8-2016

Decision-Making Guidance for Selecting Culvert Renewal Techniques

He Jin
Clemson University

DECISION-MAKING GUIDANCE FOR SELECTING CULVERT RENEWAL TECHNIQUES

A Dissertation
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy
Construction Engineering and Management

---

by
He Jin
August 2016

Accepted by:
Dr. Kalyan R. Piratla, Committee Chair
Dr. Weichiang Pang
Dr. Brandon Ross
Dr. Leidy Klotz

ABSTRACT

Deteriorating culvert infrastructure is among the primary concerns of transportation agencies across the globe and therefore, they need guidance tools for optimal inspection and rehabilitation decision making. This study developed and validated an easy-to-use decision making tool called the Culvert REnewal Selection Tool (CREST) for selecting appropriate renewal techniques to rehabilitate or replace deteriorated culverts. Eleven renewal techniques are investigated in this study as part of developing CREST; they include open-cut method (OC), internal grouting through human entry (IG), robotic grouting (RG), internal shotcrete through human entry (IS), robotic shotcrete (RS), slip lining (SL), cured-in-place pipe (CIPP), fold and form lining (FFL), spiral-wound lining (SWL), centrifugally cast concrete pipe lining (CCCP), and pipe bursting (PB). These techniques are appropriately mapped with the commonly observed defects in reinforced concrete pipe (RCP), corrugated metal pipe (CMP), and high density polyethylene (HDPE) culverts based on their general ability to address the respective defects.

This dissertation study evaluated all the eleven culvert techniques based on three decision criteria that most transportation agencies are concerned about. The criteria include cost, expected design life, and productivity. The results of the evaluation are combined with user-defined, decision criteria preferences to develop CREST using the principles of Monte-Carlo Analytical Hierarchy Process (MCAHP). Twenty-six real-world case studies are chosen in order to validate CREST for a greater practical utility.

CREST and the results of this study will provide general guidance to transportation agencies in planning and decision making of culvert rehabilitation projects.

Key Words: Culvert renewal techniques, criteria, culvert renewal selection tool

NOMENCLATURE

C: Cost criteria

DL: Expected design life criteria

P: Productivity criteria

CR: Crack defect

ID: Invert deterioration defect

JM: Joint misalignment defect

JI: Joint infiltration/exfiltration defect

CO: Corrosion defect

SD: Shape deformation defect

RCP: Reinforced concrete pipe material

CMP: Corrugated metal pipe material

HDPE: High-density polyethylene material

OC: Replacement using open-cut method

IG: Rehabilitation using internal grouting through human entry

RG: Rehabilitation using robotic grouting

IS: Rehabilitation using internal shotcrete through human entry

RS: Rehabilitation using robotic shotcrete

SL: Rehabilitation using slip lining

CIPP: Rehabilitation using cured-in-place pipe

FFL: Rehabilitation using fold and form lining

SWL: Rehabilitation using spiral-wound lining

CCCP: Rehabilitation using centrifugally cast concrete pipe lining

PB: Replacement using pipe bursting

ACKNOWLEDGMENTS

First, I would like to extend my sincere appreciation to my advisor, Dr. Kalyan R. Piratla, for his guidance and advice during my Ph.D. study at Clemson University. His excellent guidance helped me to bring up my capabilities and potential as best as I can, which strengthens my motivation to move forward.

I would like to thank Dr. Weichiang Pang, Dr. Brandon Ross, and Dr. Leidy Klotz for their guidance as members of my advisory committee, which helped me in finalizing the dissertation in an effective manner. Special acknowledgement is given to the South Carolina Department of Transportation (SCDOT) which partly supported this dissertation study under Grant SPR718.

Special acknowledgements are extended to Mr. John Varner's family (John Varner, his wife: Alana Varner, and his son: Ike Varner) and Ms. Janice W. Boggs who are my spiritual leaders and my best friends for giving me spiritual and physical supports during my life in the U.S.

I would like to give my special acknowledgements to my dear parents who always love me and cared about me. Without their selfless support, I would not have been able to accomplish my dream.

I would also like to give my acknowledgements to my lovely wife, Mingxian Lin, who cared for my daily life with her selfless love during my Ph.D. studies.

Finally, I would like to thank all my friends who supported my Ph.D. studies.

TABLE OF CONTENTS

Table of Contents (Continued)

Page

LIST OF TABLES

List of Tables (Continued)

List of Tables (Continued)

LIST OF FIGURES

List of Figures (Continued)

Figure Page

List of Figures (Continued)

CHAPTER ONE

INTRODUCTION

Culverts are pipes that facilitate the flow of water under roadways, embankments, and other similar structures. They are designed to support the super-imposed earth and live loads from passenger vehicles and trucks as well as the internal hydraulic loading from water flow. Millions of culverts currently exist underground in the United States. Majority of these culverts are managed by state departments of transportation (DOTs) while few are managed by local governments and United States Forestry Service. It has been estimated that several DOTs are responsible for more number of culverts than bridges within their jurisdiction (NCHRP, 2002). Culverts of various sizes ranging from 12 inches to over 200 inches in diameter (or width) are currently operational. They are also of different shapes such as circular, elliptical, and box (Hollingshead and Tullis, 2009). Culverts are made of different materials with 76% of the existing culverts made of concrete, 19.3% made of metal, 2.2% made of plastic, and about 2.5% with other materials in the U.S. (Taylor et al., 2014). Specifically, majority of the culverts are made of either reinforced concrete pipe (RCP), corrugated metal pipe (CMP), or high-density polyethylene (HDPE).

Several existing culvert structures are in a deteriorated state having reached the end of their useful design life and consequently, increased number of failures are reported (Perrin Jr. and Jhaveri, 2004; Yang and Allouche, 2009). For example, the Missouri Department of Transportation conducted a field evaluation of 3,897 culvert pipes and found about 46% of CMP and RCP culvert were deteriorated and in need for replacement (Perrin Jr. and Jhaveri, 2004).

Buried pipelines deteriorate due to a combination of factors that include but not limited to: a) natural material degradation and subsequent loss of structural capacity, b) lack of proper maintenance, c) fatigue loading and subsequent localized structural damage, d) design defects or construction errors that weaken the system over time, and f) adverse environments (Yazdekhasti et al., 2014). Due to their invisibility from the surface, buried culverts often get ignored until a problem such as road settlement or flooding arises. Failure of culvert structures results in the collapse of the roadway under which it is buried, as depicted in Figure 1.1, posing significant safety risk to motorists. In addition to the safety risk, culvert failures could be prohibitively expensive due to the emergency repair costs, traffic congestion and detours. Yet, transportation agencies (and other kinds of culvert asset managers) lack effective culvert management practices when compared to bridges and pavements (Najafi and Bhattachar, 2011).

Figure 1.1 A picture showing a collapsed road due to culvert failure

Transportation agencies are faced with numerous technological, managerial and financial challenges in adequately sustaining the quality of their culvert infrastructure. Technological challenges include the lack of technologies to adequately fix all defects in an economical and reliable manner. Financial challenges include lack of adequate funding to revamp the culvert infrastructure to meet the desired level of service. Managerial challenges include lack of efficient, knowledge-based tools that enable rational decision making in the face of multiple choices and constraints.

Traditionally, deteriorated culverts have been replaced using the conventional open-cut method. Open-cut method requires significant excavation depending on the cover depth of the culvert and it may lead to higher costs in addition to significant societal, environmental and safety challenges (Najafi et al., 2008). A very easily relatable societal challenge is the lane closure resulting from culvert repairs and the subsequent traffic congestion. Similarly, construction-related greenhouse gas emissions resulting from open-cut construction methods have been shown to be significant, mainly due to the amount of excavation and backfilling needed (Ariaratnam and Sihabuddin, 2009; Ariaratnam et al., 2013). Due to the increased traffic density on roadways, and economic, societal and environmental impacts of the open-cut techniques, transportation agencies are increasingly adopting trenchless construction methods for addressing their culvert infrastructure issues, especially for deeper culvert installations (Thornton et al., 2005).

Trenchless construction is a class of subsurface construction methods requiring few or no continuous trenches. There are suitable trenchless construction methods for new installation of buried pipelines, rehabilitating existing pipelines, and replacing existing pipelines with new pipelines. It should be noted that rehabilitation extends the useful design life of a deteriorated culvert structure, whereas replacement installs a new pipeline in the right-of-way of the old and deteriorated pipeline. A few popular trenchless methods suitable for new installations include pipe jacking, micro tunneling and horizontal directional drilling. Similarly, popular trenchless methods for rehabilitating existing pipelines include but not limited to grouting, slip-lining, cured-in-place lining, fold and form lining, spiral-wound lining, and centrifugally-cast concrete lining. The most popular replacement technique is pipe bursting. Both rehabilitation and replacement methods are together referred to as “renewal” methods in this dissertation study.

Research Objective and Scope of this Study

Various trenchless renewal options currently exist to address a variety of culvert infrastructure issues. While some of these techniques are comparable, others complement each other. Their suitability varies depending on several factors such as depth of cover, soil type, pipe size, pipe material, and level of access to the culvert. Personal and organizational preferences of culvert asset managers also influence the choice of the renewal technique; for example, how concerning is the cost of renewing a deteriorated culvert compared to the impact on traffic the renewal process may inflict. There are also several constraints in this decision making problem. For example, environmental regulations in some states prohibit the use of certain type of liners for renewing culvert structures. Other practical constraint may be the lack of contractors operating in some regions to execute these trenchless renewal projects. Consequently, there is a need for an analytical guidance framework that enables rational selection of a culvert renewal technique from various choices that suits the preferences of culvert managers while complying with the constraints. While a few previous studies investigated this selection problem, they are not comprehensive and readily adoptable by practitioners. The previous guidance frameworks were also not catered to specific culvert materials and defects that are commonly observed.

The objective of this study is *to comparatively evaluate various culvert renewal techniques and subsequently develop, demonstrate and validate a culvert renewal selection tool for rationally choosing an optimal culvert renewal technique based on the extent and type of defects, available financial resources, and other preferences.* The renewal techniques evaluated in this dissertation study include the conventional open-cut method, internal grouting through human entry, robotic grouting, internal shotcrete through human entry, robotic shotcrete, slip lining, cured-in-place pipe lining, fold and form lining, spiral-wound lining, centrifugally-cast concrete pipe lining, and pipe bursting. The proposed easy-to-use Culvert REnewal Selection Tool (CREST) offers transportation agencies across the world general guidance for selecting appropriate culvert renewal techniques.

Research Methodology

The study methodology entails: 1) synthesizing performance of various culvert renewal techniques through systemic literature review and determining the specific advantages, limitations, and suitability to various scenarios; 2) mapping renewal techniques to various commonly observed defects in RCP, CMP and HDPE culverts that they are able to address; 3) comparatively evaluating renewal techniques based on typical decision-making criteria and assigning quantitative ratings using the procedures of analytical hierarchy process (AHP); 4) developing a rational Culvert REnewal Selection Tool (CREST) that can select an optimal culvert renewal technique based on the evaluation results and the user preferences; 5) demonstrating the developed CREST for various application scenarios (which are devised around the commonly observed defects in different culvert materials) using Monte-Carlo method for assigning user preferences; and 6) validating the findings through documenting the selection preferences from various real-world case histories.

Organization of this Dissertation

This dissertation document is divided into eight chapters. Chapter 1 presents an overview of the problem being studied and states the research objective and methodology. Chapter 2 presents a brief review of the latest relevant literature to establish the state-of-the-art knowledge and highlight outstanding challenges that this study attempts to address. Chapter 3 presents a detailed description of all the culvert renewal methods evaluated in this study. Chapter 4 presents the comparative evaluation of culvert renewal techniques based on the reported performance of various techniques in terms of cost, expected design life, and productivity. Chapter 5 presents the mapping of renewal techniques to various culvert defects they are reportedly capable of addressing and also describes the proposed CREST for selecting an optimal renewal technique. Chapter 6 presents demonstration of the DMT for various typical application scenarios and discusses the findings in terms of their relevance, applicability, and usefulness. Chapter 7 synthesizes selection preferences of 26 representative real-world culvert renewal case studies in order to validate the findings of this study. Chapter 8 concludes this study by summarizing the findings and their implications, highlighting the study limitations, and making recommendations for future follow-up studies.

CHAPTER TWO

LITERATURE REVIEW

The choice of renewal method has an effect on the life cycle cost of a culvert structure (Venner, 2014). Consequently, it is important to rehabilitate a deteriorating culvert structure using an optimal construction method at an optimal time so that the culvert life is prolonged by the maximum extent possible at cheaper cost. Given the variety in the available construction methods and their respective capabilities and limitations, transportation agencies will benefit from a guidance framework that not only evaluates several construction alternatives but also suggests an optimal alternative for a prevailing scenario. Several previous studies which attempted to develop such guidance frameworks are briefly reviewed in this section.

Experience-Based Decision-Making Guidance

Hollingshead and Tullis (2009) briefly synthesized the description, installation procedures, and highlighted the advantages and limitations of segmental lining, spiral-wound lining, cured-in-place pipe lining, fold and form PVC lining, deformed-reformed HDPE lining, and cement mortar spray lining, in order to inform the selection of an appropriate trenchless rehabilitation technique in Utah. The aim of this synthesis report is to provide designers and project managers with a general culvert relining knowledge base to aid in the decision-making process. While the synthesis is informative, the study did not provide specific guidance for the selection of rehabilitation methods for various defects. Their brief report on culvert lining techniques was limited to providing precise selection guidance to one of the state DOTs.

Hunt et al. (2010) developed project-level guidelines on the basis of Federal Lands Highway manual for assessing the condition and performance of existing culverts for selecting corrective measures for any defects found as part of specific project development activities. Their guidelines are intended to aid users in implementing a fully integrated culvert assessment and decision-making tool that provides guidance for selecting replacement or rehabilitation alternatives along with step-by-step decision-making process maps. Although, their results seem comprehensive, their decision-making flowcharts are cumbersome and less efficient for practical use. Moreover, they did not employ scientific selection guidance when determining the rehabilitation alternatives.

Matthews et al. (2012) developed a set of decision-making flowcharts for the selection of appropriate rehabilitation and replacement technologies for corrugated metal pipelines (CMP). The technologies they investigated include slip lining, cured-in-place lining, fold and form lining, spiral-wound lining, sprayed lining, spot repairs, grouting, and pipe replacement methods. Their guidance was specifically based on three classes of defects, namely insufficient hydraulic capacity, inadequate structural capacity, and inadequate bedding support. Their study seemed to be based on authors' past experiences and it focused only on the CMP culverts.

Caltrans (2013) developed a design information bulletin as a supplement of Culver Repair Practices Manual- Volumes 1 and 2 by Federal Highway Administration (FHWA) Publication in 1995. This study provided detailed information, guidelines, and alternative methods of culvert rehabilitation and replacement techniques for improving the culvert management. The rehabilitation techniques considered include slip lining, cured-in-place lining, folded and re-formed PVC lining, machine-wound plastic lining, sprayed coating, and etc. The replacement techniques include traditional open cut method, pipe jacking, pipe ramming, micro tunneling, pipe bursting, and other techniques. This study did not provide a clear decision-making guidance for selecting the most appropriate culvert repair method that suit the defects of various severities in culverts of different sizes.

Wagener et al. (2014) presented several repair, rehabilitation and replacement options discussing design and construction methods, material composition of rehabilitation/replacement techniques, environmental limitations for addressing a multitude of culvert defects. The repair options they considered include spall repair, joint repair, and void filling. Rehabilitation methods include paved invert, cured-in-place pipe lining, slip lining, centrifugally cast liner, spiral-wound lining, close-fit lining, and shotcrete lining. Replacement methods include conventional tunneling, pipe jacking, pipe ramming, horizontal directional drilling, and pipe bursting. Although this study investigated several culvert repair methods, it did not present a decision-making guidance to select one or more appropriate rehabilitation or replacement methods for different culvert defects.

USU (2015) developed a manual for culvert rehabilitation and replacement techniques applied in Utah based on the General Culvert Barrel Rehabilitation Techniques (Caltrans, 2003) and the culvert pipe liner guide and specification (Central

Federal Lands Highway Division, 2005). The rehabilitation techniques include slip lining, spiral wound lining, cured-in-place lining, fold-and-form PVC lining, deformed-reformed HDPE lining, and cement-mortar-spry-on lining. This study simply described installation procedures of the selected culvert rehabilitation methods along with their advantages and limitations. Similar to other previous studies of this class, this study did not present a simple decision-making guidance to select the appropriate culvert rehabilitation and replacement methods for addressing the culvert defects in different sizes and stages of severities.

Scientific Decision-Making Guidance

Thornton et al. (2005) synthesized information on the state-of-the-practice in culvert lining techniques and presented a multi-criteria decision analysis (MCDA) ranking method for optimal selection of one technique. The lining techniques this study investigated include slip lining, close-fit lining, spiral-wound lining, cured-in-place pipe lining, and spray-on lining. Their ranking method is based on technology scores calculated by summing up weighted ratings of decision criteria, in Microsoft Excel. The criteria considered include design life, capacity reduction, abrasion and corrosion resistance, installation time, flow bypassing requirement, digging requirements, cost, safety, and environmental concerns. The relative importance of each criterion is determined using relative importance factors assigned by the decision-maker. Relative importance factors are then normalized to produce a set of normalized criterion weightings. Range of the rating scales was arbitrary, and rating scales were needed only to appropriately reflect the differences among various rehabilitation techniques. Although the results of this study have proven to be somewhat useful, its impact could have been broadened by including non-lining rehabilitation methods and replacement methods in the technology choices. Additionally, this study focused on macro-level guidance by just suggesting generic technology choices without identifying specific defects that each technology can address and its suitability to host culvert material type.

Chapter Summary

Although previous studies evaluated trenchless renewal techniques and proposed decision-making tools for their appropriate selection, almost none have synthesized and presented an easy to use comprehensive and scientific decision-making framework that is catered for selection of an optimal renewal technique that is suitable for specific culvert defects and culvert materials. Additionally, previous studies lacked scientific approaches, demonstration and validation of the results. To address this outstanding need, this dissertation study adopts a scientific quasi-qualitative approach for developing a decision-making tool and later demonstrated it for various typical application scenarios.

CHAPTER THREE

RENEWAL OF CULVERT STRUCTURES: CONSTRUCTION ALTERNATIVES

Several trenchless culvert renewal techniques are investigated in this study. Traditionally, open-cut method has been widely used due to its simplicity and familiarity. However, due to the increased traffic density on roadways, and economic, societal and environmental impacts of the open-cut method, transportation agencies are increasingly adopting trenchless renewal techniques for addressing their culvert issues (Thornton et al., 2005). This chapter describes all the culvert renewal techniques that are evaluated in this study for their suitability to various application scenarios. It should be noted that a few renewal techniques are deliberately excluded from this study because of their limited use. Tables 3.1 and 3.2 highlight the significant advantages and limitations of each renewal technique (Ballinger and Drake, 1995; Caltrans, 2013; Mitchell et al., 2005; Meegoda et al., 2009; Hunt et al., 2010; Hollingshead and Tullis, 2009; Syachrani et al., 2010; and Yazdekhasti et al., 2014). Furthermore, the suitability of the described renewal techniques to various shapes and sizes of culverts is synthesized and presented in Tables 3.1 and 3.2.

Open-Cut Technique (OC)

OC is the traditional and most popular method for pipe construction, repair, or replacement. OC entails excavating a trench before a buried pipeline can be manually rehabilitated or replaced, as shown in Figure 3.1, followed by backfilling the trench and restoring any disturbed surface landscape. OC is suitable for renewing culverts of all materials, size, defect, and defect severity and it can replace a deteriorated culvert with a structurally-robust brand new culvert. While OC can be employed in any scenario, it could cause societal inconvenience due to lane closure and subsequent traffic congestion and could also be expensive in high-traffic and dense land-uses for culverts buried at significant depths (COP, 2016).

Figure 3.1 Open-cut methods

Grouting: Internal Grouting through Human Entry (IG) and Robotic Grouting (RG)

Grouting is a well-known pipe rehabilitation technique for various contractors and state DOTs. Grouting is normally applied to address minor crack or joint defects for sewer and culvert pipelines. It entails filling cracks and joint voids with a Portland cement-based grouts and mortars or chemical grouts using pneumatic hose or merely flow in by gravity to enhance the culvert's strength and reduce inflow/infiltration (Wagener et al., 2014).

Normally, voids under corroded or undermined culvert inverts may also be filled by gravity-based grouting method. Voids behind the sides of culverts that are caused by piping or exfiltration will have to be pressure-grouted to ensure that the void is properly filled. However, for certain situations where the void can be accurately located, it may be possible to fill side voids by gravity feed from the roadway surface. One of the main challenges for grouting is the winter or cold weather condition. Contractors are generating a steady supply of warm water for mixing mortar and grout (MCAA, 2016). There are basically three types for grouting methods (Wagener et al., 2014):

1. Gravity flow from above the void

This type grouting entails merely feeding the grout into the void by the gravity without discharging the air or water in the void. Although this technique may work for a water-filled void, it is much preferred to pump out the water prior to grouting the void due to the result that the void will not be properly grouted in the water.

2. Grouting through a Tremie pipe or tube

This type of grouting entails introducing into the void a Tremie tube so that grout fills the void from the bottom with an upward flow of the grout. The procedure may be warranted for some site conditions where there is a potential problem of entrapment of air in the grout.

3. Pressure grouting

This type grouting entails filling voids behind the sides of culverts by sealing the interior surface of the joint with concrete mortar or a joint sealing system. Grouting procedure involves installing grout tubes at the bottom and the top of the joint or void and pumping grout into the lower tube. At this point, the air and water will flow out of the upper tube, watery grout will, then, flow out, and finally the pure grout will flow out.

Grouting could be done through human entry (IG) as well as through a robot remotely – which is referred to as robotic grouting (RG).

