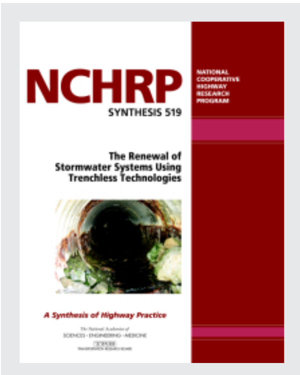

The Renewal of Stormwater Systems Using Trenchless Technologies

DETAILS

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FOREWORD

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

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

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

PREFACE

By Tanya M. Zwahlen
Staff Officer
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The objectives of this synthesis project were to summarize trenchless technologies used for the renewal of stormwater systems, including new, emerging, and underutilized methods, and to identify future research needs. This information can help highway stakeholders identify effective technologies used in the structural and functional renewal of stormwater facilities and can inform facility owners in their efforts to minimize negative impacts and maximize cost benefits.

The information contained in this synthesis was obtained using three sources. First, a literature review was conducted on all existing research concerning the use of trenchless technologies, including international experience. Second, a survey was distributed to state departments of transportation, municipalities, and special districts to identify successful examples of the use of these technologies. The survey and list of responding agencies are included as Appendix A and Appendix B, respectively. These appendices can be found on the TRB website (www.trb.org) by searching for "*NCHRP Synthesis 519*." Finally, case examples were developed involving the use of different technologies and conditions where they are applicable.

David C. Ward of Shannon & Wilson, Inc., collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on page iv. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation.

CONTENTS

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

SUMMARY

The Renewal of Stormwater Systems Using Trenchless Technologies

Aging stormwater facilities can be replaced using open-cut or trenchless replacement, or the service life of the existing stormwater facilities can be extended using trenchless renewal. This synthesis focuses primarily on the trenchless renewal of culverts typically ranging in diameter from 12 in. to over 12 ft with both circular and noncircular cross-sections. While most aging culverts consist of either corrugated metal or concrete pipe, some of the renewal methods discussed in this synthesis are also applicable to other pipe types.

Both trenchless replacement and trenchless renewal methods can reduce negative impacts associated with surface disruption by moving the work area outside of the travel lanes and concentrating the construction impacts off the roadway. Trenchless renewal can extend the service life of existing stormwater facilities by addressing decay such as corrosion, abrasion, and erosion; reducing or eliminating infiltration and exfiltration; and providing a structural repair or improving the structural capacity of culverts, pipelines, manholes, and related stormwater structures. In some situations, trenchless renewal can even improve the hydraulic capacity of the stormwater system.

The purpose of *NCHRP Synthesis 519* is to summarize trenchless technologies used for the renewal of stormwater systems. The six trenchless renewal methods described in this synthesis include (1) cured-in-place pipe (CIPP), (2) sliplining (SL), (3) modified sliplining (MSL), (4) in-line replacement (ILR), (5) spray-in-place pipe (SIPP), and (6) close-fit pipe (CFP). The use of manhole renewal and invert paving are also briefly discussed.

The information in this synthesis was gathered through a literature review, a screening survey of state departments of transportation (DOTs), and interviews. The information gathered was focused on the methods used, decision criteria used to select a renewal method, limiting factors on the applicability of specific trenchless renewal methods, successful practices, emergent or underutilized methods, and methods from other industries.

The survey was sent to the 50 state DOTs and 43 responses were received from 40 state DOTs. Survey results indicate that while 88% of the DOT respondents have experience with trenchless renewal, the majority (60%) only have experience with one or two methods. Only 8% of the DOT respondents have experience with all six primary methods.

Survey results indicate that SL and CIPP are the two most commonly used methods for stormwater system renewal. The need to maintain the existing hydraulic capacity of the stormwater system was identified both by experienced and non-experienced DOTs as a primary reason for not using trenchless renewal. Based solely on this criterion, SIPP, MSL, ILR, and CFP appear to be underutilized. These four methods do not generally result in a significant reduction in hydraulic capacity, and ILR can be used to increase the pipe size and in some cases SIPP liners, MSL, and CFP can improve the hydraulic capacity of some pipes.

Questionnaire results indicate that the primary means of selecting the trenchless renewal method is experience-based, followed closely by in-house expert/in-house consultation. This may be part of the reason that most DOTs only have experience with one or two methods and that SL and CIPP pipe are the two most commonly used methods. Over 90% of the DOTs that use one or two methods use SL, and about 60% of DOTs that use two methods use both SL and CIPP.

The DOTs are satisfied with the commonly used SL and CIPP. They are also generally satisfied or very satisfied with the ability of trenchless renewal to address defects, such as corrosion; leaks or infiltration; loose or open joints; and cracks, breaks, or splits.

Common causes of cost overruns and claims were identified as changed or differing conditions associated with the existing pipe or subsurface conditions. Of the respondents, 64% indicated that cost overruns were generally less than 10%.

DOTs can benefit from future research and synthesis of structural testing and analysis of SIPP and CIPP liners, additional published information on less commonly used ILR methods, detailed cost data, and standardized trenchless replacement and renewal selection guidelines. Some future research on these topics has already been planned. For example, a study entitled "Structural Design Methodology for Spray Applied Pipe Liners in Gravity Storm Water Conveyance Conduits" has been funded by the Transportation Pooled Fund Program.

CHAPTER 1

Introduction

This chapter provides (1) the definition of trenchless renewal; (2) background information on the objectives of the synthesis; (3) an overview of the study methodology including the study questionnaire, the literature review, and the interviews; and (4) the organization of the synthesis.

What Is Trenchless Renewal of Stormwater Systems?

Trenchless renewal includes a wide variety of methods used to upgrade, rehabilitate, repair, and renovate the performance and increase the design life of existing stormwater facilities. This synthesis focuses primarily on the trenchless renewal of culverts typically ranging in diameter from 12 in. to over 12 ft with both circular and noncircular cross-sections. While most aging culverts consist of either corrugated metal or concrete pipe, some of the renewal methods discussed in this synthesis are also applicable to other pipe types. These methods can be broadly grouped into the following categories: CIPP, SL, MSL, ILR, SIPP, and CFP (see "Definitions" section in Chapter 2).

While the application, design, and construction of these methods are varied, the underlying commonalities for the trenchless renewal methods are as follows:

- They occur along or at the existing stormwater facility location.
- They minimize negative surface disruption and impacts.

Trenchless installation methods are not covered in this synthesis. Trenchless installation methods, such as pipe ramming, auger boring, horizontal directional drilling, and so forth, do not necessarily rely on the presence of an existing facility and are therefore not considered trenchless renewal. Refer to *NCHRP Synthesis 242* (Iseley and Gokhale 1997) for more information on trenchless installation methods.

Background

Highway and transportation system stakeholders recognize the overwhelming need for effective technologies in both the structural and functional renewal of stormwater facilities. Many existing facilities are reaching or exceeding their useful service. Facility owners now more than ever have a need to minimize negative impacts and to maximize the cost benefits. For some stakeholders, trenchless technologies are replacing traditional techniques to accomplish the renewal of culverts, storm sewers, and drainage structures.

The selection of the trenchless renewal method depends on a variety of technical factors that are generally understood by experienced designers. However, many transportation system organizations have limited experience with multiple methods. This synthesis provides a summary of the methods and generally accepted applicability. A bibliography of other existing publications is provided for the inquisitive reader.

This synthesis has four objectives:

1. Provide an understanding of the successful practices and associated limiting factors for using trenchless technologies to renew stormwater facilities.
2. Characterize the decision criteria used by facility owners when choosing a renewal method.
3. Characterize how state DOTs and local agencies are using trenchless technologies.
4. Summarize new, emergent, and underutilized methods and technologies that might be used in highway applications and suggest further research needs.

Study Methodology

The methods used to gather the information for this study consisted of the following:

- A questionnaire sent to the 50 state DOTs;
- Literature search, review, and synthesis; and
- Interviews with individual DOTs, representatives of municipalities, special districts, and private sector firms.

Study Questionnaire

The questionnaire consists of primarily closed-end questions with selected opportunities for the respondents to provide clarifying details. The questionnaire is included in Appendix A, which can be found on the TRB website (www.trb.org) by searching for "*NCHRP Synthesis 519*." For respondents with experience using trenchless renewal, the questions are organized into the following seven sections:

1. **Methods used and satisfaction**. This section asks questions regarding how trenchless renewal methods are used, the relative frequency of use, and satisfaction with the methods used. This also includes characterizing whether renewal is used to temporarily defer replacement with a new system, the frequency of use for non-structural defect renewal, and the frequency of manhole and vault renewal.
2. **Defects mitigated and satisfaction**. This section asks questions to identify the relative frequency with which various defect types are addressed using trenchless methods. This includes a relative satisfaction rating associated with the mitigation.
3. **Case studies and available cost data**. This section asks questions to identify which respondents have shareable case history and cost data.
4. **Decision criteria**. This section asks questions to identify if standardized decision criteria are used to select the trenchless renewal method. Where standardized criteria are not used, the respondent is asked to describe the process used.
5. **Reasons for not using trenchless renewal when technically feasible**. This section asks questions to determine common reasons for not using trenchless renewal when trenchless renewal is technically feasible. A list of potential reasons is provided and the respondents are asked to select their common reasons and are given the opportunity to write in additional reasons.
6. **Reasons for using trenchless renewal when technically feasible**. This section asks questions to determine common reasons for using trenchless renewal. The respondents are asked to provide the top five reasons their organization selected trenchless renewal.
7. **Project cost exceedance and claims**. This section asks questions to identify the relative frequency and magnitude of project cost exceedance on trenchless renewal projects. This includes an open-ended question to identify the typical reasons.

An eighth section is provided for respondents without trenchless renewal experience. This section asks questions to determine what information might help them consider using trenchless renewal in the future. A list of reasons for not using trenchless renewal is provided. The respondents ranked their top five reasons for not using trenchless renewal.

Literature Review

The literature review consisted of three main components: references identified in the original project scope, an electronic database search, and an Internet search. The reviewed and referenced publications identified in the literature search are included in the References section of this report. A list of background materials not specifically cited in the text is included in the Bibliography at the end of this report.

To focus on current practice and emergent methods, the electronic database search focused on publications from January 2010 through January 2017. The following curated and subject-specialized databases were searched using ProQuest Dialog. These databases contain published and mostly peer-reviewed literature indexed by professionals.

- The Aqualine database indexes trade, technical, and scientific literature concerning all aspects of water resources drawn from a source list of approximately 300 journals as well as from conference proceedings, scientific reports, books, and theses.
- Civil Engineering Abstracts indexes literature from architecture, structural design, and construction engineering to environmental, seismic engineering, and forensics from more than 4,000 sources including periodicals, conference papers, trade journals, magazines, books, patents, and technical reports.
- Ei Compendex indexes engineering and technology literature in 190 disciplines including civil, environmental, and geological engineering. The literature is drawn from 6,500 primary sources including journals, transactions, reports, and special publications of engineering societies, scientific and technical associations, government agencies, universities, laboratories, research institutions, and industrial organizations; proceedings of conferences, symposia, and colloquia; monographs; standards; and seminars and reports.
- Gale Group PROMT is a multiple-industry database providing broad, international coverage of more than 60 manufacturing and services industries including engineering, manufacturing, and environmental services.
- Inspec is a bibliographic database with specialized indexing of physics and engineering literature from journals and serials, conference papers and proceedings, books and book chapters, and technical reports. Some standards, dissertations, and a small number of UK and U.S. patents are included. The database is produced by the Institution of Engineering and Technology.
- TRID is an integrated database that combines the records from Transportation Research Board's Transportation Research Information Services Database and the Organization for Economic Co-operation and Development's Joint Transport Research Centre's International Transport Research Documentation Database. TRID provides access to more than one million records of transportation research worldwide.

A keyword search of the Internet was also performed to supplement the curated and subject-specialized database search.

Interviews

Information obtained from the interviews is presented in Chapter 3. The information from the interviews was used to supplement the literature search and questionnaire results.

Organization of Synthesis

This synthesis is organized into four chapters and two appendices.

