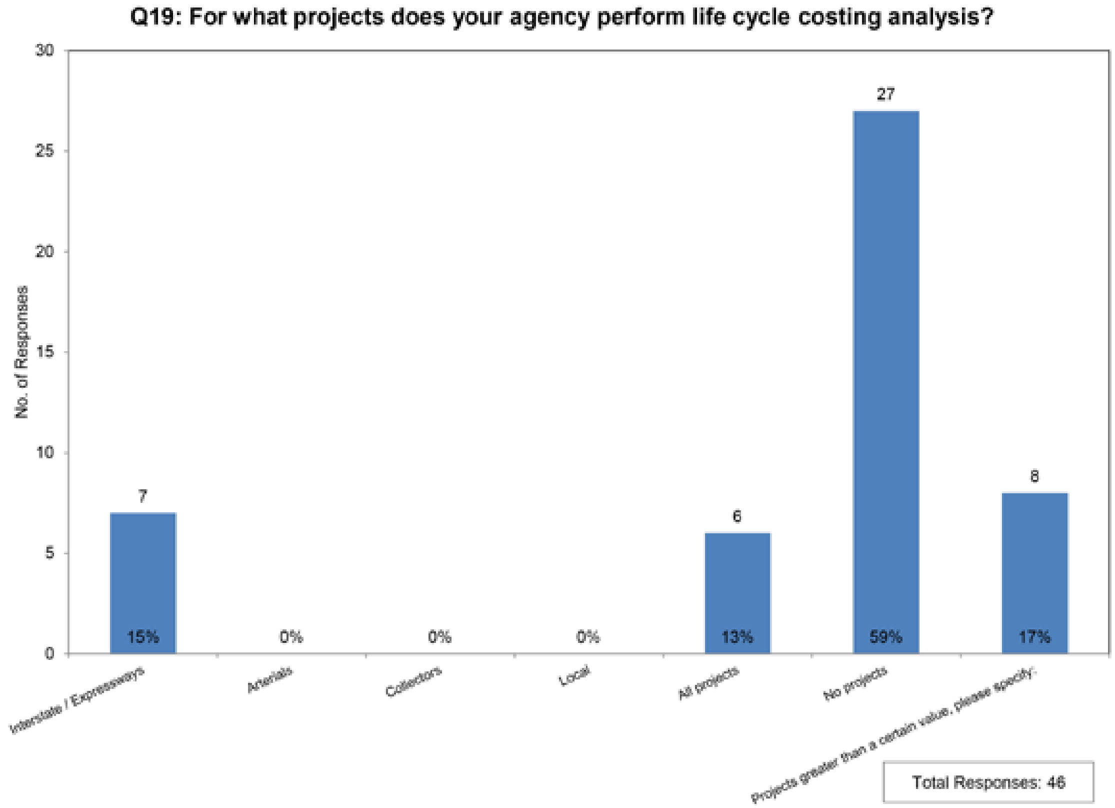

Q17A: Does your agency have specific requirements for handling and placement of pipe during construction to avoid damaging the pipe?
No. of Responses
35
30
25
20
15
10
5
0
32
13
1
70%
28%
2%
Yes
No
I don't know
Total Responses: 46


Q17B: Please select which pipe types have specific handling requirements.
No. of Responses
35
30
25
20
15
10
5
0
30
25
19
17
16
18
23
18
10
7
2
7
2
91%
76%
58%
52%
48%
55%
70%
55%
30%
21%
6%
21%
6%
Concrete
Galvanized Steel (Corrugated)
Galvanized Steel (Structural Plate, Casing)
Aluminized Steel
Polymer-Coated Steel
Aluminum
HDPE
PVC
Polypropylene
Steel-reinforced HDPE
Vitrified Clay
Ductile Iron
Fiberglass
Total Responses: 33



Q18: Which of the following rehabilitation methods has your agency used successfully?

Responding Agency	Additional Information Provided by the Responder
New Brunswick	Other: structural concrete invert
South Carolina	Other: internal joint seals, crack removal and grouting



Q19: For what projects does your agency perform life cycle costing analysis?

Responding Agency	Additional Information Provided by the Responder
Arizona	Projects greater than a certain value, please specify: $15,000,000
Minnesota	Projects greater than a certain value, please specify: None yet but collecting cost data for future.
Missouri	Projects greater than a certain value, please specify: Larger projects, typically associated with pavement selection.
Montana	We do not perform life cycle costing on all projects only when warranted during the design process when comparing options.

APPENDIX B

Summary of Service Life Calculation Methods

INTRODUCTION

This appendix to NCHRP Project 20-05 *Synthesis Topic 45-01, Service Life of Culverts*, provides a summary of 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.

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. No definitive design methods estimate 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 or water have a pH of 5.5 or less, concrete pipes should be required to have extra cover over the reinforcing steel or a protective coating.

Table B1 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 and because no specific national guidance is available, each agency must select which EMSL value(s) to use for design from the range of available methods. The limitations and range of parameters for which each method is applicable are described in detail for each method.

TABLE B1
METHODS FOR DETERMINING EMSLS FOR REINFORCED CONCRETE PIPE

Durability Method	Reference	Notes
Ohio DOT Model	Potter (1990)	Based on large data set over a wide range of pH and size values. Includes an abrasive component.
Hurd Model	Potter (1990)	Method developed for large-diameter pipes in acidic environments.
Hadipriono Model	Potter (1990)	Method includes a wide pH range.
Florida DOT Model	*Drainage Manual—Optional Pipe Material Handbook* (FDOT 2012)	Considers corrosion to be the only mechanism of degradation.

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), and

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 to not 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).

Hadipriono Model

The Hadipriono model is applicable to sites with pH values between 2.5 and 9, and is given by the following equation:

$$EMSL = -33.23 + 160.92 \times \log pH - 4.16 \times Slope^{0.5} - 0.28 \times Rise$$

where:

EMSL = estimated material service life (years),

pH = pH of the water,

Slope = pipe invert slope (%), and

Rise = vertical pipe diameter (inches).

Ohio DOT (ODOT) Model

The ODOT model comprises two separate equations, depending on the pH level.

For pH values between 2.5 and 7:

$$EMSL = \left(\frac{[0.349 \times pH^{1.204}]^{7.758}}{Slope^{0.834}}\right)\left(\frac{1 - Sediment}{Rise}\right)^{-5.912}$$

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), and

K = abrasive constant (0.9 – without abrasive flow, 1.19 – with abrasive flow).

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

$$EMSL = 1{,}000(1.107^{C}C^{0.717}D^{1.22}K^{-0.37}W^{-0.631}) - 4.22 \times 10^{10}(pH^{-14.1}) - 2.94 \times 10^{-3}(S) + 4.41$$

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 (%), and

S = sulfate content (ppm).

This equation was developed for a 60-in.-diameter pipe. The adjustment factors shown in Table B2 must be applied depending on the actual pipe size.

TABLE B2
FDOT CONVERSION FACTORS FOR DIFFERENT-SIZED CULVERTS

Pipe Diameter (in.)	Factor	Pipe Diameter (in.)	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

Figure 6-4 (Figure B1) and Table 6-5 (Table B3) of the FDOT *Optional Pipe Material Handbook* (February FDOT 2012) illustrate the use of this equation and provide a chart showing the relationship between service life, chloride concentration, and pH.