IG, shown in Figure 3.2, is facilitated by human entry and it is therefore only suitable for culverts with diameter greater than or equal to 762 mm (30 inches). In general, Portland cement-based grouts, with and without special admixtures, is adequate for culvert repair work and it is much less expensive than the foaming and chemical grouts that are used to set machinery and to resist high external and internal fluid pressures (Caltrans, 2013). Portland cement-based grouts or mortar is generally a mixture of water, cement, sand, and sometimes fine gravel. Admixture boasts superior strength and increases grout cure time and helps reduce tile grout shrinkage and cracking (Turner, 1997). While internal grouting through human entry is a simple technique for pipe rehabilitation, it has short design life and cannot be used for major structural defects (Caltrans, 2013; and Hunt et al., 2010).

Figure 3.2 Internal grouting through human entry

RG entails pulling a sealing packer mounted with CCTV camera through the point of defect in small diameter culverts (< 762mm or 30 inches) using cables, as shown in Figure 3.3. The grout is robotically sprayed at the desired defect location identified through CCTV monitor using chemical grouts to resist high external and internal fluid pressure. The most common are sodium silicate, acrylate, lignin, urethane, and resin grouts (Johns, 1995). Air or water is usually used to test the sturdiness of the grout. While cement mortar has been traditionally used for the grout mix, chemical grout is widely used for leaking joints. There are several types of chemical grouts that mix readily with water at the time of application and provide good penetration of wet joints, cracks, and surrounding soils. These compounds are available as a foam, which expands to fill the crack, a gel, or in conjunction with a carrier medium such as oil-free oakum. Since these grouts react with water to change from a free-flowing liquid to a water impermeable solid, they allow quick and effective shut-off of water that is infiltrating into the culvert. The grouts are tough and highly flexible. Properly grouted joints and cracks can withstand normal ground movement and still maintain their seal. While robotic grouting is watertight with chemical grouting material, it is inadequate in acidic water flow and does not provide any structural strength to the pipe (Caltrans, 2013; Hunt et al., 2010, and Mitchell et al., 2005).

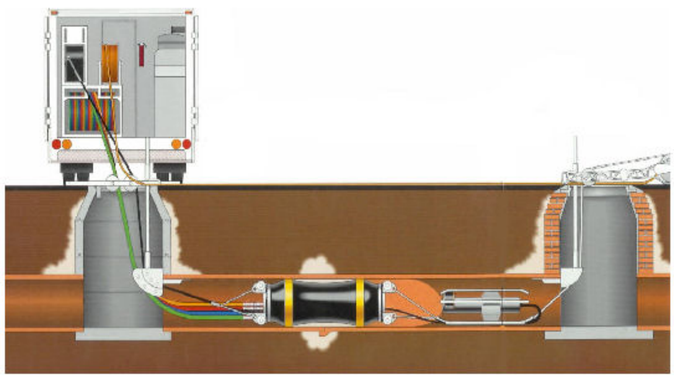


Figure 3.3 Robotic grouting

Shotcrete: Internal Shotcrete through Human Entry (IS) and Robotic Shotcrete (RS)

Shotcrete is one of the well-known pipe rehabilitation methods for state DOTs. It was invented by American taxidermist Carl Akeley in 1907 to repair the Field Columbian Museum in Chicago. It is effective to repair or protect deteriorating steel and rebar for both sewer and culvert pipelines (Caltrans, 2013). It entails pneumatically transporting and placing well-mixed Portland Cement-based mortar or concrete with compressed air. Materials used in the shotcrete include conventional concrete-portland cement, lightweight aggregate, water, and admixtures. Similar to conventional concrete work, shotcrete reinforcement includes deformed bars, welded wire fabric, and pre-stressing steel (PCA, 2015). Shotcrete is not adequate in acidic water flow because acid attacks concrete by reacting with the calcium hydroxide of the hydrated Portland cement (FHWA, 2005).

There are two basic types of mixes: a wet mix and a dry mix. For wet mix shotcrete, all of the ingredients, including water, are mixed before they are pumped. For dry mixes, the water is introduced at the nozzle through a water-ring that has several jets or orifices that disperse the water into the mix. Steel fibers may also be used, particularly with dry mixes, to provide improved flexural and shear strength, toughness, and impact resistance. Special care and equipment may be required for adding the fibers to the mix to prevent clumping or kinking of the fibers and to ensure they are properly distributed in the mix. Properly applied shotcrete has excellent bonding characteristics with concrete, masonry, rock, and steel. However, these properties are very dependent upon the use of good materials and procedures executed by a knowledgeable and experienced nozzle man. It is not recommended to place the concrete under cool temperature with lower than 40 degrees Fahrenheit. When the daily minimum temperature is less than 40 degrees Fahrenheit, shotcrete shall be insulated or heated after placement (CSI, 2009).

The procedure of shotcrete is that (Ballinger and Drake, 1995; Caltrans, 2013; Mitchell et al., 2005; Meegoda et al., 2009; Hunt et al., 2010; Hollingshead and Tullis, 2009; Syachrani et al., 2010; and Yazdekhasti et al., 2014):

1. The work area should be properly prepared for the application of both dry and wet shotcrete mixes. Steel surfaces should be cleaned of loose mill scale, rust, oil, paint, or other contaminants. For concrete surfaces, it is imperative to completely remove all spalled, severely cracked, deteriorated, loose, or otherwise unsound concrete by chipping, scarifying, sandblasting, waterblasting, or other mechanical means. For solid concrete surfaces, it may be necessary to sandblast or otherwise remove the surface layer of cement paste to facilitate bond between the existing concrete and the shotcrete.

2. Steel reinforcement, consisting of welded wire mesh fabric or plain or deformed reinforcing bars, is required for installations where shotcrete must carry structural loads or drying shrinkage cracking must be avoided.

3. Earth, concrete, and masonry surfaces should be pre-dampened so as to minimize absorption of water from the shotcrete and the creation of a weak interface bond; however, the surface should be free of standing water.

4. The shotcrete should be mixed, pneumatically transported, and placed in accordance with recommendations and guidelines contained in documents of the American Concrete Institute (ACI) and/or the shotcrete industry.

5. Immediately after finishing, shotcrete should be kept continuously moist for at least 24 hours by using ponding or sprinkling, an absorptive mat, fabric, or other covering, or a curing compound.

There are two types of shotcrete: Internal shotcrete through human entry (IS) and robotic shotcrete (RS).

IS is one of the well-known pipe rehabilitation methods. It entails manual spraying of concrete inside of pipe through a pneumatic hose at high velocity to resolve surface problems in large diameter culverts that are reinforced with steel rebar or mesh, as shown in Figure 3.4. While it is normally used where formwork is impractical, it requires space to setting up equipment and needs specially trained personnel to operate the equipment.

Figure 3.4 Internal shotcrete through human entry

RS is applicable in small diameter culverts (< 762mm or 30 inches) where human entry is not possible. It entails moving a remotely controlled robot on a track mounted with CCTV cameras, as shown in Figure 3.5. The rotary applicator sprays concrete flow to the point of defect identified through CCTV camera. Similar to IS, RS is applicable where formwork is impractical and it provides corrosion barrier to rebar; it is watertight, and it requires trained professionals to operate the specialized equipment.

Figure 3.5 Robotic shotcrete

Slip-Lining (SL)

SL is one of the oldest trenchless rehabilitation techniques which is familiar to contractors and state DOTs. SL is effective to repair leaks or restore structural stability for both sewer and culvert pipelines. It has been used since the 1940s.

A smaller sized flexible pipe is pulled or pushed into a deteriorated or failed host pipe using jacks or other equivalent equipment. The space between the host pipe and liner is grouted with a cementitious material providing a watertight seal to form a composite pipe that is stronger and smoother, as shown in Figure 3.6. Prior to inserting lining, the existing culvert must be surveyed carefully to determine the maximum diameter of the slip-lined pipe that can be inserted through the entire length of the host pipe. Any deflections in the culvert walls will become control points and any alignment changes coupled with deflections can reduce the slip liner diameter significantly. All water and debris must be removed from the existing pipe. When choosing the material for a slip liner, handling and weight of the liner and construction footprint should be main consideration according to the environment and the physical needs of the installation (Caltrans, 2013; Meegoda et al., 2009; Hunt et al., 2010; Hollingshead and Tullis, 2009; and Syachrani et al., 2010).

Two types of slip-lining techniques, mechanical (segmental) and fused (continuous) joints, are typically used in slip-lining applications with PE, HDPE, or PVC liners. The liner pipe is moved into the culvert either one section at a time or as an entire unit after individual segments are joined. The liner is pushed with jacks or machinery such as a backhoe. When the liner is in place, the space between the existing culvert and liner generally must be grouted to prevent seepage and soil migration and to establish a connection between the liner and the host pipe thus providing uniform support and eliminating point loads. Grout may be either gravity-fed into the annular space between the liner and the existing culvert or pumped through a hose or small diameter pipe (1-1/2”- 2 inch PVC) laid in the annular space. When grout is pumped, the small pipe or hose is typically removed as the space is gradually filled. When this is difficult due to field conditions, the small pipe or hose may be banded to the liner with "tees" placed a 5 ft intervals (Caltrans, 2013; Meegoda et al., 2009; Hunt et al., 2010; Hollingshead and Tullis, 2009; and Syachrani et al., 2010).

This method is much faster to complete than removing and replacing a culvert, and often will yield a significant extension of service life at less cost than complete replacement, particularly where there are deep fills or where trenching would cause extensive traffic disruptions. While SL is a simple and cheap technique offering structural capacity, it needs large pits for liner insertion and reduces the pipe size.

Figure 3.6 Slip-lining

Cured-in-Place Pipe (CIPP)

CIPP is a method that allows a new pipe formed within an old pipe. It was implemented by Eric Wood in London, England, 1971. As one of the most widely used rehabilitation methods, CIPP is applicable to water, sewer, and culvert pipelines. CIPP is effective to repair several defects due to its broader application range in terms of host pipe material, size, and shape, and its flexibility to be used as a structural or a non-structural liner.

It entails inserting a resin-impregnated (consist of polyesters and vinyl esters) tube liner or hose into the existing pipe and inverting it using pressurized water or compressed air, as shown in Figure 3.7. After inversion, the liner is expanded to closely fit the host pipe and cured using hot water, steam or ultraviolet (UV) light as shown in Figure 3.8 (Caltrans, 2013; Mitchell et al., 2005; Meegoda et al., 2009; Hunt et al., 2010; Hollingshead and Tullis, 2009; and Syachrani et al., 2010).

The flexibility of the liner before curing enables it to negotiate bends of up to 90 degrees, if necessary. CIPP can also be employed for non-circular culverts.

Figure 3.7 Cured-in-place pipe

The liner itself is made of a felt tube that is reinforced with fiberglass and coated with plastic. The felt tube is custom made for each specific site based on size, shape and structural integrity of the host pipe. The felt tube allows for the absorption of thermosetting resins. The tube is wetted with resins during the manufacturing process or on site. Most often, they are applied at the manufacturing plant by a roller for small or short sections and then the pipe is shipped in a refrigerated truck to the project site for installation, but usually done on site for long runs due to the weight and size of handling the larger liners. The CIPP requires enough room on the shoulder or roadway to set up the haul truck, water heating equipment and inversion tubing. Before installation, the host pipe need to be cleaned or made ready for installation. Any stream flow must be bypassed during construction (Caltrans, 2013; Mitchell et al., 2005; Meegoda et al., 2009; Hunt et al., 2010; Hollingshead and Tullis, 2009; and Syachrani et al., 2010).

The CIPP installation involves placing of a vertical standpipe or other apparatus at the insertion end and inverting the thermosetting, resin-impregnated tube into a deteriorated host pipe by well trained personnel with specialized equipment as required. After connecting the resin-impregnated tube to the vertical standpipe, the tube is inserted inside out (inverted) and filled with water or compressed air. During inversion, the lining tube turns inside out and travels down the pipeline resulting in the plastic outer sleeve surface becoming the inner surface of the repaired pipe with the resin system being in contact with the host pipeline. The liner tube will be expanded to inner surface of the host pipe using air pressure or hot water. Once the tube has reached to inner surface of the pipe, it is cured using either heated water, steam, or ultraviolet light (UV). If water or steam is used for curing, it must be heated continually and circulated during the curing process. The application of heat hardens the resin after a few hours, forming a joint-less pipe-within-a-pipe. Once set, remote controlled cutters are used to reinstate connections. When cured using ultraviolet light, a fiberglass tube is used and no refrigeration is necessary. Times of UV cure are quicker than the other cure methods; however, it has a thickness limitation of one inch (Caltrans, 2013; Mitchell et al., 2005; Meegoda et al., 2009; Hunt et al., 2010; Hollingshead and Tullis, 2009; and Syachrani et al., 2010).

The CIPP increases hydraulic capacity, particularly with larger pipes, due to the smoothness of the polyurethane liner, while the size of the pipe will be decreased slightly, but far less than slip lining or grouting. While CIPP do not require access pits, the toxic resins during installation could infiltrate the culvert flow and may pollute it (Wagener et al., 2014).

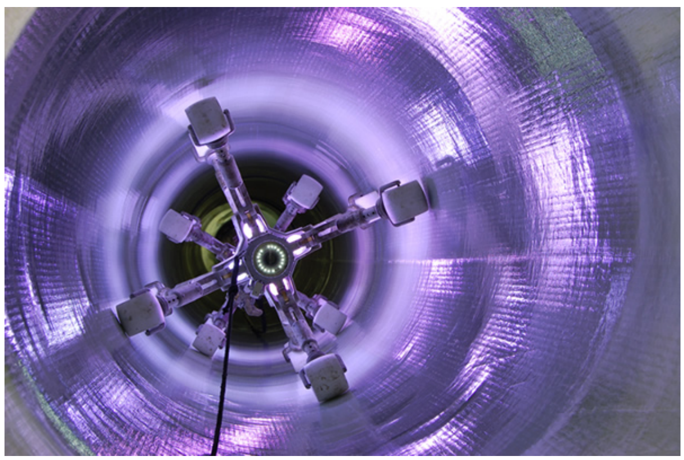


Figure 3.8 UV curing

Fold and Form Lining (FFL)

FFL is a variation of CIPP and SL. It was invented in the late 1980s by Charles Lewton-Brain. FFL is effective to repair crack or joint issue for small size sewer and culvert pipelines. FFL uses a PVC or HDPE liner that has been folded with flat or H-shape, manufactured to length, and delivered to the job site on reels (Some manufacturers deform pipe on site). The flat-shape is used for lines in the 4- to 12-inch diameter range. The H-shape is used for liners in the 15- to 30-inch diameter range. FFL entails inserting a winch cable through the host pipe and attached to the end of the pipe liner as shown in

Figure 3.9 (Caltrans, 2013; Mitchell et al., 2005; Hunt et al., 2010; and Hollingshead and Tullis, 2009).

Figure 3.9 Fold and form lining

The coiled liner is covered with a tarp and preheated with steam until malleable. The tarp is then removed and the liner is pulled through the host pipe. The liner is pulled through at a rate of 40 to 50 feet per minute depending on field conditions. After the liner is pulled through it is cut and sealed on both ends with pneumatic plugs. With both ends of the liner plugged, the liner is re-heated over several hours and pressured using steam and air until the liner expands tightly against inside of the host pipe, as shown in Figure 3.10. Pipes can be expanded up to 110% of original designed diameter (Mitchell et al., 2005). Then, the steam is replaced by compressed air to cool the liner while maintaining its shape. Once cooled, the ends of the liner are trimmed to the desired length. This overall process typically requires just less than a full work day per installation for the length of 50m culvert. Similar to CIPP, FFL can negotiate bends of up to 90 degrees due to its flexibility before curing. (Caltrans, 2013; Mitchell et al., 2005; Hunt et al., 2010; and Hollingshead and Tullis, 2009).

FFL is only applicable to smaller (< 36 inches) culverts of circular shape, and it requires additional resources for folding the pipe prior to insertion.

Figure 3.10 Steam heated liner

Spiral-Wound Lining (SWL)

SWL is a novel trenchless technique which is applicable to rehabilitate sewer and culvert pipelines. SWL entails feeding a continuous plastic strip (HDPE or PVC) with male and female interlocking edges through a winding machine that moves along the culvert to form a leak-tight, smooth, and continuous liner, as shown in Figure 3.11. During the interlocking process, a sealant is applied to make the seam watertight. Both flexible and rigid pipes can be rehabilitated with this system.

Figure 3.11 Spiral-wound lining

There are two common types of SWL: expanding liner and fixed-diameter liner.

Expanding liner entails inserting a fixed-diameter pipe into the host pipe until it reaches the desired length of insertion. The liner is then expanded two ways depending on the type of liner used; either a wire that runs through the entire spiral joint is pulled, allowing the liner to expand or a rotating machine is run through the inside of the liner. This expanding liner system utilizes a water activated polyurethane adhesive joint sealant for sealing. Steel reinforcement can be added to the liner wall to increase the structural strength of the liner. No annular space grouting is required; however, the ends of the liner are often grouted into place (Caltrans, 2013; Hunt et al., 2010; Hollingshead and Tullis, 2009; and Syachrani et al., 2010).

For the fixed-diameter liner, a continuous plastic strip that is spiral wound into the existing pipe is created by traveling machine that rotates and lays the profile against the host pipe walls as it travels through the host pipe. This technique is more suitable in the case of non-circular host culverts with strict access restrictions. This produces an integrated structure with the PVC liner tied to the original pipe through the grouting. A steel reinforced PVC lining system is also available, which includes a continuous strip of profiled reinforcing steel added to the outside of the plastic pipe (Caltrans, 2013; Hunt et al., 2010; Hollingshead and Tullis, 2009; and Syachrani et al., 2010).

The resulting liner has a smooth plastic internal surface with increased stiffness from the steel reinforcing profile. While SWL is applicable for different culvert shape and tight curves, it requires man-entry in larger diameter culvert.

Centrifugally-Cast Concrete Pipe Lining (CCCP)

CCCP is a novel trenchless rehabilitation technique for sewer and culvert pipelines. It is reportedly effective in repairing corrosion defects in CMP pipes (PIM, 2016). CCCP entails conveying spincaster manually or robotically which mounts a real-time camera to apply thin coats of fiber-reinforced cementitious material or Permacast mortar at high impacting velocity onto the inside of the pipe to form a waterproof structural enhancement layer that adheres tightly to the original pipe, as shown in Figure 3.12. The ejected material dispersion and velocity is such that unlike conventional shotcrete, where a dense shotcrete stream ejecting from the nozzle is clearly visible, the ejected material is barely visible. One simply sees material building up on the receiving surface. The rate at which the material builds up on the receiving surface depends on the diameter of the pipe, culvert or shaft and the rate at which the spinning head is pulled through the pipe or culvert. The material’s rust inhibitors prevent corrosion and inhibit abrasion. Structural stability and engineering requirements dictate how thick the layer of material should ultimately be. Compared to shotcrete, CCCP applies evenly thin coat to the interior of the culvert due to its properly calculated speed of computer-controlled mortar (Centripipe, 2016a). While CCCP has short curing time with long-term protection, it is not applicable under 45°F (Centripipe, 2016b; and Public works, 2013).

Figure 3.12 Figure 3.12 Centrifugally-cast concrete pipe lining

Pipe Bursting (PB)

PB is a well-known trenchless replacement technique that is effective in repairing several major severity defects of water, sewer, and culvert pipelines. PB entails pulling a bursting head by using a cable and winch, which receives energy from static, pneumatic or hydraulic power source, into the host culvert. As the expansion head is pulled through the existing pipe, it pushes that pipe radially outward until it breaks apart, creating a space for the new pipe as shown in Figure 3.13. The broken pieces of old pipe are forced into the surrounding soil and left in the ground forever. The bursting device also pulls the new pipeline behind it, immediately filling the void created by the old, burst pipe with the new pipe (Caltrans, 2013; Mitchell et al., 2005; and Hunt et al., 2010).

PB is widely used for the replacement of deteriorated culverts with a new pipe of the same or larger diameter. Various types of expansion heads can be used on the bursting tool to expand the existing pipeline. There are two types of bursting heads: static and dynamic heads. Static heads, which have no moving internal parts, expand the existing pipe through only the pulling action of the bursting tool. In contrast, dynamic heads provide additional pneumatic or hydraulic forces at the point of impact with the existing pipe (Caltrans, 2013; Mitchell et al., 2005; and Hunt et al., 2010).

Pipe bursting is particularly valuable in urban environments due to its fewer construction impacts that are disruptive to businesses, homeowners, and automotive and pedestrian traffic. Pipe bursting typically yields the largest increase in hydraulic capacity among all the culvert renewal techniques. There is no limit on the size of pipe that can be replaced, and successful installation of a larger pipe depends on the cost effectiveness, local ground conditions, and the ability to provide sufficient energy to break the old pipe and pull new pipe. Difficulties can arise from expansive soils, close proximity of other service lines, a collapsed wall along the pipeline, and other causes. While PB provides structure support, it cannot fix line and grade problems for host pipe. It may also pose a threat to surrounding sub-structures.

Figure 3.13 Pipe bursting

Chapter Summary

This chapter presented a detailed description of the 11 culvert renewal techniques that are evaluated in this study. Significant advantages, limitations along with their suitability to various application scenarios are also discussed.