- Chapter 1 provides background for the synthesis topic and overview of the study methodology, including the survey questionnaire.
- Chapter 2 provides an overview of the trenchless methods included in this synthesis, a summary of the advantages and challenges of the methods, and case studies. Emergent and underutilized technologies that might be applicable for trenchless renewal of stormwater systems are also included.
- Chapter 3 summarizes the current practice and experience regarding the use of the trenchless renewal methods.
- Chapter 4 summarizes the synthesis findings and identifies further research needs.
- Appendix A includes the survey questionnaire. This appendix can be found on the TRB website (www.trb.org) by searching for "*NCHRP Synthesis 519*."
- Appendix B provides the respondents' names and addresses. This appendix can be found on the TRB website (www.trb.org) by searching for "*NCHRP Synthesis 519*."

Chapter Summary

Trenchless renewal is defined as methods used to upgrade, rehabilitate, repair, and renovate the performance and increase the design life of existing stormwater facilities (primarily culverts).

The objectives of this synthesis are fourfold. First, describe the successful practices and associated limiting factors for the various renewal methods. Second, characterize the decision criteria used by DOTs for choosing a renewal method. Third, characterize how DOTs and local agencies are using trenchless technologies. Fourth, summarize new, emergent, and underutilized methods and technologies and suggest further research needs.

The methods used to gather the information for this synthesis included a questionnaire, literature search, and interviews.

CHAPTER 2

Trenchless Renewal Methods

Introduction

This chapter provides a brief overview of the different types of commonly used trenchless renewal methods. The overview of each method includes a discussion of the generally accepted applicability of the method and limiting factors. A summary of the advantages and challenges associated with each method is included in Tables 1 and 2. Case studies are included in this chapter and are summarized in Tables 3 and 4. The information in this chapter provides background for concepts and terminology needed in subsequent chapters.

Definitions

The trenchless renewal methods included in this synthesis generally follow the basic categories as outlined in Najafi (2016):

- Cured-in-place pipe (CIPP)
- Sliplining (SL)
- Modified sliplining (MSL)
- In-line replacement (ILR)
- Spray-in-place pipe (SIPP)
- Close-fit pipe (CFP)

A discussion of a potential emergent method and some newer variations of currently commonly used methods are included at the end of this chapter.

Cured-in-Place Pipe

CIPP consists of inserting a flexible, resin-impregnated fabric tube into the existing pipe, expanding (or inflating) the tube, and curing the resin using heat (e.g., hot water or steam) or ultraviolet light. The two common insertion methods are inversion and pull-in insertion. An example of the inversion method is shown in Figure 1. The pull-in method requires additional consideration of potential damage because the liner is dragged through the pipe.

CIPP is commonly used for relining complete sections of a pipe (e.g., manhole to manhole, inlet to outlet, etc.) but can also be used for spot or localized repairs. Lengths of localized repair are commonly limited to between 3 and 15 ft with a maximum length of 50 ft (Najafi 2016).

CIPP is suitable for the renewal of most structural defects and the small decrease in pipe cross-section does not typically reduce the hydraulic capacity. The method can accommodate a wide variety of diameters, typically up to about 108 in., although up to 120-in.-CIPP liners have been installed. Depending on pipe diameter, maximum reported installed lengths for CIPP are

Figure 1. Installation of a 60-in.-diameter CIPP liner using the air inversion method **(Courtesy: *Michels Corporation).***

between 1,000 and 2,000 ft (Osborn 2010). CIPP can be used on pipes with circular, noncircular, and varying cross-sections. CIPP can also accommodate typical pipe bends. The flexibility of the fabric tube can result in larger defects and offsets being reflected in the final shape. During CIPP renewal, flow through the existing pipe must be bypassed, significant infiltration must be sealed, and a pre-liner is required where pipe is missing and only soil is exposed (Najafi 2016).

The handling and disposal of styrene-contaminated cure water, which can be toxic to fish, is an important consideration when selecting CIPP for renewal of stormwater systems. Curing with ultraviolet light is one way to address the cure water handling and disposal.

When considering CIPP, it is important to know the inside pipe dimensions and any variations in the pipe cross-section. Since the CIPP liner is typically manufactured specifically for each project and it is expanded to fit the inside surface of the pipe, the size and variation in pipe size and shape must be determined prior to the start of construction.

Where access to the ends of the culvert is limited, the flexibility of the fabric CIPP liner is an advantage over more rigid renewal methods.

The following case study is for a CIPP project completed in Wisconsin using a thermosetting resin-impregnated felt liner (Grams 2017).

Problem

The problem was freeze-and-thaw damage, including concrete spalling, exposed reinforcing steel, joint separation, and exfiltration of the existing 180-ft-long, 60-in.-diameter, reinforced concrete pipe (RCP). The exfiltration was identified as increasing the potential for soil piping, erosion, ground loss, and ultimately a sinkhole that could extend to the overlying highway. The maximum depth of cover over the pipe was about 25 ft. Limiting disruption to the motorists and property owners at the ends of the culvert was also considered.

Design

The primary design concern was restoring the hydraulic function of the culvert by sealing the joints and mitigating exfiltration. The secondary concern was addressing the spalling of the concrete liner. A CIPP liner with a 50-year design lift, consisting of six layers of thermosetting resin-impregnated felt, was selected to address the hydraulic and structural concerns.

Construction

The construction was scheduled for December, a relatively dry month in Wisconsin, to mitigate the potential need to bypass flows. The CIPP liner was installed using the inversion method and air (Figure 1). Steam was used to facilitate curing of the resin. The installation required an eight-person crew and took less than 1 full day to install. The cost, including mobilization and preparation of the existing pipe, was about $650 per foot.

Summary

The CIPP liner met the design requirements for addressing both the hydraulic and structural concerns associated with the existing culvert. Performing the installation in the winter addressed potential difficulties associated with flow bypassing, and the frozen ground reduced the construction traffic impacts at the staging area.

Sliplining

SL consists of inserting a new, smaller diameter pipe into the existing pipe. Common SL pipe types include polyethylene, high-density polyethylene (HDPE), and polyvinyl chloride (PVC).

The insertion process consists of either pushing or pulling the new pipe from one end of the existing pipe to the other end (Figure 2). The annular space between the new and existing pipe is typically grouted. To prevent possible point loading of the new liner, the grout should fully encapsulate the new pipe preventing it from resting on the invert of the existing pipe (Hartley 2014). The outside diameter of the new pipe is typically between 90% to 95% of the inside diameter of the existing pipe, which can result in significant loss in hydraulic capacity (Thornton et al. 2005).

The method can accommodate diameters up to about 160 in. and lengths up to 1,000 ft. Both circular and noncircular pipelines can be sliplined. SL is usually performed with a constant cross-section diameter liner. SL is suitable for the structural renewal of existing pipes without large joint offsets or significant deformation and pipe bends less than about 6 degrees. During SL renewal, infiltration and flow in the existing pipe can typically be accommodated with the selection of the appropriate pipe material (Najafi 2016).

When considering SL, it is important to know the inside pipe dimensions and any variations in the pipe cross-section to ensure that the new pipe and grout lines will fit. The new pipe is sized to fit in the smallest diameter located within the existing pipe (Thornton et al. 2005).

***Figure 2. Sliplining a culvert* (Courtesy: *Advanced Drainage Systems, Inc.*).**

Figure 3. Spiral-wound liner surface footprint (Courtesy: Contech Engineered Solutions LLC).

Access to both ends of the pipe is needed to facilitate installation and grouting of the annular space. Joining shorter sections of pipe together during insertion can reduce the amount of required space. In addition, pipe handling stresses and installation loading need to be monitored to prevent damage.

Modified Sliplining

MSL is suitable for renewal of personnel-accessible pipes and culverts with circular and non-circular cross-sections. MSL consists of assembling a new liner consisting of pipe segments, structural plate, panels, or strips, in the case of the spiral-wound method, within the existing pipe. Examples of spiral-wound liner installation are provided in Figures 3 and 4.

Figure 4. Spiral-wound liner installation from within a manhole (Courtesy: Contech Engineered Solutions, LLC).

The annular space between the new liner and existing pipe is typically grouted. The grout is required for a structural renewal. The reduction in hydraulic capacity associated with the use of MSL can be small.

The method can accommodate the larger diameter stormwater pipes, generally greater than 48 in. and up to about 14 ft including varying cross-sections. The installation length for the spiral-wound method is limited to about 1,000 ft. Assuming sufficient access is available, there is no installation length limit for the segment, plate, or panel methods. The size and shape flexibility of panels, segments, and strips facilitates the use of MSL in noncircular pipes and where access is limited.

MSL can accommodate typical pipe bends and deformed pipe sections. During MSL renewal, infiltration and flow in the existing pipe can be accommodated, and access to both ends of the pipe is needed to facilitate grouting the annular space (Najafi 2016).

The following case study is for an SL/MSL project completed in Tennessee in April 2016 using tunnel liner plate and steel-reinforced polyethylene pipe (Herbert and Hyma 2017).

Problem

The existing approximately 400-ft-long, 72-in.-diameter, corrugated metal pipe (CMP) culvert was experiencing greater than anticipated loading and as a result was deforming and was identified to be at risk of failing. The maximum depth of cover over the pipe was 50 ft, which coincided with the area of the greatest pipe deformation.

Design

The engineer, with support from the manufacturer, identified a combination of SL and MSL as the preferred renewal methods. To mitigate the ongoing deformation and impending collapse, a structural MSL, consisting of 160 ft of 48-in. steel tunnel liner plate was proposed. For the remainder of the culvert, about 240 ft, SL with 60-in. steel-reinforced polyethylene pipe was proposed. A concrete invert liner was constructed within the 48-in. liner to improve the hydraulic efficiency and smooth the transition between the 60-in. and 48-in. liners.

Construction

The renewal process started with the MSL renewal of the length of pipe with the largest deformation. After the steel tunnel liner plate was installed, the ends bulk headed, and the annular space grouted, the contractor switched to SL renewal. The contractor used skid rails, blocking, and bracing to facilitate the alignment of the steel-reinforced polyethylene pipe. The welded pipe segments were installed from both ends and met at the previously completed section of steel tunnel liner plate. The annular space was grouted in multiple lifts (or stages) and monitoring was performed to verify that the required alignment was maintained.

Summary

The selected two-method solution maintained the required hydraulic capacity and provided two distinctly different levels of structural capacity.

In-Line Replacement

ILR is the process of replacing pipes along the existing alignment using pipe bursting or pipe removal methods. ILR generally consists of pulling or pushing tooling connected to the replacement pipe through and along the existing pipe alignment. With pipe bursting, the existing pipe is broken or split and pushed outward to make space for the new pipe. With pipe removal, the existing pipe is removed by (1) reaming or crushing the pipe into small pieces that are removed by circulating drilling mud or slurry or (2) by pulling or pushing the intact existing pipe out of the ground.

Pipe bursting, which is mainly performed using polyethylene pipe, is typically limited to pipes 36 in. in diameter or smaller that are less than about 1,000 ft long. General guidelines for pipe bursting diameters and lengths provided by the International Pipe Bursting Association (2012) are also described with relation to the relative degree of difficulty.

To assist with understanding the International Pipe Bursting Association guidelines the following terms are defined:

- "Size for size" refers to replacing the existing pipe with the same size pipe.
- "Upsize" refers to the number of standard pipe sizes larger the new pipe is than the existing pipe. For example, pipe bursting an 18-in. pipe and installing a 20-in. pipe would be one upsize.

Pipe removal includes three subcategories: pipe reaming, pipe eating, and pipe ejection. The general guidelines for pipe diameters and lengths for pipe reaming and pipe eating are generally the same as those for horizontal drilling and microtunneling, respectively. Information on the relative limitations of these methods is included in *NCHRP Synthesis 242* (Iseley and Gokhale 1997). Limitations on the applicability of pipe ejection are a function of the thrust capacity of the existing pipe, whether the replacement is size for size or an upsize, the pipe diameter, length, and original backfill soils.

