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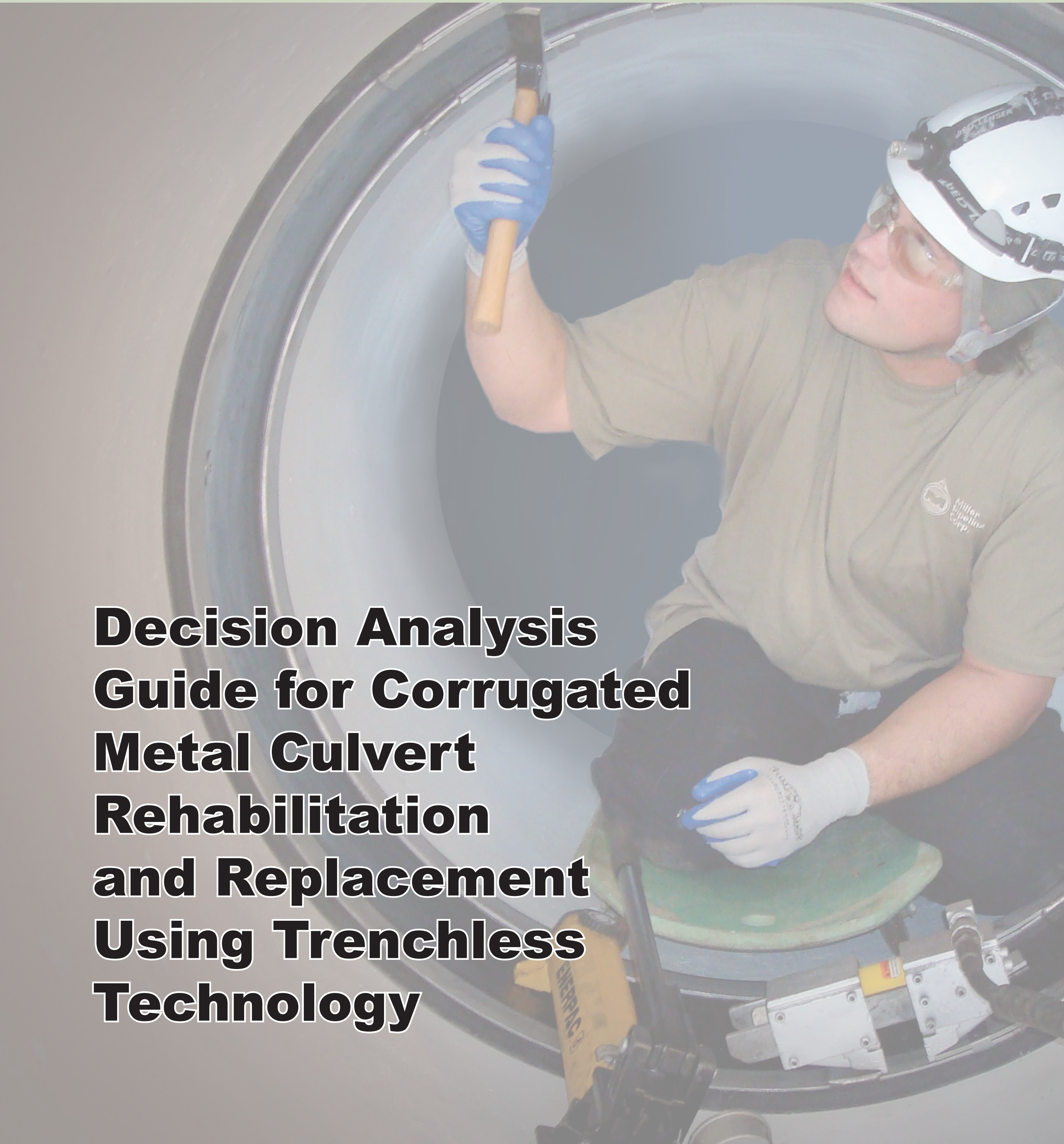

Decision Analysis Guide for Corrugated Metal Culvert Rehabilitation and Replacement Using Trenchless Technology

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Acknowledgments .... Inside Cover
Abstract.................................... vii
1 INTRODUCTION 1
1.1 General Overview.................................... 1
1.2 Forest Service 1
1.3 Guidelines 3
1.4 Aquatic Organism Passage 3
1.5 Outline 5
2 DECISIONMAKING PROCESS—Problem Description Flowcharts 7
2.1 Issue 1: Culvert Lacks Structural Capacity.................................... 8
2.2 Issue 2: Culvert Lacks Hydraulic Capacity 9
2.3 Issue 3: Culvert Has Bedding Deficiencies 9
3 CORRUGATED METAL PIPE PROBLEMS, CONDITIONS, DEFECTS—
Issue and Condition Descriptions.................................... 11
3.1 Culvert Lacks Structural Capacity 11
3.1.1 Structural Problem in the Culvert Joint 11
3.1.2 Structural Problem in the Culvert Wall 11
3.1.3 Culvert Is Collapsed 16
3.2 Culvert Requires Increased Capacity.................................... 17
3.3 Culvert Has Bedding Deficiencies 17
3.3.1 Surface Depressions.................................... 17
3.3.2 Voids Around the Culvert 18
3.3.3 Undermining.................................... 18
4 TRENCHLESS TECHNOLOGIES FOR CMPs—Rehabilitation of Corrugated
Metal Culverts 21
4.1 Sliplining of Corrugated Metal Culverts 26
4.1.1 Sliplining With Polyethylene.................................... 26
4.1.2 Sliplining With Reinforced Concrete Pipe 29
4.1.3 Sliplining With Corrugated Metal Pipe or Pipe Arch.................................... 29
4.1.4 Invert Sliplining.................................... 30
4.2 Cured-in-Place Pipe Lining.................................... 31
4.3 Fold-and-Form Lining 32

4.4 Spiral-Wound Lining 34
4.5 Sprayed Linings........ 35
4.5.1 Cement Mortar Lining 38
4.5.2 Asphalt or Paving Material Coating........ 39
4.5.3 Polyurethane 39
4.5.4 Polyurea 41
4.6 Spot Repairs........ 42
4.6.1 Stainless Steel or Polyvinyl Chloride Repair Sleeves 42
4.6.2 Internal Joint Sealing 43
4.7 Soil Stabilization 44
4.7.1 Grouting 44
4.8 Pipe Replacement Methods 45
4.8.1 Pipe Splitting 45
4.8.2 Replacement on a New Alignment........ 47
4.8.3 Open Cut Replacement 48
4.9 Inlet Modifications........ 48
4.10 More Information 48
Appendix A........ 49
A.1 Inspection and Condition Assessment of Corrugated Metal Culverts........ 49
A.1.1 Culvert Inspection and Rating Systems 49
A.1.2 Culvert Inspection Policies (Frequency of Inspections) 57
A.1.3 Durability and Service Life 62
A.1.4 Corrosion Resistance........ 69
A.1.5 Abrasion Resistance 70
A.1.6 Culvert Hydraulic Performance and Considerations Related to Rehabilitation... 72
A.1.7 Cost/Risk Analysis 74
Appendix B: Case Study of Culvert Failure Near Lincoln City, Oregon 77
B.1 Introduction 77
B.2 Conclusions and Recommendations 83
Appendix C: Links Providing Information on Rehabilitation Technologies........ 85
References........ 87

The Forest Service, an agency of the U.S. Department of Agriculture, has numerous corrugated metal pipes (also referred to as corrugated steel pipes) that have been in place since the 1950s, 1960s, and 1970s. At a typical corrosion rate, many of the culverts from this era are at the end of their useful life. Although the structural capacity of the corroded culverts may withstand earth pressures of shallow fills, it is not uncommon to see old corrugated metal pipes under deep fills undergoing various stages of collapse.

Culverts under large embankments can be replaced using conventional open-cut methods. However, such installations are costly because of the extreme quantities of earth that must be moved. Additionally, maintaining traffic is difficult, and the replacement operation may result in adverse environmental effects. Consequently, using trenchless technology is worth considering.

This publication will provide guidance in selecting which trenchless technologies may be advantageous for rehabilitating or replacing aging corrugated metal pipes based upon various observed conditions. Flowcharts are provided to aid in the selection process, and case studies are cited for methods used by other agencies for similar conditions, problems, or issues. Some of these technologies may be applicable for other pipe materials, but the focus of this report is corrugated metal pipes. Candidate culverts can range in size, although most photographs in this guide show trenchless technologies for larger culverts. The Louisiana Tech University Trenchless Technology Center, in collaboration with the National Utility Contractors Association and National Association of Sewer Service Companies, has developed trenchless technology method selection software tools such as TAG-R <http://www.tagronline.com>, but those tools do not focus on culverts.

1.1 General Overview

Service life of asphalt-surfaced road networks can be extended by overlays, and the surface life of gravel-surfaced road networks can be readily extended by replenishing gravel and blading. Metal culverts, however, provide the weak link to (easy) road network preservation. Once culvert design lives are met, metal culverts tend to rust, and subsequent piping adversely impacts both the environment—through direct deposit of sediment into streams—and safety—through voids originating beneath the road surface, eventually leading to surface washouts. Ultimately, failed culverts may catastrophically blow out as shown in figure 1. Such failures result in extreme sediment discharges into streams that adversely affect aquatic habitat, and cause extreme safety hazards.

Conventional methods of addressing culvert deterioration comprise open-cutting/trench digging and replacement. These methods can be costly, can have adverse environmental effects, and can have adverse social impacts, particularly in high population and high traffic areas. The Occupational Safety and Health Administration also requires expensive and time-consuming provisions to protect workers in deep trenches. For these reasons, trenchless technology methods, materials, and equipment are gaining increasing recognition as they can provide a multitude of cost-effective solutions to problems posed in sustaining transportation infrastructure. Conventional techniques often result in bumps or depressions across paved or unpaved roads and introduce the need for frequent road maintenance. Additionally, replacement using conventional methods does not allow for proper compaction. In contrast, trenchless technology:

- Reduces sediment pollution of streams.
- Allows traffic to be maintained.
- Reduces costs (significantly) when compared to conventional methods of digging up old deteriorated metal culverts, and replacing them.

1.2 Forest Service

A conservative analysis of culverts was recently conducted by Rob Piehl, Forest Service geotechnical engineer. Piehl estimates that approximately 220 of the Siuslaw National Forest’s 2000+ culverts have 20 to 70 feet of cover and have been in place for more than 30 years. Of these, 91 percent are corrugated metal pipe or corrugated steel pipe. Use about 30 feet of cover as a very conservative breakeven point for using trenchless technology over digging up the culvert, Piehl estimates a potential savings of $100,000 for each small-diameter pipe. Even estimating conservatively, this is a savings of more than 10 million dollars for

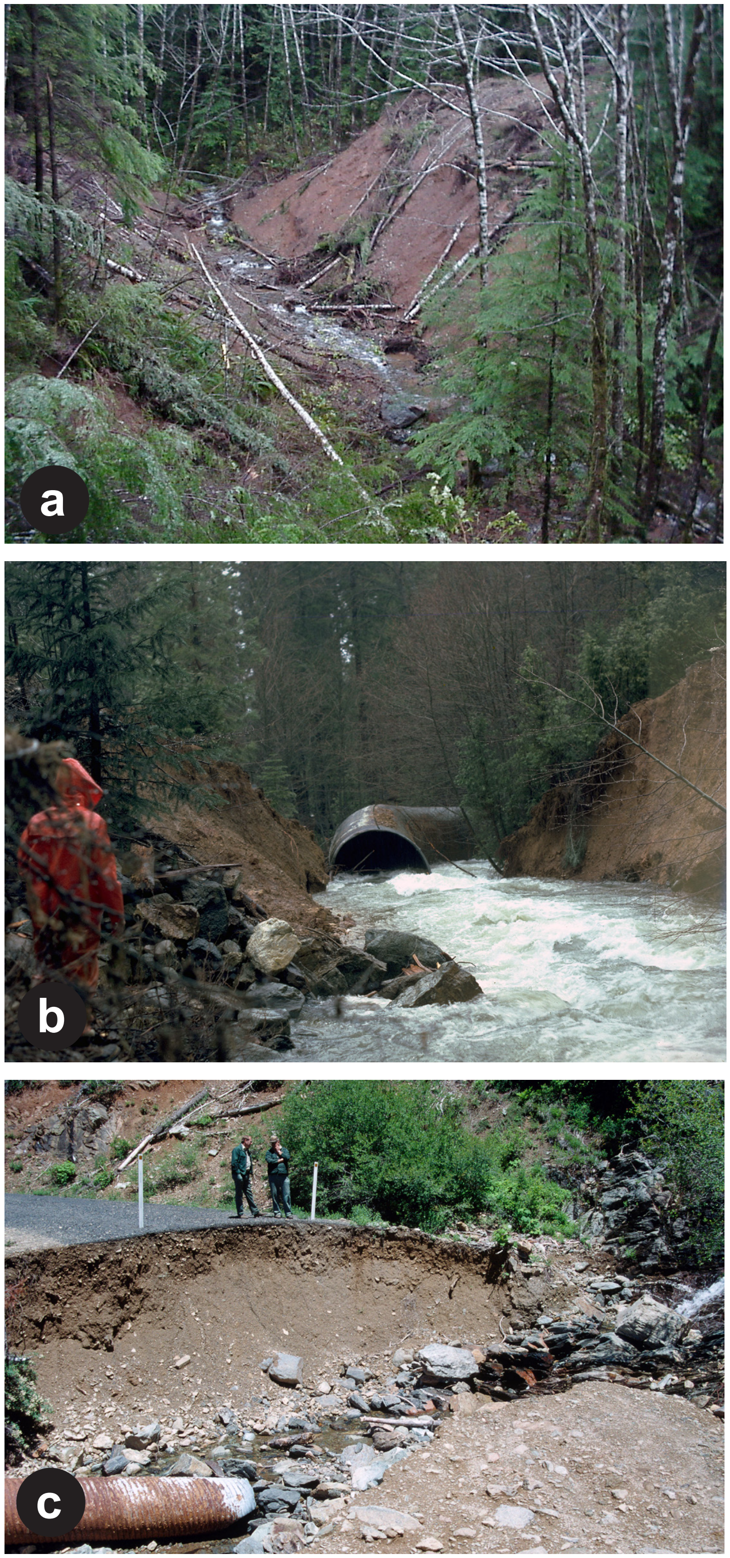


Figure 1—Culvert blowouts—a. Culvert blowout along a national forest road, b. Culvert blowout (Gordon Keller, Forest Service), c. Culvert blowout Cold Water Creek (Gordon Keller, Forest Service).

replacement of all corrugated metal pipe for the Siuslaw National Forest alone. In level terrain, the savings is not as dramatic, but still substantial.

No attempts have been made to estimate monetary savings for watershed protection; however, the concept of savings is clear based on limited disturbance during culvert replacement, as well as elimination of sediment following rusting/failure, which allows sediment to be deposited directly into streams. Additionally, safety is enhanced and potential litigation reduced.

1.3 Guidelines

There is a need for a set of decision analysis guidelines for the selection of rehabilitation and replacement construction methods for corrugated metal pipe or corrugated steel pipe culverts due to the variety of possible conditions and the numerous technologies that exist for rehabilitation of those conditions. This publication provides a flowchart that guides road managers through the rehabilitation selection process of corrugated metal pipe structures. The scope of this report is to guide the reader through the method selection process of rehabilitation technologies based primarily on the existing condition of a culvert. Although outside the scope of this report, it is critical that other factors, such as life-cycle cost, improvement of an original poor design, and aquatic organism passage be taken into consideration. Consulting any Forest Service publications and/or experts on aquatic organism passage is critical in conjunction with using this guide for selecting trenchless technology methods. Additionally, consultation with the Forest Service Handbook (Transportation Structures Handbook) 7709.56b and the Forest Service Manual 7736 will aid the user in complementary aspects of corrugated metal pipe, such as authorities, inspections, and so forth.

1.4 Aquatic Organism Passage

Although aquatic organism passage (AOP) is outside the scope of this guide, the importance of AOP consideration cannot be overemphasized. In general, the standard hydraulic method of design required for AOP when using trenchless technologies does not differ from that used for any standard open culvert, baffled culvert, fishway, etc. However, consulting references and experts in AOP is highly recommended. Several key publications include:

- “FishXing Users Manual” <http://www.fsl.orst.edu/geowater/FX3/FX3_manual.pdf>.

- “Stream Simulation: An Ecological Approach to Road-Stream Crossings” <http://www.stream.fs.fed.us/fishxing/aop_pdfs.html>.

- “Culvert Design for Aquatic Organism Passage” FHWA Hydraulic Engineering Circular No. 26.

Many States, including Vermont, Massachusetts, California, Oregon, and Washington, have their own manuals addressing AOP. Some are available on their State’s Fish and Wildlife Department Web sites; others are on their Department of Transportation Web sites.

Two upcoming AOP publications include:

- “Stream Simulation for Aquatic Organism Passage at Road-Stream Crossings,” by Daniel Cenderelli, Kim Clarkin, Robert A. Gubernick, and Mark Weinhold.
- “Modifying Existing Road-Stream Crossings for Fish Passage,” by K. Bates and M. Love.

For most techniques, a culvert rehabilitated using a trenchless technology enables AOP similar to a culvert reconstructed/reinstalled using conventional methods (e.g., trench cutting, excavating the defective culvert, and replacing). In fact, trenchless techniques typically reduce adverse impacts during the construction process itself, as disturbance/ sediment is minimized and repair typically can be accomplished in less time than is required for full reconstruction. In general, the final culvert is essentially no different than the repaired culvert, except that the defect is repaired. Thus, there is an opportunity for AOP improvement. The same criteria and guidelines must be used for culverts repaired using trenchless technology as for any culverts.

Even though utilizing trenchless technology generally reduces adverse effects to AOP by keeping sediment during reconstruction to a minimum, studies have shown some short-term adverse environmental effects for specific technologies. While this guide does not focus on AOP, one case study in Virginia is referenced (Donaldson and Baker). This study examined the potential impacts of cured-in-place pipe lining (the most widely used trenchless technology), which involves inserting a felt tube that has been impregnated with a thermosetting resin into the host pipe. The tube is then inflated (using water or air) to form a tight fit to the pipe wall and the liner is cured with hot water or steam until a new liner forms a pipe within a pipe. This process can result in short-term adverse effects. The specific results of the study and proposed changes in procedure to reduce adverse effects on AOP are outlined briefly in the cured-in-place pipe section in this report.

1.5 Outline

This guide is presented in two ways: (1) electronic format, which has clickable hyperlinks to help the reader navigate back and forth through the flowcharts and text within the report; and (2) hard copy format, which provides section reference numbers in the flowcharts to allow the reader to be able to quickly locate additional material while reading through the flowcharts. In both formats, the reader is encouraged to visit the referenced or linked sections from the decision tree to learn more about a specific defect and to become familiar with case studies provided from other agencies that have used respective methods successfully. Additionally, sections that discuss specific rehabilitation technologies are located at the end of each branch of the flowcharts.

This guide has four chapters and three appendixes:

- Chapter 1: Introduction.
- Chapter 2: Decisionmaking Process. This chapter includes flowcharts that outline the decisionmaking process for selecting a rehabilitation/replacement method for the issues/problems that occur in corrugated metal pipes. Three categories of issues/problems encountered in practice are:
  - Lack of capacity.
  - Deficient structural capacity, such as corrosion and abrasion damage.
  - Inadequate bedding support.

  Each category is divided into subcategories (e.g., minor geometrical deformations, major corrosion, invert deterioration, and so forth). A culvert structure might exhibit one or more deficiencies. The flowcharts aid the user with selecting rehabilitation/replacement method(s) that can provide an adequate solution to the observed deficiency.
- Chapter 3: Corrugated Metal Pipe Problems, Conditions, Defects. Chapter 3 provides information, descriptions, and pictures of issues or problems that commonly occur in corrugated metal pipes.
- Chapter 4: Trenchless Technologies For Corrugated Metal Pipes. Chapter 4 provides descriptions of the trenchless rehabilitation methods that can be used for corrugated metal pipe for:
  - Rehabilitation (e.g., sliplining, cured-in-place pipe, spiral-wound lining, spray-on coating).
  - Replacement (e.g., pipe bursting).

Provided are:

- Technical descriptions of each applicable method.
- Culvert repair strategies developed by transportation agencies.
- Case histories covering the rehabilitation and replacement technologies discussed in the guide. The case histories portray a wide range of culvert diameters, lengths, and cross-sectional geometries, each with a unique set of underlying defects. The case histories demonstrate that, while each trenchless construction method is most suitable for a subset of all possible rehabilitation/replacement scenarios, the trenchless technology toolbox provides engineers and designers with the flexibility to tailor custom, optimal solutions for specific deficient structures.

- Appendix A: Literature review/annotated bibliography on corrugated metal pipe; general information, inspection ratings, service life, cost, and so forth.
- Appendix B: Case study of the failure of a Forest Service culvert in Oregon's Siuslaw National Forest.
- Appendix C: Links providing information on trenchless rehabilitation technologies.