Table 3.1 Significant advantages and limitations of OC, IG, RG, IS, RS, SL, and CIPP renewal methods

Technique	Host Culvert Shape	Host Culvert Size	Advantages	Limitations
OC	All	All	• Offers structural capacity • Applicable for any culvert sizes and shapes • New pipe replacement	• Expensive in high-traffic/dense land uses • Greater societal inconvenience • Longer durations in several cases
IG and RG	All	≥36” (IG) <36” (RG)	• Effective for minor defects (crack and joint misalignment) • Watertight with chemical grouting • Simple technique to use	• Inadequate in acidic water flow • Shorter design life • Cannot be used for moderate to major structural defects
IS and RS	All	≥36” (IS) <36” (RS)	• Applicable where formwork is impractical • Provides a corrosion barrier to rebar • Watertight with chemical shotcrete	• Need specialized equipment and trained personnel • Need significant footprint for setting up of equipment • Inadequate in acidic water flow
SL	All	12~120”	• Simple and cheap technique • Can be used with live flow in host culvert • Offers structural capacity	• Reduced culvert size • Needs larger pits for liner insertion • Not easy to reconnect laterals
CIPP	All	12~64” for ultraviolet curing >120” for steam and hot water curing	• Requires no access pits • Can negotiate bends • Applicable for different culvert shapes and tight curves	• Need a lot of water or steam • Toxic resins could infiltrate ground water • Cannot be used with live flow

Table 3.2 Significant advantages and limitations of FFL, SWL, CCCP, and PB renewal methods

Technique	Host Culvert Shape	Host Culvert Size	Advantages	Limitations
FFL	Round	12~30”	• Increased liner size compared to SL • Can negotiate bends • Doesn’t need grouting	• Applicable to limited host culvert sizes and shapes • Toxic resins could infiltrate ground water • Requires additional resources for folding the pipe
SWL	All	Any size for round, 18” for box and oval	• Can be used with live flow in host culvert • Applicable for different culvert shapes and tight curves • Requires no access pits	• Larger manual systems require manned-entry • Need specialized equipment • Reduced culvert size
CCCP	Round	36~120”	• Short curing time • Long-term protection • Waterproof structural enhancement	• Used mostly for corrosion and abrasion • Not applicable under 45 °F
PB	All	12~36”	• Provide structure support • Capable of installing larger than host culvert size • Faster and cheaper than open-cut method usually	• Could pose threat to surrounding sub-structures • Not suitable for all soil conditions • Cannot fix line and grade problems of host culverts

CHAPTER FOUR

EVALUATION OF CULVERT RENEWAL METHODS

This chapter describes 1) the decision-making criteria employed for evaluating culvert renewal techniques in this study, and 2) the evaluation of culvert renewal techniques itself based on the chosen criteria.

Evaluation Criteria

Various criteria could influence the choice of a culvert renewal construction alternative. Such criteria include but not limited to cost, expected design life, capacity requirements, construction-related traffic impacts, construction productivity, excavation restrictions, culvert flow level, flow bypassing limitations, safety, culvert access requirements and construction footprint, and construction-related environmental impacts. Not all these criteria are relevant in every renewal project; specific relevant criteria depend on the particular project scenario and the related needs and restrictions. This study identifies three criteria that typically feature in many culvert-renewal decision-making frameworks (Hunt et al., 2010; Thornton et al., 2005; ProjectMax, 2006; Mitchell et al., 2005).

Cost (C)

Given the lack of adequate funding to invest in transportation infrastructure, cost is one criterion that definitely influences all decisions related to culvert infrastructure management. Cost as considered in this study only indicates the direct cost of culvert rehabilitation which includes cost of material, labor and equipment, and excludes costs of societal inconveniences such as traffic delays and detour, noise, air and water pollution.

Expected Design Life (DL)

With increasing focus on the life cycle aspects of infrastructures, the expected life time of an asset is of great importance. Transportation agencies are increasingly looking for long-term solutions while rehabilitating culverts so as to not worry about the rehabilitated asset for a long period of time. Expected design life as considered in this study indicates the estimated useful life of the culvert post renewal for any given renewal technique.

Productivity (P)

Although trenchless construction alternatives reduce the surface impact of underground construction compared to the conventional open-cut methods, they still have impact on the culvert flow and cause some disturbance to surface-based traffic. Consequently, productivity is an important criteria especially in high-traffic and densely-populated corridors.

Evaluation of Culvert Renewal Techniques

The performance of all the renewal techniques considered in this study is synthesized and comparatively evaluated based on the three chosen criteria, as shown in Table 4.1. The performance synthesis is primarily informed by the literature (Hunt et al., 2010; Thornton et al., 2005; ProjectMax, 2006; Syachrani et al., 2010; Mitchell et al., 2005). Based on the evaluated performances, the renewal techniques are categorized into groups of significant variation, as shown in Table 4.1. The group of techniques with least performance for each criterion is labeled as "Class-1," and the second worse group is labeled as "Class-2," and so on. Based on these Classes, appropriate ratings are developed for each renewal technique following the pair-wise comparison procedures of analytical hierarchy process (AHP) (Yang, 2011; Najafi and Bhattachar, 2011; and Yoo et al., 2014), as shown in Table 4.1. For example, open-cut (OC) method with reportedly "high (H)" cost is part of a group of techniques that are together labeled as "Class-1." Subsequently, the rating of 0.05 is derived using the AHP procedures and this indicates that the relative preference of OC for cost criterion is 5%.

It can be seen from Table 4.1 that IG fared best for the cost criteria followed by RS and SL and thereafter by FFL and CCCP and finally by OC, RG, IS, CIPP, SWL, and PB. Although the culvert renewal techniques are objectively compared in Table 4.1, it should be noted that neither all these techniques are equally capable of addressing all the defects nor are equally capable of adding structural capacity to a deteriorated culvert. For example, OC, SL, PB and CIPP are the only techniques that are capable of renewing a deteriorate culvert with negligible structural integrity; other techniques are suitable only when the host culvert has a reasonable structural capacity. Consequently, the suitability of these techniques needs to be appropriately assessed before these techniques are objectively compared with each other for performance evaluation. Similarly, OC, SL, CIPP and PB fared best for expected design life criteria, whereas RG, IG, FFL, SWL, and CCCP fared best for the productivity criteria, as can be seen in Table 4.1.

RG and IG are normally suitable for addressing minor to moderate non-structural culvert issues; RG more suitable for smaller size culverts whereas IG for larger size culverts. CIPP and FFL are somewhat comparable techniques with similar installation procedures; CIPP is however applicable for various scenarios due to its suitability of a host of pipe materials, sizes, shapes, and its flexibility to be used as a structural or non-structural liner, while FFL is only applicable to smaller size circular culverts (Ballinger and Drake, 1995; Caltrans, 2013; Mitchell et al., 2005; Meegoda et al., 2009; Hunt et al., 2010; Hollingshead and Tullis, 2009; Syachrani et al., 2010; and Yazdekhasti et al., 2014). OC is suitable to various scenarios, albeit the cost and societal impacts could be significant and consequently it is more suitable when construction footprint is not a major issue and the depth of burial is reasonably small. PB is one technique that is uniquely suitable for upsizing a deteriorated pipeline without needing to continuously dig trenches; it is also suitable for size to size replacement in favorable soil conditions. SL is the most straightforward and simple trenchless renewal alternative that is capable of instilling structural capacity, albeit at the cost of culvert size reduction.

The evaluated performances synthesized in Table 4.1 are for average application scenarios and may not be true in various unique scenarios. For example, the evaluation presented for the traffic-impact criteria is based on the renewal of a 50m long culvert pipe and it may change for renewing a longer (or shorter) culvert pipe and this limitation should be noted.

Chapter Summary

This chapter identified three critical criteria for evaluating the culvert renewal techniques namely, cost, expected design life, and productivity. This chapter also presented the evaluation of the culvert renewal techniques based on the three chosen criteria. A brief discussion of the performance of various techniques is also presented.

Table 4.1 Evaluation of renewal techniques

Criteria		OC	IG	RG	IS	RS	SL	CIPP	FFL	SWL	CCCP	PB
C	Performance ($/in.ft)	H	L	H	H	M	M	H	M to H	H	M to H	H
	Class	1	4	1	1	3	3	1	2	1	2	1
	Rating	0.05	0.2	0.05	0.05	0.15	0.15	0.05	0.1	0.05	0.1	0.05
DL	Performance (years)	75	10	20	50	50	75	75	50	50	50	75
	Class	7.5	1	2	5	5	7.5	7.5	5	5	5	7.5
	Rating	0.13	0.016	0.034	0.086	0.086	0.13	0.13	0.086	0.086	0.086	0.13
P	Performance (days/50m)	>1	≤0.5	≤0.5	>1	>1	>1	=1	≤0.5	≤0.5	≤0.5	>1
	Class	1	3	3	1	1	1	2	3	3	3	1
	Rating	0.05	0.13	0.13	0.05	0.05	0.05	0.10	0.13	0.13	0.13	0.05

CHAPTER FIVE

CULVERT RENEWAL SELECTION TOOL (CREST)

This chapter discusses the development of culvert renewal selection tool (CREST) for the optimal selection of culvert renewal techniques. CREST is developed in such a way that it caters to various specific application scenarios. An application scenario is characterized in this study by culvert material, culvert size, major defect type, and major defect severity. Various renewal techniques that are reportedly suitable for each application scenario are identified and subsequently, a framework for choosing the best suitable technique is proposed.

Development of Various Application Scenarios

For developing various typical application scenarios, defects that are commonly observed in each of RCP, CMP and HDPE culverts are first identified. The defects are then further classified into “major,” “moderate,” and “minor” categories depending on their severities which are defined in this study. These defect and material categories are combined with various culvert size classifications to develop the application scenarios which form the basis of CREST.

Several defects that are commonly observed in culvert structures include cracks (CR), invert deterioration (ID), joint misalignment (JM), joint infiltration or exfiltration (JI), corrosion (CO), and shape deformation (SD). While some of these are exclusively found in RCP, CMP or HDPE culverts, others are common to all materials (Caltrans, 2013; Ballinger and Drake, 1995; Mitchell et al., 2005; Matthews et al. 2012; Hunt et al., 2010; Yang and Allouche, 2009; and Yang, 2011). These defects are defined in Table 5.1 and shown in Figure 5.1. These defects are further categorized in this study into “minor”, “moderate”, and “major” types based on their severities. The “minor” type has negligible to insignificant impact on the culvert functionality; the “moderate” type has reasonable impact on culvert functionality but doesn’t lead to a complete failure of the structure; and the “major” type has significant impact potentially leading to complete failure of the structure, if left unaddressed. The defect severity categories are defined in Tables 5.2 to 5.4. Finally, a culvert size classification is proposed to further narrow down the suitable renewal techniques as some techniques are only suitable for small whereas others are suitable only for large size culverts.

For example, RG, RS, PB, and FFL are reported to be only suitable for small culverts (< 36 inch in diameter or width), whereas IG, IS, CCCP are suitable for moderate to large culverts (> 36 inch in diameter or width) and CIPP is suitable to moderate size culverts (> 36 inches and < 60 inches). SL and SWL are suitable for both small and large size culverts up to 120 inch (Ballinger and Drake, 1995; Caltrans, 2013; Mitchell et al., 2005; Meegoda et al., 2009; Hunt et al., 2010; Hollingshead and Tullis, 2009; Syachrani et al., 2010; and Yazdekhasti et al., 2014). Culverts larger than 120 inch in diameter (or width) are mostly renewed using OC and they are deliberately not considered in this study. Recently, the customized CIPP has reportedly become suitable to larger than 120 inch diameter culverts, but this fact was not considered in this study due to lack of sufficient data (Mitchell et al., 2005).

Culverts sizes are categorized into “smaller than 36 inches,” “36 inches to 60 inches,” and “larger than 60 inches.” Various application scenarios are developed in this study, as shown in Tables 5.5, 5.6 and 5.7, based on the classification of culverts in terms of material, size, prevailing defect type, and prevailing defect severity.

Figure 5.1 Common defects observed in culverts

Table 5.1 Definitions of selected defects

Types of defects	Descriptions
Crack	Crack is developed due to improper handling of the pipe during installation, improper gasket placement, or movement/settlement of pipe sections over time
Joint Misalignment	Misalignments develop due to joint separations or differential settlements of culvert sections
Corrosion	Corrosion is the degradation of metal due to its oxidation
Joint In/Exfiltration	Longitudinal joint separation leading to infiltration of external water and/or exfiltration of culvert flow
Invert deterioration	Invert of a culvert may get abraded by medium or large-sized objects (rocks) that are washed by the fast moving water
Shape deformation	The culvert is deflected, settled, or distorted due to the insufficient support from backfill or bedding

Table 5.2 Minor severity of the selected defects

Defects	Minor severity
Crack	The culvert is in good condition with less than 1/8" width of crack (with rebar exposed in RCP culverts) at single or multiple locations
Joint Misalignment	Offsets less than 1/2"
Corrosion	Less than 5% single or multiple perforations and missing areas of materials above the invert along the culvert barrel
Joint In/Exfiltration	Longitudinal joint separation of less than 1/2"; no or few bedding issues observed as a result of exfiltration
Invert deterioration	Less than 5% section loss and voids beneath invert
Shape deformation	span dimension less than 5% greater than design with symmetric shape

Table 5.3 Moderate severity of the selected defects

Defects	Moderate severity
Crack	Greater than 1/8" and less than 1" (with rebar exposed in RCP culverts) at single or multiple locations
Joint Misalignment	Offsets greater than 1/2" and less than 4"
Corrosion	Greater than 5% and less than 30% single or multiple perforations and missing areas of materials above the invert along the culvert barrel
Joint In/Exfiltration	Longitudinal joint separation of more than 1/2" and less than 6"; some visible bedding issues observed as a result of exfiltration
Invert deterioration	Greater than 5% and less than 50% section loss and voids beneath invert
Shape deformation	Span dimension greater than 5% and up to 20% greater than design

Table 5.4 Major severity of the selected defects

Defects	Major severity
Crack	Greater than 1" width of crack (with rebar exposed in RCP culverts) at single or multiple locations
Joint Misalignment	Offsets greater than 4" with partial or imminent collapse
Corrosion	Greater than 30% of the barrel surface area has multiple perforations and missing material above the invert along the culvert barrel
Joint In/Exfiltration	Longitudinal joint separation of more than 6"; significant bedding issues observed as a result of exfiltration
Invert deterioration	Greater than 50% section loss and/or voids in the invert; embankment and/or roadway damage indications as a result
Shape deformation	Flattening at top of arch or crown, reverse curvature at bottom, span dimension more than 20% greater than design, and non-symmetric shape

Mapping of Culvert Renewal Methods to Application Scenarios

The developed application scenarios are appropriately mapped with the culvert renewal techniques they are reported to be suitable for, as shown in Tables 5.5, 5.6 and 5.7 (Hollingshead and Tullis, 2009; Matthews et al. 2012; Hunt et al., 2010; ProjectMax, 2006; and Syachrani et al., 2010). For example, slip lining (SL), cured-in-place pipe lining (CIPP), fold and form lining (FFL) and pipe bursting (PB) techniques are suitable to rehabilitate or replace a significantly cracked culverts of size less than 36 inches, as shown in Table 5.5.

Table 5.5 Mapping of renewal techniques with application scenarios of RCP culverts

Size	Defect types	Severity	Rehabilitation Techniques
<36"	Crack	Minor	RG, OC
		Moderate	RG, CIPP, OC
		Major	SL, CIPP, FFL, PB, OC
	Joint misalignment	Minor	-
		Moderate	CIPP, FFL, OC
		Major	PB, OC
	Joint in/exfiltration	Minor	RG, OC
		Moderate	RG, CIPP, OC
		Major	CIPP, FFL, SWL, PB, OC
	Invert deterioration	Minor ~ moderate	RS, OC
		Major	RS, SL, CIPP, FFL, SWL, OC
36"~60"	Crack	Minor	IG, OC
		Moderate	IG, SL, CIPP, CCCP, OC
		Major	SL, CIPP, OC
	Joint misalignment	Minor	-
		Moderate	CIPP, OC
		Major	OC
	Joint in/exfiltration	Minor	IG, OC
		Moderate	IG, SL, CIPP, OC
		Major	SL, CIPP, SWL, OC
	Invert deterioration	Minor ~ moderate	IS, OC
		Major	IS, SL, CIPP, SWL, OC
60"~120"	Crack	Minor	IG, OC
		Moderate	IG, SL, CCCP, OC
		Major	SL, OC
	Joint misalignment	Minor	-
		Moderate ~ major	OC
	Joint in/exfiltration	Minor	IG, OC
		Moderate	IG, SL, OC
		Major	SL, SWL, OC
	Invert deterioration	Minor~ moderate	IS, OC
		Major	IS, SL, SWL, OC

Note: FFL is applicable only in round shape culvert

Table 5.6 Mapping of renewal techniques with application scenarios of CMP culverts

Size	Defect types	Severity	Rehabilitation Techniques
<36"	Joint misalignment	Minor	-
		Moderate	CIPP, FFL, OC
		Major	OC
	Corrosion	Minor ~ moderate	RS, CIPP, OC
		Major	RS, SL, CIPP, SWL, OC
	Joint in/exfiltration	Minor	RG, OC
		Moderate	RG, CIPP, OC
		Major	SL, CIPP, FFL, SWL, CCCP, OC
	Invert deterioration	Minor ~ major	RS, SL, CIPP, OC
	Shape deformation	Minor	-
		Moderate	SL, CIPP, FFL, OC
		Major	OC
36"~60"	Joint misalignment	Minor	-
		Moderate	CIPP, OC
		Major	OC
	Corrosion	Minor ~ moderate	CCCP, OC
		Major	IS, SL, CIPP, SWL, CCCP, OC
	Joint in/exfiltration	Minor	IG, OC
		Moderate	IG, SL, CIPP, OC
		Major	SL, CIPP, SWL, CCCP, OC
	Invert deterioration	Minor ~ moderate	IS, OC
		Major	IS, SL, CCCP, OC
	Shape deformation	Minor	-
		Moderate ~ major	SL, CIPP, OC
60"~120"	Joint misalignment	Minor	-
		Moderate ~ major	OC
	Corrosion	Minor ~ moderate	CCCP, OC
		Major	IS, SL, CIPP, SWL, CCCP, OC
	Joint in/exfiltration	Minor	IG, OC
		Moderate	IG, SL, OC
		Major	SL, SWL, CCCP, OC
	Invert deterioration	Minor ~ moderate	IS, OC
		Major	IS, SL, CCCP, OC
	Shape deformation	Minor	-
		Moderate ~ major	SL, OC

Note: FFL is applicable only in round shape culvert

Table 5.7 Mapping of renewal techniques with application scenarios of HDPE culverts

Size	Defect types	Severity	Rehabilitation Techniques
<36"	Crack	Minor	RG, OC
		Moderate	RG, CIPP, OC
		Major	SL, CIPP, FFL, OC
	Joint misalignment	Minor	-
		Moderate	CIPP, FFL, OC
		Major	OC
36"~60"	Crack	Minor	IG, OC
		Moderate	IG, SL, CIPP, OC
		Major	SL, CIPP, OC
	Joint misalignment	Minor	-
		Moderate	CIPP, OC
		Major	OC
60"~120"	Crack	Minor	IG, OC
		Moderate	IG, SL, OC
		Major	SL, OC
	Joint misalignment	Minor	-
		Moderate ~ major	OC

Note: FFL is applicable only in round shape culvert

Description of the Culvert Renewal Selection Tool (CREST)

CREST is developed in this study to assist engineers and owners in rationally selecting an optimal culvert renewal technique for a given application scenario. CREST is different from the ones previous researchers proposed in that it adopts a scientific quasi-qualitative approach which is evidence-based. It is developed using the Microsoft Excel platform and it solicits user preferences. The input data required from the user entails the particular application scenario along with quantitative information on the relative importance given to each of the three criteria in the decision-making process. This CREST is carefully developed keeping in mind that the end users may not be highly knowledge about the software tools and consequently the need for its simplicity and detailed instructions. CREST is demonstrated using various application scenarios that were previously identified in this chapter.

The evaluation of various culvert renewal techniques, as discussed in Chapter 4 and summarized in Figure 5.2, is an integral part of CREST. The user-provided criteria weightings are combined with the evaluated quantitative ratings of renewal techniques presented in Figure 5.2 to inform the selection of one or more optimal techniques using the analytical hierarchy process (AHP).

AHP is a structured technique addressing complex decisions, based on mathematical principles. In AHP, possible alternatives are relatively rated using pair-wise comparisons based on several decision criteria. The decision criteria are in turn rated using pair-wise comparisons for their relative importance to the user. It has been applied to a wide variety of decision-making problems in the past. Najafi et al. (2008) used AHP to calculate the relative weighting of different culvert defects for assessing culvert condition. Al-Barqawi et al. (2008) used AHP to assess the condition and to predict the performance of water infrastructure. Najafi et al. (2011) used AHP to calculate the performance scores for culverts to determine the magnitude of the deterioration and assist in short- and long-term planning. The AHP method helps decision-makers find one solution that best suits their goal and their understanding of the problem.

An overall score for each renewal technique is calculated using Eq. 5.1 following the AHP process.

$$S_j = \sum_{i=1}^{n} W_i * R_{i,j} \tag{5.1}$$

Where, S_j is overall score for renewal technique j; W_i is percentage weightings of criteria i; $R_{i,j}$ is performance rating of renewal technique j for criteria i; and n is the number of the decision criteria employed (n = 3 in this study).

The overall score (S_j) is the basis for the selection of a renewal technique in the proposed CREST.