The method can accommodate varying cross-sections. ILR is generally best suited for replacing brittle pipe types (e.g., vitrified clay, cast iron, plain concrete, asbestos concrete, and some plastics). Although more challenging, some successful replacement of RCP and CMP has also been accomplished using ILR. The use of pipe bursting to replace CMP has resulted in the final unburst sections being pulled out of the ground (Matthews et al. 2012 and Adamtey 2016). The last section of a pipe pulled out during pipe bursting is shown in Figure 5.

ILR is suitable for the structural renewal of existing pipes with joint offsets and significant deformation and pipe bends less than about 20 degrees (Najafi 2016). Pipe bursting and pipe reaming can exaggerate existing grade problems by lowering sagged portions of the alignment. The steerable microtunneling machine used in conjunction with pipe eating allows the method to mitigate sags of about 4 in. or more (UNITRACC 2017). During ILR renewal, the presence of groundwater, soil types (e.g., expansive clay soils), and potential concrete encasement require additional consideration during design. For pipe bursting, the potential for damaging adjacent utilities and structures should also be considered.

Figure 5. Completed pipe bursting of a CMP (Courtesy: HammerHead Trenchless Equipment).

The following case study is for an ILR project completed in Ohio in June and July 2014 using pipe bursting (Adamtey 2016).

Problem

Pipe bursting has historically been largely limited to renewal of more brittle pipe types, and more ductile pipes, such as CMP culverts, have not been considered ideal candidates for pipe bursting. A study to evaluate pipe bursting of CMP culverts was undertaken at four locations. The locations were selected as being "low risk" and "low impact" culverts if pipe bursting was not successful. The diameters of the existing pipes ranged from 12 to 24 in. and the lengths ranged from 90 to 105 ft. The depth of cover ranged from 8 to 18 ft.

Design

The study looked at using pneumatic pipe bursting for one culvert and static pipe bursting for three culverts. Pipe bursting manufacturers were included in the study process and provided the design of the bursting tools. HDPE pipe was selected as the new pipe for all four sites. The 12-in.-diameter culvert was upsized to 16 in. and the remaining culverts were replaced "size for size."

Construction

The reaction for the pipe bursting winch/rod pulling equipment was provided by a combination of steel plates and driven steel I-beams. The setup and bursting using the pneumatic head took about 10 hours, with the actual bursting taking slightly over 2 hours. The setup and bursting using the static head at each of the three sites took between 12 to 14 hours, and the actual bursting took between 30 to 45 minutes. Both the pneumatic and static bursting resulted in the last approximately 10 to 20 ft of the culverts not being burst, but rather being pulled out of the ground. The estimated construction costs ranged from about $120 to almost $200 per linear foot.

Additional Information

The overcut associated with pulling the last section of deformed, unburst pipe out of the ground resulted in ground loss around the new pipe. This ground loss ultimately resulted in surface settlement and deformation of the road shoulder that required repair. The Ohio DOT anticipates that the inspection cycle for the culvert will be the same as for any other culvert, and they expect a 100-year service life.

Summary

Pipe bursting was successfully used to install the new HDPE pipe. The ground deformation associated with the unburst pipe was unanticipated and resulted in additional effort to repair.

Spray-in-Place Pipe

SIPP consists of spraying a cementitious or polymer coating on the inside of the existing pipe (Figure 6). For larger pipes and culverts, SIPP with incorporated fibers or applied over steel reinforcement can provide renewal of structural defects. The relatively small decrease in pipe cross-section, depending on the existing pipe size, does not typically reduce the hydraulic capacity.

The method has been used on pipes with diameters between 3 and 276 in. and on pipes up to 1,476 ft long (Thornton et al. 2005). SIPP can be used on pipes with circular, noncircular, and varying cross-sections. SIPP can also accommodate typical pipe bends. During SIPP renewal,

Figure 6. Example of cementitious SIPP liner* (Courtesy: *Centri-Pipe).

the inside of the existing pipe must be clean to promote proper adhesion of the coating, flow through the existing pipe must be bypassed, and infiltration must be sealed.

The following case study is for an SIPP project completed in Indiana in September 2015 using a fiber-reinforced geopolymer resin (Keaffaber 2016).

Problem

The existing approximately 275-ft-long, 84-in.-diameter, CMP culvert is located under State Route 446 in Indiana, with the outlet directing flow to an unnamed tributary to Little Salt Creek. The depth of cover over the culvert is approximately 30 ft. A previous inspection identified through-going invert corrosion and groundwater leakage at over a dozen locations.

Design

The original plans specified a CIPP liner. The intent of the design was to address the infiltration and exfiltration and mitigate the corrosion. A SIPP alternative consisting of centrifugally cast concrete pipe was proposed and accepted as a demonstration project. The expected service life is 50 years.

Construction

Spot repair was performed to fill the invert voids using hand spraying of the mortar. After the spot repair was completed (Figure 7), a 1.5-in.-thick SIPP liner was applied in two passes using a centrifugal spray unit that was pulled through the culvert. The construction equipment was delivered to the site in a 24-ft box truck, and the work was staged from the road shoulder. No lane closures were required. The work was completed in 7 days. The construction costs were about $1,125 per linear foot.

Additional Information

An inspection approximately 18 months after construction was completed noted that while most of the original leaks were sealed, a few spots were still leaking. The contractor has agreed to fix the leaks. Regular inspections will be once every 5 years.

Figure 7. Spot repair to fill invert voids prior to application around the complete perimeter with the centrifugal spray unit (**Courtesy:** ***Milliken Infrastructure Solutions, LLC).***

Summary

The small size of the equipment limited the disturbance to traffic and a single product was used for both the spot repair and the new liner. While most of the leaks were mitigated, additional rehabilitation will be required to complete the mitigation.

Close-Fit Pipe

CFP consists of inserting a new, deformed (deformed and reformed [D&R]), or folded (fold and formed [F&F]) pipe into the existing pipe. After placement, the new pipe is expanded to its original size and shape to be tight against the inside of the existing pipe. An example of D&R pipe is shown in Figure 8. Because of the close fit, there is no annular space to grout. CFP is suitable for the renewal of most structural defects and the small decrease in pipe cross-section does not typically reduce the hydraulic capacity. The CFP material typically consists of PVC, HDPE, or medium-density polyethylene. F&F pipe, typically consisting of PVC, is more commonly used for gravity pipelines than D&R pipe (Najafi 2016).

The method can accommodate up to 30- and 60-in.-diameter renewal using F&F and D&R pipe, respectively. The maximum renewal length is about 2,500 ft, and the existing pipe needs to be circular and typically have a consistent cross-section.

The F&F variant of CFP can accommodate pipe bends up to about 30 degrees (Thornton et al. 2005). The D&R variants of CFP are generally limited to pipe without bends. Typically during CFP renewal, flow through the existing pipe must be bypassed and infiltration must be sealed (Najafi 2016).

Figure 8. Deforming the HDPE pipe in a reduction dye* (Courtesy: *City of Fort Collins).

The following case study is for a CFP project completed in Colorado in fall 2012 by swagelining a 27-in. steel-finished water main (Matthews and Randall 2014).

Problem

The existing approximately 2,500-ft-long, 27-in.-diameter, steel-finished water main was experiencing frequent corrosion-related leaks. The alignment transverses backyards in a primarily residential area and was located in an area with high groundwater. The depth of cover over the water main is about 5 to 6 ft. The potential neighborhood impacts and total construction costs for a replacement line led to rehabilitation being selected as the preferred alternative for addressing the leaks.

Design

Swagelining was selected to provide a continuous liner and maintain as much hydraulic capacity as possible. Swagelining also allows for the use of National Science Foundation–approved HDPE pipe for potable water. The expected service life is more than 50 years.

Construction

The flow in the existing pipe was bypassed and CCTV was used to verify there were no protrusions into the existing pipe and that it was clean. The new pipe was fused into a single section prior to starting the pull. During the pull the new pipe was pulled through a reduction dye, which reduced the outside diameter of the new pipe to about 90% of the inside diameter of the existing pipe. Tension was maintained during the pull to prevent the HDPE pipe from reverting to the original diameter. The pulling of the 2,500 linear feet of liner was completed in 18 hours. The HDPE pipe reverted back to the original diameter about 24 hours after the tension on the pipe was released. The construction costs were about $365 per linear foot.

Additional Information

Lessons learned using swagelining on a curved, 1,400-ft-long, 24-in. RCP transmission main, where the HDPE pipe failed in tension during the pull, were applied to the 2,500-ft-long pull. These lessons included using a reinforced concrete anchor block to provide the resistance for the reduction dye and not using swagelining on a curved alignment.

Summary

The successful renewal of the water transmission main using swagelining required deliberate preparation including bypassing the existing flow, CCTV to verify there were no obstructions and that the pipe was clean, and construction of reinforced concrete anchor block.

Summary of Advantages and Challenges

The following summary of the advantages and challenges (Tables 1 and 2) is based on Najafi (2016); Jin, Piratla, and Matthews (2015); Caltrans (2013); and Hollingshead and Tullis (2009).

Emerging Technologies

One goal of the literature review was to identify potential emerging technologies and also to identify if different methods are being used internationally. The Bibliography includes information on the international use of trenchless renewal, which is generally similar to the methods used in the United States. The literature search did reveal three potentially emergent methods used in the United States.

A steel-reinforced composite system that is a variation on SIPP and CIPP was identified during the literature search. The steel-reinforced composite system includes continuously wrapped,

Table 1. Summary of advantages and challenges of CIPP, SL, and MSL.

Method	Existing Pipe Type	Advantages	Challenges
CIPP	• Concrete • Steel • Plastic • Brick	• Small construction footprint. • Excavation typically not required. • Grouting not required. • Minimal reduction in culvert size. • No joints. • Accommodates most bends. • Noncircular and varying cross-sections.	• Flow bypass required. • Typically manufactured specifically for each project. • Toxic resins associated with some variants. • Capture and disposal of cure water requires additional consideration. • Relatively high volumes of steam and water required for some methods.
SL	• Concrete • Steel • Plastic • Brick	• Flow bypass not always required. • Structural renewal. • Can accommodate large radii bends.	• Large insertion pits and construction area typically required. Can be mitigated with use of segmental pipe. • Limited to smallest diameter of existing pipe. • Excavation may be required. • Bulkheading and grouting of annulus requires additional considerations.
MSL	• Concrete • Steel • Plastic • Brick	• Flow bypass not always required. • Structural renewal. • Smaller construction footprint. • Noncircular and varying cross-sections. • Accommodates some bends. • Grouting not always required.	• Specialized equipment needed for some products. • Excavation may be required at some bends. • Typically manufactured specifically for each project.

Table 2. Summary of advantages and challenges of ILR, SIPP, and CFP.

Method	Existing Pipe Type	Advantages	Challenges
ILR	• Unreinforced or lightly reinforced concrete • Steel • Plastic	• Structural renewal. • Can upsize existing pipe size. • Accommodates some bends.	• Flow bypass typically required. • Larger construction footprint. • Excavation may be required. • Can damage adjacent structures and improvements. • Not suitable for all soil conditions. • Can exaggerate line and grade defects.
SIPP	• Concrete • Steel • Brick	• Small construction footprint. • Noncircular and varying cross-sections. • Can incorporate reinforcement. • Larger diameter can be accommodated. • Protects against corrosion.	• Flow bypass required. • Specialized equipment and training required. • Surface preparation is critical. • Can accommodate most bends.
CFP	• Concrete • Steel • Plastic • Brick	• Annular grouting not required. • Structural renewal. • Accommodates some bends.	• Flow bypass required. • Larger construction footprint. • Limited to circular cross-sections.

high strength, steel wires embedded in a spin-cast or spray-applied cementitious or polymeric matrix and sandwiched between two epoxy-impregnated, fiber-reinforced polymer sheets. The process as described in the literature requires personnel entry and starts with applying the fiber-reinforced polymer sheets to the inside of the existing pipe, installing the steel wire, applying the cementitious or polymeric matrix, and applying a second set of fiber-reinforced polymer sheets to covert the matrix. The method was developed for renewal of prestressed concrete cylinder pipes and designed to provide the original design capacity in the event of complete failure of prestressing wires. The method was used to renew a 54-in. pipe for Miami-Dade Water & Sewer Department (Aguiar, Pridmore, and Geraghty 2015).