DECISIONMAKING PROCESS–Problem Description Flowcharts

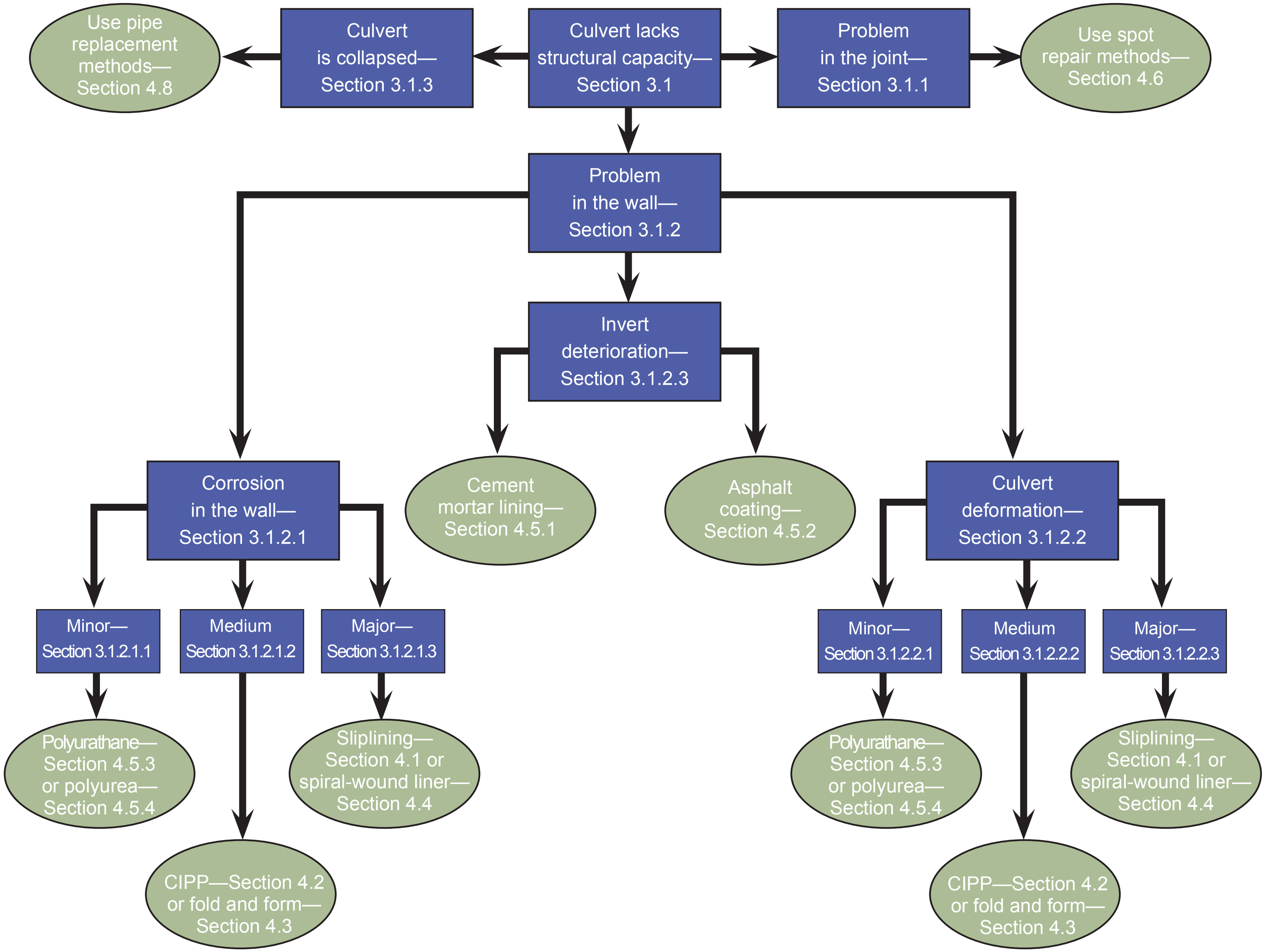
The following flowcharts can be used to guide the user through the rehabilitation/replacement method selection process for corrugated metal pipe culvert structures:

- Issue 1 outlines the selection process for a culvert that is lacking structural capacity due to corrosion, deformation, invert deterioration, etc. These issues can be in the joint (where two sections of pipe are connected) or in the wall (any part of the interior surface of the culvert).

- Issue 2 occurs when culverts lack hydraulic capacity. Although not a flowchart per se, the figure corresponding to issue 2 simply recommends the solutions for culverts lacking hydraulic capacity. No trenchless-based decisionmaking is required.

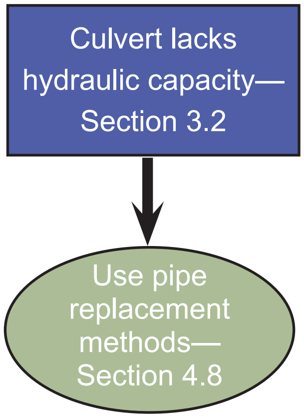
- Issue 3 guides the user through various bedding deficiency problems occurring in corrugated metal pipe.

2.1 Issue 1: Culvert Lacks Structural Capacity—Blue boxes send user to problem/issue. Green boxes send user to example/case study.



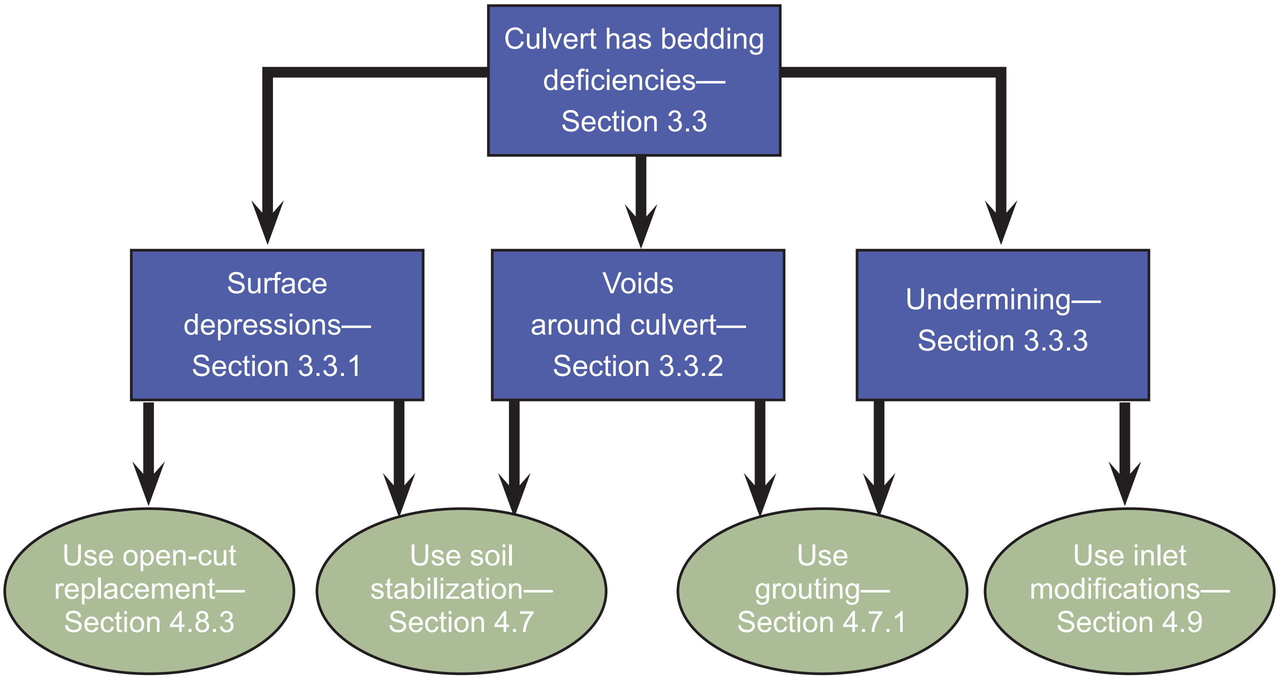
a. Culvert lacks structural capacity.

2.2 Issue 2: Culvert Lacks Hydraulic Capacity— Blue boxes send user to problem/issue. Green boxes send user to example/case study.



b. Culvert lacks hydraulic capacity.

2.3 Issue 3: Culvert Has Bedding Deficiencies—Blue boxes send user to problem/issue. Green boxes send user to example/case study.



c. Culvert has bedding deficiencies.

Figure 2—Decisionmaking process guidelines.

3.1 Culvert Lacks Structural Capacity

If the culvert is structurally deficient, it has reached a point at which it is not able to handle the anticipated load on or around the culvert and needs to be rehabilitated or replaced. Select the problem that best fits your type of structural capacity problem.

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

3.1.1 Structural Problem in the Culvert Joint

Several types of defective joints occur in corrugated metal pipe:

- Separated (open) joints–Pipe sections are aligned but separated (displaced longitudinally).
- Misaligned (offset) joints–Pipe sections are not lined up relative to each other (vertically and horizontally) and exhibit a disjuncture. Misalignment can be caused by improper installation, undermining, uneven settling of fill, or soil infiltrating into the culvert through an opened joint.
- Faulted joints–Adjacent pipe sections have a difference in elevation (a drop or a step).
- Partially opened joints–Pipe sections remain connected and aligned, but a partial joint opening is created due to the shape distortion of one pipe section (typically, a drop in the pipe crown is visible) or a relative rotation of one segment with respect to the joint plane.

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

3.1.2 Structural Problem in the Culvert Wall

A structural problem in the culvert wall includes corrosion of the culvert surface, deformation and distortion of the wall, and invert deterioration from abrasion.

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

3.1.2.1 Corrosion in the Culvert Wall

The majority of metal pipe failures can be attributed to corrosion, which can attack the inside or outside of culverts. Aggressive chemicals can:

- Be in surface waterflow (the damage is more serious in culverts with continuous flows or standing water than with intermittent flows).
- Be present in the ground water.
- Be in the soil originally.
- Be introduced through contaminants in the backfill soil.
- Be transported by surface or subsurface flows.

Soil and water conditions that are particularly aggressive or hostile to culverts are those with pH values of less than 5.0 (strongly acid) or greater than 8.5 (strongly alkaline). Water acidity can be mineral or organic. Mineral acidity comes from sulfurous wells and springs and drainage from coal or other mines. The water contains dissolved sulfur and iron sulfide that may form sulfurous and sulfuric acids. Mineral acidity with a pH as low as 2.3 has been observed. Organic acidity, which may be found in swampy land and barnyards, may have a pH as low as 4.0. Alkalinity in water is caused by strong minerals and limed and fertilized fields.

Abrasion is the wearing away of the inside surface of a corrugated metal pipe, primarily at the pipe invert, by sediment and debris being transported by the flow. All pipe materials are susceptible to abrasion. However, the wear of material in corrugated metal pipe is greater than in smooth surface pipes because there is an additional detrimental effect of abrasive material striking the upstream face of corrugations (protective coating materials applied in corrugated metal pipe typically do not fill the corrugations). Minor, medium, and major corrosion are defined below.

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

3.1.2.1.1 Minor Corrosion

Minor corrosion and abrasion can cause superficial rust and minor pitting and can be rehabilitated with a nonstructural method (figure 3a).

Figure 3a—Minor corrosion occurring in a corrugated metal culvert.

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

3.1.2.1.2 Medium Corrosion

Medium corrosion leads to scattered heavy rusting and deep pitting and can be addressed with a semistructural rehabilitation method (figure 3b).

Figure 3b—Medium corrosion occurring in a corrugated metal culvert.

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

3.1.2.1.3 Major Corrosion

Major corrosion can cause structural failure and collapse due to extreme rusting and deep pitting perforations and needs a fully structural rehabilitation method (figure 3c).

Figure 3c—Major corrosion occurring in a corrugated metal culvert (D.A. Van Dam and Associates and Ohio Department of Transportation).

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

3.1.2.2 Culvert Deformation

Deformations and distortions in the culvert wall can lead to reduced capacity and even culvert failure. Minor, medium, and major deformations are defined below.

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

3.1.2.2.1 Minor Deformation

Minor deformations include minor isolated distortions in the top half of the culvert, minor flattening of the invert, and a horizontal diameter not greater than 10 percent of the design diameter.

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

3.1.2.2.2 Medium Deformation

Medium deformations include significant distortion at isolated locations in the top half of the culvert, significant flattening of the invert, some kinks, and a horizontal diameter not greater than 15 percent of the design diameter.

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

3.1.2.2.3 Major Deformation

Major deformations include major distortions along the majority of the length of the culvert (greater than 60 percent), major kinks, flattening of the crown or invert, and a horizontal diameter greater than 20 percent of the design diameter.

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

3.1.2.3 Culvert Invert Deterioration

A culvert pipe that has a corroded or abraded invert (the bottom of the culvert) (figure 4) or a pipe that is severely pitted and perforated still may be capable of supporting its backfill and cover, but it constitutes a high risk of failure and requires a prompt repair or replacement (National Cooperative Highway Research Program 1978). Significant flattening of the invert also will require attention to prevent further deterioration.

Figure 4—Invert deterioration occurring in a corrugated metal pipe (Caltrans).

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

3.1.3 Culvert Is Collapsed

If a culvert is partially or fully collapsed, as shown in figure 5, then lining methods will not be applicable and an inline replacement, such as pipe splitting or a complete open-cut installation will be required.

Figure 5—Collapsed/punctured corrugated metal pipe—a. Punctured corrugated metal pipe (Gordon Keller, Forest Service), b. Collapsed corrugated metal pipe.

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

3.2 Culvert Requires Increased Capacity

Full flow usually is a pressure flow, although a special condition may exist where a pipe flows full with no pressure due to an inadequate design and chronic sediment that lead to debris buildup and plugging. This can cause problems, such as overtopping of roadways, failing of the culvert and the roadway above, and flooding of adjacent properties. Additionally, pressure flow poses a severe barrier to fish passage, thereby increasing the need for culvert replacement. If the culvert requires an increase in capacity, an inline replacement (pipe splitting) or an open-cut replacement with a larger diameter pipe will improve the flow.

Back to Flowchart 2.2—Culvert Lacks Hydraulic Capacity

3.3 Culvert Has Bedding Deficiencies

Bedding deficiencies can cause surface depressions above the culvert, voids around the culvert, and undermine the culvert. Material loss around culverts generally is caused by:

- Piping or internal erosion.
- Raveling through joints.

The root cause of internal erosion involves:

- Pressure gradients within the soil and adjacent to the culvert.
- Erosion of the soil and its ability to move from the system.

Erosion can occur from around the culvert's outlet; through a joint, crack, or hole in the culvert; or through a fissure or adjacent duct. Raveling occurs when the soil surrounding the culvert is lost through a joint, crack, or hole in the culvert that can be attributed to gravity. If solutions do not address these mechanisms, material losses should be expected to continue.

Back to Flowchart 2.3—Culvert Has Bedding Deficiencies

3.3.1 Surface Depressions

Surface depressions are caused by voids occurring near the culvert that undermine the pavement or ground surface above. The voids must be filled with grout or the bedding deficiencies can be repaired with an open-cut replacement.

Back to Flowchart 2.3—Culvert Has Bedding Deficiencies

3.3.2 Voids Around the Culvert

Erosion voids, sometimes referred to as piping (figure 6), can spread and reach the ground surface. Not only does this adversely impact the stability of buried metal culverts, but it can pose a potential loss of life if a void forms under a pavement. Typically, preventative measures include proper compaction practices and seepage collars.

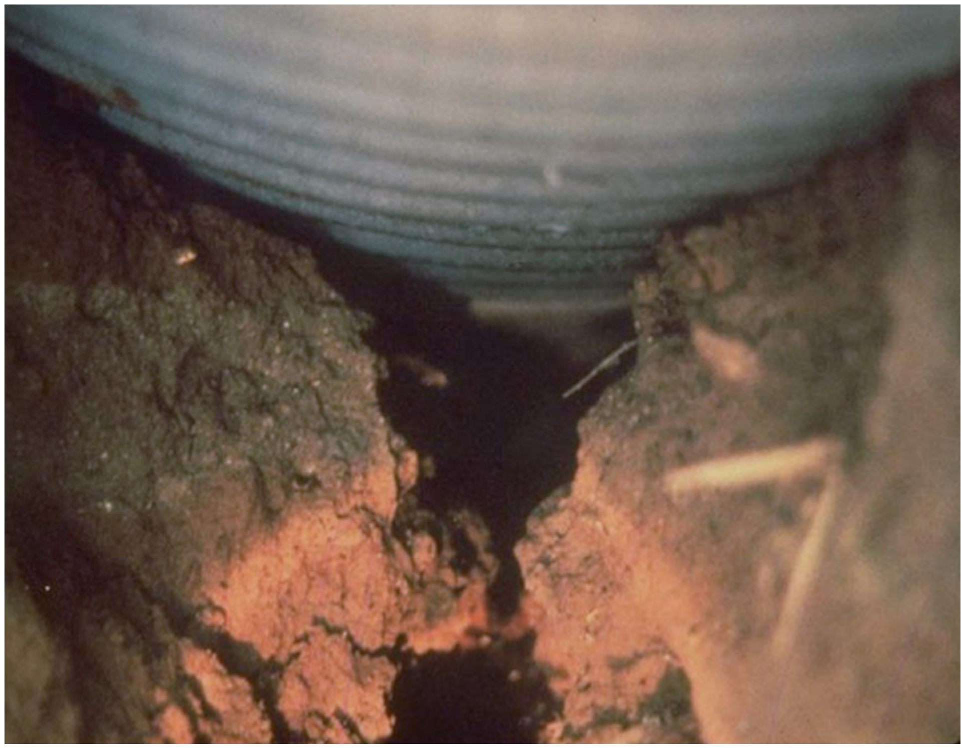


Figure 6—Piping beneath a culvert.

Back to Flowchart 2.3—Culvert Has Bedding Deficiencies

3.3.3 Undermining

A normal outcome of metal culvert pipe corrosion that has produced perforation is undermining (i.e., the formation of erosion voids in the embedment soil below and beside the structure) (figure 7). These voids, typically adjacent to severe corrosion, are due to ingress of water through the corroded zones and infiltration of backfill material under hydrostatic pressure. Undermining results in a loss of soil support for the culvert. Without an adequate soil envelope around the pipe, metal culverts have relatively little bending stiffness and are likely to deflect and exhibit shape distortion or sags and joint opening.

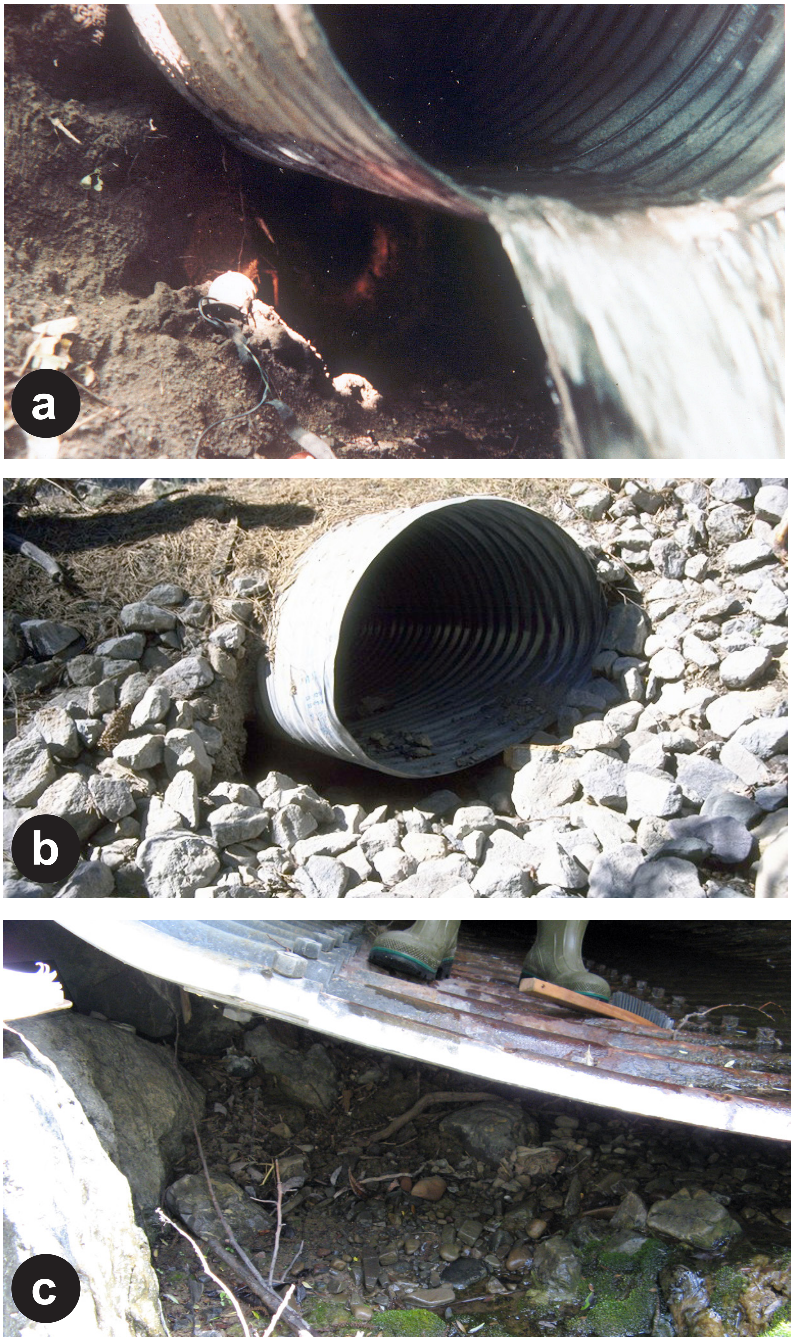


Figure 7—Undermining of a corrugated metal pipe—a. Voids around a corrugated metal pipe (Gordon Keller, Forest Service), b. Undermining (Gordon Keller, Forest Service), c. Undermining (Caltrans).

Back to Flowchart 2.3—Culvert Has Bedding Deficiencies

Based on results from a national survey (56 responding agencies), National Cooperative Highway Research Program Synthesis 303 “Assessment and Rehabilitation of Existing Culverts” (Wyant 2002) indicated that, as of 2002, very few agencies had guidance to select culvert repair methods (9 percent of responding agencies) or rehabilitation methods (7 percent of responding agencies). However, 27 percent of the responding agencies considered the following factors in their decision to either replace or rehabilitate culverts: hydraulic capacity, structural capacity, traffic volume, height of fill, remaining service life, and risk assessment (i.e., probability of failure and severity of consequences). Most of these agencies factored service life into the decision process (24 percent of responding agencies).

Another national survey (39 responding agencies) presented in National Cooperative Highway Research Program Synthesis 371 “Managing Selected Transportation Assets: Signals, Lighting, Signs, Pavement Markings, Culverts, and Sidewalks” (Markow 2007) indicated that by 2007, a growing number of agencies had guidance for maintenance and rehabilitation of culverts (the 2002 survey did not cover maintenance). Although national guidelines exist, such as the Federal Highway Administration’s (FHWA) “Culvert Repair Practices Manual” (Ballinger and Drake 1995), American Association of State Highway Transportation Officials (AASHTO) “Culvert Inspection, Material Selection and Rehabilitation Guideline” (AASHTO 1999), and “Maintenance Manual” (AASHTO 2007), guidance issued by individual agencies was identified as the primary technical source for culvert inspection, maintenance, and repair.