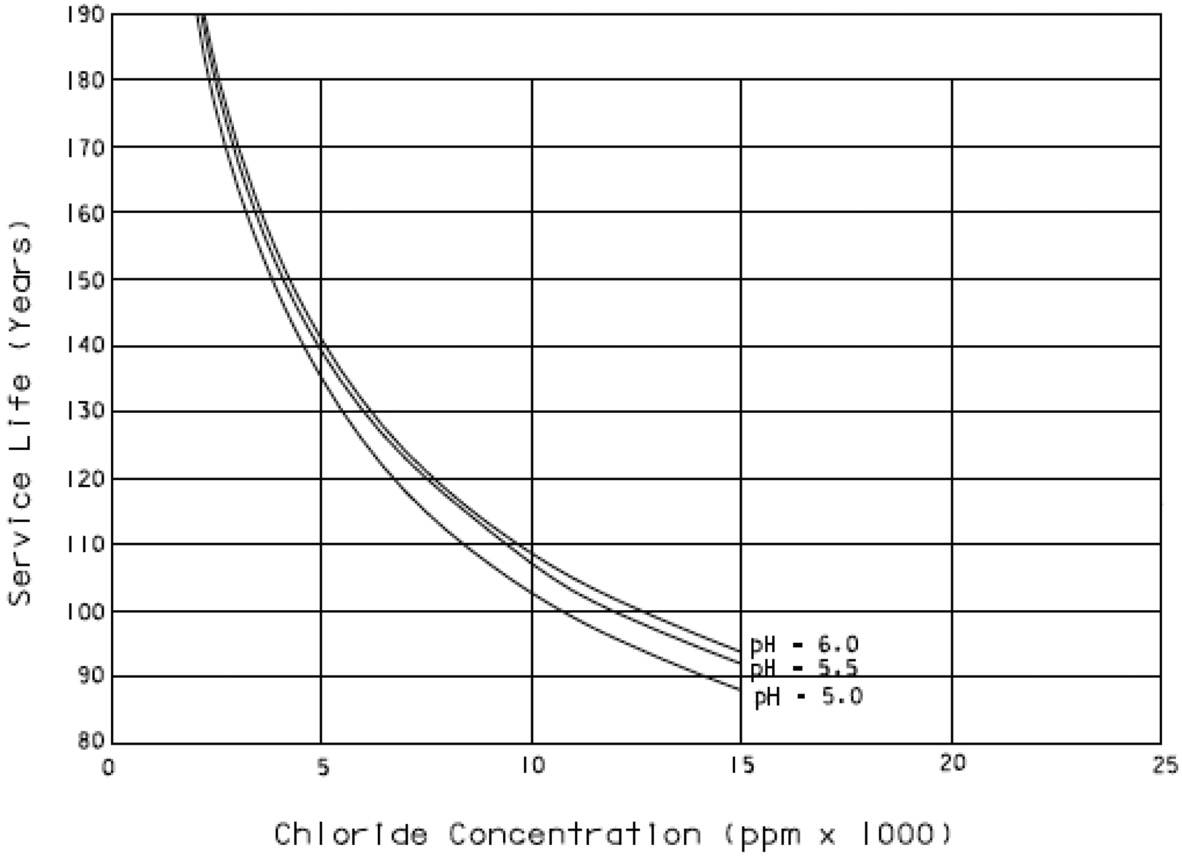


FIGURE B1 Estimated service life versus pH and resistivity for 60-in.-diameter concrete culverts, *S* = 1,500 ppm (FDOT 2012).

TABLE B3

ESTIMATED SERVICE LIFE VERSUS PH AND CHLORIDES FOR 60-IN.-DIAMETER REINFORCED CONCRETE CULVERTS AT 1,500 PPM SULFATE CONCENTRATION (FDOT 2012)

	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.

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

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.

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 B4 lists the methods that can be used to determine EMSL values for plain galvanized steel pipes.

TABLE B4
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* (Caltrans 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* (FHWA 2008)	Modification of California method. Increases 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 Material Handbook* (2012)	Modification of California method to include a minimum steel thickness of 16 gage.
NCSPA Recommendations	*Pipe Selection Guide* (NCSPA 2010)	Includes combined effects of corrosion and abrasion. Based on soil/water pH and resistivity. Service life of pipe considered to be until time of invert perforation.
Utah DOT Method	*UDOT-IMP-76-1, Pipe Selection for Corrosion Resistance* (Leatham and Peterson 1977)	Result of Utah DOT study of 58 installations. The method considers corrosion alone through the following four parameters: minimum soil resistivity, pH, total soluble salts, and sulfate content.

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.

California Method

A chart useful for application of the California method is presented in Figure B2. 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:

$$EMSL = 13.79(\log R - \log[2160 - 2490 \times \log pH])$$

where R is the minimum resistivity (ohm-cm).

The resulting EMSL value must be multiplied by a factor depending on the gage thickness (Table B5).

TABLE B5
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

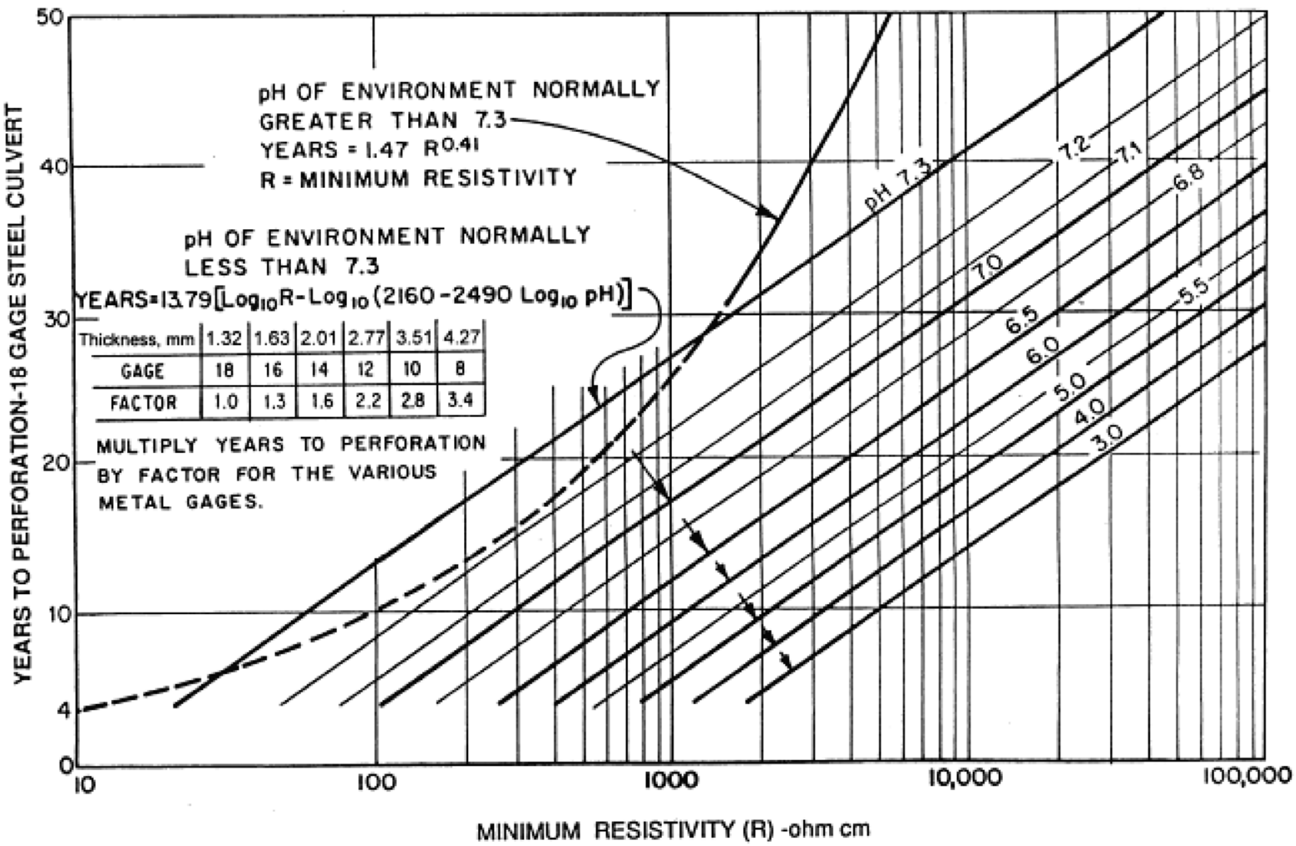


FIGURE B2 Chart for estimating years to perforation of steel culverts using California method (Caltrans 1999).

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. A chart useful for application of the AISI method is presented in Figure B3. The following equations can also be used:

For pH values greater than 7.3:

$$EMSL = 2.94 \times R^{0.41}$$

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 (Table B6).