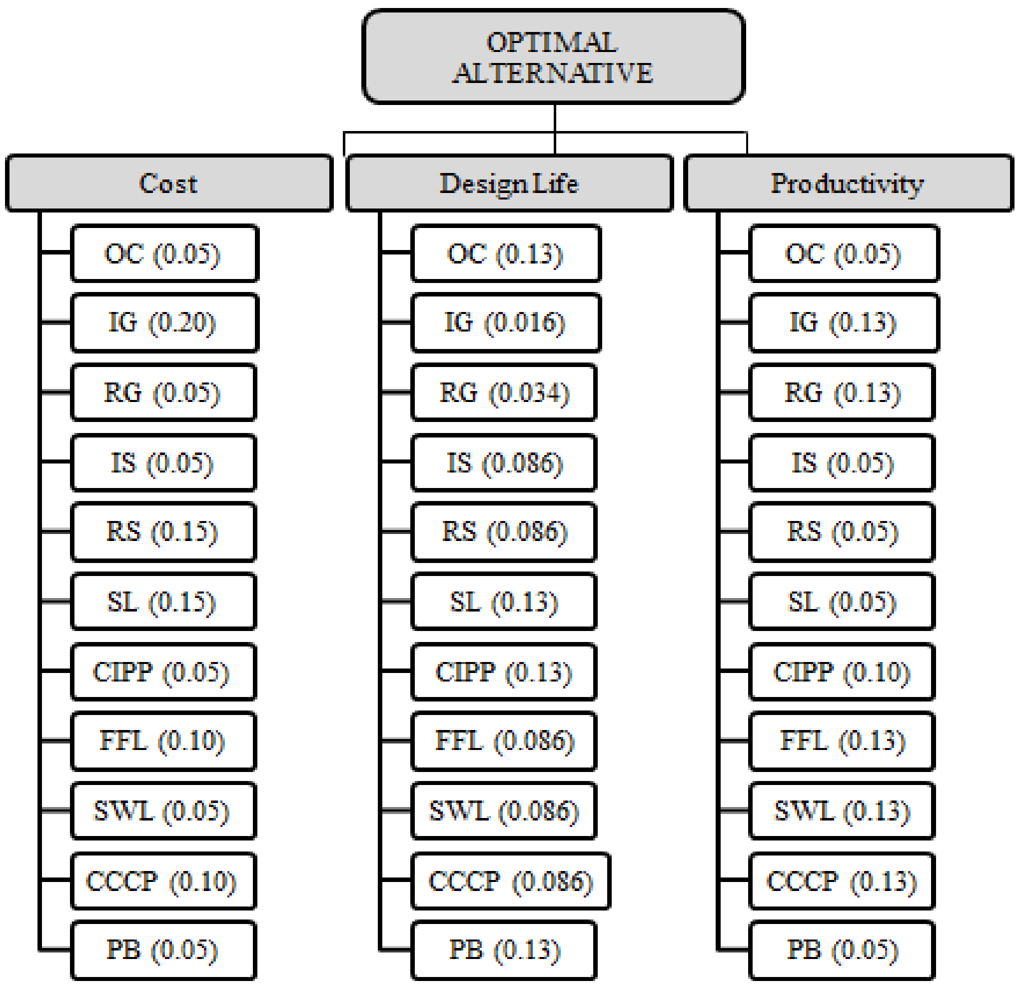


Figure 5.2 Relative ratings of the selected renewal techniques for the three decision-making criteria

Chapter Summary

This chapter presented various application scenarios that were developed to demonstrate CREST and also described CREST itself. The application scenarios are based on culvert material, culvert size, prevailing defect type, and prevailing defect severity. Various defects in RCP, CMP, and HDPE materials are defined along with three levels of severities for each defect namely, “minor,” “moderate,” and “major.” The renewal techniques are then mapped with various application scenarios based on their reported suitability. The application scenarios along with the performance evaluation of renewal techniques form the crux of the analytical hierarchy process-based tool, CREST, which is described in this chapter.

CHAPTER SIX

RESULTS AND DISCUSSION

This chapter presents the detailed results from the demonstration of CREST for various application scenarios and also a follow-up discussion in terms of the justification and applicability of the obtained results.

Demonstration of CREST

CREST is demonstrated for all the typical application scenarios developed that are presented in Tables 5.5, 5.6 and 5.7. To calculate the overall score (S_j) of each renewal technique, CREST requires user inputs for the three decision criteria in the form of percentage weightings that appropriately characterize the relative importance given to the criteria. However, the multitude of possibilities in terms of culvert defects, specific field constraints, performance expectations, location constraints, cost limitations, and environmental sensitivities makes it difficult to assign a deterministic set of weightings for the decision criteria. For example, cost can be the most decisive criteria in a renewal project when other aspects such as traffic disruption, environmental impacts are inconsequential and no specific field restrictions exist; on the contrary, cost can be a less important criterion in the case of projects with specific requirements or constraints. Given this uncertainty with user preferences in terms of criteria weightings, Monte-Carlo simulation is employed to randomly generate criteria weightings in 10,000 simulations for each application scenario. The most optimal renewal technique is identified based on the overall scores (S_j) calculated by CREST. Other practical considerations should guide the technique selection in case there is more than one technique with same *overall score*. The Microsoft Excel-based CREST is presented in Appendix-A.

Study Findings

The findings resulted from the demonstration of CREST are appropriately grouped in this chapter based on the application scenarios each renewal technique is found to be best suitable for. Application scenarios are characterized by culvert materials (including RCP, CMP, and HDPE), size (including >36", 36-60", and 60-120"), defect types (including crack, corrosion, joint in/exfiltration, joint misalignment, invert deterioration, and shape deformation), and severity (including minor, moderate, and major). The results indicate the percentage of the 10,000 Monte-Carlo simulations in which each renewal technique is found to be best suited for a given application scenario. The ranges of criteria weightings that are found to drive the selection of renewal techniques for each application scenario are subsequently identified and discussed.

Tables 6.1 to 6.14 present the percentage preferences of renewal techniques for various application scenarios. It can be observed from the percentage preferences in Tables 6.1 to 6.14 that IG and RG are feasible for addressing minor to moderate cracks and joint in/exfiltration issues, RS is feasible for minor to moderate invert deterioration issues in RCP and CMP culverts of small size and minor to moderate corrosion issues in CMP culvers of small size, and IS is feasible for addressing minor to moderate invert deterioration issues in CMP culverts of moderate size (36 to 120 inches in diameter). It can also be observed from Tables 6.1 to 6.14 that all renewal techniques, except IS, RG, and SWL, have been found to be the best choice for at least one defect. IS fared poorly with maximum selection preference of 2% for addressing $\text{ID}_{\text{RCP \& CMP, 36”} \sim \text{120”, minor-moderate}}$ application scenario (i.e., minor to moderate invert deterioration defect in RCP culverts of size ranging between 36 to 120 inches in diameter), as shown in Tables 6.1 to 6.14. The relatively poor performance of IS is due to its relatively short design life (see Table 4.1) compared to other suitable renewal alternatives such as OC. Although RG is found to have a maximum preference of 47% for $\text{Crack}_{\text{RCP \& HDPE, <36", minor-moderate}}$ and $\text{JI}_{\text{RCP \& CMP, <36", minor-moderate}}$ application scenarios, as can be seen in Tables 6.1 to 6.14, it is not the best suited method. The relatively poor performance of RG is due to its shorter design life (see Table 4.1) compared to other suitable renewal alternatives such as OC and CIPP. SWL fared relatively poorly with maximum selection preference of less than 30% for $\text{JI}_{\text{RCP \& CMP, 36“} \sim \text{120”, major}}$, $\text{Corrosion}_{\text{CMP, <36", major}}$, and $\text{JI}_{\text{RCP, <36”, major}}$ application scenarios, as can be seen in Tables 6.1 to 6.14. SWL’s relatively poor performance can be attributed to its relatively higher cost and shorter design life (see Table 4.4) compared to other suitable techniques such as SL, CIPP, and CCCP.

SL and CIPP are popular techniques which are suitable for more than 28 application scenarios, while OC, IG, RS, FFL, CCCP, and PB are suitable for more than 16 application scenarios, as can be inferred from the results presented in Tables 6.1 to 6.14. It can also be observed from Tables 6.1 to 6.14 that OC, IG, SL, and CIPP are found to be best suited for over 15 application scenarios, while RS, FFL, CCCP, and PB are found to be best suited for less than five scenarios. It has also been found that some of the techniques are almost equally suitable for a few application scenarios making them complementing options. For example, the percentage preferences of SL and CIPP were not significantly different for $\text{SD}_{\text{CMP, 36“}\sim\text{ 60”, moderate-major,}}$ $\text{Crack}_{\text{HDPE, 36“}\sim\text{ 60”, major,}}$ and $\text{ID}_{\text{CMP, <36“, minor-major}}$ scenarios, as can be observed from Tables 6.8, 6.10, and 6.14. Similarly, the percentage preferences of RG and OC were not significantly different for $\text{Crack}_{\text{RCP\&HDPE, <36“, minor}}$ and $\text{JI}_{\text{RCP\&CMP, <36“, minor}}$ scenarios, as can be observed from Tables 6.1, 6.2, 6.8, and 6.13.

While these results provide general guidance to decision-makers for culvert renewal planning, they may be less suitable to cases with specific constraints or unique requirements that warrants the use of another particular technique or prevents the use of a technique that may have been found to be highly preferred in this study.

Table 6.1 Preferences of renewal techniques for RCP culvert of size <36 inches with cracks and joint misalignment defects

Size	Defect Types	Defect Severity	Suitable Renewal Techniques	Percentage Preference	Suitable Ranges of Criteria Weightings		
					Cost	Design life	Productivity
<36"	Crack	Minor	RG	47%	0~100%	0~30%	40~100%
			OC	53%	0~100%	30~100%	0~40%
		Moderate	RG	19%	-	0~10%	70~100%
			CIPP	81%	0~100%	10~100%	0~70%
		Major	SL	38%	30~100%	20~40%	0~30%
			CIPP	33.8%	0~30%	40~100%	30~40%
			FFL	28.2%	-	0~20%	40~100%
	Joint misalignment	Moderate	CIPP	45.7%	0~40%	30~100%	0~40%
			FFL	54.3%	30~100%	0~30%	30~100%
		Major	PB	50%	-	-	-
			OC	50%	-	-	-

Table 6.2 Preferences of renewal techniques for RCP culvert of sizes <36 inch with joint in/exfiltration and invert deterioration defects

Size	Defect Types	Defect Severity	Suitable Renewal Techniques	Percentage Preference	Suitable Ranges of Criteria Weightings		
					Cost	Design life	Productivity
<36"	Joint in/exfiltration	Minor	RG	47%	0~100%	0~30%	40~100%
			OC	53%	0~100%	30~100%	0~40%
		Moderate	RG	19%	-	0~10%	70~100%
			CIPP	81%	0~100%	10~100%	0~70%
		Major	CIPP	45.7%	0~40%	30~100%	0~40%
			FFL	54.3%	30~100%	0~30%	40~100%
	Invert deterioration	Minor~ moderate	RS	70.3%	20~100%	0~60%	0~100%
			OC	29.7%	0~20%	50~100%	-
		Major	RS	0.8%	-	-	-
			SL	37.2%	30~100%	20~40%	0~30%
			CIPP	33.8%	0~30%	40~100%	30~40%
			FFL	28.2%	-	0~30%	40~100%

Table 6.3 Preferences of renewal techniques for RCP culvert of sizes 36~60 inch with crack and joint misalignment defects

Size	Defect Types	Defect Severity	Suitable Renewal Techniques	Percentage Preference	Suitable Ranges of Criteria Weightings		
					Cost	Design life	Productivity
36"~60"	Crack	Minor	IG	75.8%	10~100%	0~50%	0~100%
			OC	24.2%	0~10%	50~100%	-
		Moderate	IG	49.3%	30~90%	0~30%	0~80% & 90~100%
			SL	12.2%	-	-	0~10%
			CIPP	33.2%	0~30%	30~90%	-
			CCCP	5.3%	90~100%	90~100%	80~90%
		Major	SL	38.0%	30~100%	20~40%	0~30%
			CIPP	33.8%	0~30%	40~100%	30~40%
			SWL	0.5%	-	-	-
			CCCP	27.7%	-	0~20%	40~100%
	Joint misalignment	Moderate	CIPP	100%	0~100%	0~100%	0~100%
		Major	OC	100%	0~100%	0~100%	0~100%

Table 6.4 Preferences of renewal techniques for RCP culvert of sizes 36~60 inch with joint in/exfiltration and invert deterioration defects

Size	Defect Types	Defect Severity	Suitable Renewal Techniques	Percentage Preference	Suitable Ranges of Criteria Weightings		
					Cost	Design life	Productivity
36"~60"	Joint in/exfiltration	Minor	IG	75.8%	10~100%	0~50%	0~100%
			OC	24.2%	0~10%	50~100%	-
		Moderate	IG	52.7%	30~100%	0~30%	0~100%
			SL	12.2%	-	-	-
			CIPP	35.1%	0~30%	30~100%	-
		Major	SL	45%	30~100%	0~40%	0~40%
			CIPP	38%	0~30%	40~100%	40~60%
			SWL	17%	-	-	60~100%
	Invert deterioration	Minor~ moderate	IS	2%	-	-	-
			OC	98%	0~100%	0~100%	0~100%
		Major	SL	38.0%	30~100%	20~40%	0~30%
			CIPP	33.8%	0~30%	40~100%	30~40%
			SWL	0.5%	-	-	-
			CCCP	27.7%	-	0~20%	40~100%

Table 6.5 Preferences of renewal techniques for RCP culvert of sizes 60~120 inch with crack and joint misalignment defects

Size	Defect Types	Defect Severity	Suitable Renewal Techniques	Percentage Preference	Suitable Ranges of Criteria Weightings		
					Cost	Design life	Productivity
60"~120"	Crack	Minor	IG	75.8%	10~100%	0~50%	0~100%
			OC	24.2%	0~10%	50~100%	-
		Moderate	IG	50%	20~100%	0~40%	0~100%
			SL	33%	10~30%	40~100%	-
			CCCP	17%	0~10%	-	-
		Major	SL	38.0%	30~100%	20~40%	0~30%
			CIPP	33.8%	0~30%	40~100%	30~40%
			SWL	0.5%	-	-	-
			CCCP	27.7%	-	0~20%	40~100%
	Joint misalignment	Moderate ~ major	OC	100%	0~100%	0~100%	0~100%

Table 6.6 Preferences of renewal techniques for RCP culvert of sizes 60~120 inch with join in/exfiltration and invert deterioration defects

Size	Defect Types	Defect Severity	Suitable Renewal Techniques	Percentage Preference	Suitable Ranges of Criteria Weightings		
					Cost	Design life	Productivity
60"~120"	Joint in/exfiltration	Minor	IG	75.8%	10~100%	0~50%	0~100%
			OC	24.2%	0~10%	50~100%	-
		Moderate	IG	60.8%	20~100%	0~40%	30~100%
			SL	39.2%	0~20%	40~100%	0~30%
		Major	SL	70.5%	20~100%	0~100%	0~50%
			SWL	29.5%	0~20%	-	50~100%
	Invert deterioration	Minor~ moderate	IS	2%	-	-	-
			OC	98%	0~100%	0~100%	0~100%
		Major	SL	38.0%	30~100%	20~40%	0~30%
			CIPP	33.8%	0~30%	40~100%	30~40%
			SWL	0.5%	-	-	-
			CCCP	27.7%	-	0~20%	40~100%

Table 6.7 Preferences of renewal techniques for CMP culvert of sizes <36 inch with joint misalignment and corrosion defects

Size	Defect Types	Defect Severity	Suitable Renewal Techniques	Percentage Preference	Suitable Ranges of Criteria Weightings		
					Cost	Design life	Productivity
<36"	Joint misalignment	Moderate	CIPP	45.7%	0~40%	30~100%	0~40%
			FFL	54.3%	30~100%	0~30%	40~100%
		Major	OC	100%	0~100%	0~100%	0~100%
	Corrosion	Minor ~ moderate	RS	36.6%	40~100%	0~20%	0~20%
			CIPP	63.4%	0~40%	20~100%	10~100%
		Major	RS	1%	-	-	-
			SL	44.0%	30~100%	0~40%	0~40%
			CIPP	38%	0~30%	40~100%	40~60%
			SWL	17%	-	-	60~100%

Table 6.8 Preferences of renewal techniques for CMP culvert of size <36 inch with joint in/exfiltration, invert deterioration, and shape deformation defects

Size	Defect Types	Defect Severity	Suitable Renewal Techniques	Percentage Preference	Suitable Ranges of Criteria Weightings		
					Cost	Design life	Productivity
<36"	Joint in/exfiltration	Minor	RG	47%	0~100%	0~30%	40~100%
			OC	53%	0~100%	30~100%	0~40%
		Moderate	RG	19%	-	0~10%	70~100%
			CIPP	81%	0~100%	10~100%	0~70%
		Major	SL	38%	30~100%	20~40%	0~30%
			CIPP	33.8%	0~30%	40~100%	30~40%
			FFL	28.2%	-	0~30%	40~100%
	Invert deterioration	Minor ~ major	RS	1.3%	-	-	-
			SL	45.8%	30~100%	0~40%	0~40%
			CIPP	52.9%	0~30%	40~100%	40~100%
	Shape deformation	Moderate	SL	38%	30~100%	20~40%	0~30%
			CIPP	33.8%	0~30%	40~100%	30~40%
			FFL	28.2%	-	0~30%	40~100%
		Major	OC	100%	0~100%	0~100%	0~100%

Table 6.9 Preferences of renewal techniques for CMP culvert of sizes 36~60 inch with joint misalignment, corrosion, and joint in/exfiltration defects

Size	Defect Types	Defect Severity	Suitable Renewal Techniques	Percentage Preference	Suitable Ranges of Criteria Weightings		
					Cost	Design life	Productivity
36"~60"	Joint misalignment	Moderate	CIPP	100%	0~100%	0~100%	0~100%
		Major	OC	100%	0~100%	0~100%	0~100%
	Corrosion	Minor ~ moderate	CCCP	84.2%	0~100%	0~60%	0~100%
			OC	15.8%	-	60~100%	-
		Major	SL	38.0%	30~100%	20~40%	0~30%
			CIPP	33.8%	0~30%	40~100%	30~40%
			SWL	0.5%	-	-	-
			CCCP	27.7%	-	0~20%	40~100%
	Joint in/exfiltration	Minor	IG	75.8%	10~100%	0~50%	0~100%
			OC	24.2%	0~10%	50~100%	-
		Moderate	IG	52.7%	30~100%	0~30%	0~100%
			SL	12.2%	-	-	-
			CIPP	35.1%	0~30%	30~100%	-
		Major	SL	38.00%	30~100%	20~40%	0~30%
			CIPP	33.80%	0~30%	40~100%	30~40%
			SWL	0.50%	-	-	-
			CCCP	27.70%	-	0~20%	40~100%

Table 6.10 Preferences of renewal techniques for CMP culvert of sizes 36~60 inch with invert deterioration and shape deformation defects

Size	Defect Types	Defect Severity	Suitable Renewal Techniques	Percentage Preference	Suitable Ranges of Criteria Weightings		
					Cost	Design life	Productivity
36"~60"	Invert deterioration	Minor ~ moderate	IS	2%	-	-	-
			OC	98%	0~100%	0~100%	0~100%
		Major	SL	38.0%	30~100%	20~40%	0~30%
			CIPP	33.8%	0~30%	40~100%	30~40%
			SWL	0.5%	-	-	-
			CCCP	27.7%	-	0~20%	40~100%
	Shape deformation	Moderate ~ major	SL	48%	30~100%	0~40%	0~40%
			CIPP	53%	0~30%	40~100%	40~100%

Table 6.11 Preferences of renewal techniques for CMP culvert of sizes 60~120 inch with joint misalignment, corrosion, and joint in/exfiltration defects

Size	Defect Types	Defect Severity	Suitable Renewal Techniques	Percentage Preference	Suitable Ranges of Criteria Weightings		
					Cost	Design life	Productivity
60"~120"	Joint misalignment	Moderate ~ major	OC	100%	0~100%	0~100%	0~100%
	Corrosion	Minor ~ moderate	CCCP	84.2%	0~100%	0~60%	0~100%
			OC	15.8%	-	60~100%	-
		Major	SL	38.0%	30~100%	20~40%	0~30%
			CIPP	33.8%	0~30%	40~100%	30~40%
			SWL	0.5%	-	-	-
			CCCP	27.7%	-	0~20%	40~100%
	Joint in/exfiltration	Minor	IG	75.8%	10~100%	0~50%	0~100%
			OC	24.2%	0~10%	50~100%	-
		Moderate	IG	60.8%	20~100%	0~40%	30~100%
			SL	39.2%	0~20%	40~100%	0~30%
		Major	SL	59.4%	30~100%	20~100%	0~40%
			SWL	1.3%	-	-	-
			CCCP	39.3%	0~30%	0~30%	40~100%

Table 6.12 Preferences of renewal techniques for CMP culvert of sizes 60~120 inch with invert deterioration and shape deformation defects

Size	Defect Types	Defect Severity	Suitable Renewal Techniques	Percentage Preference	Suitable Ranges of Criteria Weightings		
					Cost	Design life	Productivity
60"~120"	Invert deterioration	Minor ~ moderate	IS	2%	-	-	-
			OC	98%	0~100%	0~100%	0~100%
		Major	SL	38.0%	30~100%	20~40%	0~30%
			CIPP	33.8%	0~30%	40~100%	30~40%
			SWL	0.5%	-	-	-
			CCCP	27.7%	-	0~20%	40~100%
	Shape deformation	Moderate ~ major	SL	100%	0~100%	0~100%	0~100%

Table 6.13 Preferences of renewal techniques for HDPE culvert of sizes <36 inch with crack and joint misalignment defects

Size	Defect Types	Defect Severity	Suitable Renewal Techniques	Percentage Preference	Suitable Ranges of Criteria Weightings		
					Cost	Design life	Productivity
<36"	Crack	Minor	RG	47%	0~100%	0~30%	40~100%
			OC	53%	0~100%	30~100%	0~40%
		Moderate	RG	19%	-	0~10%	70~100%
			CIPP	81%	0~100%	10~100%	0~70%
		Major	SL	38%	30~100%	20~40%	0~30%
			CIPP	33.8%	0~30%	40~100%	30~40%
			FFL	28.2%	-	0~20%	40~100%
	Joint misalignment	Moderate	CIPP	45.7%	0~40%	30~100%	0~40%
			FFL	54.3%	30~100%	0~30%	40~100%
		Major	OC	100%	0~100%	0~100%	0~100%

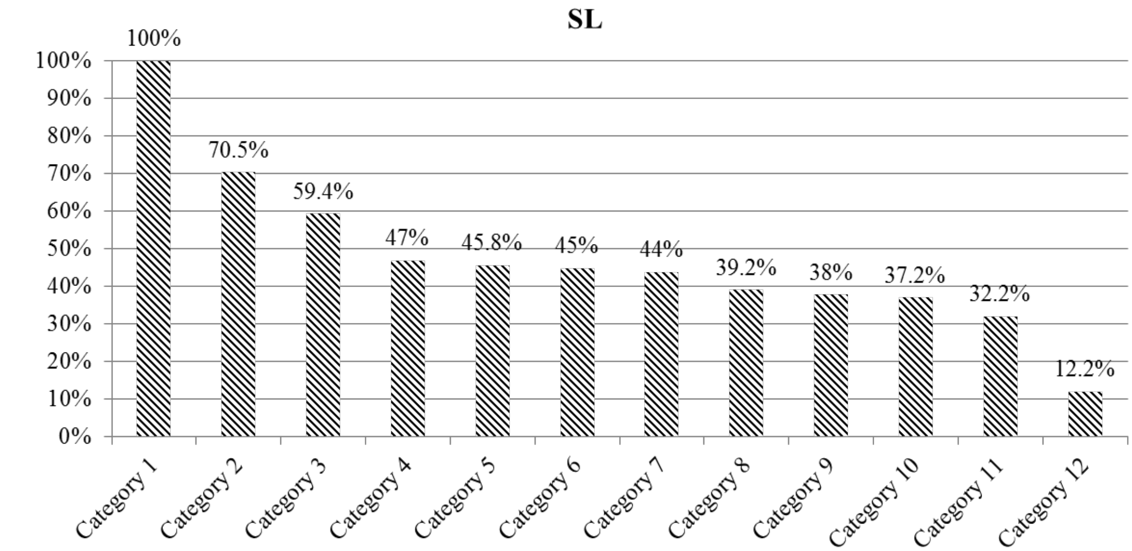
Table 6.14 Preferences of renewal techniques for HDPE culvert of sizes 36~120 inch with crack and joint misalignment defects

Size	Defect types	Severity	Rehabilitation techniques	Percentage preference	Range of percentage weightings for technology selection preference		
					Cost	Design life	Productivity
36"~60"	Crack	Minor	IG	75.8%	10~100%	0~50%	0~100%
			OC	24.2%	0~10%	50~100%	-
		Moderate	IG	52.7%	30~100%	0~30%	0~100%
			SL	12.2%	-	-	-
			CIPP	35.1%	0~30%	30~100%	-
		Major	SL	47%	30~100%	0~40%	0~40%
			CIPP	53%	0~30%	40~100%	40~100%
	Joint misalignment	Moderate	CIPP	100%	0~100%	0~100%	0~100%
		Major	OC	100%	0~100%	0~100%	0~100%
60"~120"	Crack	Minor	IG	75.8%	10~100%	0~50%	0~100%
			OC	24.2%	0~10%	50~100%	-
		Moderate	IG	60.8%	20~100%	0~40%	30~100%
			SL	39.2%	0~20%	40~100%	0~30%
		Major	SL	100%	0~100%	0~100%	0~100%
	Joint misalignment	Moderate ~ major	OC	100%	0~100%	0~100%	0~100%

The suitability of each culvert renewal technique is separately discussed. For this, all the application scenarios that each renewal technique is able to address are grouped together along with the respective selection preferences.