Two variations of ILR using pipe ramming, referred to as “pipe crushing” and “pipe swallowing,” were identified as potential emerging technologies. These variations are similar to pipe eating in that the new pipe is larger than the existing pipe and the existing pipe is removed from within the new pipe after installation. For both pipe crushing and pipe swallowing, the new casing is rammed over the existing casing and along the existing alignment. With pipe crushing, angled steel wedges welded within the inner portion of the leading section of new casing crush the existing casing during the ramming process to facilitate removal. A view of the interior of the crushed existing pipe is shown in Figure 9. The crushed pipe can be removed as a single piece. With pipe swallowing, the existing casing is broken or crushed with a separate piece of equipment, such as auger, to facilitate removal.

One relatively unique potential emergent method was identified during the literature search (Witter 2017). The method uses geosynthetic cementitious composite mats (GCCM) to reline personnel-accessible pipes. GCCM is similar but distinct from current definitions of CIPP. It is also similar to paved invert repair. GCCM includes a flexible cement impregnated cloth with a

Figure 9. Interior of existing CMP culvert during the pipe crushing **(Courtesy:** ***HammerHead Trenchless Equipment).***

PVC backing that is mechanically fastened in strips to the inside of the existing pipe. A sealant is used along the seams of the overlapped strips to help prevent infiltration. GCCM is like CIPP in that the process consists of a flexible rolled cloth used to line an existing pipe. However, unlike CIPP, it is hand-placed in strips around the inside of the existing pipe to create a continuous liner and uses cement rather than resin.

The following case study is for a GCCM project completed in Washington in September 2015 (Conrad 2016).

Problem

A portion of the existing 240-ft-long, 60-in.-diameter CMP culvert had been replaced in 2005. During a yearly inspection, corrosion, including through-going corrosion and pitting, was observed along the older 180-ft length of culvert. The maximum depth of cover was about 20 to 25 ft, and Tacoma Water's water supply pipeline crosses over the top of the culvert. Initial estimates to replace the culvert were in the $250,000 to $300,000 range. Given the relatively low cost of the GCCM materials, Tacoma Water elected to try the installation themselves.

Design

The design consisted of two 3.5-ft-wide strips of 0.3-in.-thick GCCM with a 4-in. overlap mechanically fastened. A moisture-cured sealant and a tar sealant were called for along the overlap and edge, respectively. The GCCM included a PVC backing to provide additional waterproofing.

Construction

The construction took an eight-person crew two 8-hour days to complete. Grout was placed to fill the pitted areas of the culvert. The GCCM was delivered to the site on roll and was unspooled as it was pulled into the culvert. The mats were placed longitudinally along the invert in 50- to 60-ft strips. Installation included fastening the GCCM with self-tapping screws with washers on an 8-in. pattern including along the overlap. The joints and edges were sealed. The mat was hydrated after installation. The cost of the materials and the estimated installation costs by Tacoma Water's crew was about $20,000.

Table 3. Case example summary for CIPP, ILR, and SL/MSL.

Method(s)	CIPP	ILR (Pipe Bursting)	SL/MSL
Product	Thermoset Resin-Impregnated Felt Liner	HDPE Pipe	Steel-Reinforced Polyethylene and Tunnel Liner Plate
Location	Wisconsin	Ohio	Tennessee
Existing Pipe Type	RCP	CMP	CMP
Existing Pipe Length (feet)	180	90, 105, 100, and 105	400
Existing Pipe Diameter (inches)	60	12, 18, 24, and 24	72
Final Pipe Diameter (inches)	60	16, 18, 24, and 24	48 and 60
Date	December 2016	June/July 2014	April 2016
Expected Service Life	50 years	100 years	Not Available
Inspection Schedule	Same as other culverts	Same as new construction	Not Available
Approximate Cost per Linear Foot	$650	$120 to $200	Not Available

Additional Information

No discernable change in the GCCM was observed during a 9-month, post-construction review of the installation. Tacoma Water continues to perform regular inspections of the culvert and is hopeful that they will achieve an additional 15 to 20 years of life from the renewed culvert.

Summary

The owner is very satisfied with the relative ease of installation and the additional anticipated service life.

Case Example Summary

A summary of the case studies is provided in Tables 3 and 4. The summary includes the trenchless renewal methods, project location, existing pipe type and dimensions, date of renewal, expected service life, planned inspection schedule, and project cost.

Table 4. Case study summary for SIPP, GCCM, and CFP.

Method(s)	SIPP	GCCM	CFP
Product	Fiber-Reinforced Geopolymer Mortar	Geosynthetic Cementitious Composite Mat	HDPE Pipe
Location	Indiana	Washington	Colorado
Existing Pipe Type	CMP	CMP	Steel
Existing Pipe Length (feet)	275	240	2,500
Existing Pipe Diameter (inches)	84	60	27 inside diameter
Final Pipe Diameter (inches)	81	60	27 outside diameter
Date	September 2015	September 2015	Fall 2012
Expected Service Life	50 years	15 to 20 years	Greater than 50 years
Inspection Schedule	Every 5 years	Same as other culverts	Not Available
Approximate Cost per Linear Foot	$1,125	$83	$365

Chapter Summary

This chapter provides a brief overview of CIPP, SL, MSL, ILR, SIPP, and CFP trenchless renewal methods. The generally accepted applicability of the methods and limiting factors are included in the overview. The advantages and disadvantages of these methods are provided in Tables 1 and 2. Potential emergent methods, including a steel-reinforced composite system that is a variation on SIPP and CIPP, the use of GCCM for culvert renewal, and two variations of ILR are also discussed. Case studies for projects using CIPP, SIPP, SL, MSL, CFP, and ILR (pipe bursting) are summarized in Tables 3 and 4.

CHAPTER 3

Current Practice and Experience

Introduction

This chapter synthesizes the literature search, questionnaire responses, and interviews to provide a summary of the relative frequency of use, how decisions are made to perform trenchless renewal, how methods are selected, the relative use and satisfaction with the methods, and costs and the degree to which costs are tracked. The questionnaire was sent to all 50 DOTs. A total of 43 responses were received from 40 DOTs.

The following sections summarize the results and include related supplementary information obtained from interviews and collected during the literature search.

Experience

Of the respondents, 88% have experience with using at least one method of trenchless stormwater system renewal (Figure 10). Appendix B contains the list of the questionnaire respondents. This appendix can be found on the TRB website (www.trb.org) by searching for "*NCHRP Synthesis 519*."

The number of different trenchless renewal methods used by respondents is included in Table 5. As shown in Table 5, most DOTs have experience with either one or two methods.

Methods and Frequency Used

The selection of a trenchless method requires an assessment of the current condition of the stormwater facility. While assessment is beyond the scope of this synthesis, in general, the assessment needs to identify the underlying cause of the problems that resulted in the system being selected for renewal. At a minimum, the selection of the appropriate trenchless renewal method for a project requires an assessment of the geometry and condition of the existing structure, an understanding of the current and projected functionality and performance of the structure, and general site conditions including site access. Other information, such as anticipated soil and groundwater conditions, the presence of contamination, and adjacent utilities might also be required if access pits are required, if ILR methods will be considered, or if external spot repair is required to facilitate the trenchless renewal. Some additional information on assessment is included in *NCHRP Synthesis 303: Assessment and Rehabilitation of Existing Culverts* (Wyant 2002).

The questionnaire identified the relative use of trenchless renewal by experienced agencies. The results indicate that on stormwater system projects open-cut is used 75% of the time, trenchless renewal is used 16% of the time, and trenchless installation is used 9% of the time (Figure 11).

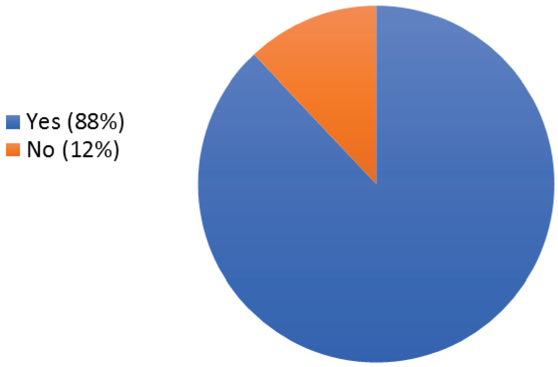

Figure 10. Experience with trenchless stormwater system renewal (40 state DOT respondents).

Table 5. Number of commonly used trenchless renewal methods (37 respondents).

Number of Methods	Count	Percentage of All Respondents	Percentage of Experienced DOTs
0	4	10%	–
1	10	24%	26%
2	13	31%	34%
3	4	10%	11%
4	5	12%	13%
5	3	7%	8%
6	3	7%	8%

The respondents were asked to identify the approximate frequency with which they performed trenchless renewal of manholes and vaults. Based on the responses, trenchless renewal of manholes and vaults is only performed about 11% of the time (Figure 12).

The questionnaire asked which trenchless renewal methods respondents have used on their projects. The ability to select "Other" and a corresponding write-in field was provided to try and identify new methods. The results, which are summarized in Table 6, identified three respondents who considered invert paving to be trenchless renewal. Masada (2017) provides a summary

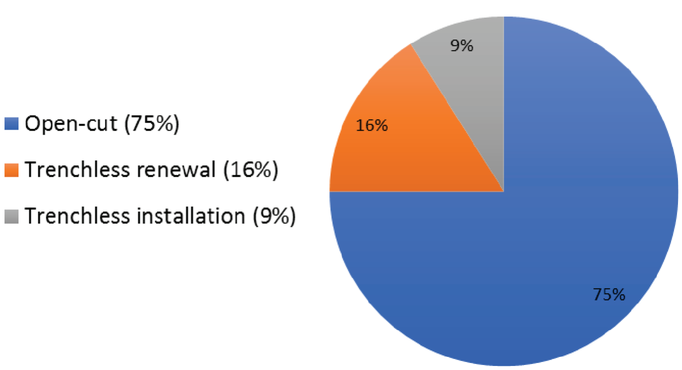

Figure 11. Frequency various construction methods are used on stormwater projects (36 respondents).

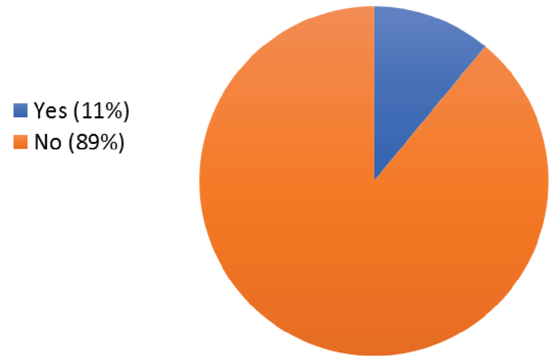

Figure 12. Frequency trenchless renewal of manholes and vaults is performed on stormwater projects (36 respondents).

of a study on the structural benefits of concrete paving of steel culvert inverts. One respondent identified the use of internal bands and joint repair as trenchless renewal.

Because each DOT could potentially use more than one method and because some DOTs provided responses at the district level, the questionnaire asked for an approximate percentage of projects completed using the various trenchless methods. The results are provided in Figure 13 and represent the weighted average frequency with which the various methods are used. Note that because the number of projects completed by each respondent are not the same, these responses do not necessarily represent the frequency they are used on a project level.

Additional information on the use of trenchless methods was obtained from follow-up interviews with respondents and from interviews with selected municipalities and special districts. Two questionnaire respondents stated that they do not currently consider either CIPP or SIPP for structural renewal. Three questionnaire respondents stated that their in-house crews perform the renewal using SL.

Interviews with municipalities and special districts did not reveal any significant differences in the methods used or the application of the methods.

Satisfaction with Methods Used

The questionnaire also asked respondents to characterize their relative success or satisfaction with the various methods as a percentage (Table 7). The satisfaction percentages range from 100%, always satisfied, to 0%, never satisfied. The number of responses (count) should

Table 6. Percentage of DOTs that have used the various renewal methods (37 respondents).