TABLE B6
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

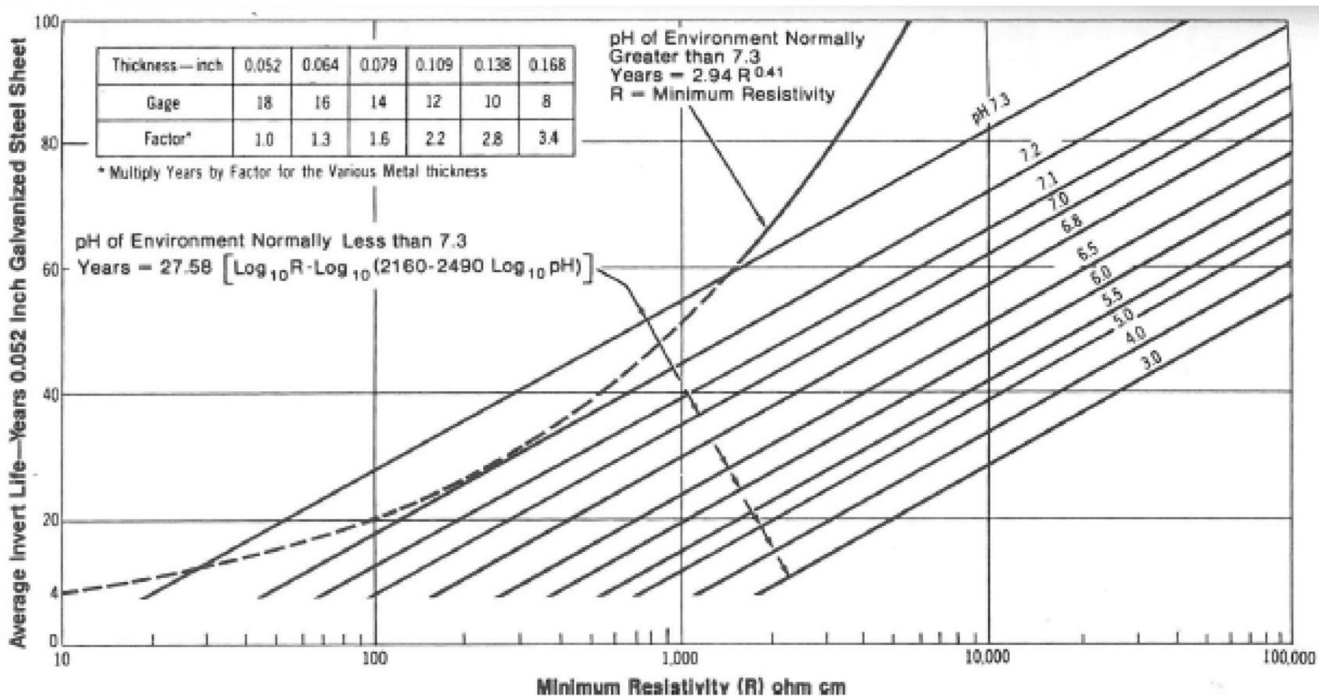


FIGURE B3 Chart for estimating average invert life using AISI method (AISI 1994).

Federal Lands Highway (FLH) Method

The Federal Lands Highway method is also a modification of the California method. A chart useful for application of the FLH method is presented in Figure B4. 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:

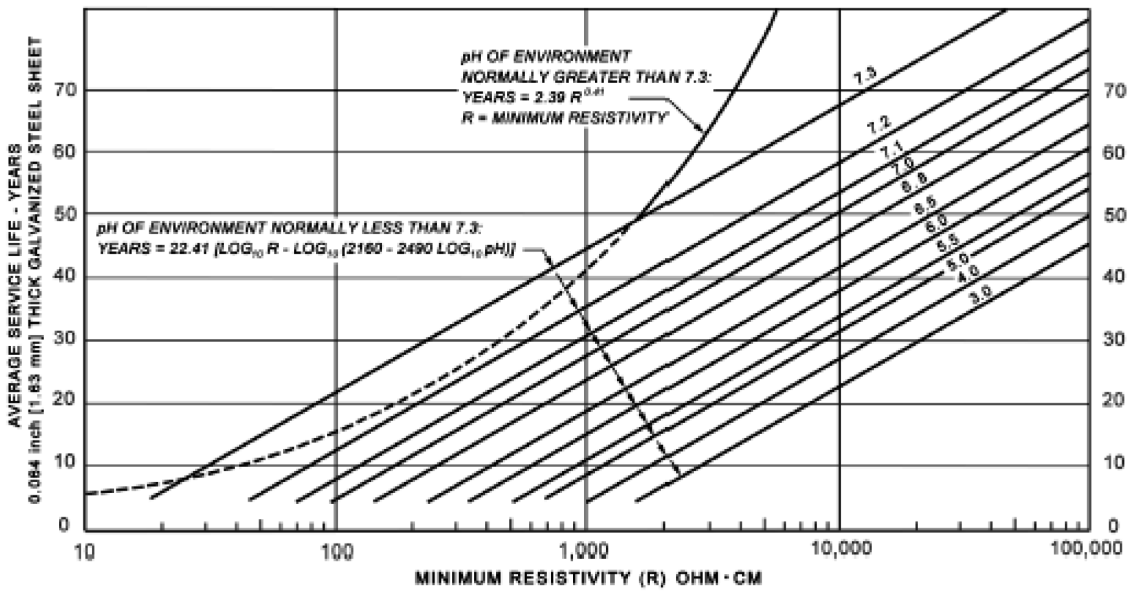
$$EMSL = 22.41(\log R - \log[2160 - 2490 \times \log pH])$$

where R is the minimum resistivity (ohm-cm).

The resulting EMSL value must be multiplied by a factor depending on the gage thickness (Table B7).

TABLE B7
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



Service Life Estimation Chart for Average Service Life of Plain Galvanized Culverts

THICKNESS FACTORS

THICKNESS, inch GAGE THICKNESS, mm	0.052 18 1.32	0.064 16 1.63	0.079 14 2.01	0.109 12 2.77	0.138 10 3.51	0.168 8 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).

FIGURE B4 Chart for estimating service life of plain galvanized steel using Federal Lands and Highway method (FHWA 2008).

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 B5 and Table B9, respectively. The following equations can also be used:

For pH values between 7.3 and 9.0:

$$EMSL = 1.84 \times R^{0.41}$$

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 (Table B8).

TABLE B8
GALVANIZED STEEL PIPE GAGE THICKNESS FACTORS—FDOT METHOD

Gage	18	16	14	12	10	8
Factor	--	1.0	1.3	1.8	2.3	2.8

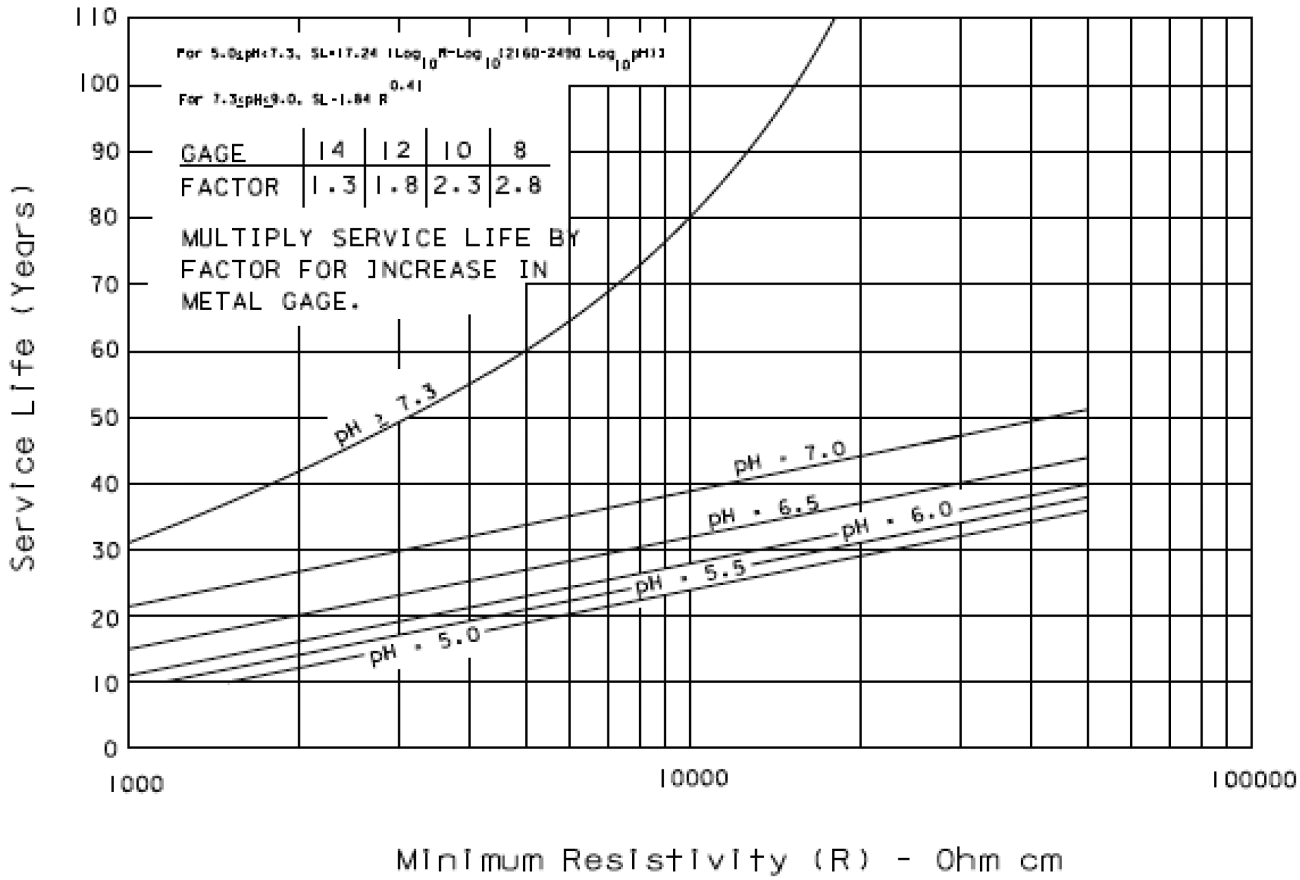


FIGURE B5 Estimated service life versus pH and resistivity for 16-gage galvanized steel using FDOT method (FDOT 2012).