Suitability of Slip-Lining (SL)

SL is found to be suitable for all the application scenarios, except joint misalignment, as shown in Figure 6.1, and this is mainly due to its straightforward procedure and relatively cheaper cost (Ballinger and Drake, 1995; Caltrans, 2013; Mitchell et al., 2005; Meegoda et al., 2009; Hunt et al., 2010; Hollingshead and Tullis, 2009; Syachrani et al., 2010; and Yazdekhasti et al., 2014). SL is found to be the best suited method for application scenarios of categories 1, 2, 3, 6, 7, 9, and 10, as can be seen in Figure 6.1. On the contrary, better suited alternatives are available for application scenarios of categories 4, 5, 8, 11, and 12, as can be inferred from Figure 6.1.

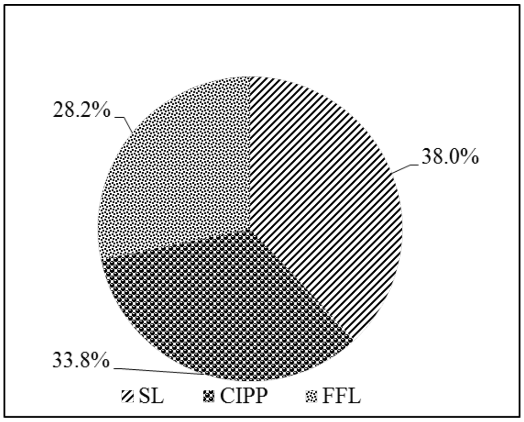


Category 1*	SD, CMP, 60~120", moderate ~ major Crack, HDPE, 60~120", major	Category 7*	Corrosion, CMP, <36", major
Category 2*	JI, RCP, 60~120", major	Category 8	Crack, HDPE, 60~120", moderate JI, RCP & CMP, 60~120", moderate
Category 3*	JI, CMP, 60~120", major	Category 9*	Crack, RCP & HDPE, <36", major JI, CMP, <36", major SD, CMP, <36", moderate
Category 4	Crack, HDPE, 36~60", major SD, CMP, 36~60", moderate ~ major	Category 10*	ID, RCP, <36", major
Category 5	ID, CMP, <36", minor ~ major	Category 11	Crack, RCP, 60~120", moderate
Category 6*	JI, RCP, 36" ~ 60", major	Category 12	Crack, RCP & HDPE, 36" ~ 60", moderate JI, RCP & CMP, 36" ~ 60", moderate

Note: “*” indicates that SL is best suited for the corresponding application scenario

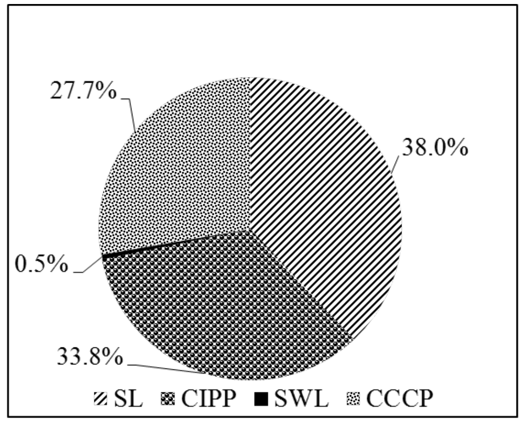
Figure 6.1 Percentage preferences of SL for various application scenarios

The percentage preferences are further consolidated to illustrate the comparative performances of renewal techniques for various application scenarios. Figures 6.2 and 6.3 illustrate such comparison for application scenarios in which SL was found to be the best choice. It can be observed from Figure 6.2(a) and also Tables 6.1, 6.8, and 6.13, that selection preference of SL for all the application scenarios identified in Figure 6.2(a) is 38%, while that of CIPP and FFL techniques are 33.8% and 28.2%, respectively. In other words, out of 10,000 Monte-Carlo simulations, SL is found to be best suitable in 3,800 simulations, while CIPP and FFL are found to be best suitable in 3,380 and 2,820 simulations respectively. The observed relatively-high percentage preference of SL technique can be attributed to the fact that SL, compared to CIPP and FFL, costs less and offers longer expected design life (see Table 4.1). Furthermore, it can be observed from Tables 6.1, 6.8, and 6.13 that SL is most likely the best choice when criteria weighting for cost is in the range of 30-100%, design life in the range of 20-40%, and productivity in the range of 0-30%. SL is usually employed in circumstances where the structural capacity of the host culvert needs to be enhanced (Caltrans, 2013). On the contrary, SL may not be favored in circumstances where culvert flow capacity upon rehabilitation may not be reduced considerably (Caltrans, 2013).



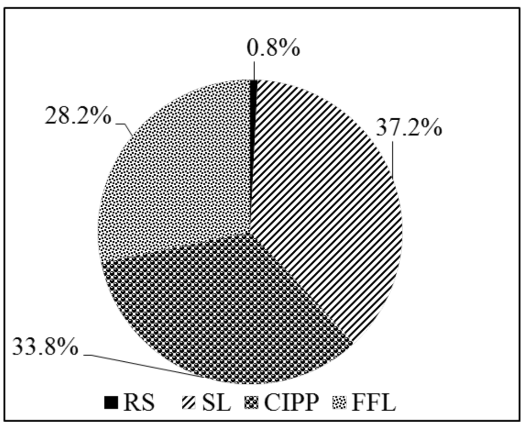
RCP	CMP	HDPE
Crack, $_{<36'', \text{major}}$		Crack, $_{<36'', \text{major}}$
	JI, $_{<36'', \text{major}}$	
	SD, $_{<36'', \text{moderate}}$	

(a)



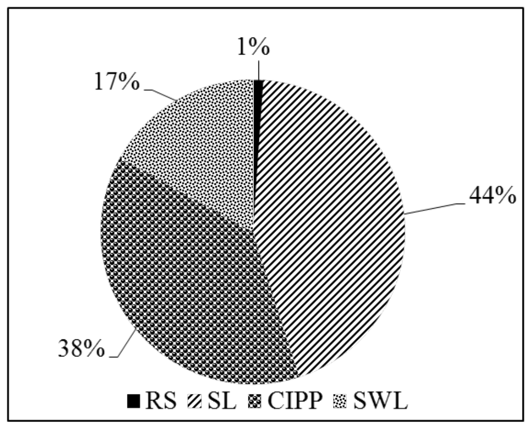
RCP	CMP	HDPE
Crack, $_{36\sim120'', \text{major}}$	Corrosion, $_{36\sim120'', \text{major}}$	
ID, $_{36\sim120'', \text{major}}$	ID, $_{36\sim120'', \text{major}}$	

(b)



RCP
ID, $_{<36'', \text{major}}$

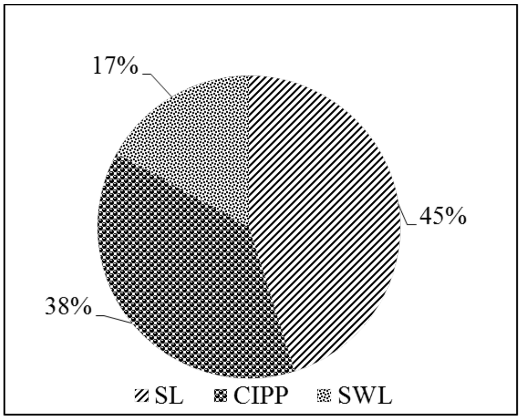
(c)



CMP
Corrosion, $_{<36'', \text{major}}$

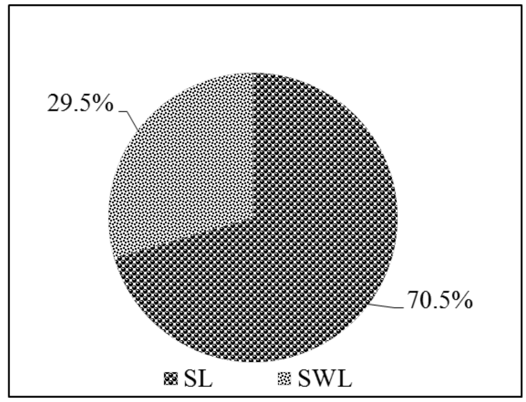
(d)

Figure 6.2 Superior performance of SL for various application scenarios (1)



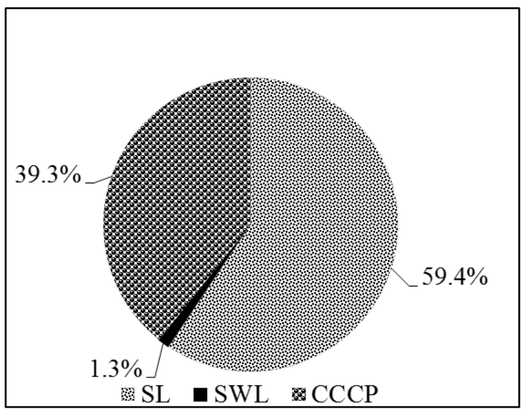
RCP
JI, $_{36" \sim 60", major}$

(e)



RCP
JI, $_{60\sim120", major}$

(f)



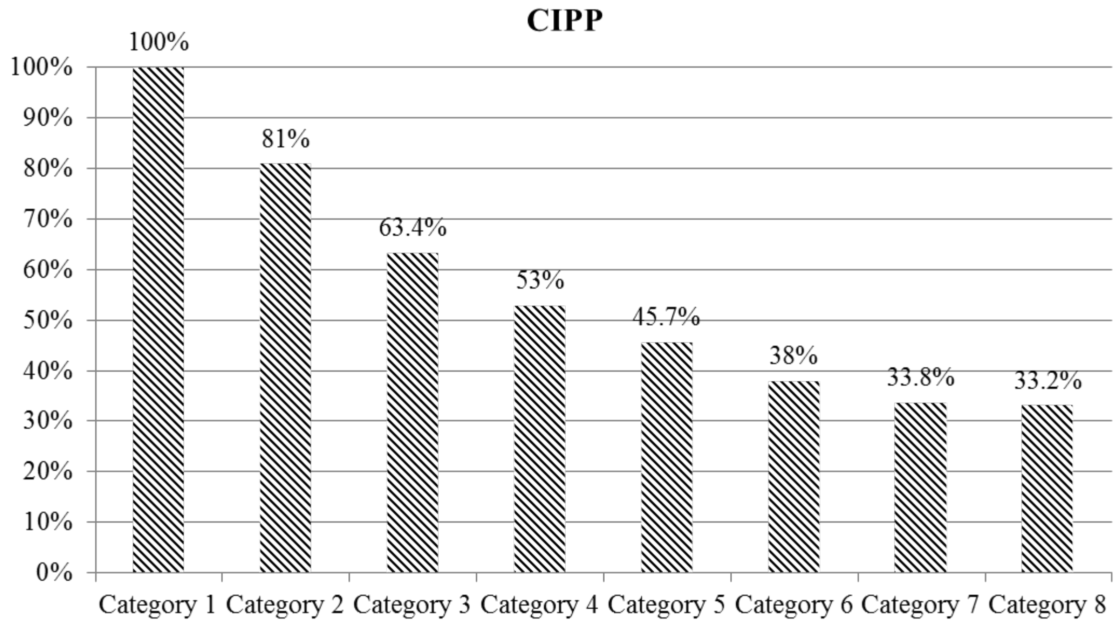
CMP
JI, $_{\mathbf{60\sim120", major}}$

(g)

Figure 6.3 Superior performance of SL for various application scenarios (2)

Suitability of Cured-in-place-pipe Lining (CIPP)

CIPP is found to be suitable for various application scenarios as can be seen in Figure 6.4, and this is mainly due to its broader application range in terms of host pipe material, size, and shape, and its flexibility to be used as a structural or non-structural liner (Ballinger and Drake, 1995; Caltrans, 2013; Mitchell et al., 2005; Meegoda et al., 2009; Hunt et al., 2010; Hollingshead and Tullis, 2009; Syachrani et al., 2010; and Yazdekhasti et al., 2014). CIPP is found to be the best suited method for application scenarios of categories 1, 2, 3, and 4, as can be seen in Figure 6.4. On the contrary, better suited alternatives are available for application scenarios of categories 5, 6, 7, and 8, as can be inferred form Figure 6.4.

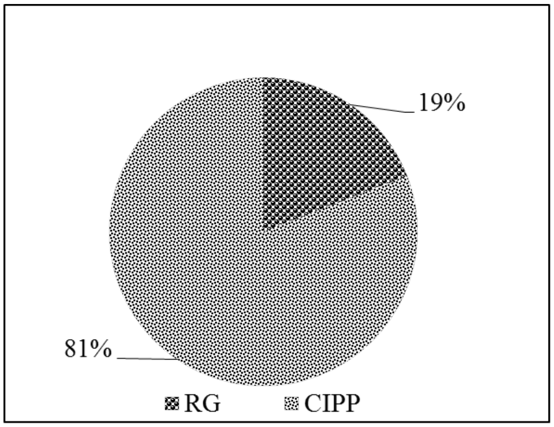


Category 1*	JM, RCP, CMP, & HDPE, 36" ~ 60", moderate	Category 5	JM, RCP, CMP, &HDPE, <36", moderate JI, RCP, <36", major
Category 2*	Crack, RCP & HDPE, <36", moderate JI, RCP & CMP, <36", moderate	Category 6	Corrosion, CMP, <36", major JI, RCP, 36" ~ 60", major
Category 3*	Corrosion, CMP, <36", minor ~ moderate	Category 7	Crack, RCP & HDPE, <36", major JI, CMP, <36", major SD, CMP, <36", moderate ID, RCP, <36", major Crack, RCP, 36~120", major
Category 4*	Crack, HDPE, 36~60", major SD, CMP, 36~60", moderate ~ major ID, CMP, <36", minor ~ major	Category 8	Crack, RCP, 36" ~ 60", moderate

Note: “*” indicates that CIPP is best suited for the corresponding application scenario

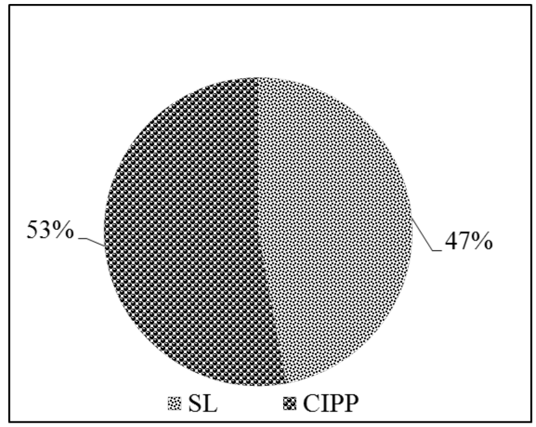
Figure 6.4 Percentage preference of CIPP for various application scenarios

Furthermore, Figure 6.5 illustrates the comparative performance of renewal techniques for application scenarios in which CIPP was found to be best choice. It can be observed from Figure 6.5(a) and also Tables 6.1, 6.8, and 6.13 that selection preference of CIPP for all the application scenarios identified in Figure 6.5(a) is 81%, while that of RG technique is 19%. The observed high percentage preference of CIPP technique can be attributed to the fact that CIPP, compared to RG, offers overwhelmingly longer design life (see Table 4.1). Furthermore, it can be observed from Tables 6.1, 6.8, and 6.13 that CIPP is most likely the best choice when criteria weighting for cost is in the range of 0~100%, design life in the range of 10-100%, and productivity in the range of 0-70%, while RG for all the scenarios identified in Figure 6.5(a) is most likely the best choice when criteria weighing for design life is in the range of only 0-10% and productivity in the range of 70-100%. CIPP is usually employed in many circumstances due to its flexibility; however, it may not be permitted in some states in circumstances where culvert flow may be at the risk of contamination from its use (Hollingshead and Tullis, 2009).



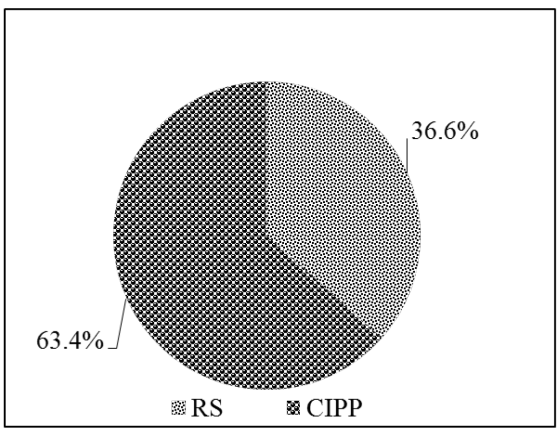
RCP	CMP	HDPE
Crack, $_{\text{<36", moderate}}$	-	Crack, $_{\text{<36", moderate}}$
JI, $_{\text{<36", moderate}}$	JI, $_{\text{<36", moderate}}$	-

(a)



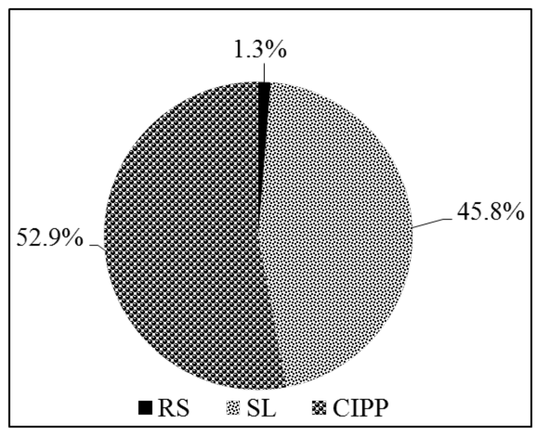
CMP	HDPE
-	Crack, $_{\text{36" ~ 60", major}}$
SD, $_{\text{36" ~ 60", moderate ~ major}}$	-

(b)



CMP
Corrosion, $_{\text{<36", minor ~ moderate}}$

(c)



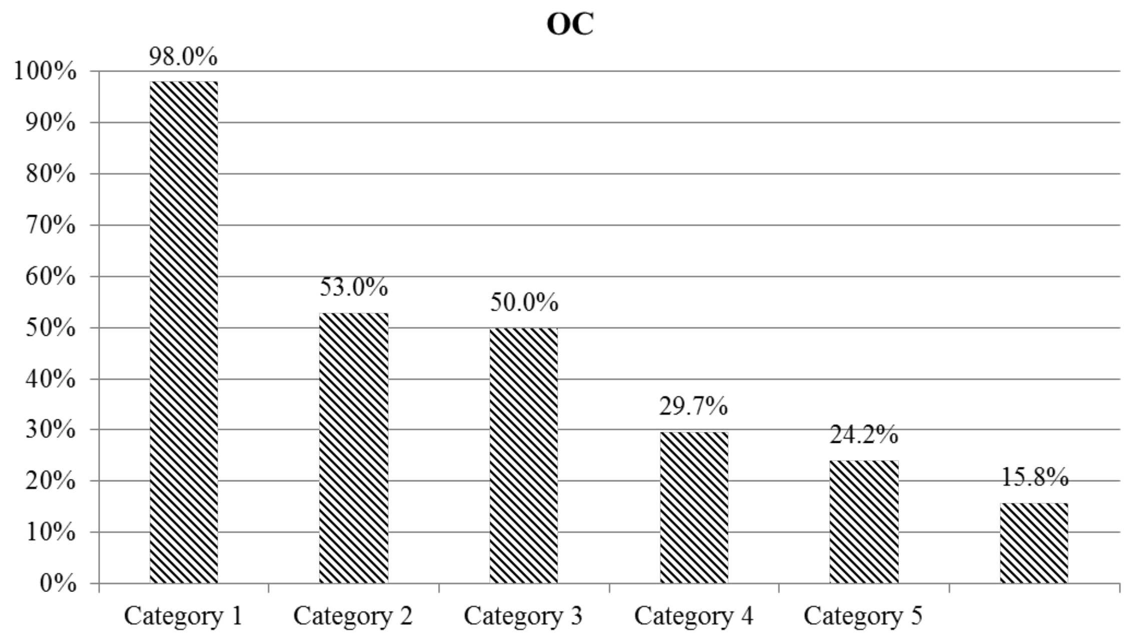
CMP
ID, $_{\textbf{<36", minor ~ major}}$

(d)

Figure 6.5 Superior performance of CIPP for various application scenarios

Suitability of Open-Cut Method (OC)

Traditional OC is found to be suitable for the application scenarios identified in Figure 6.6, and its suitability is driven by its familiarity worldwide. OC is found to be the best suited method for application scenarios of categories 1, 2 and 3 scenarios, as can be seen in Figure 6.6. On the contrary, better suited alternatives are available for application scenarios of categories 4 and 5, as can be inferred from Figure 6.6.