Methods Used		
Method	**Count**	**Percentage**
SL	33	89%
CIPP	23	62%
SIPP	14	38%
MSL	9	24%
ILR	8	22%
CFP	5	14%
Other (Paved invert)	3	8%
Other (Internal bands or joint repair)	1	3%

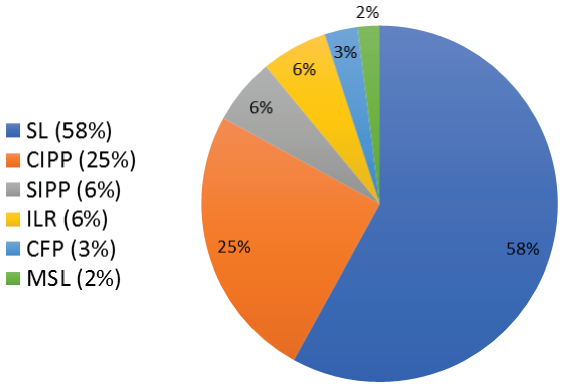

Figure 13. Relative frequency, on the respondent level, with which the various trenchless renewal methods are used (37 respondents).

be considered when reviewing the results. The results may not be representative for the less frequently used methods.

One respondent experienced with both CIPP and SL reported a lower satisfaction with CIPP than with SL. Based on a follow-up interview, the relative dissatisfaction with CIPP was clarified as being a function of a smaller sample size (i.e., they perform much more SL than CIPP) and a result of larger-than-anticipated site disturbance during construction, and not the functionality or performance of the liner.

One respondent reported a lower satisfaction with SIPP as opposed to the other methods they used. Based on a follow-up interview, the respondent noted that the SIPP liners generally exhibit more leaking than the other methods they use. The leakage was noted as a concern due to the potential for spalling and cracking of the SIPP liner because of freeze-thaw.

One respondent noted that where mountainous terrain would make SL difficult, they use CIPP. They also use CIPP at some locations because they anticipate that the CIPP liner will hold up better to fires associated with crop burning than the SL pipe.

One respondent noted that their dissatisfaction with some of their SL projects is associated with the perceived lower value of the renewed culvert compared with a replacement concrete box culvert.

Table 7. Relative satisfaction, where 100% is always satisfied and 0% is never satisfied, with the renewal method used (36 respondents).

Satisfaction with Renewal Method		
Method	**Count**	**Satisfaction Percentages**
MSL	7	91%
CIPP	22	90%
SL	32	88%
ILR	7	87%
SIPP	12	77%
Other (Paved invert)	2	75%
CFP	5	68%

Table 8. Information that would be useful for experienced agencies when considering using trenchless renewal more frequently (37 respondents).

Additional Information	Count	Percentage
Typical cost information	33	89%
Agency experience with the applicable methods (case studies)	30	81%
Decision criteria used by facility owners	28	76%
Limiting factors to the applicability of specific methods	27	73%
Emergent technologies	27	73%
Sources of claims and mitigation methods	19	51%
Settlement, heave, and vibration impacts and mitigation methods	19	51%
None of the above	1	3%
Other (Durability of trenchless repairs)	1	3%

DOT respondents did not have shareable case studies of unsuccessful application of trenchless renewal methods. Interviews with municipalities and special districts did identify several failures associated with CIPP. The failures were reported as rare and appeared to be associated with project specific issues. The hypotheses offered for the failures included insufficient original resin saturation, insufficient preparation of the existing pipe, incomplete curing, and damage to the liner prior to installation.

Increasing Trenchless Renewal Use

The questionnaire asked what information would be useful for experienced agencies when considering using trenchless renewal more frequently. The results provided in Table 8 indicate that the top three types of additional information are case studies, typical costs, and examples of decision criteria used by other agencies.

The questionnaire asked respondents to identify reasons trenchless renewal was not used even when it was technically feasible. Table 9 provides the frequency of the reasons for not performing trenchless renewal when it is technically feasible. One respondent noted that for shallow cover and low-volume roads, they prefer open-cut replacement. Another respondent noted that they do not currently perform much SL since they do have a standard specification to perform the work.

Table 9. Reasons experienced agencies elect not to use trenchless renewal when technically feasible (37 respondents).

Reason	Percentage
Condition of existing pipe (e.g., offset joints, collapse)	78%
Reduction in hydraulic capacity not acceptable	61%
Economics/costs	56%
Limited organizational experience	39%
Uncertainty regarding design life/performance of trenchless methods	36%
Preference for new construction	36%
Site access limitations (e.g., limited staging area)	28%
Faster to open-cut	19%
Environmental considerations (e.g., pH, existing fish/wildlife, and required habitat improvement [fish passage])	19%
Lack of local experienced contractors	11%
Flow bypass difficulties	11%
Presence of laterals	8%
Potential damage to existing, adjacent facilities or pavement	6%
Prior unfavorable experience	3%

Table 10. Reasons why DOTs that do not have experience with trenchless renewal do not use it (4 respondents).

Reason	Overall Rank
Reduction in hydraulic capacity not acceptable	1
Limited organizational experience	2
Preference for new construction	3
Uncertainty regarding design life/performance of trenchless methods	4
Condition of existing pipe	5
Economics/costs	6
Faster to open-cut	7
Lack of local experienced contractors	8
Presence of laterals	9
Flow bypass difficulties	10

For respondents that do not have experience with trenchless renewal, the questionnaire asked for the top five reasons for not using it. Table 10 provides an overall rank, where 1 is the highest and 10 is the lowest, for the reasons provided.

The four respondents without trenchless experience were also asked what information would be useful when considering using trenchless renewal. Table 11 provides the results as a "count" rather than a percentage because of the small sample size.

Method Selection

The survey results indicate that approximately 11% of the 38 respondents have standardized decision criteria to assist with deciding whether to perform trenchless renewal and which method to use. The criteria provided by the respondents or identified during interviews are summarized below.

The Florida DOT has a pipe repair matrix that is available on the internet (Florida DOT 2017). The matrix was developed for repair of new construction damaged during installation and identified during final pipe inspection. The potential use of three trenchless renewal methods (CIPP, SL, and SIPP) are identified in the matrix for cracks or leaks of metal or concrete pipes. The matrix also references a pipe liner standard specification, which includes additional references to MSL and the ILR (pipe bursting). Neither the matrix nor the specification provide guidance for selecting a particular method. The preface for the matrix states that it does not replace engineering judgment and "encourages the review and use of emerging repair technologies provided they are based on sound scientific principles and defendable engineering analysis."

Table 11. Information that would be useful for non-experienced agencies when considering using trenchless renewal (4 respondents).

Additional Information	Count
Decision criteria used by facility owners	4
Agency experience with the applicable methods (case studies)	3
Typical cost information	3
Limiting factors to the applicability of specific methods	2
Emergent technologies	2
Sources of claims and mitigation methods	1
Settlement, heave, and vibration impacts and mitigation methods	1

The Minnesota DOT's HydInfra Inventory and Inspection program, which includes data from inspections such as size, shape, material, and condition descriptor, in combination with a related flow chart, can provide a planning-level suggested repair (Wagener and Leagjeld 2014). Trenchless renewal methods included in the flow chart are limited to SL and CIPP. Additional site-specific data such as access, laydown area, flow diversion feasibility, and hydraulic capacity need to be considered before the suggested repair is selected as the recommended repair.

The Virginia DOT (2017) provides another example of guidelines for selecting a trenchless renewal method based on the deficiency (defect) and site access considerations. Virginia DOT identifies three methods of pipe rehabilitation. These three methods are corrugated steel pipe liner, flexible pipe liner, and smooth wall steel pipe liner. The flexible pipe liner, referred to as "Method D," covers CIPP, SL, SIPP for pipes 36 in. or larger, and the F&F variant of CFP.

The California Department of Transportation (Caltrans) has a design bulletin that supplements the 1995 FHWA publication *Culvert Repair Practices Manual—Volumes 1 and 2.* The bulletin includes a discussion of trenchless renewal and trenchless replacement methods (Caltrans 2013). The bulletin provides a summary of approaches to identifying possible replacement and renewal methods based on the culvert size, traffic, and culvert condition.

The Ohio DOT has designer guidelines for trenchless culvert repair and rehabilitation (Ohio DOT 2016). The guidelines are provided for existing structurally and non-structurally sound RCP, and metal (steel and aluminum) pipe as well as structurally sound plastic pipe. The guidelines include trenchless renewal with SL, SIPP, and CIPP.

For agencies that do not have a standardized process, Figure 14 summarizes the selection process used. "Own equipment/crews" in Figure 14 means that the selection of the method is based on the ability of in-house personnel to perform the work. "All the above" in Figure 14 refers to "Experienced-based," "in-house expert/consultation," "own equipment/crews," and "input from outside consultants" as all being methods used by the respondents.

The literature review identified publications providing decision criteria for selecting trenchless renewal methods published by non-state DOTs. These include a publication by the Federal Lands Highway and a publication by the United States Forest Service.

A manual entitled *Culvert Assessment and Decision-Making Procedures Manual for Federal Lands Highway* (Hunt et al. 2010) provides guidance for selecting replacement or rehabilitation of culverts. The manual includes an assessment tool with proposed rating codes with reference photographs and flow charts for identifying potential renewal, replacement, or repair alternatives.

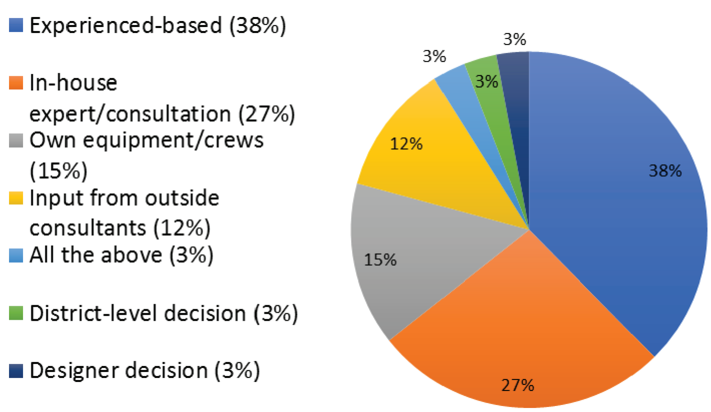

Figure 14. Decision criteria used by DOTs without a standardized process (34 respondents).

Table 12. Reasons for using trenchless renewal (34 respondents).

Reason	Overall Rank	No. of Rankings
Height of fill (cover) over structure	1	23
Limit surface disturbance	2	25
Perceived economic/cost benefit	3	22
Faster than open-cut	4	23
Temporary or permanent deferral of constructing a larger replacement pipe	5	14
Environmental considerations (e.g., existing fish/wildlife, wetland impact)	6	13
Favorable past experience	7	13
Commonly used/standard practice	8	7
Own the equipment and have in-house crews that perform the work	9	8
Lots of local experienced contractors	10	5
Other	11	2
Outcome from formalized cost benefit analysis	12	3
Outcome from formalized decision process	13	2

The assessment form illustrates the types of information that is commonly required to identify the potentially applicable trenchless renewal methods. For SL, CFP, spiral-wound liner, CIPP, and SIPP, the Federal Lands Highway manual provides a liner selection matrix with some of the typical applications and advantages and disadvantages, as well as rough comparative costs.

The United States Forest Service developed a guide for rehabilitating and replacing CMP culverts using trenchless methods (Matthews et al. 2012). The guidelines contain a flow chart for selecting from SIPP, CIPP, MSL, SL, and invert paving, depending on the condition of the CMP.

Reasons for Using Trenchless Renewal

The questionnaire asked for the top five reasons for using trenchless renewal. The two "Other" reasons were related to minimize traffic disruption and the smaller staging requirements. The responses highlight the usual assumed reasons related to cost and schedule. The top five reasons include the height of fill over the existing pipe, the desire to limit surface disturbance, perceived economic/cost benefit, the anticipation it will be faster than open-cut, and temporary deferral of constructing a larger replacement pipe. Table 12 provides an overall rank, where 1 is the highest and 13 is the lowest, and weighted score for the reasons provided. The number of rankings indicates the frequency with which it was selected as one of the top five reasons.