TABLE B9

DESIGN SERVICE LIFE VERSUS PH AND RESISTIVITY FOR 16-GAGE GALVANIZED STEEL CULVERT PIPE USING FDOT METHOD (FDOT 2012)

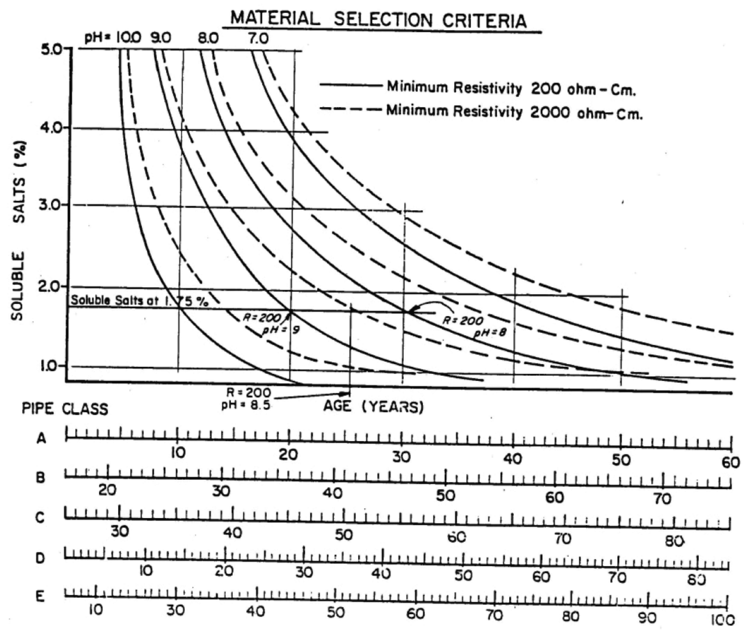
pH	1000	1500	2000	3000	4000	5000	7000	10000	15000	20000	30000	40000	≤50000
5.0	7	10	12	15	17	19	21	24	27	29	32	34	36
5.1	7	10	12	15	17	19	21	24	27	29	32	34	36
5.2	8	10	13	16	18	19	22	25	28	30	33	35	37
5.3	8	11	13	16	18	20	22	25	28	30	33	35	37
5.4	8	11	13	16	19	20	23	25	28	31	34	36	37
5.5	9	12	14	17	19	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: $(SL) = 17.24\{Log_{10}R - Log_{10}[2160-2490(Log_{10}pH)]\}$ for $5 \leq pH \leq 7.3$

$(SL) = 1.84\ R^{0.41}$ for $7.3 \leq pH \leq 9$

Utah DOT Method

The Utah DOT method was published in 1977 and is based on a study of 58 pipe culvert installations that were evaluated for durability characteristics and assigned a pipe rating to aid in numerical analysis and correlation with environmental soil and water conditions. Minimum soil resistivity, pH, total soluble slats, and sulfate content are interdependent parameters affecting pipe corrosion. The Utah DOT method monograph is presented in Figure B6.



Pipe Class A = Plain corrugated steel pipe

Pipe Class B = Bituminous Coated Corrugated Steel Pipe, Aluminum Alloy Pipe, Galvalume Pipe, Pitch-Resin adhesive coated corrugated Steel Pipe (coated on outside only).

Pipe Class C = Asbestos Bonded Bituminous Coated Corrugated Steel Pipe, Pitch-Resin Adhesive Coated Corrugated Steel Pipe (Coated on both sides).

Pipe Class D = Plain Corrugated Steel Structural Plate Pipe.

Pipe Class E = Bituminous Coated Corrugated Steel Structural Plate Pipe, Aluminum Alloy Structural Plate Pipe.

FIGURE B6 Utah DOT material selection criteria for metal pipe (Leatham and Peterson 1977).

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. The summary table (Table B10) from the Ministry of Transportation of Ontario (2007) provides an example for that agency of the allowable additional service life values used for various coatings.

TABLE B10
EXAMPLE OF DESIGN GUIDELINES FROM THE MINISTRY OF TRANSPORTATION OF ONTARIO (2007)

MTO GRAVITY PIPE DESIGN GUIDELINES
(MAY 2007)

Table C9.0
EMSL for Steel Pipe Coatings / Laminations

Coating[3]	Water Side		Soil Side Add-On Years
	EMSL	Max. Abrasion Level[2] (See Table C8)	
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 (Reference 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

Aluminized Steel (Type II) Pipe

FDOT Method

The FDOT method for estimating material service life of aluminized (type II) steel can be applied using Figure B7 or Table B12. 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:

$$EMSL = 50\left(\log R - \log\left[2{,}160 - 2{,}490 \times \log\left(7 - 4(pH - 8.5)\right)\right]\right)$$

where R is the minimum resistivity (ohm-cm).

The resulting EMSL value must be multiplied by a factor depending on the gage thickness (Table B11).

TABLE B11
ALUMINIZED STEEL (TYPE II) GAGE THICKNESS FACTORS—FDOT METHOD

Gage	18	16	14	12	10	8
Factor	--	1.0	1.3	1.8	2.3	2.8

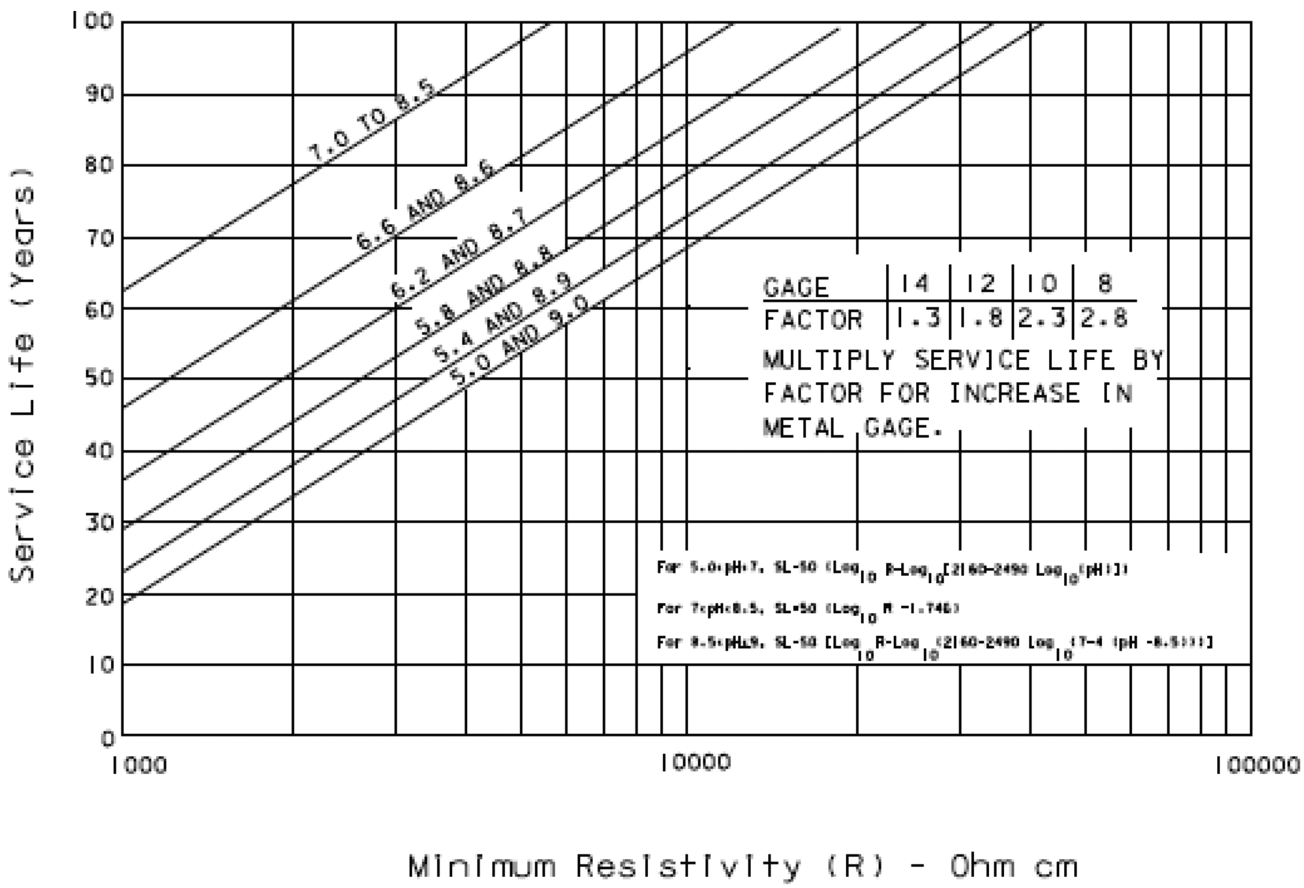


FIGURE B7 Estimated service life versus pH and resistivity for 16-gage aluminized steel type II using FDOT method (FDOT 2012).