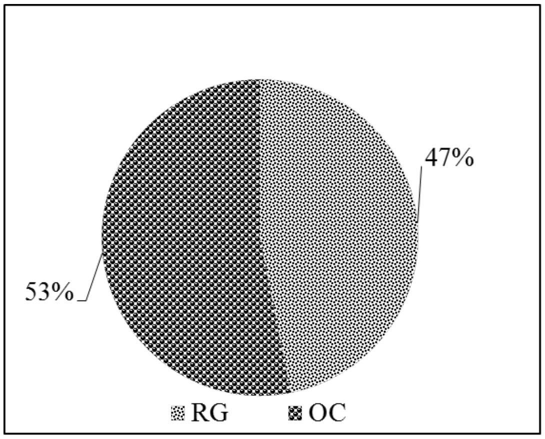


Category 1*	ID, RCP & CMP, 36“ ~ 120”, minor ~ moderate	Category 4	ID, RCP, <36", minor ~ moderate
Category 2*	Crack, RCP & HDPE<36", minor JI, RCP & CMP, <36", minor	Category 5	Crack, RCP & HDPE, 36“ ~ 120”, minor JI, RCP & CMP, 36“ ~ 120”, minor
Category 3*	JM, RCP, <36“, major	Category 6	Corrosion, CMP, 36“ ~ 120”, major

Note: “*” indicates that OC is best suited for the corresponding application scenario

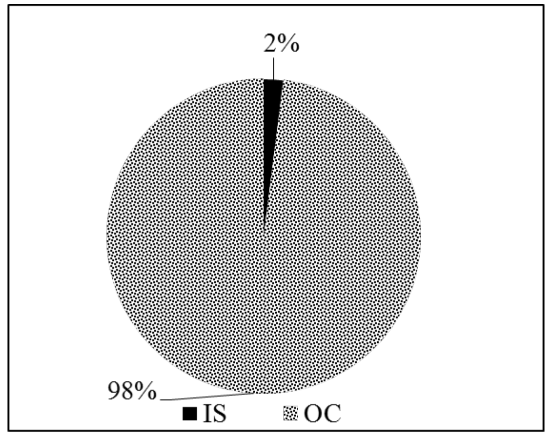
Figure 6.6 Percentage preference of OC for various application scenarios

Furthermore, Figure 6.7 illustrates the comparative performances of renewal techniques for applications scenarios in which OC technique is found to be the best choice. It can be observed from Figure 6.7(a) and also Tables 6.1, 6.2, 6.8, and 6.13 that selection preference of OC for all the application scenarios identified in Figure 6.7(a) is 53%, while that of RG is 47%. This seemingly even percentage preference of OC technique can be attributed to the fact that OC, compared to RG, offers longer expected design life, more productivity, and same range of repair cost (see Table 4.1); Furthermore, it can be observed from Tables 6.1, 6.2, 6.8, and 6.13 that RG is most likely the best choice when criteria weighting for design life is in the range of 0-30% and productivity in the range of 40-100% irrespective of the cost criterion weighting. Similarly, it can be observed from Tables 6.1, 6.2, 6.8, and 6.13 that OC is most likely the best choice when criteria weighting for design life is in the range of 30-100% and productivity in the range of 0-40% irrespective of cost criterion weighting. OC is usually employed in most circumstances except where the footprint and productivity constrained.



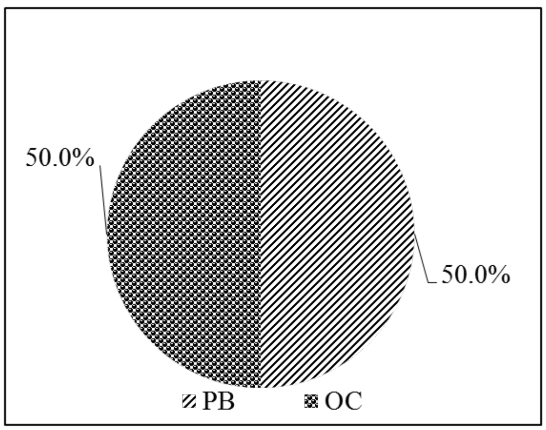
RCP	CMP	HDPE
Crack, $_{<36'', \text{minor}}$		Crack, $_{<36'', \text{minor}}$
JI, $_{<36'', \text{minor}}$	JI, $_{<36'', \text{minor}}$	

(a)



RCP	CMP
ID, $_{36'' \sim 120'', \text{minor} \sim \text{moderate}}$	ID, $_{36'' \sim 120'', \text{minor} \sim \text{moderate}}$

(b)



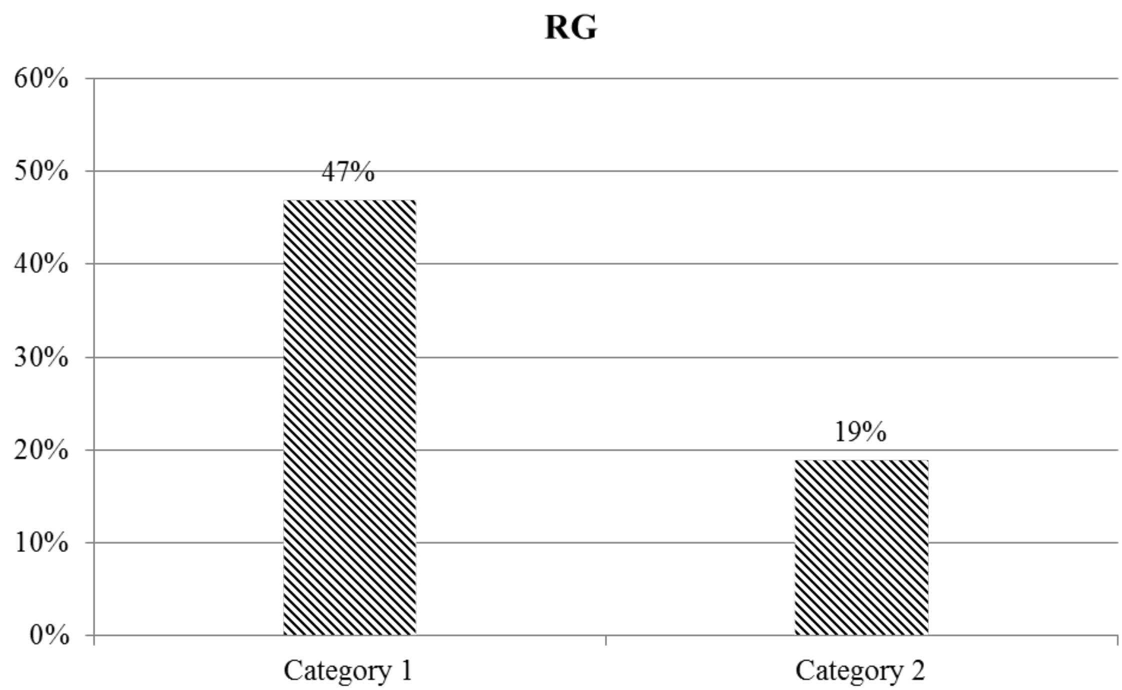
RCP
JM, $_{<36'', \text{minor}}$

(c)

Figure 6.7 Superior performance of OC for various application scenarios

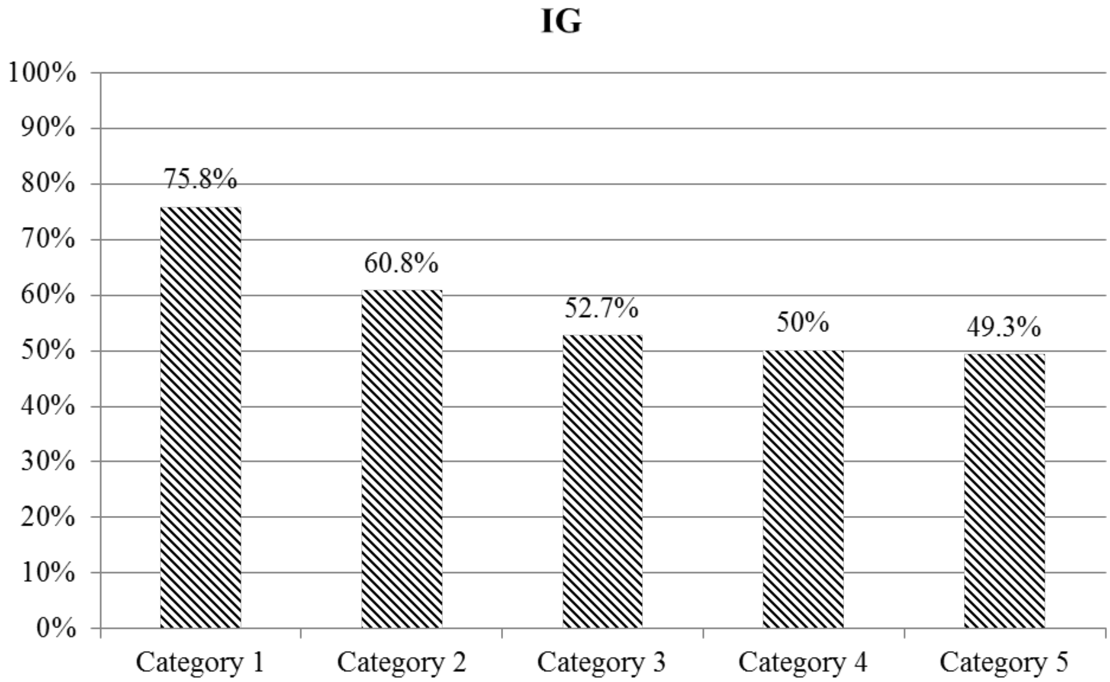
Suitability of Robotic Grouting (RG) and Internal Grouting (IG) Methods

RG and IG are found to be suitable for the application scenarios identified in Figures 6.8 and 6.9, respectively, and this suitability is mainly due to their effectiveness in addressing minor to moderate non-structural issues such as cracks and joint inflow/infiltration (Caltrans, 2013). RG is not found to be best suitable for either of the scenarios in Figure 6.8, whereas IG is found to the best suitable for scenarios of all categories, as can be seen in Figure 6.9. RG and IG are not suitable for any structurally deteriorated culverts and may not be permitted in environmentally sensitive areas due to contamination risks (Caltrans, 2013 and Hollingshead and Tullis, 2009).



Category 1	Crack, RCP & HDPE, <36", minor JI, RCP & CMP, <36", minor	Category 2	Crack, RCP & HDPE, <36", moderate JI, RCP & CMP, <36", moderate

Figure 6.8 Percentage preference of RG for various application scenarios

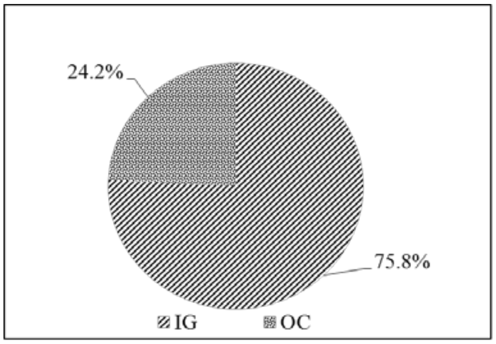


Category 1*	Crack, RCP & HDPE, 36" ~ 120", minor JI, RCP & CMP, 36" ~ 120", minor	Category 4*	Crack, RCP, 60" ~ 120", moderate
Category 2*	Crack, HDPE, 60~120", moderate JI, RCP & CMP, 60~120", moderate	Category 5*	Crack, RCP, 36" ~ 60", moderate
Category 3*	Crack, HDPE, 36" ~ 60", moderate JI, RCP & CMP, 36" ~ 60", moderate		

Note: “*” indicates that IG is best suited for the corresponding application scenario

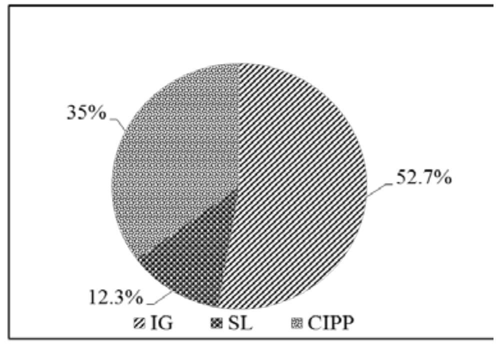
Figure 6.9 Percentage preference of IG for various application scenarios

Furthermore, Figure 6.10 illustrates the comparative performance of various culvert renewal techniques for application scenarios in which IG technique is found to be best choice. It can be observed from Figure 6.10(a) and also Tables 6.3, 6.4, 6.5, 6.6, 6.9, 6.11, and 6.14 that selection preference of IG for all the application scenarios identified in Figure 6.10(a) is 75.8%, while that of OC technique is 24.2%. The observed high percentage preference of IG technique can be attributed to the fact that IG, compared to OC, costs less and less productive, even though OC technique offers exceedingly longer design life (see Table 4.1). Furthermore, it can be observed from Tables 6.3, 6.4, 6.5, 6.6, 6.9, 6.11, and 6.14 that IG is most likely the best choice when criteria weighting for cost is in the range of 10-100%, design life in the range of 0-50%, and productivity in the range of 0-100%. It should also be noted that IG is only suitable for addressing non-structural issues in culverts and it may be sensible to go with it when suitable compared to OC (a structural solution) which may be more expensive and inconvenient.



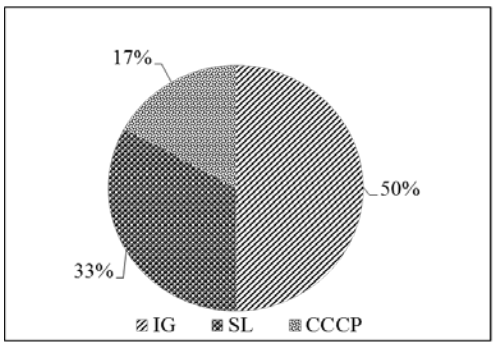
RCP	CMP	HDPE
Crack, $_{36'' \sim 120'', \text{minor}}$	-	Crack, $_{36'' \sim 120'', \text{minor}}$
JI, $_{36'' \sim 120'', \text{minor}}$	JI, $_{36'' \sim 120'', \text{minor}}$	-

(a)



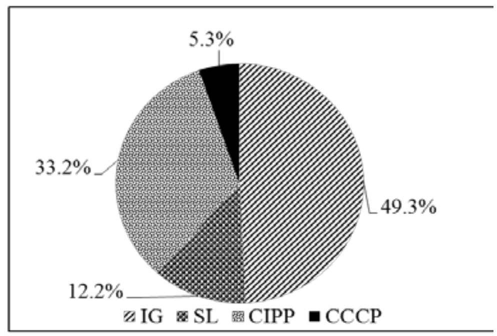
RCP	CMP	HDPE
-	-	Crack, $_{36'' \sim 60'', \text{moderate}}$
JI, $_{36'' \sim 60'', \text{moderate}}$	JI, $_{36'' \sim 60'', \text{moderate}}$	-

(b)



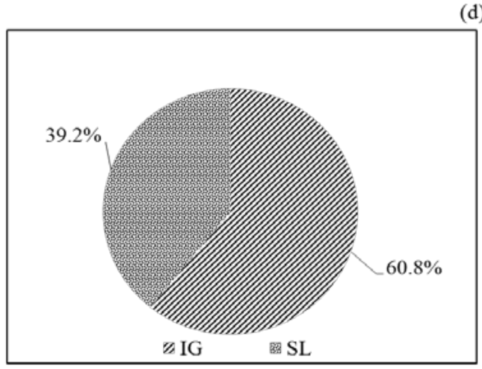
RCP
Crack, $_{60'' \sim 120'', \text{moderate}}$

(c)



RCP
Crack, $_{36 \sim 60'', \text{moderate}}$

(d)



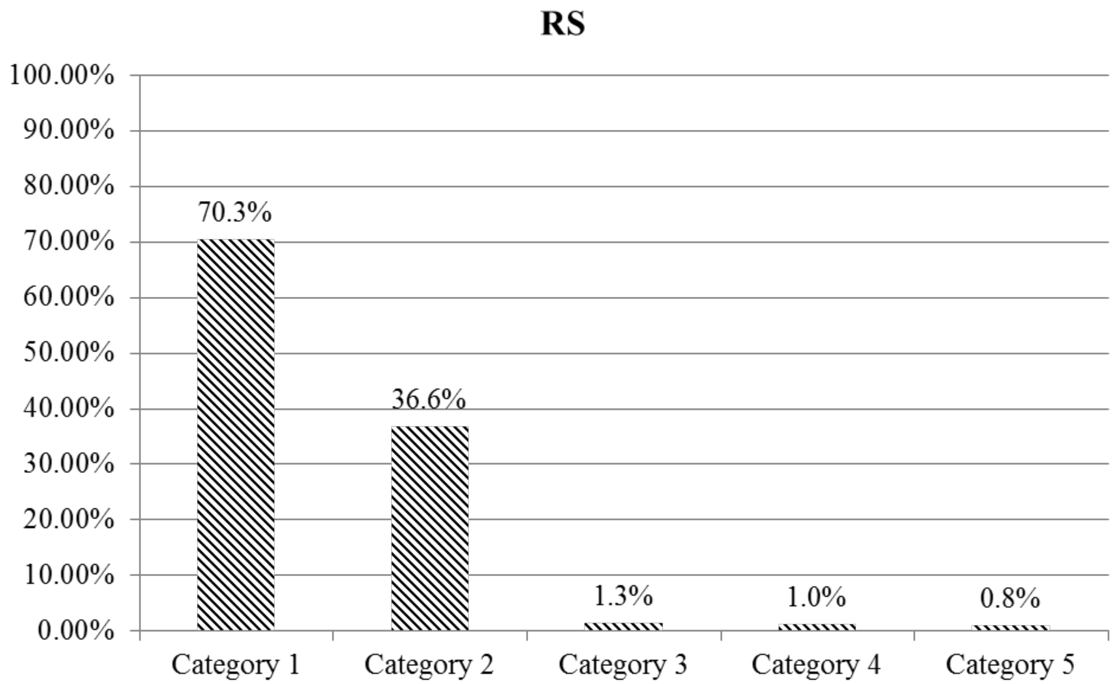
RCP	CMP	HDPE
-	-	Crack, $_{60 \sim 120'', \text{moderate}}$
JI, $_{60 \sim 120'', \text{moderate}}$	JI, $_{60 \sim 120'', \text{moderate}}$	-

(e)

Figure 6.10 Superior performance of IG for various application scenarios

Suitability of Robotic Shotcrete (RS) and Internal Shotcrete (IS) Methods

RS and IS are found to be suitable for application scenarios in Figure 6.11and 6.12 and this is mainly due to their effectiveness in creating a corrosion barrier for metal (Caltrans, 2013). RS is found to be the best suited method for application scenarios of category 1, as can be seen in Figure 6.11. On the contrary, better suited alternatives are available for applications scenarios of categories 2, 3, 4, and 5, as can be inferred from Figure 6.11. However, IS, compared to RS, is not selected as the best choice for any application scenario. RS and IS are usually employed for providing corrosion barrier to rebar in RCP and to CMP culverts; however, similar to RG and IG, it may not be permitted in environmentally sensitive areas due to contamination risks (Caltrans, 2013).