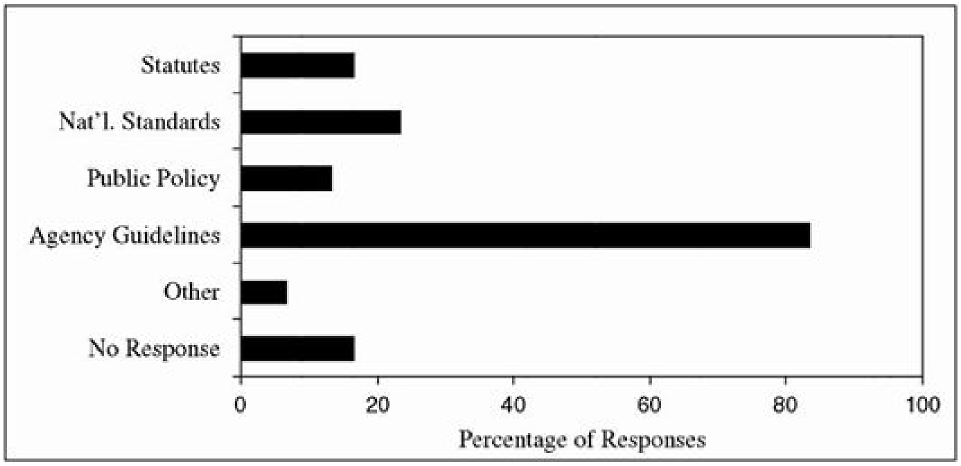


Figure 8—Technical management guidance for maintenance and rehabilitation of culverts (Markow 2007).

Table 1—Additional individual agency guidelines

Agency Title (reference)	Comments
Minnesota DOT "Culvert Renewal" (Johnson and Zollars 1992)	Reviews sliplining and cured-in-place (CIPP) lining options for both corrugated metal and concrete culverts. Seven different liners are investigated for corrugated metal pipe (CMP): (1) smooth polyethylene with mechanical joints (2) smooth polyethylene with fused joints (3) corrugated polyethylene(4) spiral ribbed polyvinyl chloride (5) fiberglass (6) spiral ribbed coated steel arch and (7) CIPP liners.
FHWA "Culvert Repair Practices Manual" (two volumes) (Ballinger and Drake 1995)	Outlines different culvert repair strategies, showing objectives and work options of each (table 2). Outlines several methods for trenchless rehabilitation of culverts, of which sliplining, flexible tube lining (CIPP), and cement mortar lining apply to CMPs. To replace CMPs, manual describes traditional open-cut method and several trenchless excavation methods for installing new culverts. Three primary economic analyses methods to aid in selecting or prioritizing culvert projects are outlined: (1) first-cost analysis, (2) life-cycle cost analysis, and (3) benefit-cost analysis.
Caltrans "Culvert Restoration Techniques" (Aryani and Al-Kazily 1993)	Outlines rehabilitation and installation methods and techniques similar to the FHWA's "Culvert Repair Practices Manual" (referencing its 1992 draft). Covers fold-and-form liners as well as pipe jacking (for new pipes 48 inches in diameter or larger) and microtunneling (for new pipes up to 36 inches in diameter).
Caltrans "Supplement to FHWA Culvert Repair Practices Manual" (2002)	Provides updated information on rehabilitation methods. Includes sprayed epoxy or polyurethane coatings, and man-entry relining with pipe segments (i.e., fiberglass reinforced cement liners and fiberglass reinforced plastic liners). Also, specific procedural guidance on culvert performance and assessment is shown.

Table 1—Additional individual agency guidelines (continued)

Agency Title (reference)	Comments
FHWA "Culvert Pipe Liner Guide and Specifications" (Thornton et al. 2005)	Provides more in-depth information about many culvert rehabilitation methods, including method description, advantages/limitations, cost information, and general installation guidelines. Lists applicable standards/specifications, contractors, and manufacturers of systems on the U.S. market. Methods apply to corrugated metal, plastic, and concrete culverts and include: sliplining (segmental and continuous), close fit lining (swage lining, rolldown lining, deform/reform lining, fold-and-form lining, spirally wound lining, and CIPP), and spray-on lining (cement mortar lining and epoxy lining).
Virginia DOT (VA DOT 2008)	Developed its own guidelines for selection of culvert rehabilitation method (table 3).

Table 2—Types of culvert repair strategies (Ballinger and Drake 1995)

Strategy	Objective	Work options
Routine maintenance	To keep a culvert in a uniform and safe condition by repairing specific defects as they occur.	● Debris and sediment removal. ● Thaw frozen culverts.
Preventive maintenance	More extensive strategy than routine maintenance intended to arrest light deterioration and prevent progressive deterioration.	● Joint sealing. ● Invert paving. ● Concrete patching. ● Scour prevention. ● Ditch cleaning, repair. ● Mortar repair.
Rehabilitation	Take maximum advantage of the remaining unusable structure in a culvert to build a reconditioned culvert.	● Repair of basically sound endwalls and wingwalls. ● Repair of scour. ● Invert paving. ● Pave streambed. ● Stabilize slope. ● Install debris collector. ● Add apron, cutoff wall. ● Improve inlet configuration.
Upgrade to equal replacement	Upgrade to provide service that is equal to that provided by a new structure.	● Add, repair, or replace appurtenant structures. ● Line the barrel. ● Provide safety grates or safety barriers. ● Lengthen the culvert.
Replacement	Provide a completely new culvert with a new service life.	Can be accompanied by: ● Realignment. ● Hydraulic structural and safety improvements. ● Change in culvert shape or material.

Table 3—Virginia Department of Transportation flexible liner type selection guideline (VADOT 2008)

Pipe Deficiency or Site Limitation	Concrete	Corrugated Metal	Plastic
Minor cracks	A, B, C, D, E, F	NA	A, B, C, D, E, F
Major cracks and/or spalls.	A, B, D, E	NA	A, B, C, D, E
Joints separated by greater than 1 inch.	A, B, C, D, E	A, B, C, D, E	A, B, C, D, E
Coating removed, no corrosion.	NA	A, B, C, D, E, F	NA
Coating removed, minor corrosion.	NA	A, B, C, D, E, F	NA
Coating removed, major corrosion.	NA	A, B, C, D, E	NA
Minor deformation, less than 5 percent of inside diameter.	NA	A, B, C, D, E, F	A, B, C, D, E
Intermediate deformation, 5 percent to 7 percent of inside diameter.	NA	A, B, D, E, F	A, B, D, E
Major deformation, greater than 7 percent of inside diameter.	NA	A, B, D, E	A, B, D, E
Height of cover.	*	*	*
Access (limited space to end of pipe, accessible by manhole or drop inlet).	A, B	A, B	A, B
Bends in pipe.	A, B	A, B	A, B

** Note: An economic evaluation should be performed to determine the feasibility of excavating and replacing rather than lining the existing pipe.*

LEGEND:
A — Cured-in-place pipe (Insituform, CIPP COR72AT470, Am-Liner, National Liner).
B — Fold and form flexible liner (U-Liner).
C — Thin-walled high-density polyethylene slipliner (Spirolite, Snap-Tite, Danby).
D — Thick-walled high-density polyethylene slipliner (N-12, CONTECH A-2, CONTECH A-2000, Ultraliner).
E — Polyvinyl chloride slipliner (Easy Liner, Lamson Slipliner).
F — Spray-on polymer (Polyspray Full Structural, Poly-Triplex Liner System).
NA — Not applicable.

4.1 Sliplining of Corrugated Metal Culverts

The FHWA "Culvert Repair Practices Manual" lists different pipe materials that could be used for sliplining of corrugated metal pipes and provides guidelines for sliplining and grouting of the annular space (Ballinger and Drake 1995).

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

4.1.1 Sliplining with Polyethylene

Three types of polyethylene pipe can be used for sliplining: (1) smooth polyethylene with mechanical joints, (2) smooth polyethylene with fused joints, and (3) corrugated polyethylene pipe (Johnson and Zollars 1992).

Newton (1999) discusses the practicality of continuous sliplining of failing culverts with polyethylene pipe. In the 1990s, some of the major railroads installed this type of liner with very positive results. A coupling system for jointing high-density polyethylene pipes by screwing together bell-and-spigot ends (e.g., Thread-Loc®) is available.

North Dakota Department of Transportation incurred severe damage to some polyethylene liners installed in corrugated metal pipes due to ditch fires. "Cost Effective Non-Flammable Pipe Liners" (Katti et al. 2003) investigates options to address the flammability of these liners. The research reviews several coatings that could be applied to the inside of polyethylene liners, cast-in-place liners (manufactured by Inliner, Insituform, U-Liner), and Hobas pipe. The Hobas pipe was found to be the best solution; however, it has to be fitted with concrete end caps to ensure fire resistance.

In 2007, the Cascade Complex fires in the Payette National Forest in Idaho resulted in the destruction of 142 high-density polyethylene culverts ranging in diameter from 18 to 36 inches, 41 wood culvert inlet headwalls, and 50 high-density polyethylene culvert downspouts (figure 9). The Forest Service and the FHWA recommend concrete or masonry headwalls for flammable plastic culverts and liners in forest environments where fire is a possibility.

Figure 9—Cascade complex fire, Idaho (Charlie Showers, Forest Service)—a. Catch basin with timber lag headwall. b. Burned off culvert inlet in a catch basin with timber lag headwall, top view.

Ohio Department of Transportation reported sliplining a corrugated metal pipe culvert under a highway with a pressure-rated high-density polyethylene culvert liner. The existing culvert was 102 inches in diameter and 835 feet long, and the high-density polyethylene pipe was 72 inches in diameter. The slipliner pipe was delivered to the site in sections, and after aligning, the individual segments were welded from the inside. After welding, the pipe was inserted into the culvert and the annular space grouted.

Figure 10—Sliplining corrugated metal pipe in Ohio (D. A. Van Dam & Associates).

Oregon Department of Transportation reported sliplining corrugated metal pipe with high-density polyethylene pipe. A 200-foot long, 36-inch-diameter pipe (Harbor Hole Culvert Rehabilitation Project) was sliplined with a 30-inch-diameter high-density polyethylene pipe, and the annular space was subsequently grouted (John Woodroof, Oregon Department of Transportation, personal communication).

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

4.1.2 Sliplining With Reinforced Concrete Pipe

A case study of segmental sliplining a twin-barrel metal culvert with precast concrete pipe (Woodbridge, VA) was illustrated in the appendix of FHWA's "Culvert Repair Practices Manual" (Ballinger and Drake 1995). The host corrugated metal pipes were 96-inch vertical oval pipes. After the concrete slab was cast to fill erosion holes under the invert and to establish grade, the 66-inch concrete pipe sections were installed, and the annular space was grouted.

Vaillancourt (2002) describes a case study of segmental sliplining with reinforced concrete pipe for Maine Department of Transportation (Jepson Brook Culvert Rehabilitation in Lewiston, ME). The existing corrugated metal pipe, 1,048 feet long and 144 inches in diameter, was relined with a 108-inch reinforced concrete pipe structure. The reinforced concrete pipe segments were installed by pushing in place the segments inside the corrugated metal pipe. A special cart was fabricated to drive the precast concrete segments inside the pipe. Jacks were used to lift the segments off the ground while the cart was pushed along the existing tunnel with a Bobcat loader. At the target location, the jacks were lowered and the pipe homed with the previously positioned pipe using two 6-ton come-alongs anchored in two holes that were later used for pumping grout between the old metal and new concrete pipes. The process was repeated for each pipe segment.

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

4.1.3 Sliplining With Corrugated Metal Pipe or Pipe Arch

If corrugated pipes or pipe-arch sections are used for sliplining of corrugated metal pipes, install either timber skids or a concrete sidewalk in the invert so that the liner may be slid into position. They may not be needed if the culvert is less than 150 feet long and the corrugated metal pipe is 36 inches or less in diameter (Ballinger and Drake 1995).

Duncan (1984) describes using a corrugated structural plate arch for sliplining a corroded structural steel plate culvert by Montana Department of Transportation. In a case study near Hardin, MT, the failing culvert with a cross section of 14 feet by 9 feet 8 inches and 260 feet in length was sliplined. The plate arch used for sliplining was assembled onsite from 3- by 1-inch corrugated sheets to form an 11 foot 10 inch by 7 foot 3 inch cross section. The arch plates were asbestos-bonded asphalt-coated to enhance their durability.

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

4.1.4 Invert Sliplining

Ikerd (1984) describes the use of steel-armor plates to repair corrugated metal inverts by the Alabama Department of Transportation. In a project completed in 1974, a triple-barrel culvert was repaired. Each barrel was 84 inches in diameter and 517 feet long, and had inverts that were severely deteriorated by abrasion. Anchors were welded to the existing pipe inverts and a concrete mortar bed was placed along the pipes. Next, the steel plates were lowered vertically into the mortar bed. An overhead monorail system attached to the crown of pipe transported the steel plates (figure 11).

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

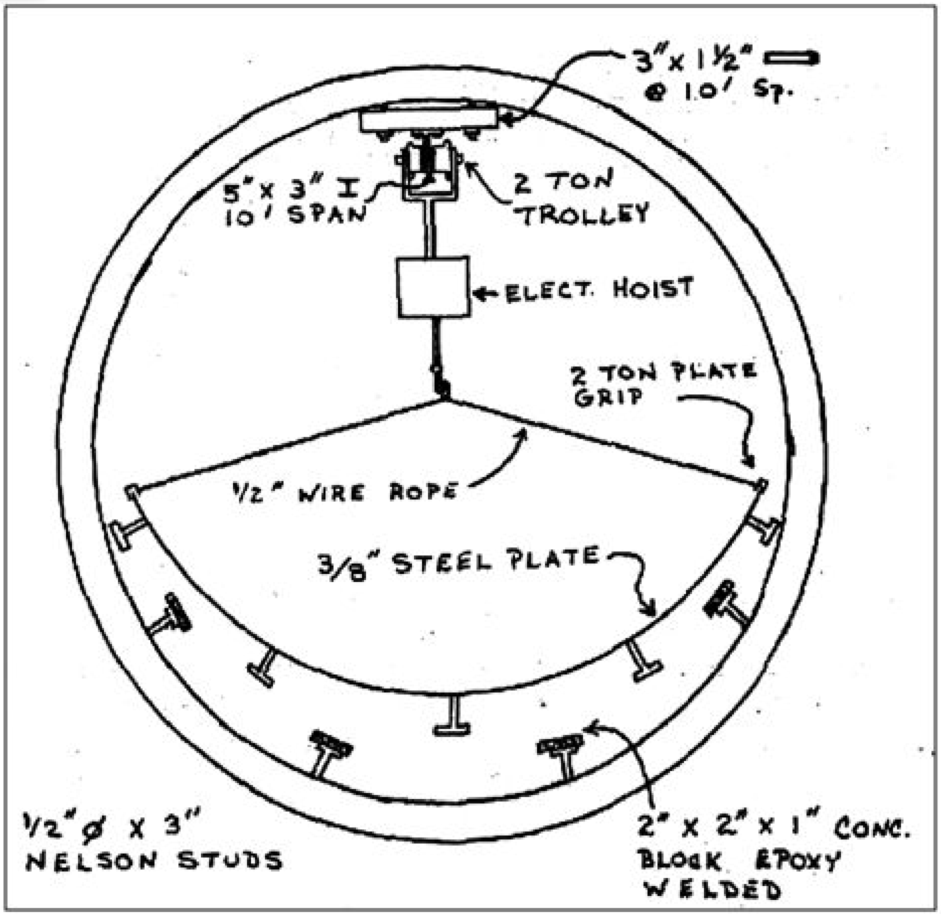


Figure 11—Installation of steel plates (Ikerd 1984).

4.2 Cured-in-Place Pipe Lining

The main components of cured-in-place pipe liners are a fabric tube (needled felt or equivalent woven or nonwoven material) and a thermosetting resin (unsaturated polyester, epoxy vinyl ester, or epoxy with catalysts). For installation, the resin-saturated tube is inserted into the culvert by inversion or winching, the liner is expanded to closely fit the size and shape of the host pipe (using air or water pressure), and the resin is subsequently cured at ambient or elevated temperature (using steam, hot water, or ultraviolet light). Figure 12a shows a liner being pulled into a 36-inch corrugated metal pipe, and figure 12b shows the inside of the pipe after curing. The cured-in-place pipe relining can restore both structural and hydraulic capacities. It offers an advantage when access to the culvert is limited. A third-party test (Southwestern Laboratories 2004) demonstrated a significant increase in culvert pipe strength after installing a cured-in-place pipe liner. The ultimate load bearing strength increased from 1,377 pound force foot (lbf/ft) to 3,095 lbf/ft, and D-Load strength increased from 689 pound force per square foot (lbf/ft^2) to 1,548 lbf/ft^2.

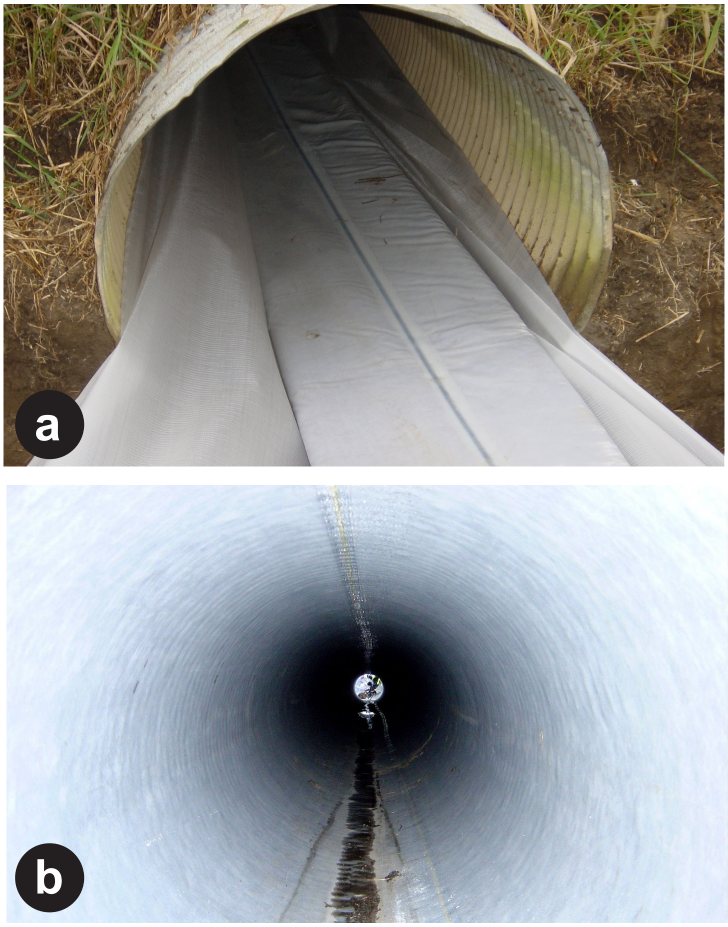


Figure 12—Cured-in-place pipe lining (Insituform)— a. Cured-in-place pipe being pulled in pipe, b. Cured-in-place pipe after cutting.

As mentioned in section 1.4, some adverse affects of styrene on aquatic organism passage have been reported. Virginia Department of Transportation studied the effect of styrene released from cured-in-place pipe installations and results showed elevated levels of styrene in five of seven installation locations (Donaldson and Baker 2008). This led Virginia Department of Transportation to suspend the use of styrene cured-in-place pipes that convey surface or stormwater until modifications to their specifications and inspection policies could be made. Subsequently, they have indicated that using ultraviolet light significantly reduces the length of time of elevated styrene levels <http://www.virginiadot.org/business/resources/const/cdmemo-0811.pdf>.

Sukley and St. John (1994) reported the use of cured-in-place pipe liners for rehabilitation of corrugated metal pipes by the Pennsylvania Department of Transportation. The process (Insituform, polyester fiber-felt and polyurethane resin) was utilized in 48-year-old asphalt and corrugated metal pipe on State Route 0358 in Mercer County. Despite its relatively high cost, the project resulted in an overall savings and the method was recommended for use statewide.

In 2005, the city of Baytown, TX, relined a 60-inch egg-shaped galvanized corrugated metal pipe, 90 feet long, with a cured-in-place pipe liner (Poly-Triplex of Texas, fiberglass and vinyl liner tube, epoxy resin). Relining was carried out in sections <http://www.polytriplexoftx.com/baytown.html>.

In 2002, the city of Brighton, CO, relined a galvanized corrugated steel pipe culvert under the highway used for irrigation water (oval shape, 30 inches wide, and 110 feet long) with a cured-in-place pipe liner (Poly-Triplex of Texas, fiberglass and polyvinyl chloride vinyl liner tube, epoxy resin) (Hessheimer, personal communication).

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

4.3 Fold-and-Form Lining

Fold-and-form liners are made of polyvinyl chloride. For installation, the liner is deflected into a U shape during the manufacturing process so it can be easily pulled inside the pipe; steam or air pressure is used to expand the liner to fit closely the size and shape of the host pipe (figure 13).

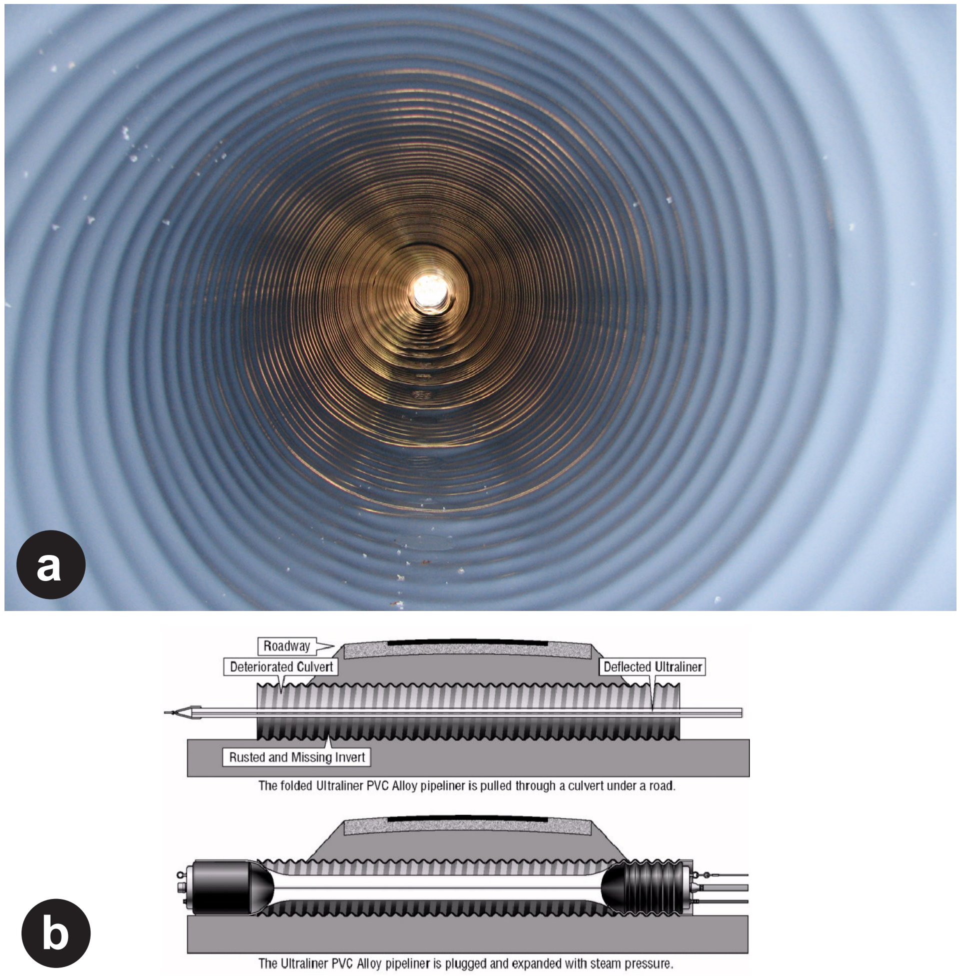


Figure 13—Installation of fold-and-form liner (Ultraliner)—a. Looking down the center of a culvert in which a fold and form liner has taken on the shape of the host culvert. b. The folded pipeliner is pulled through a culvert under a road, then the pipeliner is plugged and expanded under steam pressure.