The survey asked for the approximate percentage of trenchless renewal projects that were performed to temporarily defer replacement. Based on the results, about 30% of trenchless renewal projects are performed for temporary renewal. This value was calculated using a weighted average of the results of the survey provided in Table 13. Note that because the number of projects

Table 13. Frequency with which trenchless renewal is performed for temporary mitigation (35 respondents).

Trenchless Renewal Performed for Temporary Mitigation										
Never	10%	20%	30%	40%	50%	60%	70%	80%	90%	Always
10	10	3	1	0	3	0	1	1	3	3

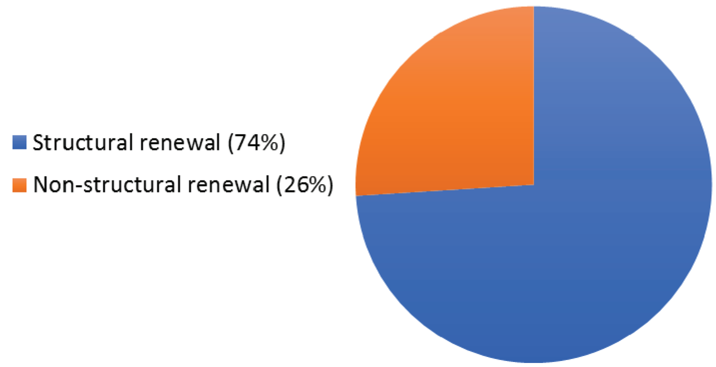

Figure 15. Frequency trenchless renewal is performed for structural versus non-structural renewal (36 respondents).

completed by each respondent is not the same, these responses do not necessarily represent the frequency that the renewal is considered temporary on a project level.

The questionnaire asked for a relative percentage of projects where the renewal was considered to be for non-structural reasons. Based on the results, about 26% of trenchless renewal projects are performed for non-structural reasons (Figure 15). This value was calculated using a weighted average of the results of the survey provided in Table 14. Note that because the number of projects completed by each respondent are not the same, these responses do not necessarily represent the frequency that the renewal is performed for non-structural reasons on a project level.

Defects Commonly Mitigated and Satisfaction

The survey results indicate that trenchless renewal is most commonly used to mitigate corrosion; leaks or infiltration; loose or open joints; and cracks, breaks, or splits. The experience of respondents mitigating defects is summarized in Table 15.

Because each DOT could potentially attempt to mitigate more than one defect, respondents were asked for an approximation of the relative frequency with which the defects were mitigated.

Table 14. Frequency trenchless renewal is performed for non-structural reasons (36 respondents).

Trenchless Renewal Performed for Non-Structural Reasons										
Never	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**Always**
19	3	2	1	2	2	0	1	0	2	4

Table 15. Experience with mitigating defects using trenchless renewal (36 respondents).

Defect	Count	Percentage
Corrosion	34	90%
Leaks or infiltration	30	79%
Loose or open joints	29	76%
Cracks, breaks, or splits	27	71%
Cavitation or erosion	14	37%
Flattened or oval pipes	10	26%
Sags	5	14%
Alignment offsets	5	13%

Table 16. Relative frequency with which mitigation is attempted (38 respondents).

Defect	Relative Frequency Mitigation Attempted					
	Never	<10%	10% to 40%	40% to 60%	60% to 90%	Always
Alignment offsets	31	3	1	1	0	0
Loose or open joints	9	2	10	6	7	2
Flattened or oval pipes	26	4	1	2	2	1
Sags	31	1	3	1	0	0
Cracks, breaks, or splits	11	2	8	8	7	0
Cavitation or erosion	23	4	2	4	2	1
Corrosion	3	4	8	11	8	2
Leaks or infiltration	8	3	12	10	2	1

The questionnaire asked for one of six frequency categories shown in Table 16 to be selected based on the answers to the proceeding question on which defects were commonly mitigated. Table 16 provides a count of the responses for each category. The data shows the same trend: corrosion is the most frequent defect mitigated, followed by attempting to mitigate leaks or infiltration; loose or open joints; and cracks, breaks, or splits.

The questionnaire asked for a qualitative response opinion on the ability of trenchless renewal to mitigate the previously defined defects. With the exception of the responses indicating dissatisfaction with mitigating flattened or oval pipes, sags, and the eight "neutral" responses, the DOTs overall indicated they were satisfied or very satisfied with the ability of trenchless renewal to mitigate most defects. Table 17 provides a summary of the responses.

Costs

Of the 38 respondents, 24% indicated that they had shareable trenchless renewal costs. The costs were not obtained as part of the survey.

The questionnaire asked for the frequency that cost overruns occurred in four categories. The magnitudes in these categories were 0% to 10%, 10% to 20%, 20% to 30%, and greater than 30%. To characterize the relative frequency with which cost overrun occur, the data from the survey are summarized in Figure 16.

The respondents were asked to identify the most common reason for cost overruns. A total of nine respondents provided answers. The following answers were provided:

- Changed conditions.
- Limited number of contracts.
- Overruns are typically low because the work is paid for by the linear foot of existing pipe and the quantity is usually fairly accurate.

Table 17. Relative satisfaction with mitigation attempted (36 respondents).

Defect	Relative Satisfaction with Mitigation Attempted				
	Very Dissatisfied	Dissatisfied	Neutral	Satisfied	Very Satisfied
Alignment offsets	0	0	0	5	0
Loose or open joints	0	0	1	18	8
Flattened or oval pipes	1	0	0	6	3
Sags	0	1	1	3	0
Cracks, breaks, or splits	0	0	0	20	5
Cavitation or erosion	0	0	2	9	2
Corrosion	0	0	2	22	9
Leaks or infiltration	0	0	2	19	7

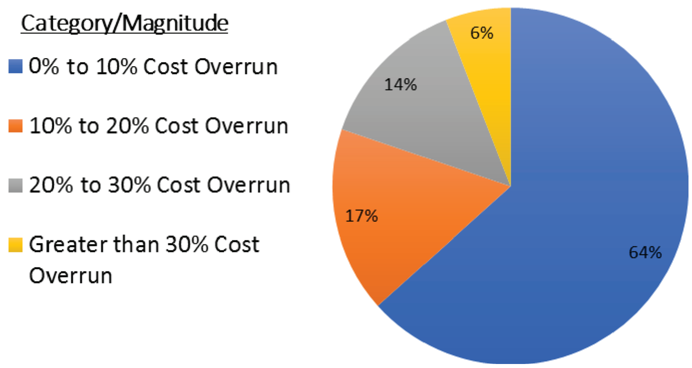

Figure 16. Weighted average frequency with which cost overruns occur (32 respondents).

- Rare due to mostly bid items.
- Building the pit.

One respondent uses master agreements with fixed costs that are determined before the project begins so that they do not have overruns.

The questionnaire asked respondents to select the common reasons for construction claims on trenchless renewal projects. The most common reason identified by the 29 respondents was a difference in the existing pipe condition (59%), followed by differing groundwater/soils conditions (40%). Comments regarding the most common reason for construction claims provided by respondents are summarized below:

- Existing pipe condition and/or size different than anticipated (three comments).
- Differing site conditions (two comments).
- Additional liner thickness required.
- Wrong method selected for conditions.
- Difficulty with the annular void filling.

Six respondents noted that they have not had any construction claims on trenchless renewal projects.

Underutilized Methods

Both experienced and non-experienced DOTs identified concerns about the ability to maintain the existing hydraulic capacity as one of the main reasons for not using trenchless renewal. Therefore, CFP, MSL, ILR, and SIPP, which typically do not result in a significant reduction in hydraulic capacity and could potentially improve the hydraulic capacity of existing stormwater systems, appear to be underutilized.

Chapter Summary

The following list contains a summary based on the synthesis of the literature search, questionnaire responses, and interviews:

- Of the respondents, 88% have experience with some form of trenchless renewal of stormwater systems.
- SL is the most commonly used trenchless renewal method.
- The respondents are generally satisfied with the SL (88%).

- Of the DOTs, 24% use only one trenchless renewal method.
- Of the DOTs, 55% have experience with two methods.
- About 88% of the respondents do not use a standardized decision criterion to assist with selecting the trenchless renewal method; the decision is most commonly made based on past experience.
- The most common reason for using trenchless renewal is the height of cover over the existing pipe.
- The most common reason for experienced DOTs not to use trenchless renewal is the condition of the existing pipe.
- The most common reason for non-experienced DOTs to not use trenchless renewal is the condition of the unacceptable reduction in hydraulic capacity.
- The respondents are generally satisfied or very satisfied with the ability of trenchless renewal to mitigate the common defects, such as corrosion; leaks or infiltration; loose or open joints; and cracks, breaks, or splits.
- The most common cause of cost overruns and claims is changed or differing conditions associated with the existing pipe (59%).
- Of the respondents, 64% indicated that cost overruns were generally less than 10% of the original project cost.
- CFP, MSL, ILR, and SIPP may be underutilized relative to the other SL and CIPP.

A more detailed summary is provided in Chapter 4.

CHAPTER 4

Conclusions

Of the surveyed state DOTs, 88% have current experience with some form of trenchless renewal of stormwater systems. Respondents indicated it is used on about 16% of the stormwater projects. The trenchless renewal of vaults and manholes is performed on only about 11% of respondents' projects.

Trenchless renewal methods are commonly considered to be "permanent" (70%) rather than a temporary repair to defer replacement. Trenchless renewal is also commonly considered to be a structural repair (74%).

It is uncommon for the decision to use trenchless renewal and the decision on which method to use to be made based on a standardized decision criterion. Only 11% of respondents identified they had an established procedure. The remaining respondents overwhelmingly relied on previous experience (38%), in-house experts (27%), or the fact that they had their own equipment and experienced crews (15%) to decide which trenchless method to use.

The four most common reasons, in order from more common to less common, for using trenchless renewal were identified as follows:

- Height of fill (cover) over the structure
- Limiting surface disturbance
- Perceived economic/cost benefit
- Faster than open-cut

The three most common reasons, in order from more common to less common, for DOTs with trenchless renewal experience for not using trenchless renewal when it is technically feasible were identified as follows:

- Condition of existing pipe
- Reduction in hydraulic capacity not acceptable
- Economics/costs

The five most common reasons, in order from more common to less common, for DOTs without trenchless renewal experience for not using trenchless renewal were identified as follows:

- Reduction in hydraulic capacity not acceptable
- Limited organizational experience
- Preference for new construction
- Uncertainty regarding design life/performance of trenchless methods
- Condition of existing pipe

The five most common types of information, in order from more common to less common, that DOTs identified as being helpful for increasing the use of trenchless renewal were as follows:

- Typical cost information
- Agency experience with applicable methods (case studies)
- Decision criteria used by facility owners
- Limiting factors to the applicability of specific methods
- Emergent technologies

The same top five types of information, in a slightly different order, were identified by DOTs without trenchless renewal experience as being most helpful for considering using trenchless renewal.

The surveyed DOTs have the most experience with SL (89%), CIPP (62%) and SIPP (38%). On a DOT basis, as opposed to on a project basis, SL is the most commonly used method (56%), with CIPP being used less than half as often (25%) and SIPP being used about 6% of the time. The relatively low number of responses regarding experience with MSL, CFP, and ILR make it difficult to characterize the frequency with which these methods are used.

The respondents are generally satisfied with SL (88%) and CIPP (90%). The reported satisfaction rates for the other methods may not be representative because they are not frequently used.

The respondents are generally satisfied or very satisfied with the ability of trenchless renewal to mitigate common defects, such as corrosion; leaks or infiltration; loose or open joints; and cracks, breaks, or splits.

Common causes of cost overruns and claims were identified as changed or differing conditions associated with the existing pipe (59%) or subsurface conditions (40%). Of the respondents, 64% indicated that cost overruns were generally less than 10%, and 6% noted experience with cost overruns exceeding 30%.