TABLE B12

DESIGN SERVICE LIFE VERSUS PH AND RESISTIVITY FOR 16-GAGE ALUMINIZED STEEL CULVERT PIPE USING FDOT METHOD (FDOT 2012)

	Resistivity												
pH	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 $8.5 < pH \leq 9.0$

Aluminum Pipe

Estimates of service life for aluminum pipe can be made based on an FDOT method, applied through the use of Figure B8 or Table B13. The EMSL valued 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.

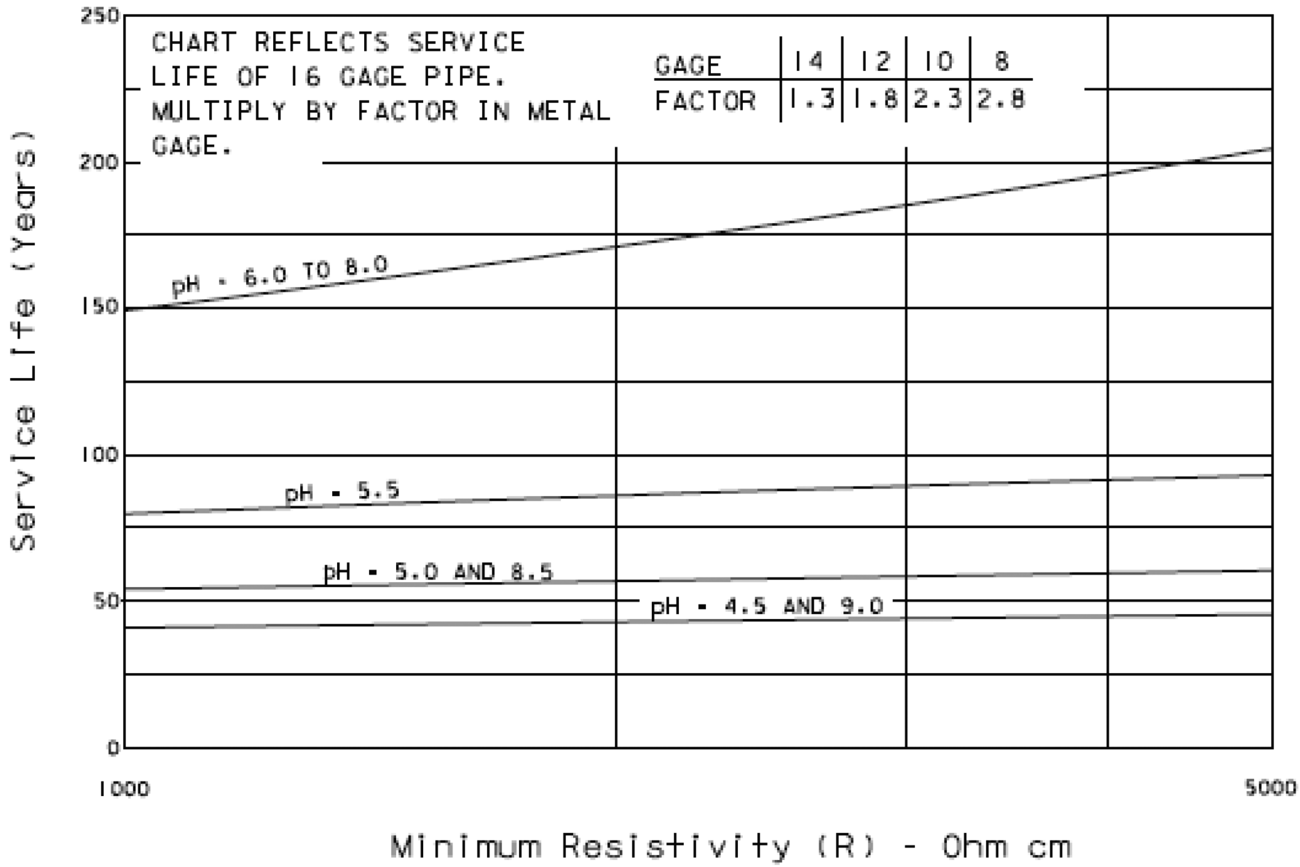


FIGURE B8 Estimated service life versus pH and resistivity for aluminum using FDOT method (FDOT 2012).

TABLE B13
DESIGN SERVICE LIFE VERSUS PH AND RESISTIVITY FOR 16-GAGE ALUMINUM CULVERT PIPE USING FDOT METHOD (FDOT 2012)

pH	Resistivity															
	≥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)

APPENDIX C

Example Service Life Calculations

INTRODUCTION

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.

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 nonaggressive case. The three different cases differ in the assumed environmental parameters, as indicated in Table C1. The assumed environmental values represent the worst case for either the soil side or water side of the culvert.

TABLE C1
ASSUMED ENVIRONMENTAL PARAMETERS

Case	pH	Resistivity (Ω-cm)	Sulfates (ppm)	Chlorides (ppm)
Nonaggressive	7.5	2,000	250	25
Moderate	6.5	1,000	500	50
Aggressive	4.5	500	1,000	100

Additional parameters that have been taken as constant regardless of the material type being analyzed are summarized in Table C2.

TABLE C2
ADDITIONAL PARAMETERS REQUIRED FOR DURABILITY ASSESSMENT

Parameter	Value
Invert slope	1%
Pipe length	50 ft
Inside pipe diameter	36 in.
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 in.
Sediment depth (concrete pipe)	1/8 in.
Gage (metal pipe)	16

NONAGGRESSIVE CASE

The following results were obtained by using the aforementioned equations and charts to estimate material service life for the nonaggressive case (Table C3).

TABLE C3
ESTIMATED MATERIAL SERVICE LIFE FOR NONAGGRESSIVE CASE

Pipe Material	Approach	EMSL (years)
Concrete	Hurd Model	>500[a]
	Hadipriono Model	94
	ODOT Model	>500
	FDOT Method	116
Galvanized Steel	California Method	43
	AISI Method	86
	FLH Method	54
	FDOT Method	42
Aluminized (Type II)	FDOT Method	78
Aluminium	FDOT Method	171

[a] 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.

MODERATELY AGGRESSIVE CASE

The following results were obtained by using the aforementioned equations and charts to estimate material service life for the moderate case (Table C4).

TABLE C4
ESTIMATED MATERIAL SERVICE LIFE FOR MODERATE CASE

Pipe Material	Approach	EMSL (years)
Concrete	Hurd Model	>500
	Hadipriono Model	84
	ODOT Model	>500
	FDOT Method	90
Galvanized Steel	California Method	16
	AISI Method	31
	FLH Method	19
	FDOT Method	15
Aluminized (Type II)	FDOT Method	63
Aluminium	FDOT Method	149

AGGRESSIVE CASE

The following results were obtained by using the aforementioned equations and charts to estimate material service life for the aggressive case (Table C5).

TABLE C5
ESTIMATED MATERIAL SERVICE LIFE FOR 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 II)	FDOT Method	0 (not allowed)
Aluminium	FDOT Method	39

DISCUSSION OF RESULTS

A number of observations can be made based on these results:

- Wide variability exists in the EMSL values for different pipe types.
- A wide range of values can be obtained for a single pipe type depending on the service life method used.
- Taking an average value of multiple methods is not recommended given the potential for significant variation in calculated values across methods.
- As seen from the results of the concrete EMSL calculations, many of the current methods produce unstable and unrealistically high results for certain environmental values and must be used with appropriate engineering judgment.
- The variability of results from available methods for concrete and metal pipe and the lack of available service life methods for other pipe material types reinforce the need for continued fundamental research into the topic of material service life prediction for culverts.