In 2001, Georgia Department of Transportation reported the use of fold-and-form liners (Ultraliner PVC Alloy Pipeliner) to rehabilitate corrugated metal pipe. Seven deteriorated culverts in the roadbed, ranging from 15 to 30 inches in diameter and from 40 to 80 feet in length, were relined successfully. They selected this method for several reasons:

- No digging was required.
- No chemicals were used.
- No need to block more than one lane of traffic for more than 4 hours.
- Inexpensive. The least expensive method identified at the time.

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

4.4 Spiral-Wound Lining

Spiral-wound liners are fabricated in the field from a continuous plastic strip with male and female edges. During the winding process, the male and female edges self-interlock and form a leak-tight joint. With this method, an annular space between the host pipe and the liner is created, which generally is grouted with a cementitious material. The strip can be made of polyvinyl chloride (with or without steel reinforcement) or high-density polyethylene, can have external ribs to increase the stiffness, and can anchor in the cement grout injected in the annulus space between liner and host pipe.

Figure 14—Spiral winding of a 14-foot corrugated metal storm sewer (Sekisui SPR).

San Diego County, CA, reported using spiral winding (Rib Loc Ribsteel™) to rehabilitate a 36-inch corrugated metal storm culvert under Honey Springs Road in San Diego that was deteriorated and was on the verge of collapse—the invert of the culvert had rusted out, and the supporting bedding soil had been eroded away. Prior to relining, the invert was rebuilt with 4 tons of stone and then sealed with quickset mortar so that the grout pumped into the annulus would not migrate into the stream. The project specified installation of a 33-inch outside diameter pipe liner but due to deformation in the host pipe, the largest fixed diameter liner that could be installed was 30 inches <http://www.ribloc.com.au>.

South Carolina Department of Transportation used spiral winding (Sekisui SPR) to reline a corroded culvert under Interstate 95 in Santee, SC. The culvert was 84 inches in diameter and 212 feet long. The whole project took about 3 weeks and was completed smoothly, with minimal interruption of highway traffic. Only one highway lane had to be closed at a time, for a total of 12 hours (Breland, personal communication).

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

4.5 Sprayed Linings

Sprayed linings can be used for spot repair of damaged culverts or to form a continuous lining within an existing culvert. Lining materials can be cementitious (cement mortar) or noncementitious (e.g., epoxy, urethane, polyurethane, polyurea).

Walker and Guan (1997) reviewed the application parameters and the performance of five primary types of sprayed liners used in North America for the internal lining of steel pipelines in potable water service (table 4). The performance of these lining systems—when subjected to eight relevant American Society for Testing and Materials (ASTM) standards—is shown in table 5. Thirteen different spray-applied coating systems that can be used for protection (factory applied) or rehabilitation (field applied) of steel water pipelines were included in the study.

Primeaux (1989) introduced the concept of 100 percent solids spray elastomer polyurea coatings that differentiated polyurea coatings (products based on isocyanates/amines) from polyurethane coatings (products based on isocyanates/polyols). Since then, 100 percent solids polyurea spray elastomers have been promoted as a new coating technology with polyurea advantage (Broekaert 2002). In 2000, the industry formed its own association, the Polyurea Development Association (<http://www.pda-online.org>) to promote market awareness, and the understanding and acceptance of polyurea technology through the development of educational programs, product standards, safety, environmental, and usage recommendations.

Guan (2003a) reviewed the chemistry, history, and recent developments of 100 percent elastomeric polyurethane, 100 percent elastomeric polyurea, and 100 percent solids rigid (structural) polyurethane. Newly developed ceramic-modified 100 percent solids rigid polyurethane coatings meet the challenge of highly abrasive or high-flow applications, and offer ultimate durability and impact resistance. Another improvement of 100 percent solids polyurethane/polyurea involves incorporating a nonleachable antimicrobial additive, which enables these coatings to provide long-term corrosion protection. Still another significant

Table 4—Application parameters and attributes of sprayed liners used in rehabilitation of steel pipes. (Walker and Guan 1997)

	Solvent amine-based epoxy	100 percent solids epoxy	100 percent solids elastomeric polyurethane	100 percent solids rigid polyurethane	Cement mortar
Surface preparation	SSPC SP10 (NACE 2)	SSPC SP10 (NACE 2)	SSPC SP10 (NACE 2) SSPC SP5 (NACE 1)	SSPC SP10 (NACE 2)	Hand cleaning to remove corrosion
Surface profile	2.0 mil (0.05 mm)	2.0 mil (0.05 mm)	3.5 mil (0.088 mm)	2.5 mil (0.063 mm)	Not applicable
Recommended lining thickness	11–20 mils (0.28–0.5 mm)	10–20 mils (0.25–0.5 mm)	20–125 mils (0.5–3.175 mm)	15–20 mils (0.38–0.5 mm)	188–500 mils (4.775–1.27mm)
Number of coats to thickness	1–3 coats	1–2 coats	1 coat	1 coat	1 application
Application temperature range	40–100 °F	40–100 °F	0–150 °F	-10–150 °F	40–100 °F
Cure to handle time at 70 °F	4–14 hours	10 hours	4–6 hours	30–90 minutes	1 day or more
Time to service at 70 °F	1–4 days	1–4 days	2 days	2 days	1–7 days

Table 5— Performance of sprayed liners used in rehabilitation of steel pipes (Walker and Guan 1997)

	Solvent amine-based epoxy	100 percent solids epoxy	100 percent solids elastomeric polyurethane	100 percent solids rigid polyurethane	Cement mortar
Adhesion (ASTM D4541)	1,280 psi	925 psi	1,000 psi	2,000 psi	0 psi
Impact resist (ASTM D2794) non aged samples	38 in lbs	15 in lbs	80 in lbs	50 in lbs	2 in lbs
Impact resist (ASTM D2794) aged samples	10 in lbs	5 in lbs	75 in lbs	50 in lbs	2 in lbs
Abrasion resistance: average weight loss	122 mg	183 mg	15 mg	50 mg	1,500 mg
Flexibility (ASTM D522)	Failure at 180° over a 2-inch mandrill	Failure at 180° over a 2-inch mandrill	Pass at 180° over a 2-inch mandrill	Pass at 180° over a 2-inch mandrill	Failure at 180° over a 2-inch mandrill
Cathodic disbondment (ASTM G95)	15 mm average	15 mm average	30 mm average	8 mm average.	N/A
Salt spray resistance (ASTM B117)	Pass 1,000 hours	Pass 1,000 hours	Pass 1,000 hours	Pass 1,000 hours	Fail
Water absorption (ASTM D570)	2-percent weight change	2-percent weight change	6-percent weight change	2-percent weight change	7-percent weight change
Chemical resistance (ASTM D714)	Pass	Pass	Pass	Pass	Pass

improvement is the development of a 100 percent solids, rigid aliphatic polyurethane coating, which has much better adhesion (when applied over nonprimed steel or galvanized surfaces), faster initial film development, and superior corrosion and chemical resistance.

4.5.1 Cement Mortar Lining

Cement mortar lining may be used to line corroded corrugated steel culverts ranging in diameter from 12 inches to 23 feet, but it is mostly appropriate for culverts that are less than 30 inches in diameter (Caltrans 2002). The mortar is made of one part cement to one part sand. For small diameters (12 to 24 inches), the cement mortar is spray-applied by robot. Construction thickness from 1/8 inch to 3/4 inch per pass is possible, and two passes typically result in a 1-inch minimum thickness over the crests or peaks of the corrugation pattern. Prior to using this technique any voids around the pipe must be pressure grouted.

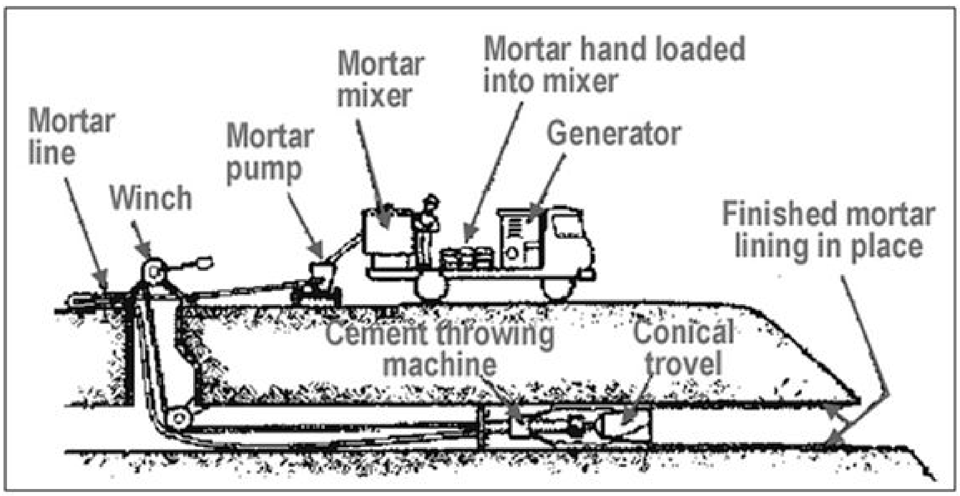


Figure 15—Cement mortar lining (Caltrans 2002).

Cement mortar lining systems are very economical but provide poor corrosion protection in a corrosive environment (Walker and Guan 1997). New York Department of Transportation recommends lining with shotcrete if the structural integrity of a culvert is sufficient and corrosion on the entire circumference of the culvert is minor (generally less than 20 percent total perforations). If signs of minor corrosion are limited to the bottom of the culvert (i.e., less than 30 percent of the bottom 1/4 of the pipe is perforated), paving the invert with Portland cement concrete is the preferred method (New York Department of Transportation 2001). Cement mortar does not bond to the steel surface but is held in place by its rigidity and shape (Walker and Guan 1997, Galka and Yates 1984).

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

4.5.2 Asphalt or Paving Materials Coating

Asphalt or concrete paving materials have been used as a coating for inverts when they become eroded due to the movement of abrasive materials through the culvert as per ASTM A 849 M. Asphalt materials may be used for minor erosion, but for a major eroded invert, one would need a reinforced concrete material to prevent further deterioration. However, this is used infrequently and is outside the scope of this publication.

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

4.5.3 Polyurethane

Guan (2003b) described an advanced 100-percent solids rigid polyurethane coating technology used for rehabilitating (steel) pipelines. Traditionally, most pipe rehabilitation field applications have been based on 100 percent solids elastomeric polyurethane; however, since the mid-1990s, the movement in North America has been toward the development and use of 100 percent solids rigid polyurethane coatings. The 100 percent solids rigid polyurethane forms a 3-dimensional cross-linked structure resulting in a coating with superior resistance to chemicals, water penetration, and extreme temperatures. The sprayable resin has a 1:1 mixing ratio with balanced viscosities between two reactive components, which enables easier metering of the components in the field.

In 2007, in Norristown, PA, a galvanized corrugated steel pipe culvert 60 inches in diameter and 1,800 feet long was spray-relined with polyurethane. The lining was sprayed in one coating (thickness 300 mils) with a proprietary heated plural component spray system. The application required a very clean and very dry surface. The applied surface preparation procedure is proprietary for the systems used (Jerry Gordon, Sprayroq, Inc., personal communication).

In the Nevada Irrigation District in northern California, several corrugated metal pipes were rehabilitated with sprayed polyurethane (CIM 1000, 2-component asphalt-extended polyurethane, elastomeric). The black asphalt-extended urethane requires a clean, dry, and structurally sound surface, or else the coating may adhere poorly and blister. To prevent rust, the epoxy primer may be used on freshly blasted steel prior to coating with black Chevron Industrial Membrane (CIM). The coating is spray-applied using properly configured air-assisted, airless, plural-component spray equipment. Two coats are applied to reach a thickness of 60 mils. The cure time is 4 hours (Stan Terry, CIM Industries, personal communication).

Figure 16—Polyurethane spray (Sprayroq, Inc.)—a. Culvert in Norristown, PA, before rehabilitation, b. Culvert during application of SprayWall® (Sprayroq Inc).

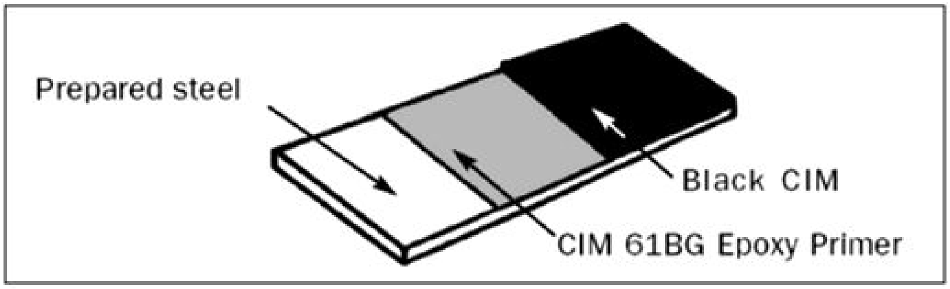


Figure 17—Black asphalt-extended polyurethane applied over epoxy primer (CIM Industries).

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

4.5.4 Polyurea

Polyurea cures rapidly (5 to 15 seconds) and provides a high degree of chemical resistance. O'Malley (2005) discusses the importance of adequate surface preparation for proper adhesion when polyurea is used as a protective coating. Near-white metal blast cleaning of steel surfaces according to the National Association of Corrosion Engineers (NACE 1994) is required, but yellowing and delamination still can occur if moisture is present on the surface during application. This is particularly the case for thin-layer applications (typical thickness for protective coatings is 60 to 120 mils).

Polyurea spray elastomer technology for structural rehabilitation of culverts is applied in thicknesses between 250 and 2,000 mils as the liner is designed to resist soil loads, traffic loads, and hydrostatic ground water pressure. Like cement mortar lining, polyurea lining with such thickness holds in place by its rigidity and shape. Preparation is not as critical as with protective coatings (Donald Dancey, personal communication).

A number of agencies have already approved polyurea coatings for rehabilitation of culverts and sewer pipelines, such as the Virginia Department of Transportation (2008), and the Florida and Ohio Departments of Transportation. Polyurea coatings are under review by Departments of Transportation in 35 other States with evaluations nearing final approval stage (Hunting Specialized Products, Inc. 2008).

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

4.6 Spot Repairs

4.6.1 Stainless Steel or Polyvinyl Chloride Repair Sleeves

Localized damaged areas within corrugated metal pipes can be repaired by applying prefabricated stainless steel or polyvinyl chloride sleeves. The sleeves come in various diameters and standard lengths (e.g., Link-Pipe™ polyvinyl sleeves are available in diameters from 36 to 108 inches with standard lengths of 18, 24, and 36 inches). Although multiple adjacent sleeves can be used, this method typically is used to repair relatively short sections of long culverts. They can repair structurally damaged culverts but also can be used to restore missing pipe sections without excavation or to provide infiltration sealing of joints. The sleeves are positioned inside the culvert while folded (figure 18) and jacked (snapped) into expanded shape.

Figure 18—Polyvinyl chloride sleeve <http://www.linkpipe.com>.

In 2007, in Atlanta, GA, a 60-foot long, 47-inch-diameter corrugated metal pipe was repaired (Link-Pipe polyvinyl sleeve) using multiple, back-to-back, polyvinyl chloride sleeves <http://www.linkpipe.com/culverts.htm>.

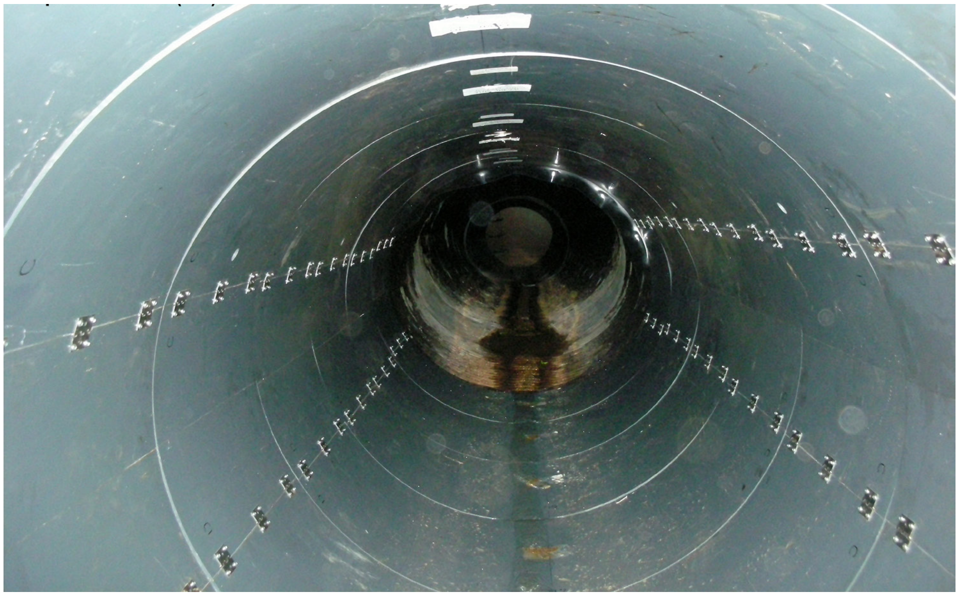


Figure 19—Polyvinyl chloride sleeve used in Atlanta, GA <http://www.linkpipe.com/culverts.htm>.

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

4.6.2 Internal Joint Sealing

Individual leaking joints in man-entry corrugated metal pipes can be repaired effectively with flexible rubber seals. Such seals ensure a noncorrosive, bottle-tight connection around the full inside circumference of the pipe joint area (figure 20).

Figure 20—Internal joint sealing with flexible rubber seals (Miller Pipeline Corporation).

In 2007, the Oregon Department of Transportation used internal mechanical seals to repair corrugated metal pipes. A 100-foot-long, 48-inch-round culvert (Bauch Creek Irrigation Culvert Project), in otherwise good condition, had two failed joints with infiltration that were repaired (John Woodroof, personal communication).

Back to Flowchart 2.1—Culvert Lacks Structural Capacity

4.7 Soil Stabilization

Soil stabilization around culvert pipes is a viable method for addressing problems caused by washouts and soil-bedding loss around culverts. Such washouts often result from fast-moving, high-volume waterflow through the culvert and development of a head pressure against the surrounding soils. While not a traditional trenchless repair method, these voids can be filled with pourable grouts using a tube to fill the voids from top to bottom.

Back to Flowchart 2.3—Culvert Has Bedding Deficiencies

4.7.1 Grouting

Polymer compaction-grouting uses a high-density, hydroinsensitive polymer that is injected from the culvert pipe into the soil. It expands from its original liquid volume and reaches its strength within a short time—filling, densifying, and stabilizing low-density compressible soils. A manufacturer (Uretek 2008) reports that the injected material expands up to 20 times and attains its full strength within 15 minutes after curing. It is lightweight (10 percent the weight of cement grouts), environmentally neutral, and has a manufacturer's 10-year warranty against significant shrinkage.

In 2002, the New Mexico Department of Transportation reports having used a polymer compaction-grouting method (Uretek Deep Injection Process) to fix stability issues with a corrugated metal pipe under a highway. The multiplate culvert was 14 feet high, 21 feet wide, and 155 feet long. It was 22 feet below the road surface, which had settled as much as 6 inches. Penetrometer tests revealed strong base and subbase soils above the crown of the culvert but poor soil compaction and large, deep voids in several key weight-bearing locations around the culvert itself. For this application, small 5/8-inch holes were drilled through the corrugated pipe using a radial pattern. The densified soil was pushed upward and restored the road to profile.

Pressure grouting also is used routinely to fill voids in the soil alongside culverts caused by piping or exfiltration. Usually, grouting is carried out from inside the culvert using two grout tubes, one directed to the bottom of the void and the other to the top of void. The grout is pumped through the bottom grout tube until it fills the void and starts to flow out through the upper tube. Voids can sometimes be filled from the roadway surface provided the voids can be located accurately. Portland cement-based grouts and mortars, as well as chemical and foaming grouts, can be used (Balinger and Drake 1995). Pumping shotcrete provides an alternative for filling large voids under culverts.

Back to Flowchart 2.3—Culvert Has Bedding Deficiencies

4.8 Pipe Replacement Methods

4.8.1 Pipe Splitting

It is possible to conduct a trenchless replacement of a corrugated metal pipe (North American Society for Trenchless Technology 2005). However, a specially designed tool is needed because corrugated metal tends to bunch up during a standard bursting application, which relies on the static pressure of a bursting head that must be larger than the size of the host pipe to break it up while being pulled or pushed through pipe. Typically, the cutting sleeve used on ductile pipe materials, such as steel or ductile iron, is designed to keep the pipe rounded. Two large blades shear and separate the metal pipe and do not allow ovaling. The expander at the rear separates the sheared pipe and also pulls in the new high-density polyethylene replacement pipe simultaneously. Standard roller blades used for splitting ductile iron or steel pipes are not suitable for corrugated metal pipes.