Category 1*	ID, RCP, <36", minor ~ moderate	Category 4	Corrosion, CMP, <36", major
Category 2	Corrosion, CMP, <36", minor ~ moderate	Category 5	ID, RCP, <36", major
Category 3	ID, CMP, <36", minor ~ major		

Note: “*” indicates that RS is best suited for the corresponding application scenario

Figure 6.11 Percentage preference of RS for various application scenarios

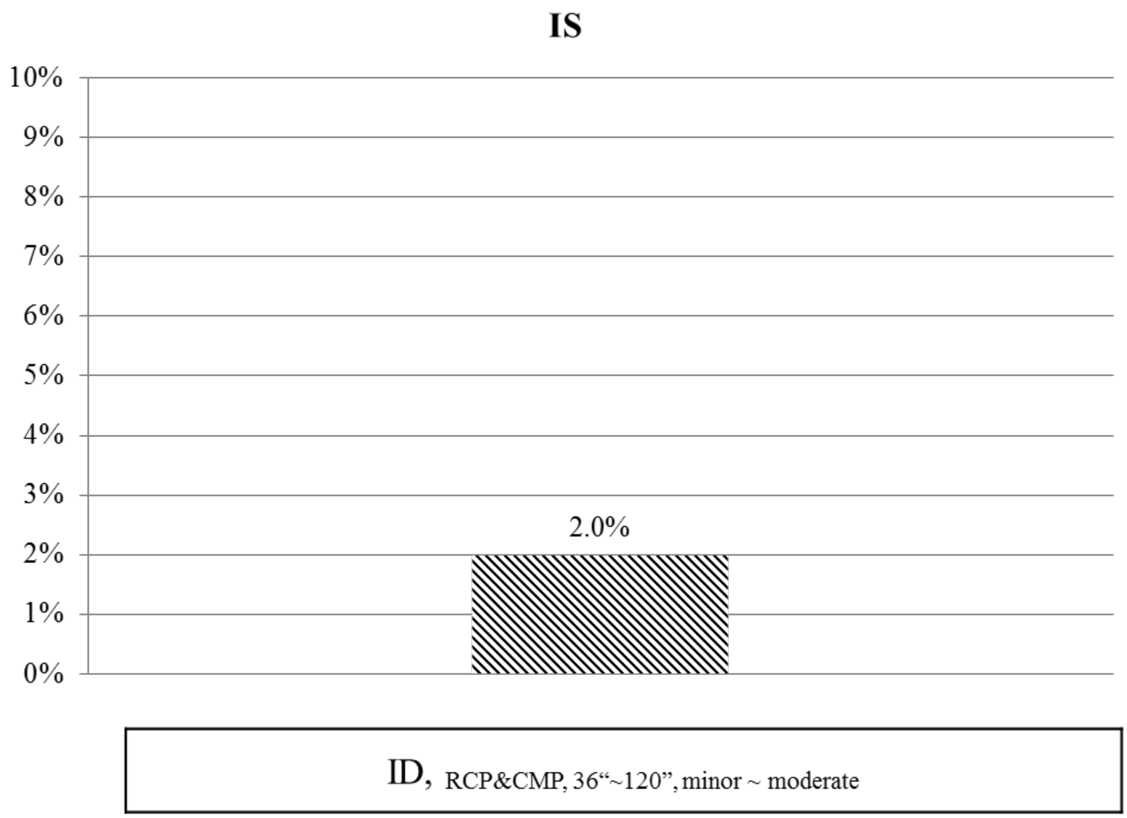


Figure 6.12 Percentage preference of IS for various application scenarios

Furthermore, Figures 6.13 illustrates the comparative performance of various culvert renewal techniques for application scenarios in which RS was found to be the best choice. It can be observed from Figure 6.13 that RS is best preferred only for ID $_{\text{RCP, <36", minor ~ moderate}}$ scenario with a selection preference of 70.3% while that of OC technique is 29.7%, as shown in Figure 6.13 and Table 6.2. The observed higher percentage preference of RS technique can be attributed to the fact that RS, compared to OC, costs less, even though RS technique offers a little shorter design life (see Table 4.1). It can also be observed from Table 6.2 that RS for ID$_{\text{RCP, <36", minor-moderate}}$ scenario in Figure 6.13

is most likely the best choice when criteria weighting for cost is in the range of 20-100%, design life in the range of 0-60%, and productivity in the range of 0-100%.

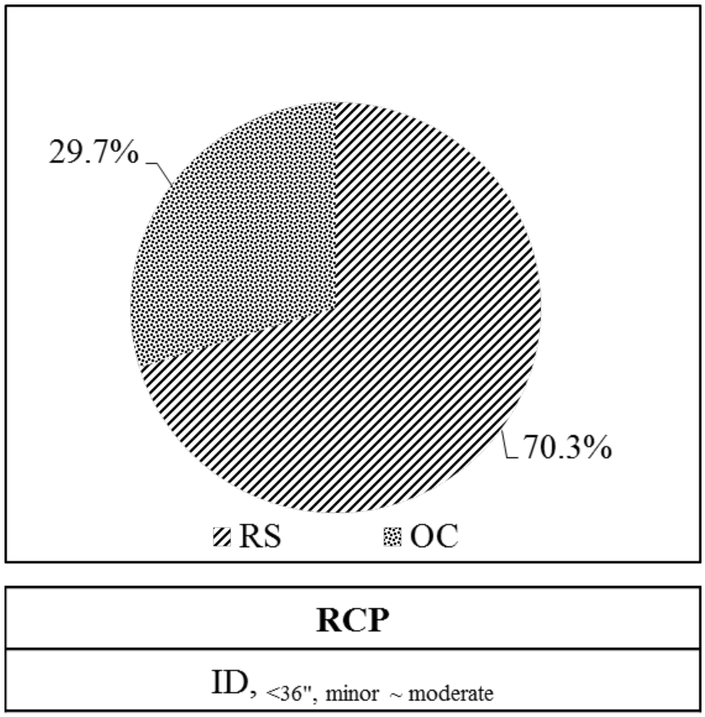
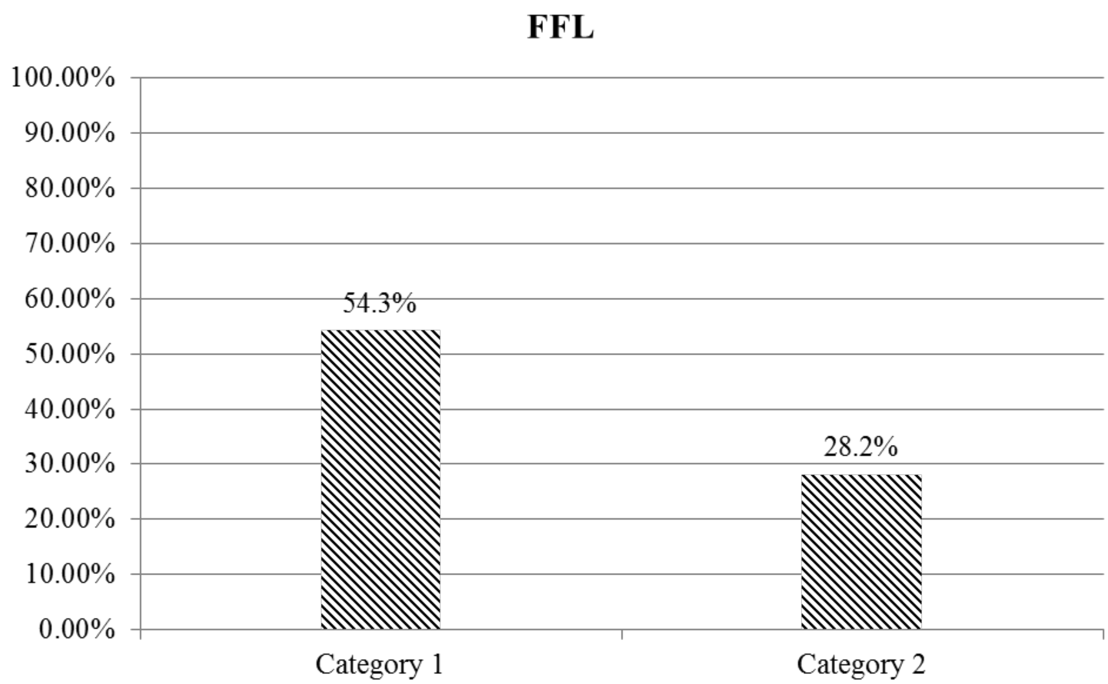


Figure 6.13 Superior performance of RS for various application scenarios

Suitability of Fold and Form Lining Method (FFL)

FFL is found to be suitable for application scenarios identified in Figure 6.14, and this is mainly due to its limitations of culvert size – it is only suitable for culverts which are less than 36 inches in diameter. FFL is found to be the best suited method for application scenarios of category 1, as can be seen in Figure 6.14. On the contrary, better suited alternatives are available for application scenarios of category 2 as can be inferred from Figure 6.14. FFL may be preferred in situations where negligible reduction in culvert capacity is desired (Hunt et al., 2010). On the contrary, FFL may not be favored in non-circular or larger (i.e., >36 inches) diameter culverts (Ballinger and Drake, 1995; Caltrans, 2013; Mitchell et al., 2005; Meegoda et al., 2009; Hunt et al., 2010; Hollingshead and Tullis, 2009; Syachrani et al., 2010; and Yazdekhasti et al., 2014).

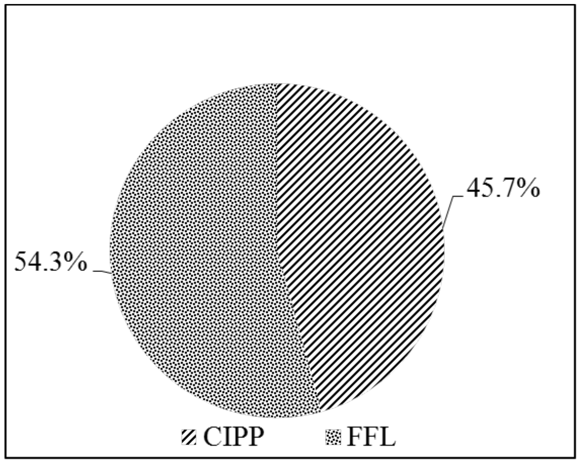


Category 1*	JM, RCP, CMP, &HDPE, <36", moderate JI, RCP, <36", major	Category 2	Crack, RCP & HDPE, <36", major JI, CMP, <36", major SD, CMP, <36", moderate ID, RCP, <36", major

Note: “*” indicates that FFL is best suited for the corresponding application scenario

Figure 6.14 Percentage preference of FFL for various application scenarios

Furthermore, Figure 6.15 illustrates the comparative performances of various culvert renewal techniques for application scenarios in which FFL is found to be best choice. It can be observed from Figure 6.15(a) and also Tables 6.1, 6.2, 6.7, and 6.13 that selection preference of FFL for all the application scenarios identified in Figure 6.15(a) is 54.3% while that of CIPP technique is 45.7%. The observed relatively high percentage preference of FFL technique can be attributed to the fact that FFL, compared to CIPP, offers longer expected design life and less productivity (see Table 4.1). Furthermore, it can be observed from Tables 6.1, 6.2, 6.7, and 6.13 that FFL is most likely the best choice when criteria weighting for cost is in the range of 30~100%, design life in the range of 0~30%, and productivity in the range of 40~100%, whereas CIPP is best suited when criteria weighting for cost is in the range of 0~40%, design life in the range of 30~100%, and productivity in the range of 0~40%.

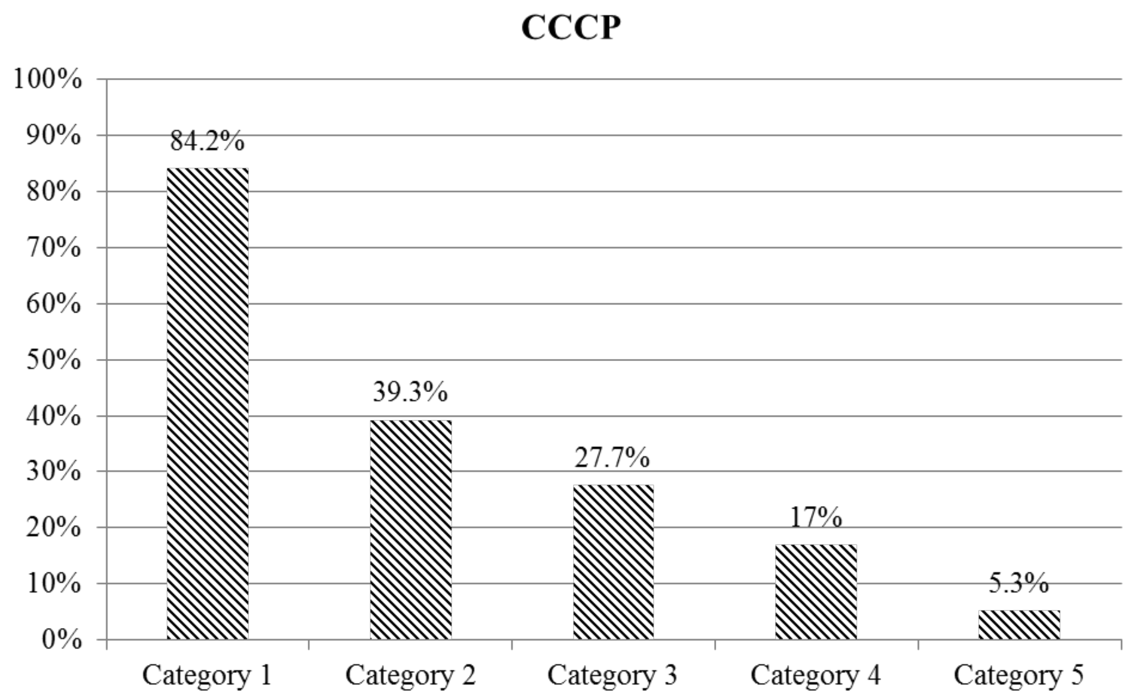


RCP	CMP	HDPE
JM, $_{<36", moderate}$	JM, $_{<36", moderate}$	JM, $_{<36", moderate}$
JI, $_{<36", major}$		

Figure 6.15 Superior performance of FFL for various application scenarios

Suitability of Centrifugally-Cast Concrete Pipe Lining (CCCP)

CCCP is found to be suitable for application scenarios identified in Figure 6.16. CCCP is found to be the best suited method for application scenarios of category 1, as can be seen in Figure 6.16. On the contrary, better suited alternatives are available for application scenarios of categories 2, 3, 4, and 5, as can be inferred from Figure 6.16.

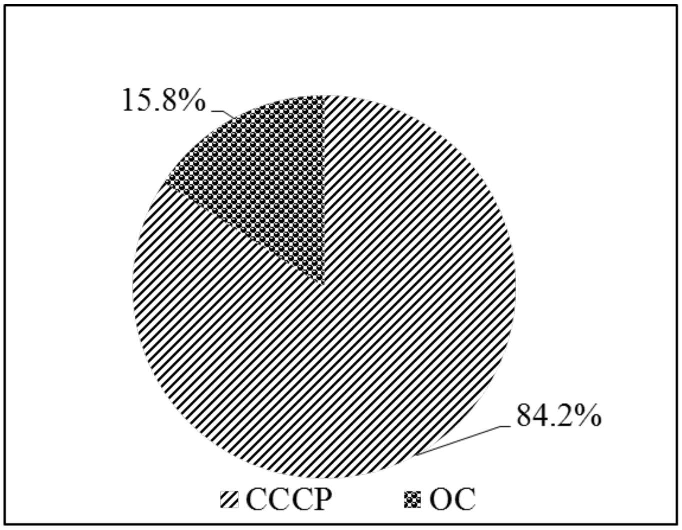


Category 1*	Corrosion, CMP, 36" ~ 120", major	Category 4	Crack, RCP, 60" ~ 120", moderate
Category 2	JI, CMP, 60~120", major	Category 5	Crack, RCP, 36" ~ 60", moderate
Category 3	Crack, RCP, 36~60", major Corrosion, CMP, 36~120", major ID, RCP & CMP, 36~120", major		

Note: “*” indicates that CCCP is best suited for the corresponding application scenario

Figure 6.16 Percentage preference of CCCP for various application scenarios

Furthermore, Figure 6.17 illustrates the comparative performances of culvert renewal techniques for application scenarios in which CCCP was found to be the best choice. It can be observed from Figure 6.17 that CCCP is best preferred only for Corrosion $_{\text{CMP, 36-120", minor-moderate}}$ scenario. It can be observed from Figure 6.17 that selection preference of CCCP for the application scenario in Figure 6.17 is 84.2%, while that of OC technique is 15.8%. The observed high percentage preference of CCCP technique can be attributed to the fact that CCCP, compared to OC, costs less and has considerably less productivity, even though CCCP technique offers relatively shorter expected design life (see Table 4.1). OC and CCCP fundamentally offer different capabilities and it is sensible to go with CCCP when it is suitable compared to OC which is a structural solution that is expensive and inconvenient to the owner. It can also be observed from Tables 6.9 and 6.11 that CCCP is most likely the best choice for the Corrosion $_{\text{CMP, 36-120", minor-moderate}}$ scenario when criteria weighting for cost is in the range of 0-100%, expected design life in the range of 0-60%, and productivity in the range of 0-100%.

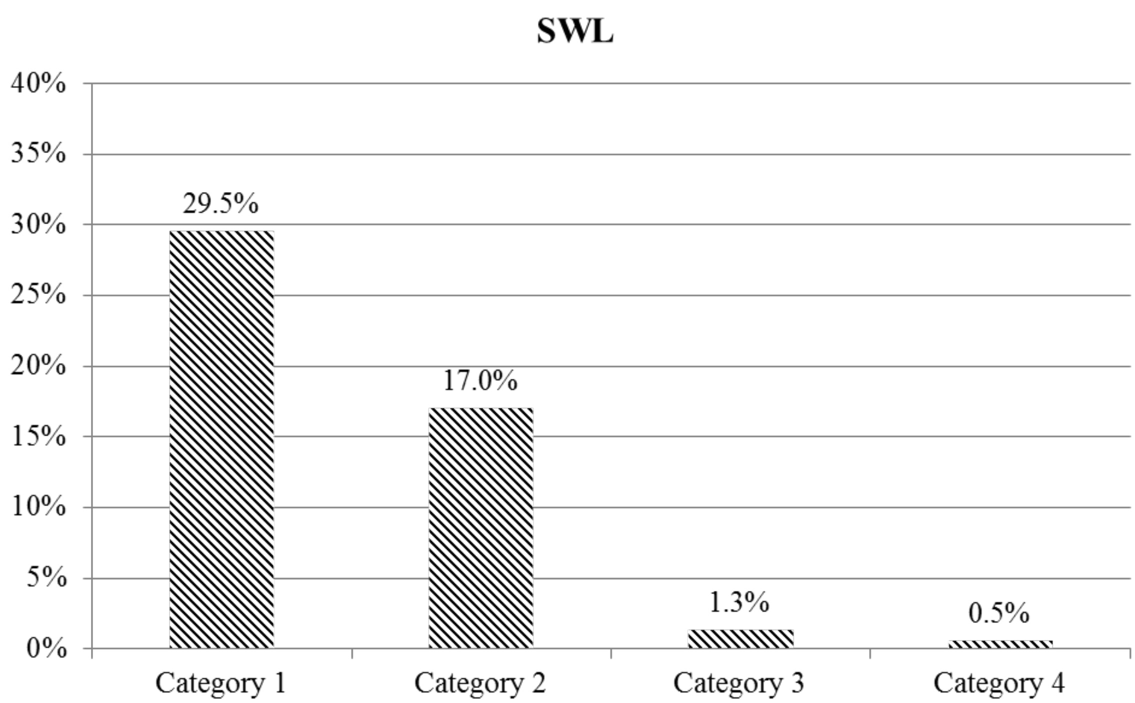


CMP
Corrosion, 36~120", minor ~ moderate

Figure 6.17 Superior performance of CCCP for various application scenarios

Suitability of Spiral-Wound Lining Method (SWL)

SWL is found to be suitable for application scenarios identified in Figure 6.18 due to its suitability to certain major defect severity scenarios (see Table 4.1). SWL is not found to be best suited for any of the scenarios identified in Figure 6.18. SWL may be preferred when there is not a lot of working space available on the jobsite; however, it may not be favored at all in situations where culvert flow capacity upon rehabilitation may not be reduced.

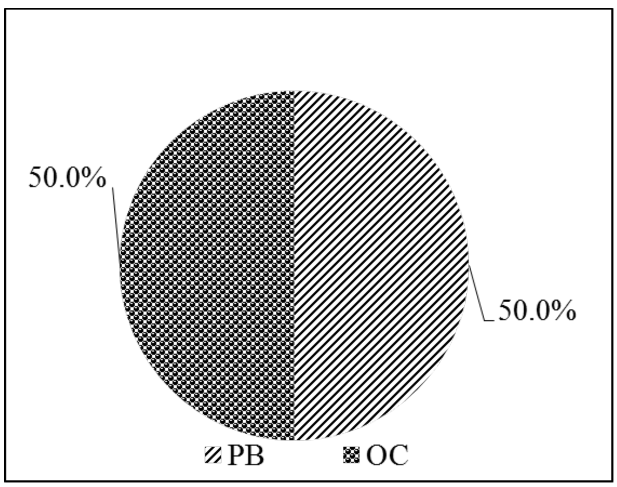


Category 1	JI, RCP, 60~120", major	Category 3	JI, CMP, 60~120", major
Category 2	JI, RCP, 36~60", major Corrosion, CMP, <36", major	Category 4	Crack, RCP, 36~60", major Corrosion, CMP, 36~120", major ID, RCP & CMP, 36~120", major

Figure 6.18 Percentage preference of SWL for various application scenarios

Suitability of Pipe Bursting Method (PB)

Figure 6.19 illustrates the comparison for application scenarios in which PB was found to be the best choice. It can be observed form Figure 6.19 and Table 6.1 that selection preference of PB and OC are same with 50% each for JM, $_{\text{RCP, <36“, major}}$ scenario. This is due to the similar performance of PB as that of OC, as shown in Table 4.1. PB is often used in RCP culverts with small size diameter; however, it may not be favored in CMP culverts with large diameter. PB is uniquely suited to upsize the culvert size and this capability has not been considered in any of the applications scenarios and this is one of the reasons for the observed low preferences of PB technique.



RCP
JM, <36“, major

Figure 6.19 Superior performance of PB for various application scenarios

Chapter Summary

This chapter presented the findings of this study resulted from the demonstration of CREST for various application scenarios using 10,000 Monte-Carlo simulations for each scenario. The resulting findings were discussed and appropriate justifications were provided. The limitations in terms of the applicability of the findings are also discussed in this chapter.

CHAPTER SEVEN

VALIDATION OF THE FINDINGS

In order to strengthen the findings presented in Chapter 6, this chapter describes the validation effort undertaken and summarizes the results of the same. Validation is a scientific process used to confirm that the research approach is indeed suitable for meeting the desired objectives. In the context of this study, validation measures the capability of the proposed analytical model to truly predict the desired outcome in terms of optimal selection of culvert renewal techniques. A validated tool or model can be used to judge the quality, reliability and consistency of analytical results (Ludwig Huber, 1998). Validation techniques are usually different for quantitative and qualitative research studies (Golafshani, 2003). There is less clarity on the need and appropriateness of various validation techniques for qualitative studies and it is suggested to be affected by the researcher's perception of validity (Creswell and Miller, 2000). As a result, several previous researchers have themselves devised validation techniques that they considered appropriate (Davies and Dodd, 2002; Lincoln and Guba, 1985; Seale, 1999; and Stenbacka, 2001).