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. These software programs are

- HiDISC 1.0 developed for the Ministry of Transportation of Ontario (MTO) (not yet publically released)
- CSLE (Culvert Service Life Estimator) 2014 developed by FDOT

  Available: http://www.dot.state.fl.us/rddesign/Drainage/ManualsandHandbooks.shtm

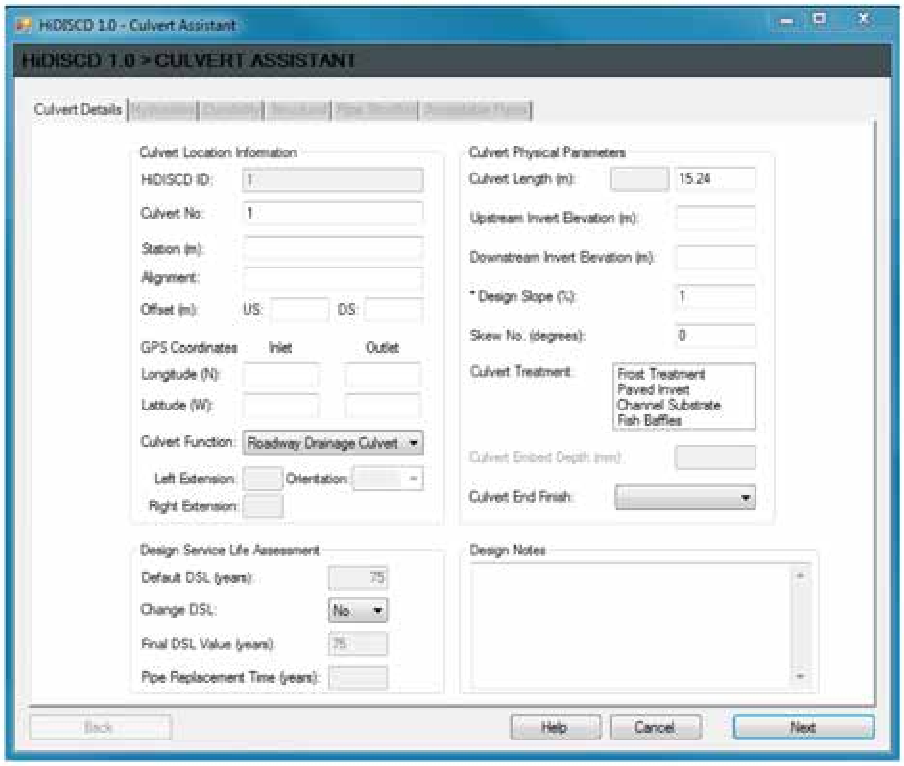
- AltPipe v 6.08 developed by Caltrans

  Available: http://dap1.dot.ca.gov/design/altpipe/

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 nonaggressive case (Figure C1).