In 2005, DeKalb County, GA, reports having burst a 10-foot-long 15-inch-diameter corrugated metal pipe using a 14-inch Grundocrack Koloss with a 24-inch rear expander. It was upsized with a 24-inch high-density polyethylene pipe (figure 21). The original corrugated metal pipe culvert, sheared opened and expanded, remained in the ground except for the last 8-foot-long section, which was pushed out (Eddie Ward, personal communication).

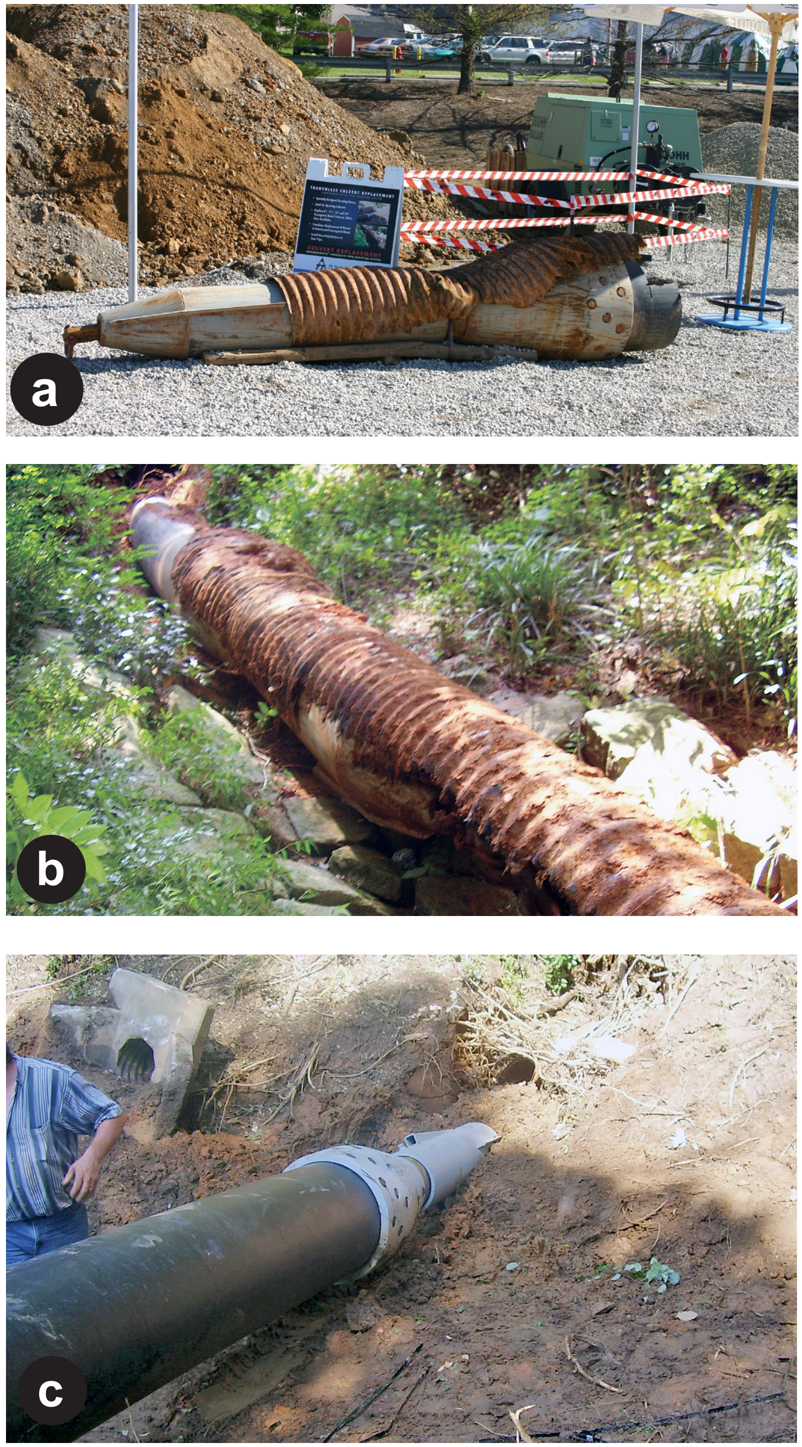


Figure 21—Bursting (TT Technologies)—a. Bursting head with cutting sleeve and rear expander (TT Technologies), b. Pipe bursting/pipe splitting of a corrugated metal culvert, c. Pipe bursting with an upsize of a culvert.

Back to Flowchart 2.1—Culvert Lacks Structural Capacity or
Flowchart 2.2—Culvert Lacks Hydraulic Capacity

4.8.2 Replacement on a New Alignment

When a new culvert replaces a deteriorated and/or hydraulically undersized culvert and is installed on a different alignment than the original, the existing culvert can be either abandoned or repaired. An abandoned culvert should be filled with concrete or another structural fill to ensure stability of the road surface in the face of continuing culvert deterioration.

Knoyle (2007) describes a replacement case study with a new concrete culvert on Highway 274 in Ottawa, Ontario, Canada. An existing corrugated metal pipe, 265 feet in length and 60 inches in diameter, in two sections (190 feet and 75 feet, installed at a 15-degree horizontal angle) was abandoned, and a concrete culvert 70 inches in diameter was installed with jack-and-bore tunneling. An Akkerman steerable shielded tunnel boring machine was used.

Jacking and tunneling involves pushing the pipe through an embankment with hydraulic jacks as an auger boring head bores a hole of the same size. Then the auger is removed and the steel pipe remains in place, serving as the new culvert. As with any culvert, the replacement culvert can serve for aquatic passage and, if there is a moderate or higher gradient through the system, baffles or fishway weirs can be installed. Often, a level pipe is jacked through a fill and a fishway is constructed on the downstream side to bring fish up to that pipe (Bates and Love 2011).

Back to Flowchart 2.1—Culvert Lacks Structural Capacity or
Flowchart 2.2—Culvert Lacks Hydraulic Capacity

4.8.3 Open-Cut Replacement

In some cases, a complete (conventional) open-cut replacement will be necessary to repair the highly corroded or collapsed corrugated metal pipe culvert structure. This construction method uses traditional and conventional means and is outside the scope of this report.

Figure 22—Conventional open-cut trench (Scott Kelman, Forest Service).

Back to Flowchart 2.3—Culvert Has Bedding Deficiencies

4.9 Inlet Modifications

Inlet modifications can help reduce undermining when the flow is not actually entering into the culvert. Inlet modification is not a specific rehabilitation technology and is outside of the scope of this publication.

Back to Flowchart 2.3—Culvert Has Bedding Deficiencies

4.10 More Information

For more information about the use of trenchless technologies on Forest Service culverts, refer to “Summary of Trenchless Technology for Use with USDA Forest Service Culverts” (Piehl 2005). The Piehl report summarizes the trenchless technologies considered to be most appropriate for Forest Service roadway culvert applications. It is intended to help Federal land management agency engineers, as well as engineers from other agencies, determine where and when to use these technologies.

This appendix includes a literature search on inspection and condition assessment of corrugated metal culvert pipes.

A.1 Inspection and Condition Assessment of Corrugated Metal Culverts

A knowledge base has been developed on culvert inspection procedures, culvert rating systems, and culvert durability. Municipalities and departments of transportation use this information to determine a culvert's remaining service life and the level of deterioration of their culvert infrastructure. Highway agencies develop culvert inspection programs, which incorporate formalized inspection scheduling and documentation. The following section provides an overview of inspection and rating systems developed by transportation agencies across the United States for corrugated metal pipes.

A.1.1 Culvert Inspection and Rating Systems

The "Culvert Inspection Manual" (Arnoult 1986) provides field inspection guidelines for identifying defects in corrugated metal culverts, rating the severity of defects, and assigning the condition ratings score. Instruction for both visual inspection and required measurements is provided for different culvert barrel shapes. For creating the record of culvert inspection, the Federal Highway Administration (FHWA) modified the standard structure inventory and appraisal sheet from the National Bridge Inspection Program into a standard culvert inspection form. The FHWA's condition rating system rates corrugated metal culverts on a 0- to 9-point scale based on shape, seams and joints, and metal condition (table A.1).

"Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges" (FHWA 1995), a guide for State, Federal, and other agencies on how to report the number and condition of the Nation's bridges to Congress, includes one item (item #62) that evaluates the alignment, settlement, joints, structural condition, scour, and other items associated with culverts. Inspection and rating of culverts is based on the "Culvert Inspection Manual" (1986).

Kurdziel (1988) reviewed condition rating systems of metal culverts used in durability studies and publications in 14 States. Once a metal culvert had deteriorated past superficial rust, there was little agreement on rating, and most studies did not show a uniform systematic progression of deterioration. For example, describing a condition as moderate signs of deterioration does not explain the condition, so specific degrees of deterioration should be listed (depth of rust, degree of pitting, and so forth). A new material rating system with detailed and unique description for each rating was proposed (table A.2). The degree of perforations spans over three ratings instead of one or two, which was the case in many State scales.

Table A.1— FHWA's criteria for condition rating of (round and vertical oval) corrugated metal culvert barrels (Arnoult 1986)

Rating	Shape	Horizontal diameter	Seams and joints	Metal (A-aluminum, S-steel)
9	New condition.			
8	Good, smooth curvature in barrel.	≤ 10 percent of design	Tight, no openings.	• A: superficial corrosion, slight pitting. • S: superficial rust, no pitting.
7	Generally good, top half of pipe smooth, minor flattening. of bottom	≤10 percent of design.	Minor cracking at few bolt holes, minor joint or seam openings.	• A: moderate corrosion, no attack core alloy. • S: moderate rust, slight pitting.
6	Fair, top half smooth curvature, bottom half flattened significantly.	≤ 10 percent of design.	Minor cracking at bolts, evidence of backfill infiltration.	• A: significant corrosion, minor attack core alloy. • S: fairly heavy rust, moderate pitting.
5	Generally fair, large distortion in top half, extreme invert flattening.	10-15 percent greater than design.	Moderate cracking at bolt holes along seam near pipe bottom .	• A: significant corrosion, moderate attack core alloy • S: scattered heavy rust, deep pitting.
4	Significant distortion through-out length of pipe, lower third kinked.	10-15 percent greater than design.	Moderate cracking at bolt holes on one seam near top of pipe.	• A: extensive corrosion, significant attack core alloy. • S: extensive heavy rust, deep pitting.
3	Poor with extreme deflection at isolated locations, flattening of crown, crown radius	> 15 percent greater than design.	3-inch-long cracks at bolt holes on one seam.	• A: extensive corrosion, scattered perforations. • S: heavy rust, deep pitting, scattered perforations.
2	Critical pipe distortion/ deflection, crown flattening, crown radius > 30 feet.	> 20 percent greater than design.	Plate cracked from bolt to bolt on one seam.	• A: extensive perforations due to corrosion. • S: extensive perforations due to rust.
1	Partially collapsed with crown in reverse curve.	Failed.	Road closed to traffic.	
0	Pipe totally failed.		Road closed to traffic.	

Table A.2—Proposed metal condition ratings (Kurdziel 1988)

Rating	Condition	Description
9	Excellent	New condition, galvanizing intact, no corrosion.
8	Very good	Discoloration of surface; galvanizing partially gone.
7	Good	Superficial or pinpoint rust spots, no pitting.
6	Fair	Moderate rust, rust flakes tight, shallow pitting of surface, galvanizing gone.
5	Fair-marginal	Heavy rust and scale, moderate pitting, slight thinning of core metal.
4	Marginal	Extensive heavy rust, thick and scaling rust coatings, deep pitting, and significant metal loss (approximately 25 percent).
3	Poor	Rust/pitting halfway through core metal (some deflection or penetration when struck with pick or geology hammer).
2	Very poor	Extreme deterioration and pitting, three quarters or core metal gone, first perforations.
1	Critical	Extensive or large perforations.
0	Failure	Invert completely deteriorated, culvert beginning to bend, warp or sag, collapse of culvert is imminent.

Pennsylvania Department of Transportation (PennDOT) performs both inventory and condition surveys of culverts along its highways. Several parameters related to culverts are rated during the field inspection and entered into the Drainage eSTAMPP Survey Form: physical condition, structural condition, flow condition, and roadway deflection (table A.3). PennDOT also rates appurtenances. Overall culvert condition is expressed in the form of a single-digit number that describes the physical condition of the culvert (PennDOT 2008).

California Transportation Department (Caltrans) implements systematic condition evaluation only for culverts classified as bridges. Although there is no statewide culvert inspection program, Caltrans developed culvert inspection condition tables for the 2-year culvert pilot project that was completed in June 2003. The rating system is in lieu of the FHWA rating system and is compatible with the Caltrans Culvert Inventory database. Condition rating of metal culvert barrels is rated on a 0-to-4 point scale based on waterway adequacy, shape, seams and joints, and culvert material. Feasible actions are listed in table A.4 for each condition rating.

Minnesota Department of Transportation (MN/DOT 2006) performs inventory and condition surveys of culverts using the HydInfra management system. This management system was launched in 1996 and has been used for managing inventory, inspection, and maintenance activities on State highway drainage systems. An inspector is asked to indicate a distress or a condition of the culvert by coding a number of parameters as Yes/No. The structural condition of pipe is rated on a 0-to-4 point scale (table A.5). The pipe inventory inspection and maintenance report is a typical output from HydInfra showing specifics of culverts (and other components of the system) and the result of their inspection (MN/DOT 2006).

Table A.3—PennDOT criteria for condition rating of pipes (PennDOT 2008)

Code	Physical condition	Structural condition	Flow condition	Roadway deflection
0	Like new, no defects.	No displacement, as installed, good.	Open.	None.
1	Moderate to heavy rust/pitting, large loss of interprotection, weathered joints.	Sag or structural components displacement < 20° joint separation.	< ½ clogged.	> 1-inch surface distress.
2	Broken, rust pitted, weathered joints.	Sag or structural components displacement > 20° joint separation.	½ or more clogged.	---
3	Extensive deterioration, rotted to fully deteriorated bottom, loss of invert.	Collapsed or failed.	Unknown (excess vegetation).	---
4	Unknown (excess vegetation).	Unknown (excess vegetation).	Unknown (inaccessibility).	---
5	Unknown (heavy flow).	Unknown (heavy flow).	“0” with PID.	---
6	Unknown (complete clogging).	Unknown (complete clogging).	“1” with PID.	---
7	Unknown (inaccessibility).	Unknown (inaccessibility).	“2” with PID.	---
8	---	---	“3” with PID.	---
9	---	---	“4” with PID.	---

Table A.4—Caltrans criteria for condition rating of corrugated metal culvert barrels–steel and aluminum (Caltrans 2003)

Condition	Waterway Adequacy	Shape	Seams, Joints	Material	Feasible Actions
0	No deficiencies.	No deficiencies.	No deficiencies.	No deficiencies.	0-Do nothing.
1	Minor debris and sediment, less than 25-percent blockage.	Good condition. Minor isolated distortions in top half. Minor flattening of invert. Horizontal diameter not greater than 10 percent of design.	Tight, no openings. Minor cracking at bolt holes.	● Steel: Superficial rust, minor pitting. ● Aluminum: Superficial corrosion, minor pitting.	0-Do nothing. 1-Debris removal. 3-Flush sediment. 14-Invert repair (paving/arm). 18-Undetermined. 19-Other.
2	Significant debris and sediment, between 25 percent and 50-percent blockage	Significant distortion at isolated locations in top half. Significant flattening of invert. Some kinks present. Horizontal diameter greater than 15 percent of design.	Significant cracking at bolt holes. Partial separation at seams. Infiltration of backfill through seams and joints.	● Steel: Scattered heavy rusting and deep pitting. ● Aluminum: Scattered heavy corrosion and deep pitting.	0-Do nothing. 1-Debris removal. 3-Flush sediment. 12-Joint sealing. 14-Invert repair (paving/arm). 15-Culvert barrel lining 16-Replace a section barrel. 18-Undetermined. 19-Other.
3	Between 50 percent and 75 percent blockage. Flooding of roadway and/or adjacent properties.	Major distortions throughout length of pipe. Major kinks and deflections. Flattening of crown and/or invert. Horizontal diameter greater than 20 percent of design.	Major cracking at bolt holes. Deflections of seams. Open joints. Infiltration of backfill.	● Steel: Extreme rusting, deep pitting, perforations present. ● Aluminum: Extreme corrosion, deep pitting, perforations present.	1-Debris removal. 3-Flush sediment. 12-Joint sealing. 14-Invert repair (paving/arm). 15-Culvert barrel lining. 16-Replace a section barrel. 17-Replace culvert barrel. 18-Undetermined. 19-Other.
4	Over 75 percent blockage.	Partially collapsed or complete collapse of crown.	Failed.	● S: Extensive rust, perforations. ● A: Extensive corrosion, perforations.	17-Replace culvert barrel. 18-Undetermined. 19-Other.

Table A.5—MN/DOTs coding in HydInfra for culvert inspection (MN/DOT 2006)

Code	Parameter	Code	Parameter
Y or N	Plugged?	Y or N	Misalignment?
Y or N	Deformed?	Y or N	Joints separation?
Y or N	Standing water?	Y or N	Holes?
Y or N	Infiltration?	Y or N	Inslope cavity?
Y or N	Silt present?	Y or N	Road void?
Y or N	Piping?	Y or N	Road stress?
Y or N	Cracks?	Y or N	Erosion?
Y or N	Spalling/flaking?	0-1-2-3-4	Structural condition?
Y or N	Pitting/rusting?		

Ohio Department of Transportation (ODOT) has a culvert inspection rating system that rates 16 items on a 0-to-9 point scale (table A.6). The inspector should select the lowest rating that best describes either the shape condition or the culvert barrel condition. The shape of the structure is the most critical factor in flexible culverts, and this should be kept in mind when selecting the rating (ODOT 2003).

Cahoon et al. (2002) investigated 33 parameters that describe the condition of an existing culvert for possible use as predictors of overall culvert condition. These 33 parameters were recorded at 460 culverts distributed geographically throughout Montana. An ordered probit statistical model indicated that 9 of the initial 33 potential predictors were statistically significant (table A.7). Measurements of these nine parameters can be used in the resulting model to classify a culvert into a 1-to-5 condition ranking, in which 5 is the best condition and 1 is the worst. The model matched the overall rating assigned by the field observers in 61.7 percent of culverts observed.

Table A.6—Corrugated metal culvert coding for the culvert inspection report form (ODOT 2003)

Code	Category	Description
9	Excellent	New condition; galvanizing intact; no corrosion.
8	Very Good	Discoloration of surface; galvanizing partially gone along invert but no layers of rust.
7	Good	Discoloration of surface, galvanizing gone along invert but no layers of rust. Minor pinholes (with an area less than 3 in^2/ft^2) in pipe material located at ends of pipe (length ≤4 feet and not located beneath roadway).
6	Satisfactory	Galvanizing gone along invert with layers of rust. Sporadic pitting of invert. Minor pinholes (with an area less than 6 in^2/ft^2, 4 percent) in pipe material located at ends of pipe (length ≤4 feet and not located beneath roadway).
5	Fair	Heavy rust and scale. Pinholes (with an area less than 15 in^2/ft^2, 10 percent) throughout pipe material. Section loss and perforations at ends. Holes in metal at end in invert and not located under roadway.
4	Poor	Extensive heavy rust; thick and scaling rust throughout pipe; deep pitting; perforations throughout invert with an area less than 30 in^2/ft^2, 20 percent. Overall thin metal, allows for an easy puncture with chipping hammer.
3	Serious	Extensive heavy rust; thick and scaling rust throughout pipe; deep pitting. Perforations throughout invert with an area less than 36 in^2/ft^2, 25 percent. Overall thin metal, easy puncture with hammer. End section corroded away.
2	Critical	Perforations throughout invert with an area greater than 36 in^2/ft^2, 25 percent.
1	Imminent Failure	Pipe partially collapsed.
0	Failed	Total failure of pipe.

Table A.7—Statistical modeling of culvert condition rating (Cahoon et al. 2002)

Predictors statistically significant	Input values
1. Age of culvert.	Integer years
2. Scout at outlet.	0, 1, or 2
3. Evidence of major failure.	0 or 1
4. Degree of corrosion.	0, 1, or 2
5. Invert of culvert worn away.	0, 1, or 2
6. Sedimentation of cross section.	0 to 100%
7. Physical blockage.	0 to 100%
8. Joint separation.	0 or 1
9. Physical damage.	0, 1, or 2

The Ohio Research Institute for Transportation and the Environment proposed a new culvert inspection rating system that considers 30 to 33 items on the 0-to-9 point scale. The system was developed from data collected at 60 culvert sites, of which 25 were metal. The statistical analysis indicated that age, rise, flow abrasiveness, pH, flow velocity, and culvert material type were significant variables for the culvert rating system (Mitchell et al. 2005).

The Federal Lands Highway field pack provides standard Federal Lands Highway culvert assessment forms as well as assessment and maintenance flowcharts that guide the user through a typical maintenance process (FLH 2010). The National Cooperative Highway Research Program Report 303 (Wyant 2002) also provides a culvert assessment form which may provide more information as to a typical inspection process.

A.1.2 Culvert Inspection Policies (Frequency of Inspections)

Information on Forest Service culvert inspection can be found in the Forest Service Manual (FSM) 7700, chapter 7730–Road Operation and Maintenance <http://www.fs.fed.us/cgi-bin/Directives/get_dirs/fsm?7700!> as well as other publications. Forest Service direction, as stated in FSM 7736.01, is that large culverts are to be inspected every 2 years. More specifically, in addition to the authorities listed in FSM 7722.01 and 7730.1, the National Bridge Inspection Standards (23 CFR Part 650) require biannual inspection on public roads of bridges with spans over

6.1 meters (20 feet) in length and of culverts with openings measuring more than 6.1 meters (20 feet) along the centerline of the road (as well as multiple pipes where the distance between openings is less than or equal to half of the pipe). Additional Forest Service culvert inspection guidance is available in:

- Forest Service Handbook (FSH) 7736.01 (FSM 7700–Travel Management, chapter 7730–Road Operation and Maintenance, 7736–Bridge Operation, 7736.01–Authority).
- FSH 7709.56b, Transportation Structures Handbook, chapter 8–Operation <http://www.fs.fed.us/dirindexhome/fsh/7709.56b/7709.56b,0_code.txt>.
- "Culvert Inspection Manual, Supplement to the Bridge Inspector's Reference Manual," Report No. FHWA NHI 03-001. October 2002. (Groenier, Forest Service, personal communication 2010).