These findings, combined with literature search and interviews, suggest the following research opportunities.

A comprehensive review of structural testing and analysis of SIPP and CIPP liners. SIPP and CIPP do not significantly reduce the existing hydraulic capacity. However, uncertainty regarding the design and structural performance of these two methods is limiting the acceptance and use by some of the interviewed DOTs. A document providing a comprehensive review of the structural testing and analysis of these methods could further their use.

Second application renewal. Researching the potential limitations on future renewal or repair resulting from the initial use of a renewal method could be considered. As a result of the relatively short time-in-service of trenchless renewal methods, the re-application of renewal methods on previously renewed pipes is not well documented.

Additional published information on less commonly used ILR. ILR could potentially address the top two identified reasons provided for not using trenchless renewal when it is technically feasible (deteriorated condition of the existing pipe and unacceptable reduction of hydraulic capacity). While this synthesis provides some information on ILR used for trenchless renewal of stormwater systems, a publication focused on the successful use, limitations, advances in equipment and tooling, and costs could be of value to DOTs.

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Detailed cost data on trenchless renewal methods. While 88% of DOTs have experience with trenchless renewal, only 24% of experienced respondents said that they had shareable cost data. The wide range of costs for the methods available in the literature, combined with the low percentage of DOTs with data to share, suggests that collecting the requisite data and the data analysis to provide cost data will be challenging.

Practitioner's guide. The process of performing an assessment and using the results to select a preferred renewal method is beyond the scope of this synthesis. While some DOTs and other agencies have guidelines, a comprehensive report or practitioner's guide could be beneficial to those agencies without standard guidelines or sufficient organizational experience.

References

Adamtey, S. A. *Replacement of Corrugated Metal Pipe Culverts Using Pipe Bursting*. PhD dissertation. Indiana State University, Terre Haute, 2016, 124 pp.

Aguiar, L., A. Pridmore, and M. Geraghty. Miami-Dade Implements Hybrid FRP Trenchless Repair System. In *Proceedings for Pipelines 2015: Recent Advances in Underground Pipeline Engineering and Construction*, Baltimore, Maryland, August 23–26, 2015, pp. 1257–1267.

Caltrans. *Caltrans Supplement to FHWA Culvert Repair Practices Manual*. Caltrans Design Information Bulletin No. 83-03, Caltrans, Sacramento, October 31, 2013, 202 pp.

Conrad, R. Concrete Cloth is an Emerging Technology for Culvert Remediation. *Environmental Science & Engineering Magazine,* April 2016, pp. 50–51.

Florida Department of Transportation. *Pipe Repair Matrix*. Tallahassee, 2017 [Online]. Available: http://www.fdot.gov/construction/ContractorIssues/PipeMatrix/MatrixMain.shtm. Accessed May 1, 2017.

Grams, W. CIPP Used to Reline Wisconsin Culvert in Winter. March 20, 2017 [Online]. Available: https://trenchlesstechnology.com/cipp-relining-in-the-winter/. Accessed May 1, 2017.

Hartley, N. *Culvert Rehabilitation Guidance*. State of Maine Department of Transportation, Augusta, December 18, 2014.

Herbert, D. E., and J. Hyma. Carter Street Culvert Rehabilitation. In *Proceedings of the North American Society for Trenchless Technology 2017 No-Dig Show*, Washington, D.C., April 9–12, 2017, 7 pp.

Hollingshead, T., and B. P. Tullis. *In-Situ Culvert Rehabilitation: Synthesis Study and Field Evaluation*. Report No. UT-09.16, Utah Department of Transportation, Salt Lake City, June 2009, 33 pp.

Hunt, J. H., S. M. Zerges, B. C. Roberts, and B. Bergendahl. *Culvert Assessment and Decision-Making Procedures Manual for Federal Lands Highway*. Report FHWA-CFL/TD-10-005, Federal Highway Administration Central Federal Lands Highway Division, Lakewood, CO, 2010, 222 pp.

International Pipe Bursting Association. *Guideline for Pipe Bursting*. Owings Mills, MD, January 2012, 34 pp.

Iseley, D. T., and S. B. Gokhale. *NCHRP Synthesis of Highway Practice 242: Trenchless Installation of Conduits Beneath Roadways*. TRB, National Research Council, Washington, D.C., 1997, 76 pp.

Jin, H., K. R. Piratla, and J. C. Matthews. Decision-Making Guidance for Culvert Rehabilitation and Replacement Using Trenchless Techniques. In *Proceedings for Pipelines 2015: Recent Advances in Underground Pipeline Engineering and Construction*, Baltimore, Maryland, August 23–26, 2015, pp. 1443–1451.

Keaffaber, D. GeoSpray™ GeoPolymer Mortar System and Concrete Cloth for Structural Rehabilitation/Repair of Sewer and Storm Infrastructure. Presented at the Center for Technology and Training 2016 Michigan Bridge Conference, Lansing, May 23, 2016, 105 pp. [Online]. Available: http://ctt.mtu.edu/sites/ctt/files/resources/bridge2016/conference/08keaffaber.pdf.

Masada, T. *Structural Benefit of Concrete Paving of Steel Culvert Inverts*. Report FHWA/OH-2017-21, Ohio Research Institute for Transportation and Environment, Athens, 2017, 446 pp.

Matthews, K., and O. Randall. A Tale of Two Swagelines—Contrasting Conditions Assess the Versatility of Swagelining in Ft. Collins, Colorado. In *Proceedings of the North American Society for Trenchless Technology 2014 No-Dig Show*, Orlando, FL, April 13–17, 2014, 5 pp.

Matthews, J. C., J. Simicevic, M. A. Kestler, and R. Piehl. *Decision Analysis Guide for Corrugated Metal Culvert Rehabilitation and Replacement Using Trenchless Technology*. U.S. Department of Agriculture, Forest Service, Washington, D.C., December 2012, 93 pp.

Najafi, M. *Pipeline Infrastructure Renewal and Asset Management*. McGraw-Hill Education, New York, NY, 2016, 568 pp.

Ohio Department of Transportation. *Designer Guidelines for Trenchless Culvert Repair and Rehabilitation*. Office of Hydraulic Engineering, Columbus, 2016 [Online]. Available: http://www.dot.state.oh.us/Divisions/Engineering/Hydraulics/Location%20and%20Design%20Volume%202/Pages/Designer-Guidelines.aspx.

Osborn, L., ed. *Trenchless Renewal of Culverts and Storm Sewers.* Manuals and Reports on Engineering Practice, No. 120, American Society of Civil Engineers, Reston, VA, 2010, 103 pp.

Thornton, C. I., M. D. Robeson, L. G. Girard, and B. A. Smith. *Culvert Pipe Liner Guide and Specifications*. Report FHWA-CFL/TD-05-003, Federal Highway Administration Central Federal Lands Highway Division, Lakewood, CO, July 2005, 169 pp.

UNITRACC. "Pipe Eating." 2017 [Online]. Available: http://www.unitracc.com/know-how/fachbuecher/rehabilitation-and-maintenance-of-drains-and-sewers/rehabilitation/replacement-en/replacement-by-the-trenchless-method-en/unmanned-techniques-en/pipe-eating-en. Accessed May 1, 2017.

Virginia Department of Transportation, Location and Design Division. Chapter 8, Culverts. In *Drainage Manual,* Richmond, 2017 [Online]. Available: http://www.virginiadot.org/business/resources/LocDes/DrainageManual/drain-manual-chapter-08.pdf.

Wagener, B. D., and E. E. Leagjeld. *Culvert Repair Best Practices, Specifications and Special Provisions—Best Practices Guidelines*. Report MN/RC 2014-01, Minnesota Department of Transportation, St. Paul, January 2014, 94 pp.

Witter, J. *Alternative Stream Channel Maintenance at Bridge Crossings*. Report FHWA/OH-2017-6, The Ohio State University, Columbus, February 2017, pp. 172–178.

Wyant, D. C. *NCHRP Synthesis of Highway Practice 303: Assessment and Rehabilitation of Existing Culverts*. Transportation Research Board of the National Academies, Washington, D.C., 2002, 74 pp.

Bibliography

Adamtey, S. A., L. M. Onsarigo, and A. Atalah. Case Study of the Replacement of Corrugated Metal Pipe (CMP) Culverts Using Pipe Bursting. In *Proceedings of the North American Society for Trenchless Technology 2016 No-Dig Show*, Dallas, TX, March 20–24, 2016, 9 pp.

Alam, S., R. L. Sterling, E. Allouche, W. Condit, J. Matthews, A. Selvakumar, and J. Simicevic. A Retrospective Evaluation of the Performance of Liner Systems Used to Rehabilitate Municipal Gravity Sewers. *Tunnelling and Underground Space Technology*, No. 50, 2015, pp. 451–464.

Alkhrdaji, T., S. Rocca, and N. Galati. PCCP Rehabilitation Using Advanced Hybrid FRP Composite Liner. In *Proceedings for Pipelines 2013*, Fort Worth, TX, June 23–26, 2013, pp. 672–681.

Alkhrdaji, T., S. Rocca, and J. Thomas. The Development of a Novel Steel Reinforced Composite (SRC) Liner for the Rehabilitation of Deteriorated PCCP. In *Proceedings for Pipelines 2012*, Miami Beach, Florida, Aug. 19–22, 2012, pp. 1192–1202.

American Society of Civil Engineers and Water Pollution Control Federation. *Existing Sewer Evaluation and Rehabilitation*. Manuals and Reports on Engineering Practice No. 62, American Society of Civil Engineers, New York, NY, 1983, 106 pp.

American Society of Civil Engineers. *Emerging Concepts for the Design of Pipeline Renewal Systems*. Pipeline Infrastructure Task Committee Report, Reston, VA, 2007, 42 pp. [Online]. Available: https://www.uta.edu/ce/cuire/Emerging%20Concepts%20in%20Pipeline_Renewal_Design%20Final%20Version.pdf.

Ardani, A., J. Mallela, and G. Hoffman. *Montana Demonstration Project: Innovative Culvert Rehabilitation Using Trenchless Technologies*. Federal Highway Administration, Washington, D.C., 2009, 35 pp.

Ariaratnam, S. T., J. S. Lueke, and J. K. Michael. Current Trends in Pipe Bursting for Renewal of Underground Infrastructure Systems in North America. *Tunnelling and Underground Space Technology*, No. 39, 2014, pp. 41–49.

Becerril, G. D., and I. D. Moore. Performance of Deteriorated Corrugated Steel Culverts Rehabilitated with Sprayed-on Cementitious Liners Subjected to Surface Loads. *Tunnelling and Underground Space Technology*, No. 47, 2015, pp. 222–232.

Bologna, C., A. Pridmore, M. Geraghty, and J. Alexander. Power Generation Case Study: Feasibility of Carbon Fiber and Alternate Repair Methods. In *Proceedings for Pipelines 2011*, Seattle, WA, July 23–27, 2011, pp. 533–541.

Bowles, J. Condition Assessment, Asset Management and Trenchless Rehabilitation Planning. Presented at the Ohio Transportation Engineering Conference, Columbus, 2016, 30 pp. [Online]. Available: http://www.dot.state.oh.us/engineering/OTEC/2016%20Presentations/Wednesday/51/Bowles_51.pdf.

Combeer, G., and S. Melville. Spiral Wound Pipe Rehabilitation Developments for the Middle-Eastern and Asian Markets. In *Proceedings of the 31st International No-Dig Conference and Exhibition*, Sydney, Australia, Sept. 1–4, 2013, pp. 142–150.

Donaldson, B. M. *Water Quality Implications of Culvert Repair Options: Vinyl Ester Based and Ultraviolet Cured-in-Place Pipe Liners.* Report No. VCTIR 13-R2, Virginia Center for Transportation Innovation and Research, Richmond, November 2012, 24 pp.

Earth Tech Team. *Warranty Inspection, Supplement to the Pilot Project Report: Regional Infiltration and Inflow Control Program, King County, Washington.* Report prepared for King County Department of Natural Resources and Parks Wastewater Treatment Division, Earth Tech Team, Seattle, WA, August 2006, 29 pp.