MTO HiDISC 1.0

Data Input—Culvert Details



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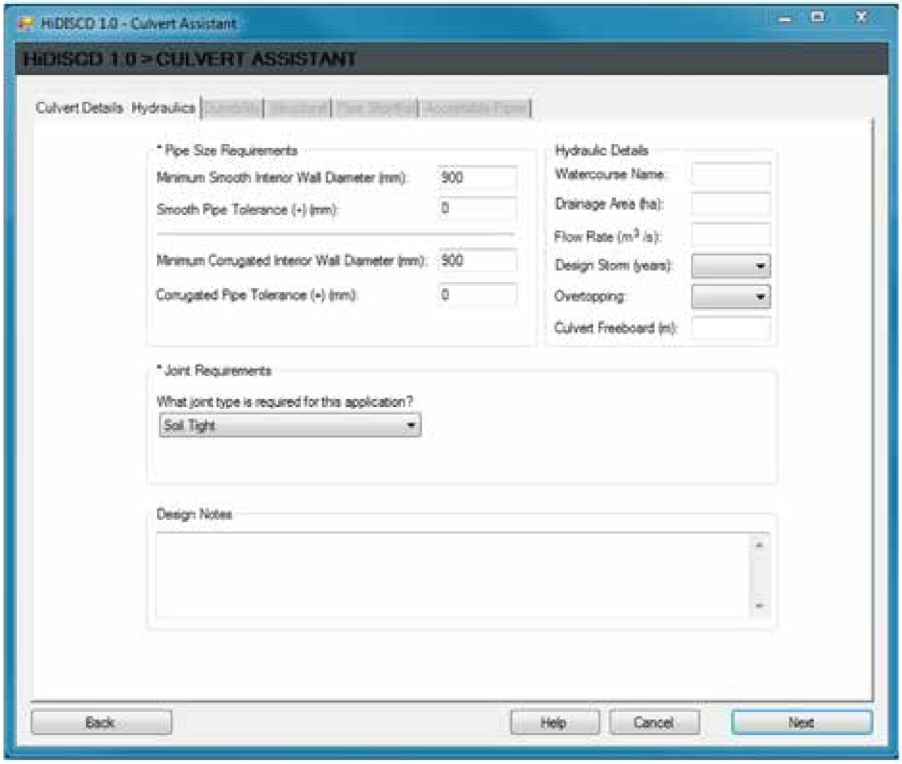
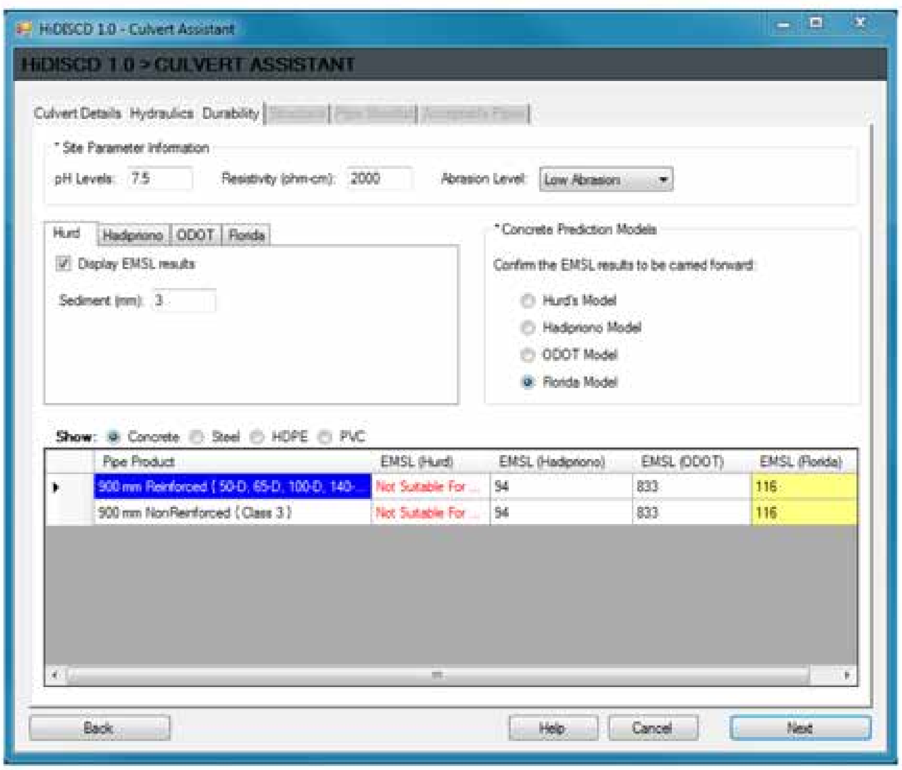
<td>
</td>
</tr>
<tr>
<td>Data Input—Durability</td>
<td>
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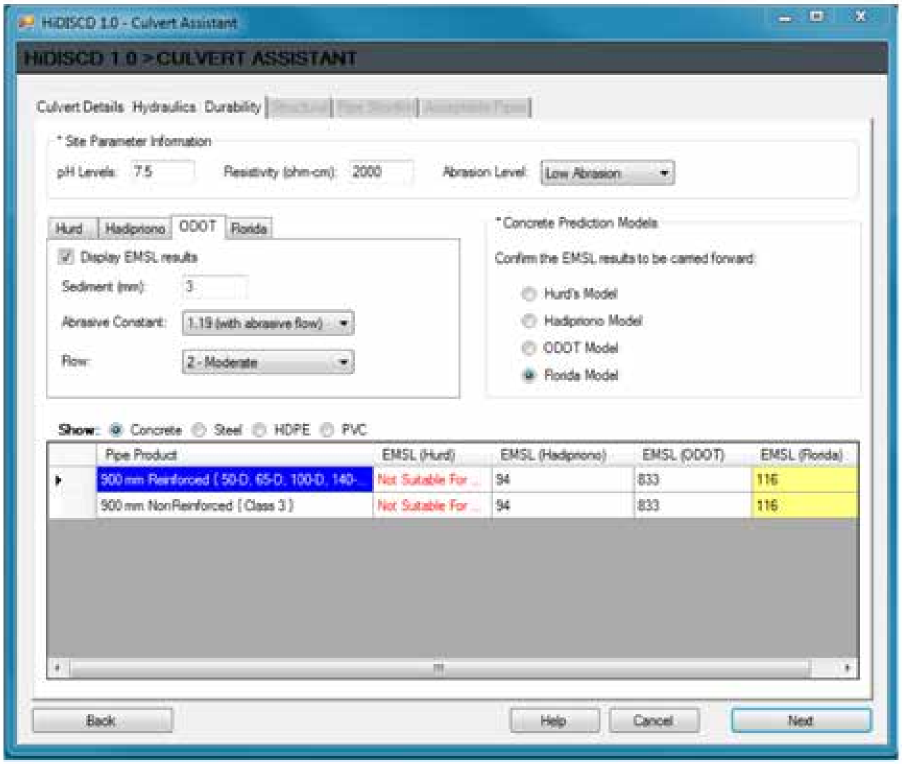
<tr><td>Data Input—Durability</td><td>
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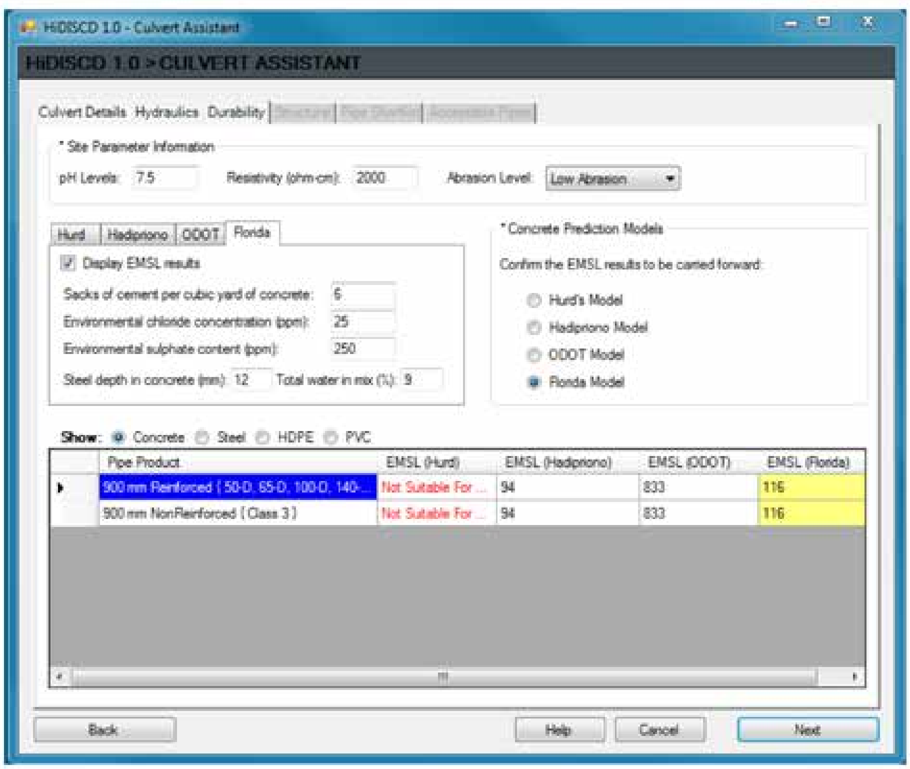
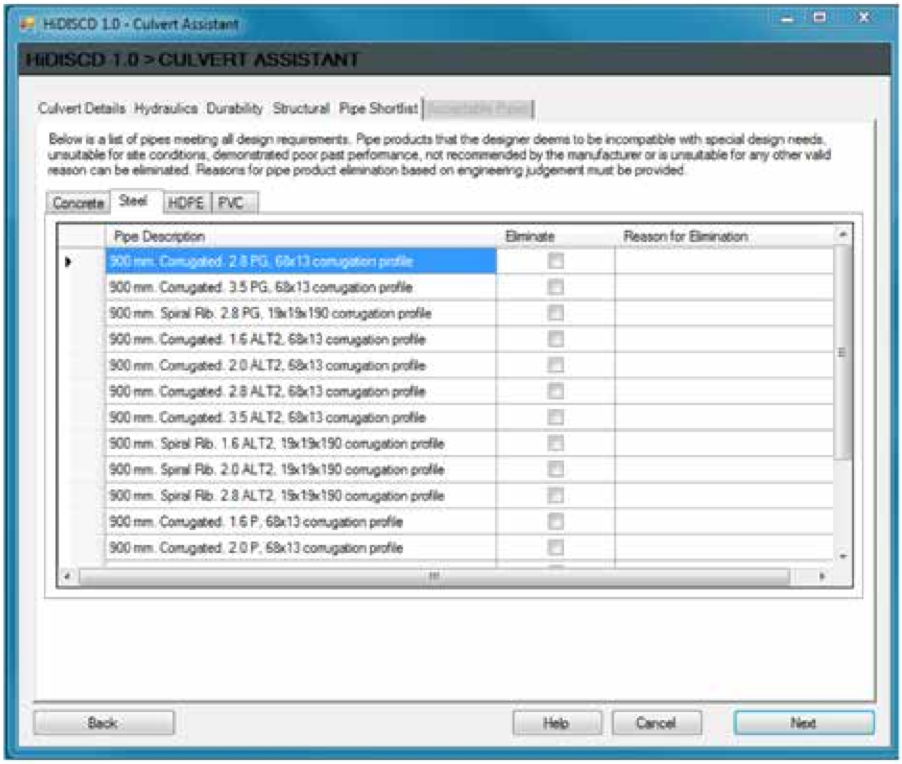
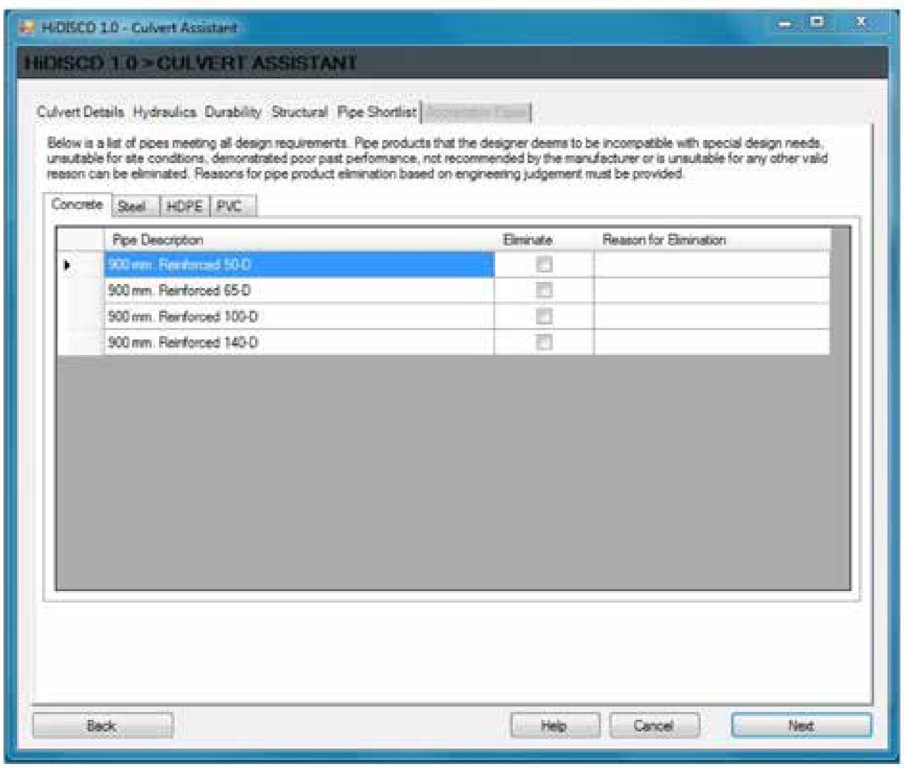
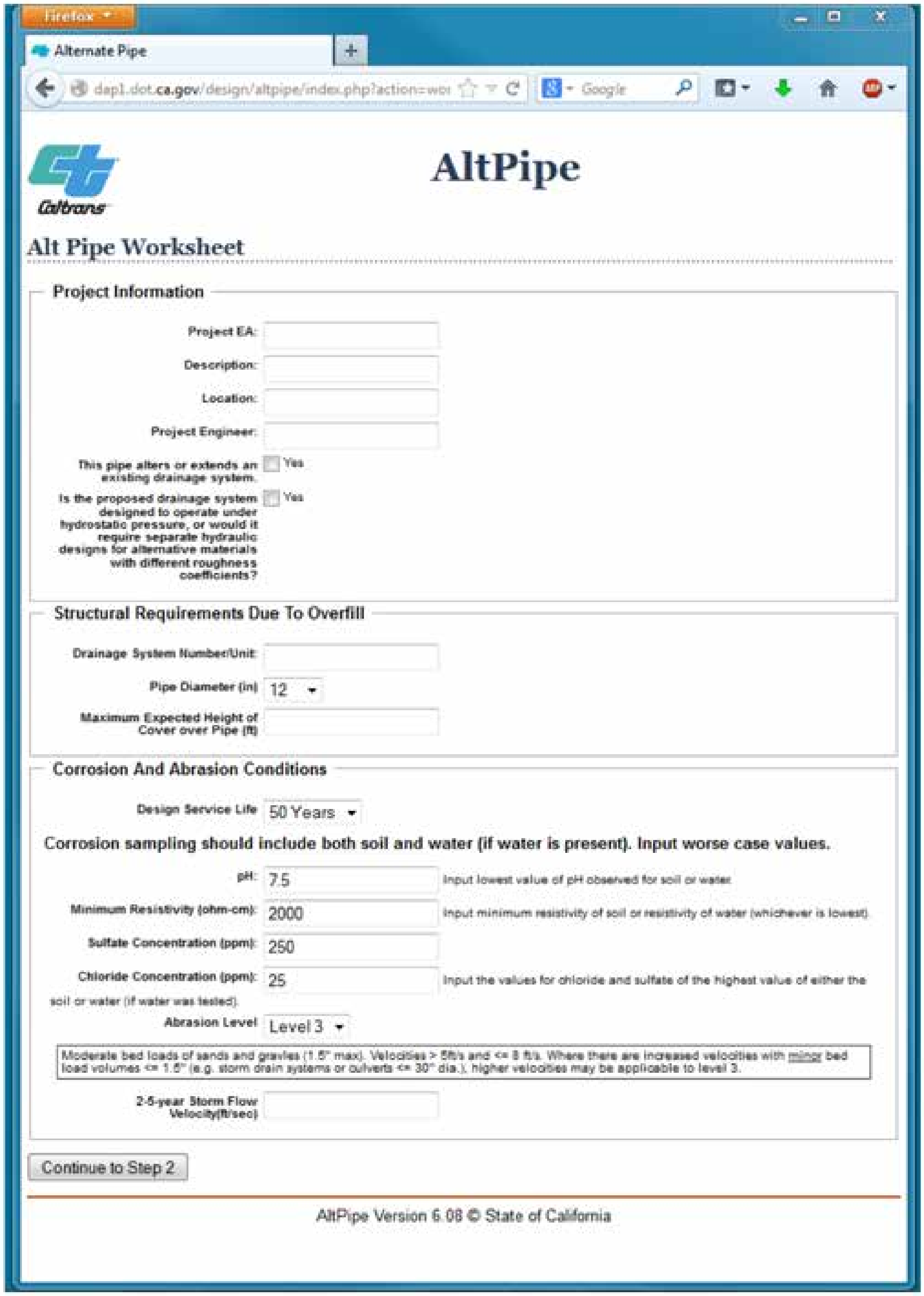
<tr><td>Data Input—Durability</td><td>
</td></tr>
</table>