Ring (1984) had suggested that culverts should be inspected at least every 3 years, and more often where the conditions are harsh.

The FHWA "Culvert Inspection Manual" requires the inspection of culverts once every 2 years. However, States may perform the inspections less frequently with FHWA approval, which is issued on a case-by-case basis if justified. For instance, if conditions are mild, the FHWA may approve inspection every 4 years. (As stated previously, this applies only to Forest Service culvert inspection Arnoult 1986.)

National Cooperative Highway Research Program Report 303 (Wyant 2002) indicates that as of 2002, there was no standard State and local culvert inspection cycle being followed by all highway agencies. There were more State Departments of Transportation with guidelines (37 percent) than local agencies (33 percent) and Federal agencies (25 percent). Most local agencies responding to the survey indicated that they use the guidelines outlined in the FHWA "Culvert Inspection Manual" (1986). These conclusions are based on results from a national survey on culvert inspection policies and procedures to which a total of 75 agencies replied.

Texas Department of Transportation (TxDOT) requires routine inspection of culverts every 4 years (TxDOT 2002).

In Ohio, all bridges with spans greater than 10 feet are required to be inspected annually; however, no Federal or State requirements mandate frequent inspections of short-span culverts. Culverts less than 10 feet in span are inspected sporadically under varying Ohio Department of

Transportation (ODOT) district procedures. ODOT recommends that highway culverts having spans between 1 and 10 feet are inspected once every 5 years (ODOT 2003).

Another nationwide survey, conducted in 2003-2004 by the Ohio Research Institute for Transportation and Environment, indicates that approximately 60 percent of State Departments of Transportation have developed culvert inspection policies. The majority of these State Departments of Transportation specified a 1- to 2-year inspection cycle; and a small percentage specified a 3- to 5-year cycle. Some States have dual frequency requirements (e.g., MN/DOT inspects large culverts with span greater than 10 feet in a 1- to 2-year cycle and smaller culverts in a 5-year cycle; VADOT inspects large culverts (span greater than 10 feet) on a 2-year cycle and smaller culverts in a 4-year cycle). Most States that inspect culverts apply a numerical rating system (Mitchell et al. 2005).

The inspection program used by the New York State Department of Transportation has a scale from 1 to 7, along with 8 for not-applicable cases and 9 for conditions-unknown cases. Culverts with ratings of 5, 6, or 7 are inspected every fourth year, those with ratings of 3 or 4 are inspected every second year, and those with ratings of 1 or 2 are rated annually (NYSDOT 2008).

Meegoda et al. (2004) developed inspection frequency guidelines that rate corrugated metal pipe at three levels based on several factors (table A.8). A four-point condition State assessment system was developed (based upon the Caltrans system) that includes quantifiable section losses, specific surface features, and prescribed responses associated with each condition state (table A.9). A Markov deterioration model was used to predict the future condition state of new corrugated metal pipe in urban and rural settings. The transition probabilities were based upon inspection data and corrosion studies. The model was extended to predict the future condition of new corrugated steel culvert pipe in both settings over a 30-year life. The model does not take into account the effects of maintenance or rehabilitation.

Meegoda et al. (2005) proposed a new culvert information management system, which would be a subsystem of New Jersey Department of Transportation's transportation asset management system. The proposed management system is based on the condition of the culvert during the previous year and the predicted survival probability of the corrugated steel pipe with service time data developed from an ASTM study. The proposed management system can analyze decisions to inspect, rehabilitate, or replace culverts, or do nothing, at both project

Table A.8—Proposed inspection frequency for corrugated metal pipe culverts (Meegoda et al. 2004)

Rating Level	I	II	III
Inspection frequency	10 years.	3 years.	1 year.
Basis for time interval	Self-cleaning design (10-year flood) for small diameter corrugated steel culvert pipe.	FHWA guidelines.	Reported problems.
Corrosion/sediment	Free of corrosion and debris.	Evidence of corrosion and/or debris.	Reported clogging or collapse.
Abrasion	Low abrasion. Minor bedloads of sand and gravel $V < 1.5$ m/s.	Moderate abrasion. Bedloads of sand, gravel 1.5 m/s $< V < 5$ m/s.	Severe abrasion. Heavy bedloads of gravel, rock $V > 5$ m/s.
pH	$5.8 < pH < 8.0$.	$5.0 < pH < 5.8$.	$pH < 5.0$.
Corrosion/erosion (conductivity maps, historical data)	Low or none.	Medium.	High.
Pipe age	10 years.	15 years.	30 years (design life).

Table A.9—Condition state assessment system (Meegoda et al. 2004)

Condition state	Suggested corrective action:
No evidence of active corrosion of the structure with any measurable section loss.	Do nothing.
Surface or freckled rust is formed on the structure, flaking, minor section loss ≤10 percent of thickness.	Clean and paint.
Flaking and swelling with surface pitting, but any section loss due to active corrosion is measurable and does not affect the strength or serviceability of the structure. Section loss: 10 to 30 percent of thickness.	Clean and paint or reline.
Corrosion is advanced, heavy section loss > 30 percent of section thickness.	Reline or replace.

and network levels. At the project level, inspection or rehabilitation and replacement costs are compared with failure risks and costs. At the network level, the costs are optimized to meet the annual maintenance budget by prioritizing needed inspection, rehabilitation, and replacement activities.

Bhattachar et al. (2007) developed a framework for culvert inventory and inspection by providing necessary protocols and condition rating systems. Culvert inventory data collection consists of 55 questions grouped in 6 modules. The basic condition assessment also has six components (table A.10). Any culvert with a performance score below 2.5 (red zone) requires an advanced condition assessment (i.e., it is inspected for specific problems that have caused the deterioration).

Table A.10—Modules for culvert inventory and inspection (Bhattachar et al. 2007)

Culvert inventory modules	Basic condition assessment modules
1. General identification of the culvert location.	1. General identification of the culvert location.
2. Structural information.	2. Site information (climate, water level, pH, soil resistivity, etc.).
3. Additional information to identify culvert components.	3. Culvert identification (shape, material, end treatment, etc.).
4. Hydraulics of the culvert.	4. Condition assessment (condition of inverts, end protection, roadway, embankment, footings, overall culvert condition).
5. Safety features.	5. Performance score calculated using relative weights for all components.
6. Culvert inventory (identification of past repair/rehabilitation).	6. Zoning of culverts based on performance score: > 3.5 indicates green zone (safe); between 2.5-3.5 yellow zone (intermediate); < 2.5 red zone (danger).

A.1.3 Durability and Service Life

The "Synthesis of Highway Practice 50: Durability of Drainage Pipe" (National Cooperative Highway Research Program 1978) defines durability as the material's ability to resist degradation as a result of chemical or electrochemical corrosion and mechanical abrasion. When limited by material performance, useful service life of culverts depends on their durability. Culvert durability is usually affected by two mechanisms: corrosion and abrasion. The manual also pointed out that there is no widely agreed upon definition for failure of a culvert, short of collapse. One way of defining the service life of a culvert is by the number of years of relatively maintenance-free performance. The culvert that has reached its service life may still have many years until failure.

Bealey (1984) reports that durability of culverts was identified as an issue of concern by more than 60 percent of State transportation agencies. A total of 33 States and numerous researchers had published 131 reports on durability of pipe materials, of which 63 percent were concerned with corrugated metal pipe.

The FHWA's "Durability of Special Coatings for Corrugated Steel Pipe" (Potter et al. 1991) investigated whether various coatings applied to plain galvanized corrugated steel pipe can give a culvert the desired design life of at least 50 years. The study showed that culverts that are bituminous coated and paved, polymer coated (ethylene acrylic acid film) or concrete lined, under proper conditions, can have an expected service life extended to at least 50 years.

The National Cooperative Highway Research Program's "Synthesis of Highway Practice 254: Service Life of Drainage Pipe" (Gabriel and Moran 1998) provided details on elements influencing material durability considered in the selection of drainage pipe. These elements include life expectancy of various types of pipe protection systems in different environments based on parameters such as pH, resistivity, abrasion, and flow conditions. Protection strategies that influence material durability were also addressed. The report cited the usage of thermosetting liners (cured-in-place liners) and preformed thermoplastic materials (high density polyethylene or polyvinyl chloride liners) as a significant change, and noted that linings for metal culverts continued to encounter durability problems.

FHWA's "Durability Analysis of Aluminized Type 2 Corrugated Metal Pipe" (Ault and Ellor 2000) reviewed various methods used for predicting culvert durability. Two of the most commonly used methods for predicting durability of metal culverts in soils are the California Test Method 643 and the ANSI/AWWA method. These methods estimate the combined effects of soil corrosion, water corrosion, and abrasion on the service life of corrugated metal pipe culverts.

California Test Method 643 (Caltrans 1999) calculates combined effects of soil corrosion, water corrosion, and abrasion on durability of galvanized corrugated steel pipe culverts that have not yet received maintenance treatment. The method was originally developed in 1959 based on corrosion testing of 7,000 corrugated metal pipes located in one area of California (Beaton and Stratfull 1962), but was refined over the years and was last updated in 1999. Two environmental factors are combined for estimating the service life (years to perforation) (figure A.1) of metal culverts: (1) pH of soil and water and (2) the minimum electrical resistivity of the site and backfill materials (table A.11). Using these parameters, the probable maintenance-free service life of a galvanized steel culvert in a given location can be estimated by using a chart (figure A.2). The service life is characterized as years to first perforation for a 16-gauge galvanized corrugated steel pipe (2-ounces per square foot zinc coating). A correction factor is given for different culvert pipe thickness (gauge between 18 and 8).

Table A.11—Typical resistivity values (Wilson and Oates 1969)

SOIL		WATER	
Classification	**ohm-cm**	**Source**	**ohm-cm**
Clay	750 - 2,000	Seawater	25
Loam	3,000 - 10,000	Brackish	2,000
Gravel	10,000 - 30,000	Drinking water	4,000 +
Sand	30,000 - 50,000	Surface water	5,000 +
Rock	50,000 - infinity	Distilled water	infinity

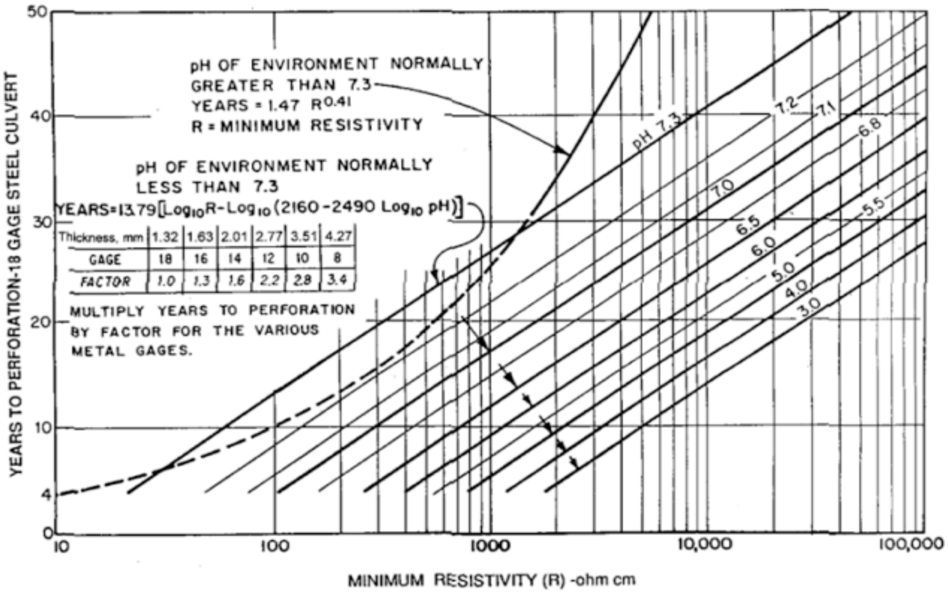


Figure A.1—California method chart for estimating years to perforation (Caltrans 1999).

American Iron and Steel Institute method (AISI 1994, CSPI 2007) is very similar to the California method except that the vertical axis is expressed as the invert's average years of service life. It is believed that the consequences of small perforations in storm sewers are usually minimal. The AISI method takes the position that service life is limited by 25 percent average metal loss in the invert, whereas only 13 percent average metal loss occurs at the first perforation. Therefore, culvert durability prediction with the AISI method is about double the California method (Ault and Ellor 2000) (figure A.2).

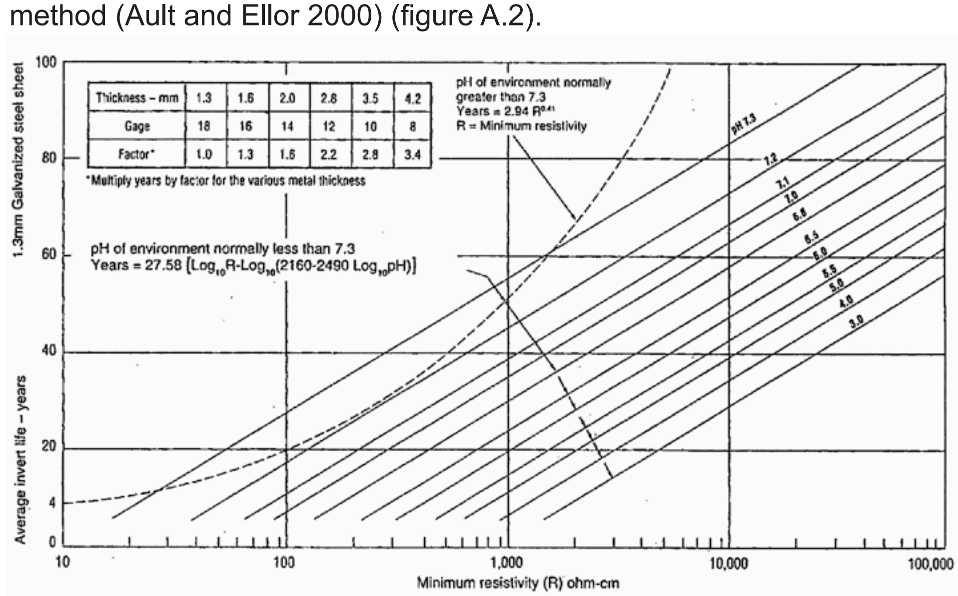


Figure A.2—AISI method chart for estimating years of service life (CSPI 2007).

The Florida method was derived from the California method and predicts durability of aluminized type-2 coated corrugated steel, concrete, and aluminum alloy culverts. A service life estimation graph is shown in figure A.3. Florida Department of Transportation has established that the life of aluminized type-2 coating is approximately 2.9 times that of galvanized coating (Ault and Ellor 2000 referencing Cerlanek and Powers 1993).

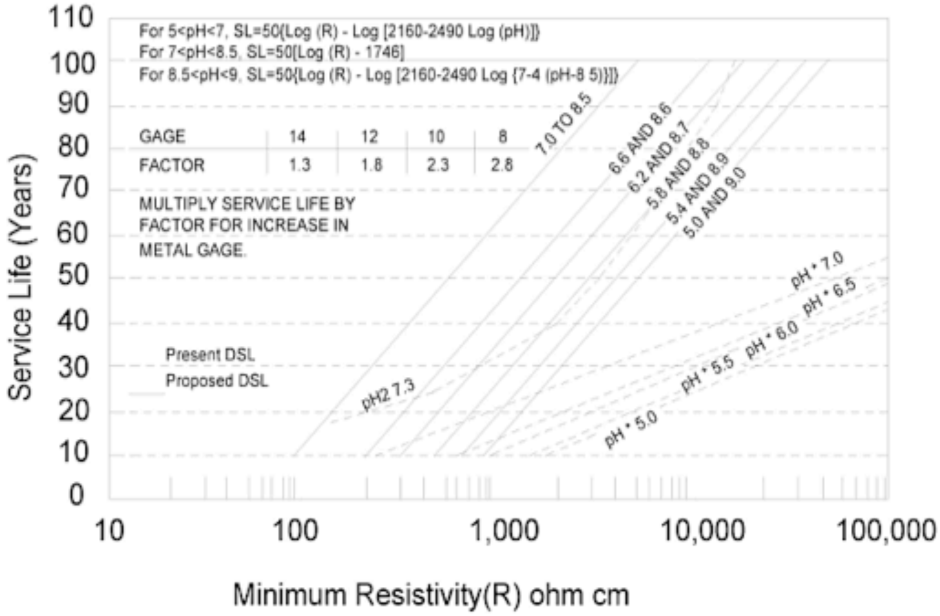


Figure A.3—Florida method for estimating years of service life of aluminized type-2 coated pipes (Ault and Ellor 2000 referencing Cerlanek and Powers 1993).

Florida Department of Transportation has developed a software program (figure A.4) for determining types of culvert material whose expected service life will meet or exceed the required design service life. The design service life, pipe size, pH, resistivity, chlorides, and sulfates are input variables; the program provides a listing of those materials that meet the design service life.

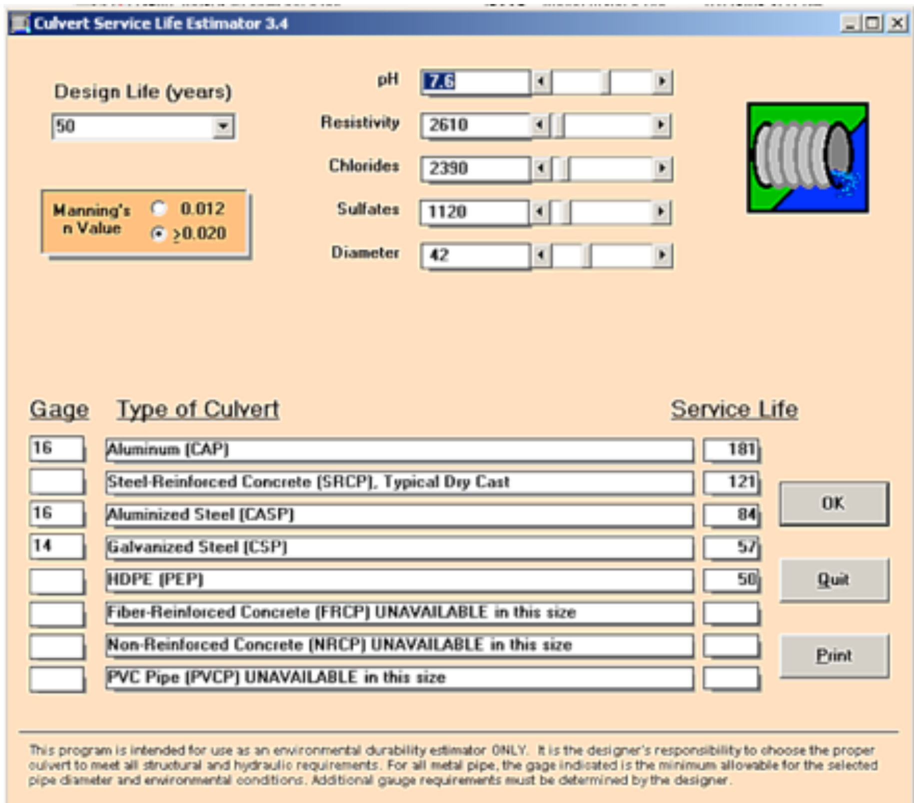


Figure A.4—Culvert service life estimator (FDOT 2008).

The New York method was developed by the New York State Department of Transportation (NYSDOT) based on a survey of almost 800 culverts. Curves were developed to estimate the average annual metal loss from percent of culverts parameter, which is based on site conditions (figure A.5). The curves indicate that durability can be substantially increased by the use of bituminous coatings and paved inverts. Service life is determined mostly by the condition of the pipe along the invert (CSPI 1990). Another reference (Ault and Ellor 2000) indicates that the New York method uses a numerical rating durability index instead of a chart. The durability index is calculated for a location based on several criteria: geographical area (relative soil corrosiveness), abrasion (bed load, gradient, and relative abrasiveness), flow condition (continuity), and service rating (side drains or driveway pipes versus cross drains).

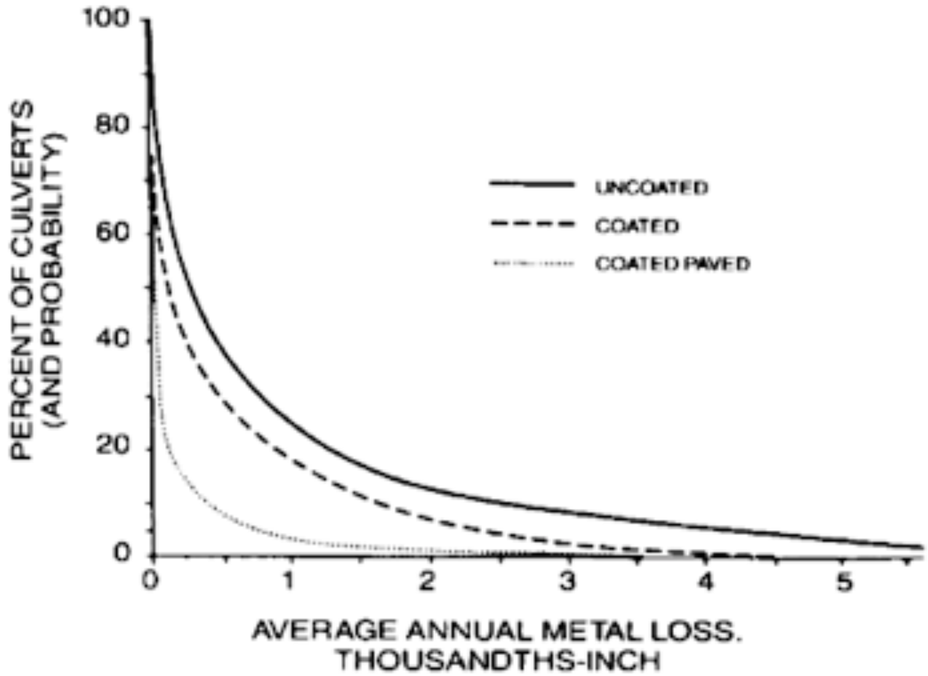


Figure A.5—New York curves (CSPI 1990).

The National Corrugated Steel Pipe Association's "Corrugated Steel Pipe Durability Guide" (2000) includes an AISI chart for predicting service life of corrugated steel pipe and provides a table showing added service life for various coatings at four abrasion levels. A total of 10 nonmetallic coatings are considered in the guide (table A.12).