Gresham, Smith and Partners. *Final Cost Benefit Analysis for Culvert Replacement.* Report for Ohio Department of Transportation Office of Statewide Planning and Research, Gresham, Smith and Partners, Columbus, May, 2016.

Gruver, D. District 8 Case Studies of Pipe Rehabilitation Techniques. Presented at the Ohio Transportation Engineering Conference, Columbus, Oct. 28, 2014, 135 pp. [Online]. Available: http://www.dot.state.oh.us/engineering/OTEC/2014%20OTEC%20Presentations/Tuesday,%20Oct.%2028/50-D131-3-5/gruver.pdf.

Hu, B., and R. W. K. Chan. A Deployable Stent for Structural Repair of Water Pipes. In *Proceedings for the 8th Australasian Congress on Applied Mechanics,* Melbourne, Australia, Nov. 25–26, 2014, pp. 715–722.

Huang, J., Z. Chen, J. Zhai, and A. H. Jun. A Rapid Trenchless Strengthen and Rehabilitation Method for a Large Diameter GRP Pipe in a Mountain City. In *Proceedings of the International Conference on Pipelines and Trenchless Technology*, Wuhan, China, October 19–22, 2012, pp. 1181–1188.

Ishmuratov, R., V. Orlov, and A. Andrianov. The Spiral Wound Pipeline Rehabilitation Technique for Pipe Networks: An Application and Experience in Moscow City. In *Proceedings of the 31st International No-Dig Conference and Exhibition*, Sydney, Australia, Sept. 1–4, 2013, pp. 296–302.

Iwasa, Y., M. Watanabe, and H. Yamashiro. Sewerage Pipeline Rehabilitation Method: Development of SPR Method for High Degree Curves. In *Proceedings of the 28th International No-Dig Conference and Exhibition*, Singapore, November 8–10, 2010, pp. 456–460.

Jin, H. *Decision-Making Guidance for Selecting Culvert Renewal Techniques*. PhD dissertation. Clemson University, Clemson, SC, 2016, 133 pp.

Koo, D. H., H. M. Song, J. I. Cho, and C. K. Jang. Development of an Automated Air Pressure Inversion System Using Vertical Roller Brackets (ABL System) for Steam Cured CIPP Installation. In *Proceedings of the International Conference on Pipelines and Trenchless Technology*, Beijing, China, October 26–29, 2011, pp. 1335–1343.

Kou, J., and W. Yang. Application Progress of Oil and Gas Pipeline Rehabilitation Technology. In *Proceedings of the International Conference on Pipelines and Trenchless Technology*, Beijing, China, October 26–29, 2011, pp. 1285–1292.

Krishna, S. L., M. P. Astuti, and B. T. Tan. Singapore's Experience in Using Different Methods of Trenchless Technology for Sewer Rehabilitation. In *Proceedings of the 28th International No-Dig Conference and Exhibition*, Singapore, November 8–10, 2010, pp. 449–455.

Kuliczkowski, A., U. Kubicka, and A. Parka. The Comparative Analysis of Standards Used in Poland for Trenchless Rehabilitation of Sewage Pipes and the Problems in Design of Resin Liners. *Tunnelling and Underground Space Technology*, No. 25, 2010, pp. 795–801.

Kuliczkowski, A., R. Langer, A. Wojcik, and D. Lichosik. Modernization of the Cracow Non-Circular Sewers Using Glassfiber Reinforced Plastic Panels. In *Proceedings of the 29th International No-Dig Conference and Exhibition*, Berlin, Germany, May 2–5, 2011, pp. 214–221.

Laurent, E., P. Belloir, and H. Haubruge. Polyethylene Pipes in Non-Conventional Installations: PE100-RC Development Milestones and Perspectives. In *Proceedings of the 29th International No-Dig Conference and Exhibition*, Berlin, Germany, May 2–5, 2011, pp. 389–398.

Li, B., Z. Wang, D. Li, and C. Zang. Discussions on the Application of Pipe Bursting Method for Pipeline Rehabilitation. In *Proceedings of the International Conference on Pipelines and Trenchless Technology*, Xi'an, China, October 16–18, 2013, pp. 748–759.

Lim, S. Spiral Wound Liner for Circular and Non-Circular Conduits. In *Proceedings of the 34th International No-Dig Conference and Exhibition*, Beijing, China, October 10–12, 2016, pp. 400–405.

Lou, K., S. Zhang, R. Wang, X. Si, and X. Han. The Research Development of Tubular Textile Composites Application on the Trenchless Pipeline Inversion Lining Rehabilitation Technology. *Key Engineering Materials*, Vol. 671, 2016, pp. 306–14.

Matthews, J. C. Large-diameter Sewer Rehabilitation Using a Fiber-Reinforced Cured-in-place Pipe. *Practice Periodical on Structural Design and Construction*, Vol. 20, No. 2, 2015, pp. 1–5.

Matthews, J. C., and J. C. Gutierrez Monsalve. Trenchless Infrastructure Construction Techniques Used in Colombia. *Practice Periodical on Structural Design and Construction*, Vol. 14, No. 4, 2012, pp. 166–170.

Najafi, M. *Trenchless Technology: Pipeline and Utility Design, Construction and Renewal*. McGraw-Hill, New York, NY, 2005, 489 pp.

Najafi, M. *Technology Piping: Installation and Inspection*. McGraw-Hill, New York, NY, 2010, 480 pp.

Najafi, M. *Trenchless Technology: Planning, Equipment and Methods*. McGraw-Hill, New York, NY, 2013, 608 pp.

Najafi, M., S. Salem, D. Bhattachar, B. Salman, and R. Patil. *An Asset Management Approach for Drainage Infrastructure and Culverts*. Project 06-08, Midwest Regional University Transportation Center, Madison, WI, 2007, 299 pp.

Persson, B. Ultraviolet Cured Structural Lining: Overcoming the Challenges. In *Proceedings of the 28th International No-Dig Conference and Exhibition*, Singapore, November 8–10, 2010, pp. 248–256.

Rosenberg, D., and A. B. Pridmore. Combining CFRP Lining Systems with Other Pipeline Rehabilitation Technologies. In *Proceedings for Pipelines 2012*, Miami Beach, Florida, Aug. 19–22, 2012, pp. 1418–1427.

Royer, J. R., and D. D. Koo. Comparative Analysis of Geopolymer Technology for Sewer System Rehabilitation. In *Proceedings for Pipelines 2015: Recent Advances in Underground Pipeline Engineering and Construction*, Baltimore, Maryland, August 23–26, 2015, pp. 1343–1354.

Salem, S., and M. Najafi. *Use of Trenchless Technologies for a Comprehensive Asset Management of Culverts and Drainage Structures*. Project 07-15, Midwest Regional University Transportation Center, Madison, WI, 2008, 267 pp.

Shi, J., Y. Wang, and C. W. W. Ng. Buried Pipeline Responses to Ground Displacements Induced by Adjacent Static Pipe Bursting. *Canadian Geotechnical Journal*, Vol. 50, No. 5, 2013, pp. 481–492.

Sterling, R., S. Alam, E. Allouche, W. Condit, J. Matthews, and D. Downey. Studying the Life-cycle Performance of Gravity Sewer Rehabilitation Liners in North America. *Procedia Engineering*, Vol. 165, 2016, pp. 251–258.

U.S. Environmental Protection Agency, Office of Water. *Collection Systems O&M Fact Sheet—Trenchless Sewer Rehabilitation*. Report EPA 832-F-99-032, Washington, D.C., September 1999.

Wedgner, A., and C. X. Wang. Why Replace Existing Pipelines When They Can Be Rehabilitated Using Polyethylene Pipes and Liners? In *Proceedings of the International Conference on Pipelines and Trenchless Technology*, Xiamen, China, November 13–15, 2014, pp. 478–489.

Wilde, W. J., C. A. Grant, and P. K. Nelson. *Manual for Controlling and Reducing the Frequency of Pavement Utility Cuts.* Report FHWA-RD-02-%%%, Federal Highway Administration, Washington, D.C., [n.d.], 181 pp. [Online]. Available: https://www.fhwa.dot.gov/utilities/utilitycuts/mantoc.cfm.

Wong, W. Long Term Performance of CIPP. In *Proceedings of the 34th International No-Dig Conference and Exhibition*, Beijing, China, October 10–12, 2016, pp. 125–133.

Xin, J. Application of Trenchless Pipeline Rehabilitation Technology. In *Proceedings of the International Conference on Pipelines and Trenchless Technology*, Xiamen, China, November 13–15, 2014, pp. 473–477.

Yu, J., W. Wang, and P. Du. Research on the Key Construction Technology of Lining Rehabilitation of Drain Pipeline with Short Pipes in Beijing. In *Proceedings of the 34th International No-Dig Conference and Exhibition*, Beijing, China, October 10–12, 2016, pp. 273–277.

Glossary

Annulus: the free space between the new and existing pipe that is typically grouted in conjunction with trenchless renewal.

Close-fit pipe (CFP): a trenchless renewal method consisting of inserting a new, deformed, or folded pipe into the existing pipe and after insertion expanding the new pipe to its original size and shape to be tight against the inside of the existing pipe.

Culvert: a buried hydraulically designed structure used to convey surface water and stormwater runoff by gravity from one side of an embankment to another. Used interchangeably with pipe in this report.

Cured-in-place pipe (CIPP): a trenchless renewal method consisting of inserting a flexible, resin-impregnated fabric tube into the existing pipe, expanding or inflating the tube, and curing the resin using heat or ultraviolet light.

In-line replacement (ILR): a trenchless renewal method consisting of replacing existing pipes along the existing alignment using pipe bursting or pipe removal methods.

Manhole: a surface accessible structure that allows access to a pipe. Sometimes called a maintenance hole.

Modified sliplining (MSL): a trenchless renewal method consisting of assembling a new liner consisting of pipe segments, structural plate, panels, or strips, in the case of the spiral-wound method, within a personnel-accessible existing pipe.

Pipe: a tube or conduit for conveying fluid. Typically constructed of steel, aluminum, concrete, polyethylene, high-density polyethylene, or polyvinylchloride when used in a stormwater system. Used interchangeably with culvert in this report.

Pipe bursting: an ILR method of splitting or pushing outward the existing pipe coincident with installing a new pipe.

Pipe removal: an ILR method of reaming or crushing the existing pipe into pieces or pulling or pushing the intact existing pipe out of the ground while installing the new pipe.

Renewal: to upgrade, rehabilitate, and renovate the performance and increase the design or service life of an existing stormwater facility.

Repair: reconstruction of a short section of pipe or small section of liner within a stormwater facility. Distinct from rehabilitation in that there is no change to anticipated design or service life of the complete sections of a pipe (e.g., manhole to manhole, inlet to outlet, etc.).

Replacement: installing a new pipe along an alignment using methods that do not rely upon the presence of an existing pipe to facilitate construction.

Sliplining (SL): a trenchless renewal method consisting of inserting a new, smaller diameter pipeline into the existing pipe. Typically includes grouting the annular space between the new and existing pipe.

Spray-in-place pipe (SIPP): a trenchless renewal method consisting of spraying a cementitious or polymer coating on the inside of the existing pipe.

Storm sewer: see culvert.

Acronyms and Abbreviations

CFP	close-fit pipe
CIPP	cured-in-place pipe
CMP	corrugate metal pipe
D&R	deformed and reformed
DOT	department of transportation
F&F	fold and formed
GCCM	geosynthetic cementitious composite mats
HDPE	high-density polyethylene
ILR	in-line replacement
MSL	modified sliplining
PVC	polyvinylchloride
RCP	reinforced concrete pipe
SIPP	spray-in-place pipe
SL	sliplining

APPENDIX A

Survey Questionnaire

Appendix A contains the survey questionnaire. It can be found on the TRB website (www.trb.org) by searching for "*NCHRP Synthesis 519*."

APPENDIX B

Agencies Responding to Questionnaire

Appendix B contains a list of all respondents to the survey questionnaire. It can be found on the TRB website (www.trb.org) by searching for “*NCHRP Synthesis 519*.”

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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