Output—Steel	
Output—Concrete	

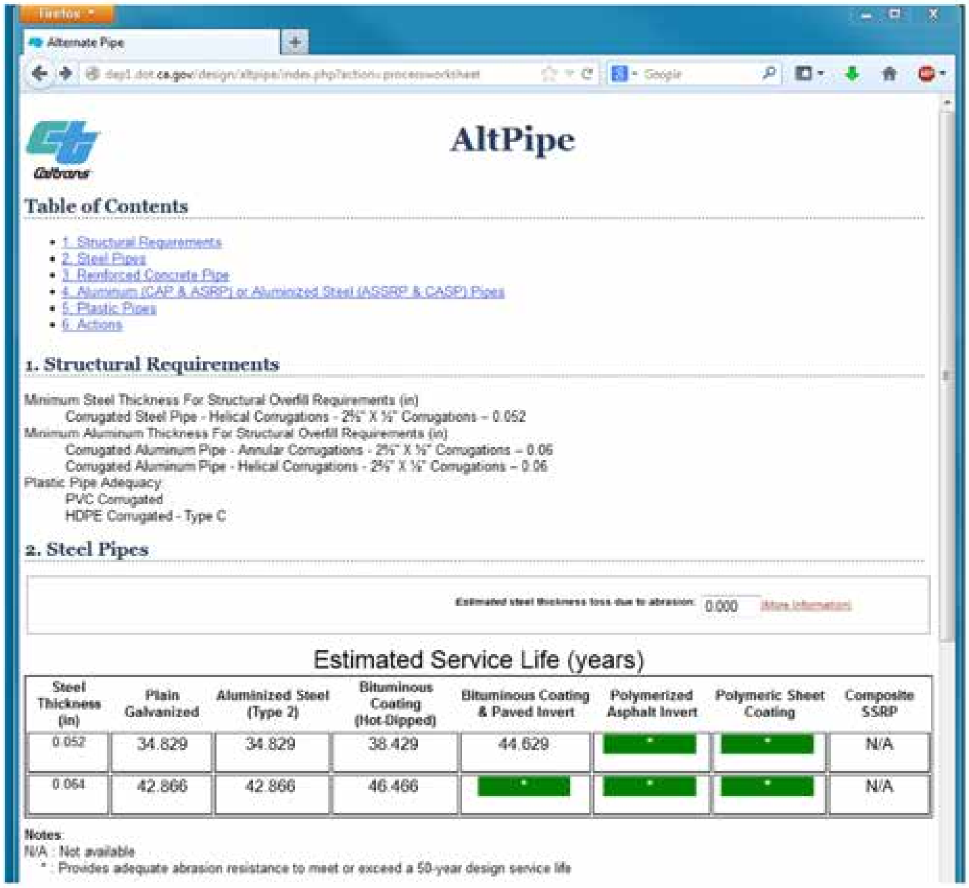
CSLE 2013 (version 5.1.3.2)—FDOT	
Data Output	

AltPipe (version 6.08)—Caltrans

Data Input



Output—Steel



Output—Concrete, Aluminium, and Plastic

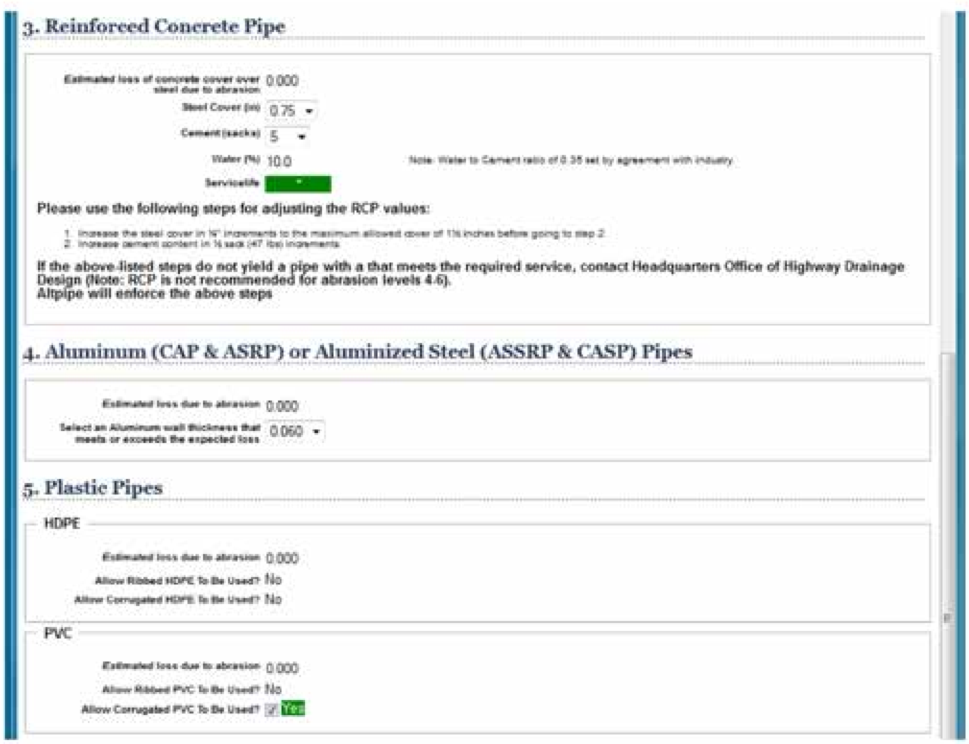


FIGURE C1 Software screenshots of analysis for nonaggressive case.

Abbreviations 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

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