Table A.12—Estimated added service life for nonmetallic coatings at different abrasion levels in years (NCSPA 2000)

Abrasion levels	Level 1 & 2	Level 3	Level 4
Asphalt coated	10	N/R	N/R
Asphalt coated and paved	30	30	30
Polymerized asphalt invert coated*	45	35	N/R
Polymer precoat	80+	70	N/R
Polymer precoat and paved	80+	80+	30
Polymer precoat with polymerized asphalt invert coated	80+	80+	30
Aramid fiber asphalt coated	40	N/R	N/R
Aramid fiber asphalt paved	50	40	N/R
High-strength concrete lined	75	50	N/R
Concrete invert paved (75 mm [3 in] cover)	80+	80+	50

(N/R = not recommended)

Guidelines to evaluate abrasion levels

1. Nonabrasive (no bedload regardless of velocity or storm sewer application).

2. Low abrasion (minor bedloads of sand and gravel and velocities of 5 ft/sec or less).

3. Moderate abrasion (bedlaods of sand and small stone or gravel with velocities 5-15 ft/sec.

4. Severe abrasion (heavy bedloads of gravel and rock with velocities > 15 ft/sec.

The National Corrugated Steel Pipe Association's paper "New Approaches to Determining Corrugated Steel Pipe Service Life" (NCSPA 2006) recognized that environmental conditions affect sacrificial coatings (galvanized) differently than they do barrier coatings (aluminized and polymer) of corrugated steel pipe. A galvanized coating is soluble in water. Soft water is more detrimental to galvanized coating than hard water because the latter has an excess of calcium carbonate, which is deposited on the pipe wall in the form of scale, thereby protecting the underlying galvanized coating. The National Corrugated Steel Pipe Association recommends galvanized pipe only in locations where calcium carbonate concentration is greater than 50 parts per million (which corresponds to the resistivity level greater than or equal to 10,000 ohm-cm). When installed in the right environmental conditions, a galvanized corrugated steel pipe can provide a 50-year service life. Barrier coatings provide a more uniform and predictable service life across several predetermined ranges for pH and resistivity criteria. An aluminized coating can perform well for up to 75 years and a polymer coating can function for 100 years or more.

A.1.4 Corrosion Resistance

Missouri Department of Transportation performed field inspections of 3,897 culverts throughout the State of Missouri, of which 2,255 were corrugated metal pipes. The study identified 45.6 percent of the corrugated metal pipes as needing replacement. Some of the corrugated metal pipe deterioration could be attributed to a change in the pipe gauge to a lighter gauge (i.e., thinner wall) over the past 30 years (Gift and Smith 2000).

Kansas Department of Transportation documented that more rapid deterioration of corrugated metal pipe has been quantified since the late 1970s, when standards changed to allow a lighter gauge metal in pipe construction. While the lighter gauge pipes may have had adequate structural support from surrounding soils, the change in standard was reported to lessen pipe design life by nearly 20 years because there was less metal to corrode at the same corrosion rate. The data in the report supported the decision to prohibit the use of corrugated metal pipe for crossroad installations in some districts in Kansas (Stratton et al. 1990).

The National Corrugated Steel Pipe Association had the corrosion resistance of polymer coated corrugated steel pipe investigated by the Corrpro Companies (National Corrugated Steel Pipe Association 2002b). In Wisconsin, five polymer-coated corrugated steel pipe culverts were inspected, as well as three other culverts (epoxy coated, aluminized steel pipe type 2, and aluminum). All culverts were in a severe corrosive environment (low pH, low electrical resistivity of soil and water, and anaerobic sulfate-reducing bacteria in organic rich soil). The polymer-coated corrugated steel pipe performed equally well or better than the other materials/coating systems. Only the epoxy-coated pipe showed signs of corrosion at one end.

A.1.5 Abrasion Resistance

The State of California Division of Highways evaluated the thickness of aluminum culverts required to achieve a 25-year maintenance-free service life in abrasive flow conditions. For a 10-year storm and in low-flow conditions less than 7 feet per minute, both uncoated and bituminous-coated corrugated aluminum pipe can be used. Cross drains are the exception: corrugated aluminum pipe must be bituminous coated or paved, and may be used only in flow conditions less than 5 feet per minute. Wear rates of corrugated aluminum pipe and steel pipe were compared: at the same thickness, aluminum pipe would perforate by abrasion 10 times sooner than steel pipe (Nordlin and Stratfull 1965).

Caltrans' "Evaluation of Abrasion Resistance of Pipe and Pipe Lining Materials" (DeCou and Davies 2007) evaluated 18 different pipe materials for their resistance to abrasion over a 5-year period in a natural stream setting. Among the materials tested were galvanized corrugated steel pipe, corrugated aluminized steel pipe type 2, and several galvanized corrugated steel pipes with different coatings. Abrasion wear of pipes, liners, and linings in the field was found to be nonlinear with time (i.e., abrasion rate was found to be event driven and dependent on the number and size of events during any given year). None of the protective coatings for steel was found suitable in extremely abrasive environments with high-flow velocities, but these results would have limited applicability to other sites statewide.

The National Corrugated Steel Pipe Association had the abrasion resistance of polymer-coated corrugated steel pipe investigated (National Corrugated Steel Pipe Association 2002a). In New York, the field performance of 20 corrugated steel pipes was evaluated. All culverts featured asphalt paved over a polymer coating. The asphalt paving showed excellent adhesion to the polymer coating. The combined asphalt paving and polymer coating performed well at severe abrasive sites. The sites exhibiting various levels of corrosion on the plain galvanized end sections of the culverts also reported satisfactory performance for the polymer coating. The age of inspected pipes was 9 to 13 years, but the condition of pipes was typical of several hundred other culverts in that geographic area.

Ault (2003) discusses laboratory testing and field evaluations of polymer-coated corrugated steel pipe. Laboratory testing comprised of 5 abrasion tests while field investigation was performed on 44 culverts in 8 States. A service life model for polymer-coated corrugated steel pipe was created, which included four distinct phases (figure A.6). While it is not possible to put a timeframe to each of these phases, the field studies indicate that pipes between 6 and 27 years old were still in the polymer-degradation phase.

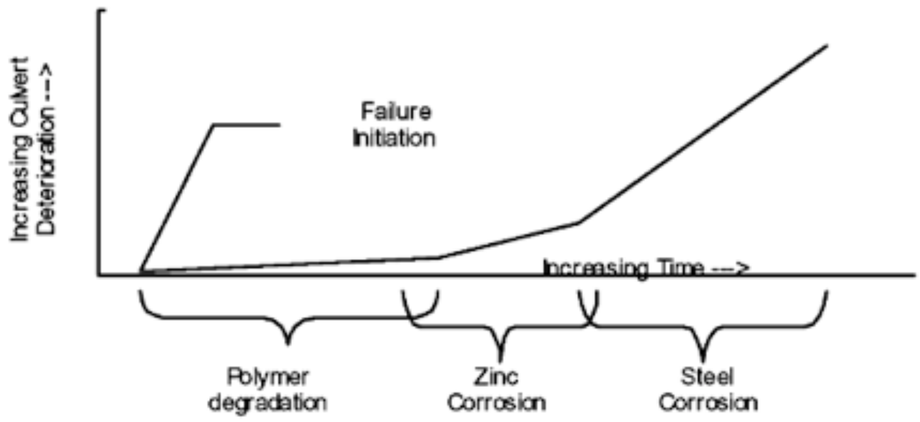


Figure A.6—Service life model for polymer-coated corrugated steel pipe (Ault 2003).

The Ohio Department of Transportation inspected a large number of corrugated metal pipes between 1972 and 1975: 386 structural steel plate pipes and 624 corrugated steel pipes. Of the 624 corrugated steel pipes, 127 were bituminous coated (AASHTO M 190 Type A) and 302 were bituminous coated with paved inverts (AASHTO M 190 Types B and C). These culverts were nearly all 42 inches or larger in size. The collected data at each site included:

- Pipe size, material type, and wall thickness.
- Pipe protection, depth, and velocity of dry weather flow.
- Abrasive material present and apparent effect.
- Sediment and debris amount and type, or both.
- pH of water, streambed, and embankment.
- Electric resistivity of water, streambed, and embankment.
- Protection description and protection rating.
- Base pipe description and base pipe rating.
- Chemical qualitative tests.
- Metal cores.

Detailed analyses were performed to evaluate the effects of various environmental factors on the durability of concrete pipe, galvanized corrugated steel pipe, and bituminous protection of corrugated steel pipe. Equations and graphs were presented to predict the service life of these culvert materials. The study indicated that the environmental conditions in Ohio were aggressive compared to most other States (a large area in Ohio is characterized by nonneutral pH flow and abrasive geological materials). Corrugated metal pipes were shown to be susceptible to corrosion and abrasion, depending on the type of coating and service conditions. Corrosive actions intensify under soil conditions with low pH, low resistivity, and increased moisture and temperature. Abrasive actions increase with increased drainage flow velocities and coarser, heavier bed loads. Thermoplastic culverts were found to provide higher levels of corrosion and abrasion resistance (Meacham et al. 1982).

Temple et al. (1985) investigated the performance of coated and uncoated galvanized steel and aluminum drainage pipes in Louisiana. One pair of each type of culvert was installed at 10 site locations in 1973. Test sites were selected on the basis of pH and electrical resistivity of the soil. Every 2 years, one designated culvert of each of the pairs was removed and subjectively rated by a panel. The study showed that the best resistance to corrosion at the majority of test sites had (1) a 14-gauge asbestos-bonded asphalt-coated galvanized steel pipe and (2) 16-gauge galvanized steel pipe with a 12-mil (0.30-mm) interior and 5-mil (0.13-mm) exterior polyethylene coating.

A.1.6 Culvert Hydraulic Performance and Considerations Related to Rehabilitation

Culvert hydraulics generally are concerned with culvert performance under a wide range of headwater and tailwater elevations for different culvert shapes, materials, and inlet configurations. As open hydraulic systems, culvert flows operate under inlet or outlet control conditions. The flow capacity of culverts operating in outlet control is determined by the tailwater depth, pipe slope, roughness, and length, and is normally calculated using Manning's equation. The flow capacity of culverts operating under inlet control is determined by inlet geometry, pipe-barrel cross-sectional area, and headwater depth.

The FHWA's "Hydraulic Charts for the Selection of Highway Culverts" (Herr and Bossy 1965) contains a series of performance curves and nomographs for calculation of culvert performance under both inlet and outlet control for many commonly used entrance configurations and culvert materials.

The FHWA's "Hydraulic Design of Highway Culverts" (Norman et al. 2005) is a comprehensive culvert design publication. Culvert design methods are presented for both conventional culverts and culverts with inlet improvements. Inlet control, outlet control, and critical depth design charts, many of which are newly developed, are included for a variety of culvert sizes, shapes, and materials. New dimensionless culvert design charts are provided for the design of culverts lacking conventional design nomographs and charts.

Charbeneau et al. (2006) developed a two-parameter model describing the hydraulic performance of highway culverts, which can accurately represent the FHWA performance curves.

Ead et al. (2000) investigated the velocity field in turbulent open-channel flow in a circular corrugated pipe at different slopes and discharges. The Manning coefficient n was found to be equal to 0.023.

Newton (1999) showed that flow capacity of corrugated metal pipe sliplined with high-density polyethylene pipe was not reduced despite diameter reduction (table A.13). The Manning coefficient for high-density polyethylene pipe was 0.009.

Table A.13—Corrugated metal culvert flow capacity when sliplined with Culvert Renew® (Newton 1999)

Original Pipe ID (CMP) (inches)	New Pipe ID (sliplined) (inches)	% of Original CMP Flow
12	10	164
15	12	147
18	15	164
21	15	109
24	18	124
27	21	136
30	24	147
33	27	156
36	30	156
48	36	124
54	40	120
60	42	103

Kozman (2006) developed a simplified approach to estimate hydraulics of corrugated metal pipe culverts relined with closed-fit liners. Several man-entry culverts (galvanized and bituminous-coated corrugated metal pipe) in Ohio and California that had been exposed to heavy corrosion and abrasion over the years were relined with cured-in-place pipe or deformed/reformed high-density polyethylene. The culverts were inspected 2.5 years after relining, and measurements were taken of the inside diameter, interior roughness, and upstream end geometry. Actual thickness of installed liners measured in the field was between 0.63 inches and 1.20 inches for cured-in-place pipe and 0.63 inches and 0.75 inches for high-density polyethylene.

Estimations were made for entrance-loss coefficients, Manning coefficient, and flow capacity for each culvert inspected. Manning coefficient for cured-in-place pipe segments was 0.0138 to 0.0167 before lining and 0.0109 to 0.0135 after lining; and for high-density polyethylene segments, 0.0140 before lining and 0.0082 to 0.0086 after lining. Percentage flow capacity maintained was 93 to 139 percent for cured-in-place pipe and 135 to 142 percent for high-density polyethylene. The research demonstrated that close-fit liners can be used to restore or increase the flow capacity of deteriorated culverts. Finished interior roughness of close-fit liners (e.g., high-density polyethylene, cured-in-place pipe) is dependent on interior roughness and condition of the host pipe, and liner material properties, thickness, and installation procedures.

Wallace et al. (2007) investigated hydraulic performance of cured-in-place relined corrugated metal pipe on twin corrugated metal pipe culverts near South Haven, MI, (originally 7 feet 8 inches by 5 feet 5 inches and 228 feet long). Field measurements were taken and hydraulic calculations made for the 100-year peak flow conditions. Cast-in-place pipe lining reduced the cross sectional area of the corrugated metal pipe culvert from 33.0 square feet to 28.9 square feet. Manning coefficient dropped from 0.034 to 0.013. The relative importance of these two outcomes of the lining process was explored by detailed comparison of the energy losses that occur under outlet control when the barrel is full (at the design flow, the hydraulics of these culverts was governed by outlet control). It was found that the improvement in total energy loss due to reduced surface roughness requires certain minimal length of pipe to offset the negative impact of cross-area reduction. In this particular case, it was calculated to be 38 feet.

A.1.7 Cost/Risk Analysis

Based on a survey of the United States and Canada, Perrin and Jhaveri (2004) suggested that very few agencies (3 out of 25 responding agencies) apply some sort of life-cycle cost analysis, and the majority

(15 out of 25 responding agencies) document failures on a cursory or memory basis. A method was developed to compute total cost of installing a culvert over a given design life, usually 100 years. The total cost is the sum of installation/replacement cost and user-delay cost. Several examples of culvert failures were reviewed to illustrate various costs (normal and emergency replacement costs, user-delay costs, etc.) and demonstrate how a longer design life would result in significant cost savings in the long run.

Lian and Yen (2003) performed a comparative study of eight different risk calculation methods on the occurrence probability of inadequate capacity of a culvert to pass floods.

The New York State Department of Transportation (NYSDOT 2008) is currently proposing a ranking metric called the performance indicator for screening culverts and prioritizing their needs. This parameter is calculated not only from the items directly related to the condition of culverts but also elements from the channel rating, thus including a risk element. Risks associated with large culverts can be safety risks (e.g., structural collapse, sinkholes, etc.) or operational risks (e.g., roads overtopping during storm events, inundation of upstream facilities due to backwater effects, etc.). However, a performance target (table A.14) based on culvert condition rating and culvert operational condition (the capacity to carry a storm of given return period with a given headwater-to-diameter ratio) remains an important indicator of structural safety, remaining life, and a proxy for the value of the structure. For evaluating the system management performance, tracking the investment metric with the average condition rating is proposed, as relative trends over time would indicate the effectiveness of capital investment.

Table A-14 Large culvert performance target definitions (NYSDOT 2008)

	Operational condition	**Condition rating**
Good	50-year storm capacity, Hw/D ≤ 1.5.	Structure general recommendation ≥ 6.
Acceptable	50-year storm capacity, Hw/D ≤ 1.5.	Structure general recommendation 5.
Deficient	25 to 50-year storm capacity, Hw/D ≤ 1.5.	Structure general recommendation 4.
Deteriorated	<25-year storm capacity, Hw/D ≤ 1.5.	Structure general recommendation ≤ 3.

B.1 Introduction

The photos in figures B.1 through B.4 were taken during a routine inspection:

Figure B.1—Looking at the culvert inlet.

Figure B.2—Looking closely at the inlet of the 24-inch corrugated metal pipe.

A casual observer would likely assume that this old culvert on Road 1924 at milepost 0.1 is fine, but the Forest Service inspector looks closely to observe the pipe's condition.

Figure B.3—Looking into the inlet using strong light.

Figure B.4—Looking into the outlet using strong light.

Note that the culvert invert (bottom) has lost the bituminous coating and galvanizing due to scour and the steel is rusted (figures B.2 and B.3), but generally appears sound. Tapping on the steel with a hand pick confirms that this is true. The shape is normal (i.e., round). The pipe is nearly 140 feet in length, so even with a strong flashlight it is not possible to see the middle portion of the pipe. Also, note that no light is visible from the opposite end (figures B.3 and B.4). The apparent reason for this is that the pipe is sagging along its midportion, apparently due to settlement under the deep embankment (the ends are under a shallow embankment, so they have not settled). It is possible that during construction, the culvert was placed without the normally required camber, thus contributing to the sag. It is also possible that when this culvert was installed, insufficient care was giving to subexcavating the weak organic soil overlaying the valley bottom and backfilling with incompressible aggregate bedding. The water drops from the outlet into a plug pool, but the standing water near the downstream third of the culvert (figure B.4) reinforces the belief that this pipe has an extreme belly in it.

The inexperienced inspector might conclude that, although the pipe is old, the steel is rusting, and the installation was not perfect, the culvert appears to be functioning normally, and there is no cause for serious concern.

The experienced inspector recognizes the need for more information, particularly because of the depth of roadway embankment and the culvert's age.

However, there is no record of when the road was constructed. The agency did not keep records when the majority of these roads were constructed as the result of the logging boom of the 1950s, 1960s, and 1970s. Very few remaining employees recall construction of these roads. We can only conclude that this pipe is quite old, at least 30 years, and possibly 40 or more.

Since the surface of steel plate will oxidize at an average rate of several mils (mil=0.01 inches) per year depending on soil/water pH and conductivity, it is only a matter of time before the effective structural thickness of the metal corrugations will give way to the high earth pressures under a deep embankment. A zinc coating (galvanizing) prolongs the life of the pipe about 15 years, but since the gravel moving along the streambed has scoured the bottom of the culvert to bare steel, its value is limited.

By considering corrosion rates of zinc and steel, it is likely that the structural capacity of this culvert is insufficient for the conditions.

The most critical portion of the pipe is along the middle third where the loading on the culvert is greatest. When the embankment is high, the pipe is typically too long to see the middle portion, as is the case with this pipe. Also, it is not safe to crawl down this pipe to take a closer look. Therefore, a contractor was hired to video the inside of the culvert (figures B.5 through B.8).

Figure B.5—Camera (with leg extensions) entering outfall.

Figure B.6—Looking closed circuit television camera on roadway.

Photos in figures B.7 and B.8 were taken from the closed circuit television footage.

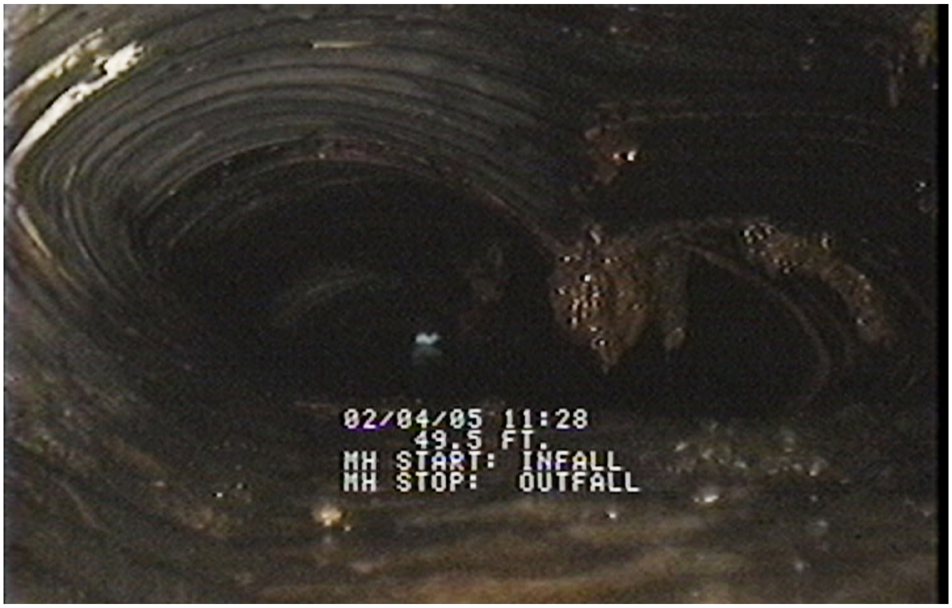


Figure B.7—Inside the culvert looking upstream, 50 feet from the inlet, Road 1924 milepost 0.1.

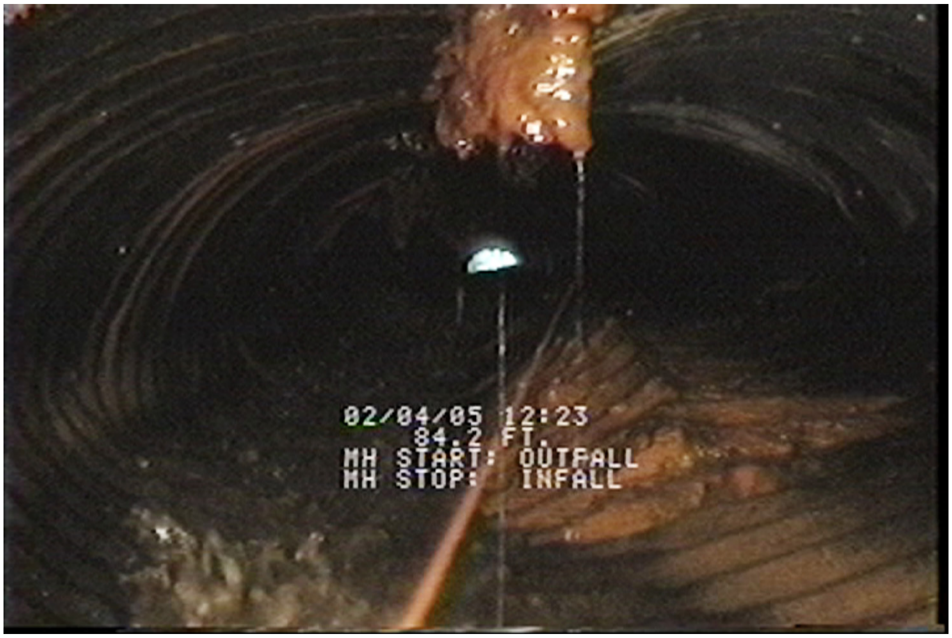


Figure B.8—Inside the culvert looking upstream, 84 feet from the outfall, Road 1924 milepost 0.1. (The orange line is a sewer string used to pull the camera up through the culvert.)

As seen from the closed circuit television images, this culvert has failed. The corrugated steel has buckled on the top, bottom, and both sides. The vertical space on one side is about 8 to 9 inches (on the left in figure B.9), and the vertical space of the opposite side of the pipe is about 4 inches. The top of the culvert is being forced downward by the weight of the roadway embankment, estimated to be about 3,800 pounds per cubic foot. The top has split and minerals are forming as soil is washed into the pipe from above. Note that water is running off the stalactite (figure B.9), indicating that the water table outside the culvert is above the pipe, probably due to streamwater flowing along a porous annular space outside of the pipe. (Note that 2005 was a very dry winter in this area.) The bottom of the corrugated steel is split and buckling upward because of horizontal soil forces and a weak invert. The lateral edges of the steel are creased, and the top and bottom are bending inward around the creases.

Very little structural capacity of the pipe remains. As the steel continues to oxidize, it will become even weaker, and the embankment will continue to crush the steel together until the culvert can no longer pass stormflows. In its current condition, the water flowing through the culvert is probably pressurized during high flows along the failure shown in figures B.8 and B.9. As the pipe continues to flatten, water will further pressurize the flows along the annular space outside the culvert and accelerate the soil erosion. This process will continue to wash soil from around the pipe and may eventually form a sinkhole and road subsidence.

This type of phenomenon frequently is seen when pipe joints pull apart, which was the case in a nearby culvert (Road 1700, milepost 1.2) that was replaced in 2005 using trenchless methods. However, if flow is restricted to the extent that water will pond behind the fill, a more severe failure mechanism may occur. Additionally, there is an increased risk of debris plugging along the area of collapse. In this extreme case, the stream will erode the face of the downstream fillslope as the water overtops the roadway. The most extreme failure may then occur if the roadway embankment (under these circumstances, essentially an unintended dam) suddenly fails in a large-scale mass movement of about 5,000 to 10,000 cubic yards.

Two failures such as this occurred literally around the corner on Road 1900 during a storm in 1999. That failure resulted in debris torrents, which extended into Drift Creek. A debris torrent is a large mass of soil, rocks, and wood debris partially suspended in water that scours out the soil as it moves rapidly downstream. Drift Creek is an important anadromous fishery.

If such a catastrophic failure occurred at Road 1924 milepost 0.1, it is conceivable that a resultant debris torrent also could carry with it the larger roadway embankment (about 15,000 cubic yards) located one-tenth of a mile downstream on Road 1900. The environmental damage resulting from the failure of this old pipe can be significant.

In the case of catastrophic failure, the monetary cost of replacing the roadway segment is on the order of $500,000. If the two embankments are removed by stormwater, an estimated 15,000-25,000 cubic yards of suitable earth materials would have to be hauled from offsite in order to reconstruct the roadway.

The culvert replacement cost (in 2006) using a trenchless method such as pipe ramming was in the vicinity of $100,000. Using such a trenchless method has the advantage of allowing the road to remain open other than for brief periods; for example, traffic delays would occur to off-load equipment and materials. Road 1924 is the only vehicle road access (due to roadway blowout/debris torrents mentioned above) to a church camp under permit with the Forest Service. The cost to replace the culvert using traditional open-cut methods is approximately $200,000, and this approach would require closing the roadway for at least 1 month during the summer (construction) season.

B.2 Conclusions and Recommendations

Careful inspection of the culvert in question revealed that the culvert at milepost 0.1 on Road 1924 has failed. Further collapse will occur as the pipe continues to rust, and this will result in additional complications. The current cost of culvert replacement would be approximately $200,000 using conventional methods, or approximately $100,000 using trenchless techniques.

If a catastrophic embankment failure were to occur, it would most likely do so during a flood event. Although it is not possible to predict the probability of a catastrophic embankment failure in any given timeframe, the possibility of environmental damage is judged to be significant, and the consequence or degree of damage is relatively high. If catastrophic embankment failure occurs as a result of the inevitable complications, the expected cost of replacement could be about $300,000 to $500,000.

The following list comprises sources and references that provide additional information about the technologies described in chapter 4.

Trenchless Technology Center <http://www.latech.edu/tech/engr/ttc/index.html>.

Trenchless Assessment Guide for Rehabilitation <http://www.undergroundconstructionmagazine.com/new-software-sheds-light-rehab-method-selection>.

North American Society for Trenchless Technology <http://www.nastt.org>.

International Society for Trenchless Technology <http://www.istt.com>.

Underground Construction Technology Association <http://www.uctaonline.org>.

Trenchless Technology Magazine <http://www.trenchlessonline.com>.

Underground Construction Technology Online <http://www.uctonline.com>.

The National Technology and Development Center's national publications are available on the Internet at <http://www.fs.fed.us/eng/pubs/>.

Forest Service and U.S. Department of the Interior, Bureau of Land Management employees also can view videos, CDs, and National Technology and Development Center's individual project pages on their internal computer network at <http://fsweb.sdtdc.wo.fs.fed.us/>.

For additional information on trenchless technologies, contact Maureen Kestler at SDTDC. Phone: 603-455-1157 (c), 909–599–1267 ext 251. Email: mkestler@fs.fed.us.

A American Association of State Highway and Transportation Officials (AASHTO). 1999. AASHTO highway drainage guidelines (volume 14)–culvert inspection, material selection and rehabilitation guideline. Washington, DC: American Association of State Highway and Transportation Officials.

AASHTO. 2007. Maintenance and management of roadways and bridges, 4th edition. ISBN 1-56051-376-6. Washington, DC: American Association of State Highway and Transportation Officials. 372 p.

American Iron and Steel Institute. 1994. Handbook of steel drainage and highway construction products, 5th edition. Washington, DC: American Iron and Steel Institute.

Arnoult, J.D. 1986. Culvert inspection manual, supplement to the bridge inspector's training manual. FHWA IP-86-2. McLean, VA: U.S. Department of Transportation, Federal Highway Administration. 220 p.

Aryani, C.; Al-Kazily, J. 1993. Culvert restoration techniques. FHWA/CA/TL-93-14. Sacramento, CA: California State University. 143 p.

Ault, J.P.; Ellor, J.A. 2000. Durability analysis of aluminized type 2 corrugated metal pipe. FHWA-RD-97-140. McLean, VA: U.S. Department of Transportation, Federal Highway Administration. 101 p.

Ault, J.P. 2003. Performance of polymer coated corrugated steel pipe. Washington, DC: Transportation Research Board 82 Annual Meeting Jan 12-16, 2003.

B Ballinger, C.A.; Drake, P.G. 1995. Culvert repair practices manual, Volume 1 (Appendix). FHWA-RD-95-089. McLean, VA: U.S. Department of Transportation, Federal Highway Administration. 330 p.

Ballinger, C.A.; Drake, P.G. 1995. Culvert repair practices manual, Volume 2 (Appendix). FHWA-RD-95-089. McLean, VA: U.S. Department of Transportation, Federal Highway Administration. 321 p.

Bates, K.K.; Love, M.L. [In preparation]. Modifying existing road-stream crossings for fish passage. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center.

Bealey, M. 1984. Precast concrete pipe durability–state of the art. Transportation Research Record 1001, Symposium on Durability of Culverts and Storm Drains. 88–94.

Beaton, J.L.; Stratfull, R.F. 1962. Field test for estimating service life of corrugated metal pipe culverts. Highway Research Board Proceedings, Vol. 41, 1962. 255–272.

Bhattachar, D.V.; Najafi, M.; Salem, O.; Funkhouser, P.; Salman, B. 2007. Development of an asset management framework for culvert inventory and inspection. Boston, MA: Pipelines.

Breland, Thomas, South Carolina Department of Transportation. Personal communication.

Broekaert, M. 2002. Polyurea spray coatings. The technology and latest developments. Everberg, Belgium: Paint and Coatings Industry, Huntsman Polyurethanes. 16 p.

C

Cahoon, J.E.; Baker, D.; Carson, J. 2002. Factors for rating condition of culverts for repair or replacement needs. Transportation Research Record. Volume 1814. 197–202.

California Department of Transportation (Caltrans). 1999. Method for estimating the service life of steel culverts. California Test 643. Sacramento, CA: California Department of Transportation. 10 p.

Caltrans. 2002. Caltrans supplement to FHWA culvert repair practices manual. Design Information Bulletin No. 83-01. Sacramento, CA: California Department of Transportation. 136 p.

Cenderelli, D.A.; Clarkin, K.; Gubernick, R.A.; Weinhold, M. [In preparation]. Stream simulation for aquatic organism passage at road-stream crossings. Transportation Research Board Journal for the Low Volume Roads Conference, Orlando, FL, TRB, Washington, DC.

Cerlanek, W.D.; Powers, R.G. 1993. Drainage Culvert Service Life Performance and Estimation. Report No. 93-4A. Tallahassee, FL: State of Florida, Department of Transportation.

Charbeneau, R.J.; Henderson, A.D.; Sherman, L.C. 2006. Hydraulic performance curves for highway culverts. Journal of Hydraulic Engineering. 132(5): 474–481.

Corrugated Steel Pipe Institute. 1990. Field inspection confirms durability of corrugated steel pipe. June 1990. 3 p.

Corrugated Steel Pipe Institute. 2007. Handbook of steel drainage and highway construction products. Canadian edition. American Iron and Steel Institute and Corrugated Steel Pipe Institute. 482 p.

D

Dancey, D. Innovative Painting and Waterproofing, Inc. Personal communication.

DeCou, G.; Davies, P. E. 2007. Evaluation of abrasion resistance of pipe and pipe lining materials. FHWA/CA/TL – CA01-0173. Sacramento, CA: Caltrans Office of Highway Drainage Design. 109 p.

Donaldson, B.M.; Baker, A.J. 2008. Understanding the environmental implications of cured-in-place pipe rehabilitation technology. FHWA/VTRC 08-R15. Richmond, VA: Virginia Transportation Research Council.

Duncan, C.R. 1984. Innovated repair of a large failing structural steel plate pipe arch culvert. Transportation Research Record 1001, Symposium on Durability of Culverts and Storm Drains. 98–101.

E

Ead, S.A.; Rajaratnam, N.; Katapodis, C.; Ade, F. 2000. Turbulent open-channel flow in circular corrugated culverts. Journal of Hydraulic Engineering. 126(10): 750–757.

F

Federal Lands Highway. 2010. Federal Lands Highway culvert assessment and decision making procedures manual field pack. 27 p.

Florida Department of Transportation. 2008. Drainage handbook. Tallahassee, FL: Florida Department of Transportation, Office of Design, Drainage Section. 78 p.

Forest Service Stream-Simulation Working Group. 2008. Stream simulation: an ecological approach to road stream crossings. 0877 1801—SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center. <http://www.stream.fs.fed.us/fishxing/aop_pdfs.html>.

G

Gabriel, L.H.; Moran, E.T. 1998. Service life of drainage pipe. Synthesis of Highway Practice 254, Washington, DC: Transportation Research Board, National Cooperative Highway Research Program. 39 p.

Galka, R.J.; Yates, A.P.J. 1984. Pipe protection: a review of current practice. ISBN: 0906085942. Teddington, Middlesex, England: Paint Research Association. 109 p.

Gift, A.; Smith, B. 2000. Culvert study report. RI91-11. Jefferson City, MO: Missouri Department of Transportation.

Gordon, Jerry. Sprayroq, Inc. Personal communication.

Guan, S.W. 2003a. 100% solids polyurethane and polyurea coatings technology: chemistry, selection and application. Coatings World. 8(3): 49–58.

Guan, S.W. 2003b. Advanced 100% solids rigid polyurethane coatings technology for pipeline field joints. Paper #03043. Corrosion NACE Expo 2003. San Diego, CA, Mar 17-20, 2003. 14 p.

H

Herr, L.A.; Bossy, H.G. 1965. Hydraulic charts for the selection of highway culverts. McLean, VA: U.S. Department of Transportation, Federal Highway Administration. 56 p.

Hessheimer,D.M. City of Brighton, CO. Personal communication.

Hunting Specialized Products Inc. 2008. PolySpray. Cincinnati, OH: Hunting Specialized Products, Product Information Package. <http://www.ktc.uky.edu/kytc/kypel/prodDetail.php?proID=10847>.

I

Ikerd, S.R. 1984. Invert replacement of corrugated metal structural plate pipe. Transportation Research Record 1001, Symposium on Durability of Culverts and Storm Drains. 102–103.

J

Johnson, D.; Zollars, J. 1992. Culvert renewal. Report No. MN/RO-92/02. Maplewood, MN: Minnesota Department of Transportation. 48 p.

K

Katti, D.; Katti, K.; Yazdani, F. 2003. Cost effective non-flammable pipe liners. Prepared for North Dakota Department of Transportation. 52 p.

Kilgore, R.T.; Bergendahl, B.S.; Hotchkiss, R. 2010. Culvert design for aquatic organism passage. FHWA-HIF-11-008 HEC-26. Hydraulic Engineering Circular No 26. Washington, DC: U.S. Department of Transportation, Federal Highway Administration, Federal Lands Highways.

Knoyle, J. 2007. Canadian culvert set to last another 100 years. Trenchless World, Dec 2007. 8–9.

Kozman, D.P. 2006. A simplified approach to estimating hydraulic properties of lined pipelines. UCT 2006 Conference, Atlanta, GA, Jan 24-26, 2006. 15 p.

Kurdziel, J.M. 1988. Culvert durability rating systems. Transportation Research Record No. 1191. Culverts and Tiebacks. 132–140.

L

Lian, Y.; Yen, B.C. 2003. Comparison of risk calculation methods for a culvert. Journal of Hydraulic Engineering. 129(2): 140–152.

M

Markow, M.J. 2007. Managing selected transportation assets: signals, lighting, signs, pavement markings, culverts, and sidewalks. NCHRP Synthesis of Highway Practice 371. Washington, DC: Transportation Research Board, National Cooperative Highway Research Program. 198 p.

Meacham, D.G.; Hurd, J.O.; Shisler, W.W. 1982. Ohio culvert durability study. ODOT/L&D/82-1. Columbus, OH: Ohio Department of. Transportation. 173 p.

Meegoda, J.N.; Juliano, T.M.; Ayoola, G.M.; Dhar, S. 2004. Inspection, cleaning, condition assessment and prediction of remaining service life of corrugated steel culvert pipes. Washington, DC: TRB 83 Annual Meeting. 16 p.

Meegoda, J.N.; Juliano, T.M.; Ratnaweera, P.; Abdel-Malek, L. 2005. Framework for inspection, maintenance, and replacement of corrugated steel culvert pipes. Transportation Research Record, Volume 1911. 22–30.

Minnesota Department of Transportation. 2006. HydInfra. Saint Paul, MN: Minnesota Department of Transportation. 2 p. <http://www.dot.state.mn.us/bridge/Hydraulics/HydInfra.html>.

Mitchell, G.; Masada, T.; Chang, T.; Sargand, S. 2005. Risk assessment and update of inspection procedures for culverts. FHWA/OH-2005/002. Columbus, OH: Ohio Department of Transportation. 428 p.

N

National Association of Corrosion Engineers. 1994. Joint surface preparation standard: near-white metal blast cleaning. NACE No. 2 - SSPC SP10, ISBN 1575901080. National Association of Corrosion Engineers. 12 p.

National Cooperative Highway Research Program. 1978. Durability of drainage pipe. Synthesis of Highway Practice 50, Washington, DC: Transportation Research Board, National Cooperative Highway Research Program.

National Corrugated Steel Pipe Association. 2000. Corrugated steel pipe durability guide. National Corrugated Steel Pipe Association. 6 p.

National Corrugated Steel Pipe Association. 2002a. Field Performance Evaluation of Polymer Coated CSP Structures in NY. 21 p.

National Corrugated Steel Pipe Association. 2002b. Field Performance Evaluation of Polymer Coated CSP Structures in WI. 15 p.

Newton, C. 1999. Slip lining gives new life to old or deteriorating culverts! AREMA 1999 Annual Conference, Chicago, IL. Sep 12-15, 1999, American Railway Engineering and Maintenance-of-Way Association. 6 p.

New York Department of Transportation. 2001. Design guidelines for rehabilitation of culvert and storm drain pipe. EI 01-029. Albany, NY: New York State Department of Transportation. 8 p.

Nordlin, E.F.; Stratfull, R.F. 1965. A preliminary study of aluminum as a culvert material. Highway Research Record, No.95. Washington, DC: Highway Research Board. 1–70.

Norman, J.M.; Houghtalen, R.J.; Johnson, W.J. 2005. Hydraulic design of highway culverts. FHWA-NHI-01-020. Hydraulic Design series No. 5. 368 p.

North American Society for Trenchless Technology. 2005. Pipe bursting; best practices; achieving quality results. PowerPoint Presentation. <http://www.nastt.org/pdf/PowerPoint/PipeBursting.pdf>.

O

Ohio Department of Transportation. 2003. Culvert management manual. Columbus, OH: Ohio Department of Transportation. 78 p.

O'Malley, C.L. 2005. Polyurea coatings–if you knew what could go wrong. Las Vegas, NV: PACE 2005 Painting and Coatings Exhibition.

P

Pennsylvania Department of Transportation. 2008. Drainage condition survey field manual. Publication 73. Harrisburg, PA: Pennsylvania Department of Transportation. 42 p.

Perrin, Jr. J; Jhaveri, C.S. 2004. The economic costs of culvert failure. TRB 83 Annual Meeting. Washington, DC. 20 p.

Piehl, R. 2005. Summary of trenchless technology for use with USDA Forest Service culverts. 0577 1201—SDTDC. San Dimas, CA: U. S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center. 26 p.

Potter, J.C.; Lewandowski, L.; White, D.W. 1991. Durability of special coatings for corrugated steel pipe. FHWA/FLP-91/006. McLean, VA: U.S. Department of Transportation, Federal Highway Administration. 68 p.

Primeaux II, D.J. 1989. Spray polyurea—versatile high performance elastomer for the polyurethane industry. Polyurethanes '89, SPI 32nd Annual Technical/Marketing Conference, San Francisco, CA. 126–130.

R

Ring, G.W. 1984. Culvert durability? Where are we? Transportation Research Record N1001. Symposium on Durability of Culverts and Storm Drains. 9 p.

S

Stratton, F.W.; Frantzen, J.A.; Meggers, D.A. 1990. Cause of accelerated deterioration of corrugated metal pipe installed after 1974. FHWA/KS-90/3. Topeka, KS: Kansas Department of Transportation. 73 p.

Southwestern Laboratories. 2004. D-Load Bearing Tests of Poly-Triplex PTLS-11600 Liner. POL056-04-28-57624-1. Houston, TX: Southwestern Laboratories. 2 p.

Sukley, R.; St. John, B. 1994. Evaluation of insituform pipe rehabilitation. PA-94-002-84-103. Harrisburg, PA: Pennsylvania Department of Transportation. 107 p.

T

Temple, W.H.; Cumbaa, S.L.; Gueho, B.J. 1985. Evaluation of drainage pipe by field experimentation and supplemental laboratory experimentation. Report No. 174. Baton Rouge, LA: Louisiana Department of Transportation. 54 p.

Terry, Stan. CIM Industries. Personal communication.

Texas Department of Transportation. 2002. Bridge inspection manual. Austin, TX: Texas Department of Transportation. 147 p.

Thornton, C.I.; Robeson, M.D.; Girard, L.G.; Smith, B.A. 2005. Culvert pipe liner guide and specifications. FHWA-CFL/TD-05-003. McLean, VA: U.S. Department of Transportation, Federal Highway Administration. 169 p. <http://www.cflhd.gov/programs/techDevelopment/hydraulics/culvert-pipe-liner/>.

U

U.S. Department of Agriculture, Forest Service. 1994. Transportation structures handbook. FSH 7709.56B. Washington, DC: U.S. Department of Agriculture, Forest Service.

U.S. Department of Agriculture, Forest Service. 2006. FishXing Users Manual. U.S. Department of Agriculture, U.S. Forest Service. <http://www.fsl.orst.edu/geowater/FX3/FX3_manual.pdf>.

Uretek USA. 2008. Culvert and storm sewer repair. Roads and Bridges Case Studies Web site <http://www.roadsbridges.com/index.cfm?&fuseaction=showProblemSolver&appDirectory=rb&problemSolverID=236> Accessed April 15, 2008.

V

Vaillancourt, G. 2002. Inner strength. Concrete Products. Oct 1, 2002. Chicago, IL. 2 p. <http://www.concreteproducts.com/index.php/departments/materials/13622-inner-strength.html>.

Virginia Department of Transportation. 2008. Pipe rehabilitation methods and selection process. IIM-LD-244. Richmond, VA: Virginia Department of Transportation. <http://www.extranet.vdot.state.va.us/locdes/electronic%20pubs/iim/IIM244.pdf>.

W

Walker, D.; Guan, S. 1997. Protective linings for steel pipe in potable water service. NACE International Conference, Northern Region, Toronto, Ontario, Nov 10-11, 1997, 18 p.

Wallace, R.; Najafi, M.; Kinash, O. 2007. Hydraulic analysis of Roger's Creek corrugated metal pipe CIPP-lined culverts at I-196 near South Haven, Michigan, final report. Arlington, TX: University of Texas, The Center for Underground Infrastructure Research & Education. 35 p.

Ward, E. TT Technologies. Personal communication.

Wilson, C.L.; Oates, J.A. 1969. Corrosion and the maintenance engineer. Journal of the Electrochemical Society. 116(4): 178C.

Woodroof, J. Oregon Department of Transportation. Personal communication.

Wyant, D.C. 2002. Assessment and rehabilitation of existing culverts. Synthesis 303. Washington, DC: Transportation Research Board, National Cooperative Highway Research Program. 82 p.

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