A novel approach, called practice-based reflective validation (PRV), has been devised and employed in this quasi-qualitative study to validate both CREST and the resulting findings presented in Chapter 6. In the PRV approach, expert knowledge for determining culvert renewal method selection preferences in real world is tapped. Several design consultants (or experts) work closely with culvert asset managers to thoroughly understand each culvert renewal scenario and subsequently evaluate the most suitable technique that meets the preferences (i.e., in terms of budget, traffic impacts, and etc.) of the owners. The assumptions made in this kind of validation method are that the expert decisions are rational and unbiased. Instead of surveying these experts, which could be a time consuming procedure and may also result in insignificant response rate, various real-world culvert renewal case studies are documented. The rationale is that the expertise of design consultants is embedded in the selection preferences of real-world culvert renewal projects and therefore, these case studies will serve as a good measure of the validity of CREST. Twenty six real-world case studies are documented to employ the PRV approach. The twenty six cases captured a wide range of application scenarios as shown in Table 7.1. All these cases involved either RCP or CMP culverts which are the most concerning culvert materials to transportation agencies. These case studies are collected from both consultants' and contractors' websites. To ensure the reliability of the validation, it is ideal to obtain data from consultants/contractors that are capable of using several of the studied renewal methods; however, there were few contractors that are experienced in multiple trenchless renewal techniques. Consequently, data is obtained from consultants/contractors who are experienced with as many renewal techniques as possible. The actual renewal technique selected in each of the 26 cases is compared to the predicted technique from CREST, as shown in Tables 7.2, 7.3 and 7.4.

Twenty-two (85%) out of the 26 documented projects are from 12 different states in the U.S., whereas the remaining five (15%) are from other countries. The information gathered for each project includes year of renewal, asset owner, contractor, culvert material, shape, size, length, major defect, and selected renewal technique. Appendix B presents all these details for all the 26 case studies.

A validation measure called *validation score* is defined and used in the proposed PRV approach to quantify the comparison of the predicted and actual renewal technique selections in each of the 26 case studies. The *validation score* (VS_j) is calculated using Eq. 7.1.

$$VS_j = \frac{PP_{i,j}}{\max_{k \in n} PP_{k,j}} \qquad 7.1$$

Where, VS_j is validation score for application scenario j, $PP_{i,j}$ is the percentage preference of the actual renewal technique i as per CREST for application scenario j; n is the number of renewal techniques considered to be suitable for a given application scenario j.

CREST has been used to estimate selection preferences of various suitable culvert renewal methods to each of the 26 project scenarios documented. The validation score will be one when the best suitable renewal method as per CREST is same as the actual renewal technique used in a given project. The validation score will proportionately diminish if the predicted best suitable method is different from the actual renewal method. The comparison of the actual renewal technique selected and the predicted preferences of various suitable renewal methods are presented in Table 7.2 for RCP culvert projects, and Table 7.3 for CMP projects. As can be observed from Tables 7.2 and 7.3, the actual renewal method selected and the predicted best suitable method (as per CREST) is the same in 13 out of the 26 cases (or 50% of the cases) resulting in a validation score of 1. It can be observed from Tables 7.2 and 7.3 that the actual renewal method is the second best suitable method as per CREST in four cases resulting in a validation score 0.89. Similarly, validation scores in Tables 7.2 and 7.3 for all the other cases can be interpreted. The mean and median validation scores for the 26 case studies synthesized are 0.8 and 0.95 respectively, which highlights the trustworthiness of CREST and the findings of this study.

It is understandable that in a few cases, the actual technique selections are different from the predicted techniques which are derived for average application scenarios. It can be observed from the comparison presented in Tables 7.2 and 7.3 that SWL method has been used in a few projects where SL was found to be best suitable as per CREST. Case study #2 is an example for this disparity. In case study #2, the culvert in Lakehurst Naval Air Station, NJ has deteriorated to an extent where it is no longer hydraulically or structurally adequate. Without considering any other constraints in this project, it seems that SL would be suitable and it has even been determined by CREST as the best choice. In reality however, this project had tight space constraints which probably made the project team go with SPR™ PE technique, a type of SWL method, that enabled the project team re-line the culvert by accessing it through the manhole structure (Contech, 2014a).

To further fine tune the predicted results based on the unique constraints observed in some of the synthesized case studies, the predictive model has been run again with specific range of criteria weightings. For example, assess the percentage preference of the predicted culvert renewal techniques in case study #2 where space constraints uniquely challenged the project are re-evaluated using CREST through 10,000 Monte-Carlo simulations after a fourth space constraints criteria. It has been found that SWL is the second best suitable method with a selection preference of 29.3%, while the selection preferences of SL, CIPP, and CCCP techniques are 25.4%, 30.6%, and 14.8%, respectively. Furthermore, another 100 Monte-Carlo simulations are conducted on the basis of specific ranges of weightings to the four decision criteria after acquiring as much practical information as possible for case study #2. The space constraints criterion is considered as the most significant with weightings between 30% and 40% and productivity criteria is considered as second most significant criteria with weightings between 20% and 30%. Cost and design life criteria are considered with weightings between 15% and 25%. It has been found that SWL is the most preferred technique with a selection preference of 89%, while that of CCCP technique is 11%. These adjusted predictions for case study #2 demonstrate that capability of CREST in accommodating unique constraints as long as the user provides appropriate criteria weightings.

Similarly, other disparities observed in this validation effort can be attributed to the unique project constraints that are difficult to generalize.

Table 7.1 Selected culvert defects and case studies for validation

Material	Major defect	# of Case studies
RCP	Crack	2
	Invert deterioration	5
	Multiple defects	3
CMP	Corrosion	10
	Invert deterioration	2
	Joint separation	1
	Multiple defects	3

<u>Chapter Summary</u>

This chapter described the practice-based reflective validation (PRV) procedure followed to validate CREST. Twenty six real-world culvert renewal projects were synthesized and the actual construction methods were compared to the predicted ones using CREST. The actual and predicted renewals methods were found to be the same in 50% of the document projects. A measure called the validation score is proposed and used to quantitatively analyze the comparison of actual renewal methods to the predicted ones. With mean and median validation scores of 0.8 and 0.95, CREST is found to produce results that reasonably reflect the current practice in the industry.

Table 7.2 Validation of findings for RCP

Case	Year	Shape	Size (in)	Length (ft)	Major defect	Actual technique selection	References	Predicted choice	Validation score
1	Unknown	Circular	24	18	Crack	SL	Contech, 2016	SL: 38% CIPP: 33.8% FFL: 28.2%	1
2	2014	Circular	48	786	ID	SWL	Contech, 2014a	SL: 38% CIPP: 33.8% CCCP: 27.7% SWL: 0.5%	0.013
3	2014	Circular	54	703	ID	SWL	Contech, 2014a		0.013
4	2012	Circular	54	300	Crack	SL	Contech, 2012a		1
5	2010	Circular	96	500	ID	SL	Contech, 2010		1
6	2012	Box	120	80	ID	SL	Contech, 2012b		1
7	2013	Circular	144	360*2	ID	SL	Contech, 2013		1
8	2012	Circular	72	Unknown	Multiple	SL	Contech, 2012c		1
9	2014	Circular	96	42	Multiple	SL	Contech, 2014b		1
10	2014	Circular	120	1500	Multiple	SL	Contech, 2014c		1

Table 7.3 Validation of findings for CMP

Case	Year	Shape	Size (in)	Length (ft)	Major defect	Actual technique selection	References	Predicted choice	Validation score
11	2010	Circular	36	160	Corrosion	CIPP	Insituform, 2010	SL: 38% CIPP:33.8% CCCP:27.7% SWL: 0.5%	0.89
12	2010	Circular	36	160	Corrosion	CIPP	Insituform, 2010		0.89
13	2010	Circular	36	80	Corrosion	CCCP	MDOT, 2012		0.73
14	2013	Circular	45	550	Corrosion	SWL	MDOT, 2012		0.013
15	2010	Circular	48	260	Corrosion	CIPP	Insituform, 2010		0.89
16	2010	Circular	48	260	Corrosion	CIPP	Insituform, 2010		0.89
17	Unknown	Circular	60	220	Corrosion	CCCP	Milliken, 2015a		0.73
18	2013	Circular	66	25	Corrosion	CCCP	Milliken, 2013		0.73
19	2015	Circular	132	106	Corrosion	SL	Contech, 2015a		1
20	2014	Circular	74	38*2	ID	SL	Contech, 2014e		1
21	2014	Ellipse	72	2208	ID	SL	Contech, 2015b		1
22	Unknown	Circular	66	130	Multiple	CCCP	Milliken, 2015c		0.73
23	Unknown	Arch	72	700	Multiple	CCCP	Milliken, 2015d	SL: 59.4%, CCCP:40.6%,	0.68
24	2012	Circular	120	86	Multiple	SL	Contech, 2012d		1
25	2013	Circular	18~36	6000	Corrosion	SL	Contech, 2014d	SL: 44% CIPP: 38.1% SWL: 16.9% RS: 1.1%	1
26	Unknown	Circular	120	300	JI	CCCP	Milliken, 2015b	SL: 59.4%, CCCP:39.3%, SWL: 1.3%	0.66

CHAPTER EIGHT

CONCLUSIONS AND RECOMMENDATIONS

Healthy culvert infrastructure is crucial for continuous and safe functioning of transportation systems that serve our societies. Due to the culverts being out of sight, they often get ignored when it comes to financial resource allocation, and the resulting consequences are becoming evident in the form of increasing number of culvert failures. Among several challenges that culvert infrastructure managers currently face, decision-making tools that provide guidance in the selection of appropriate rehabilitation techniques is paramount. This study evaluated 11 culvert renewal techniques and proposed a decision-making tool called the Culvert REnewal Selection Tool (CREST) for the selection of an optimal method given the prevailing defect in a known culvert material and severity. The renewal alternatives evaluated in this study include open-cut method, internal grouting through human entry, robotic grouting, internal shotcrete through human entry, robotic shotcrete, slip-lining, cured-in-place pipe, fold and form lining, spiral-wound lining, centrifugally-cast concrete pipe lining, and pipe bursting. CREST is based on the principles of analytical hierarchy process (AHP) in which the renewal alternatives are rated for three criteria that most likely influence the culvert rehabilitation or replacement decision making process. The three influential criteria considered include cost, expected design life, and productivity. CREST determines the optimal culvert renewal techniques given the application scenario (which is defined by culvert material, size, prevailing defect and defect severity) and user preferences in terms of percentage weightings for the three decision criteria.

CREST is demonstrated for various application scenarios that cover different culvert materials, sizes, defects and severities. The application scenarios cover the reinforced concrete pipe (RCP), corrugated metal pipe (CMP), and high density polyethylene (HDPE) materials. The size ranges covered include “<36 inches,” “≥ 36 inches and < 60 inches,” and “≥ 60 inches and < 120 inches.” Various defects that are commonly observed in RCP, CMP and HDPE culverts are covered by categorizing their severities into “minor,” “moderate,” and “severe.”

User-defined criteria weightings are required to determine the optimal culvert renewal technique preferences for the application scenarios. Numerous factors influence the criteria weightings in real-world decision making and those factors include but not limited to culvert defects, specific field constraints, performance expectations, location severities, cost limitations, and environmental sensitivities. Given the multitude of factors that influence the criteria weightings and the associated uncertainty, 10,000 Monte-Carlo simulations are used to randomly generate and assign criteria weightings for demonstrating CREST for each application scenario.

Findings from the demonstration of CREST for various application scenarios include:

- IG and RG are suitable for repairing minor to moderate cracks and joint in/exfiltration issues.

- RS is suitable for repairing minor to moderate invert deterioration issues in smaller (<36 inches in diameter or width) RCP and CMP culverts and minor to moderate corrosion issues in smaller size (<36 inches in diameter or width) CMP culverts.
- IS is suitable for repairing minor to moderate invert deterioration issues in larger (≥ 36 inches in diameter or width) CMP culverts.
- All renewal techniques, except IS, RG, and SWL, are suitable for at least one application scenario. This is due to their relatively lower ratings for the three decision criteria.
- SL and CIPP are suitable for over 28 application scenarios, while OC, IG, RS, FFL, CCCP, and PB are suitable for less than 16 scenarios. The greater suitability of SL and CIPP is due to their familiarity, practicality, and broader applicability.
- OC, IG, SL, and CIPP are found to be best suitable for over 15 scenarios, while RS, FFL, CCCP, and PB are found to be best suitable for less 5 scenarios

Twenty-six online representative case studies are selected for validating the findings obtained from the use of CREST. The predicted preferences of CREST were found to match the actual preferences in 50% of the 26 case studies. A novel *validation score* has been developed to quantify the comparative performance of preferences from CREST with the actual preferences. With a mean validation score of 0.8 and median score of 0.95, CREST seemed to have performed well in comparison to actual preferences which are derived by design consultants who are experts in the field of culvert infrastructure rehabilitation. The proposed CREST along with the obtained results will provide guidance to transportation agencies around the world in better decision making in their culvert rehabilitation projects. Most importantly, this study and the findings presented within will educate various transportation agencies that are under informed of the benefits of trenchless construction and rehabilitation methods.

Limitations of this study

Several other criteria that are not considered in the proposed approach could influence the decision making process for culvert renewal technique selection in reality. These criteria however vary depending on the specific project considerations and it is therefore difficult to account for them while demonstrating CREST in this study. Consequently, the findings presented in this study should be used cautiously as they may not suit several application scenarios that have unique requirements or specific constraints.

Another major limitation is the fact that the performance evaluation of various culvert renewal techniques, which is an integral part of the decision making tool, is purely informed by the synthesis of published literature after reasonable interpretations were made. The performance of various renewal techniques will most definitely vary depending on the specific application scenario and consequently, the performance evaluation presented in this study should be construed as representative of only the average application scenarios. Availability of performance data for various application scenarios in the future may help build a more accurate evaluation database and subsequently a more accurate decision making tool.

When culverts exhibit two or more deficiencies, the decision-maker needs to select a renewal technique which is suitable for addressing all the prevailing defects. Accommodating multiple defects in CREST should be considered in future studies.

APPENDICES

Appendix A

Microsoft Excel Spreadsheet for CREST

Table A.1 depicts the way the developed CREST is set up in Microsoft Excel and Tables A.2 to A.8 present the detailed results for a sample run CREST

Table A.1 Input of user-defined weightings and the ratings of the renewal techniques

Criteria	Input user-defined Weightings	Ratings										
		OC	RG	IG	RS	IS	SL	CIPP	FFL	SWL	CCCP	PB
Cost	%	0.05	0.05	0.20	0.15	0.05	0.15	0.05	0.10	0.05	0.10	0.05
Design life	%	0.13	0.034	0.016	0.086	0.086	0.13	0.13	0.086	0.086	0.086	0.13
Productivity	%	0.05	0.13	0.13	0.05	0.05	0.05	0.10	0.13	0.13	0.13	0.05

Generate

Table A.2 Output for overall scores and percentage preferences for RCP of <36”

Size	Defect types	Severity	Renewal Techniques	Overall score	Percentage preference
<36"	Crack	Minor	RG	5	46.9%
			OC	5	53.1%
		Moderate	RG	5	19.1%
			CIPP	5	80.9%
			OC	5	0%
		Major	SL	5	38%
			CIPP	5	33.8%
			FFL	15	28.2%
			PB	5	0%
			OC	10	0%
	JM	Minor	Ignorance	-	-
		Moderate	CIPP	5	45.7%
			FFL	5	54.3%
			OC	5	0%
		Major	PB	10	50%
			OC	10	50%
	JI	Minor	RG	5	46.9%
			OC	20	53.1%
		Moderate	RG	15	19.1%
			CIPP	5	80.9%
			OC	10	0%
		Major	CIPP	5	45.7%
			FFL	5	54.3%
			SWL	10	0%
			PB	5	0%
			OC	5	0%
	ID	Minor - moderate	RS	5	70.3%
			OC	15	29.7%
		Major	RS	15	0.8%
			SL	15	37.2%
			CIPP	15	33.8%
			FFL	5	28.2%
			SWL	15	0.0%
			OC	15	0.0%

Table A.3 Output for overall scores and percentage preferences for RCP of 36~60”

Size	Defect types	Severity	Renewal Techniques	Overall score	Percentage preference
36”-60”	Crack	Minor	IG	5	75.8%
			OC	10	24.2%
		Moderate	IG	5	49.3%
			SL	20	12.2%
			CIPP	20	33.2%
			CCCP	20	5.3%
			OC	5	0.0%
		Major	SL	15	38.0%
			CIPP	5	33.8%
			SWL	5	0.5%
			CCCP	5	27.7%
			OC	5	0.0%
	JM	Minor	Ignorance	-	-
		Moderate	CIPP	20	100%
			OC	5	0%
		Major	OC	10	100%
	JI	Minor	IG	10	75.8%
			OC	5	24.2%
		Moderate	IG	20	52.7%
			SL	15	12.2%
			CIPP	5	35.1%
			OC	10	0%
		Major	SL	5	45.1%
			CIPP	5	38%
			SWL	10	16.9%
			OC	5	0%
	ID	Minor - moderate	IS	5	2%
			OC	5	98%
		Major	IS	15	0%
			SL	15	38.0%
			CIPP	15	33.8%
			SWL	15	0.5%
			CCCP	5	27.7%
			OC	15	0.0%

Table A.4 Output for overall scores and percentage preferences for RCP of 60~120”

Size	Defect types	Severity	Renewal Techniques	Overall score	Percentage preference
60”-120”	Crack	Minor	IG	15	75.8%
			OC	5	24.2%
		Moderate	IG	10	49.9%
			SL	5	33.2%
			CCCP	20	16.9%
			OC	20	0%
		Major	SL	20	38.0%
			CIPP	5	33.8%
			SWL	15	0.5%
			CCCP	5	27.7%
			OC	5	0.0%
	JM	Minor	Ignorance	-	-
		Moderate - major	OC	15	100%
	JI	Minor	IG	5	75.8%
			OC	5	24.2%
		Moderate	IG	5	60.8%
			SL	10	39.2%
			OC	10	0%
		Major	SL	5	70.5%
			SWL	20	29.5%
			OC	15	0%
	ID	Minor - moderate	IS	5	2%
			OC	10	98%
		Major	IS	5	0.0%
			SL	5	38.0%
			CIPP	10	33.8%
			SWL	5	0.5%
			CCCP	5	27.7%
			OC	5	0.0%

Table A.5 Output for overall scores and percentage preferences for CMP of <36”

Size	Defect types	Severity	Renewal Techniques	Overall score	Percentage preference
<36"	JM	Minor	Ignorance	-	-
		Moderate	CIPP	5	45.7%
			FFL	5	54.3%
			OC	5	0%
		Major	OC	20	100%
	Corrosion	Minor - moderate	RS	15	36.6%
			CIPP	5	63.4%
			OC	5	0%
		Major	RS	15	1.1%
			SL	15	44.0%
			CIPP	5	38.1%
			SWL	5	16.9%
			OC	5	0%
	JI	Minor	RG	5	46.9%
			OC	5	53.1%
		Moderate	RG	15	19.1%
			CIPP	5	80.9%
			OC	5	0%
		Major	SL	5	38%
			CIPP	20	33.8%
			FFL	15	28.2%
			SWL	10	0%
			CCCP	10	0%
			OC	5	0%
	ID	Minor - major	RS	20	1.3%
			SL	15	45.8%
			CIPP	5	52.9%
			OC	15	0%
	SD	Minor	Ignorance	-	-
		Moderate	SL	5	38%
			CIPP	5	33.8%
			FFL	5	28.2%
			OC	5	0%
		Major	OC	15	100%

Table A.6 Output for overall scores and percentage preferences for CMP of 36~60”

Size	Defect types	Severity	Renewal Techniques	Overall score	Percentage preference
36" - 60"	JM	Minor	Ignorance	-	-
		Moderate	CIPP	15	100%
			OC	5	0%
		Major	OC	15	100%
	Corrosion	Minor - moderate	CCCP	5	84.2%
			OC	15	15.8%
		Major	IS	5	0.0%
			SL	5	38.0%
			CIPP	5	33.8%
			SWL	5	0.5%
			CCCP	5	27.7%
			OC	5	0.0%
	JI	Minor	IG	15	75.8%
			OC	5	24.2%
		Moderate	IG	5	52.7%
			SL	5	12.2%
			CIPP	20	35.1%
			OC	15	0%
		Major	SL	10	38.00%
			CIPP	10	33.80%
			SWL	5	0.50%
			CCCP	20	27.70%
			OC	15	0.00%
	ID	Minor - moderate	IS	5	2%
			OC	15	98%
		Major	IS	5	0.0%
			SL	5	38.0%
			CIPP	5	33.8%
			SWL	5	0.5%
			CCCP	5	27.7%
			OC	15	0.0%
	SD	Minor	Ignorance	-	-
		Moderate - major	SL	15	47.1%
			CIPP	5	52.9%
			OC	5	0.0%

Table A.7 Output for overall scores and percentage preferences for CMP of 60~120"

Size	Defect types	Severity	Renewal Techniques	Overall score	Percentage preference
60" - 120"	JM	Minor	Ignorance	-	-
		Moderate - major	OC	15	100%
	Corrosion	Minor - moderate	CCCP	15	84.2%
			OC	5	15.8%
		Major	IS	5	0.0%
			SL	5	38.0%
			CIPP	5	33.8%
			SWL	5	0.5%
			CCCP	15	27.7%
			OC	5	0.0%
	JI	Minor	IG	5	75.8%
			OC	5	24.2%
		Moderate	IG	20	60.8%
			SL	15	39.2%
			OC	10	0%
		Major	SL	10	59.4%
			SWL	5	1.3%
			CCCP	20	39.3%
			OC	15	0%
	ID	Minor - moderate	IS	5	2%
			OC	15	98%
		Major	IS	5	0.0%
			SL	5	38.0%
			CIPP	5	33.8%
			SWL	5	0.5%
			CCCP	5	27.7%
			OC	15	0.0%
	SD	Minor	Ignorance	-	-
		Moderate - major	SL	15	100%
			OC	5	0%

Table A.8 Output for overall scores and percentage preferences for HDPE

Size	Defect types	Severity	Renewal Techniques	Overall score	Percentage preference
<36"	Crack	Minor	RG	10	46.9%
			OC	10	53.1%
		Moderate	RG	5	19.1%
			CIPP	15	80.9%
			OC	5	0%
		Major	SL	5	38%
			CIPP	5	33.8%
			FFL	15	28.2%
			OC	5	0%
	JM	Minor	Ignorance	-	-
		Moderate	CIPP	5	45.7%
			FFL	5	54.3%
			OC	15	0%
		Major	OC	15	100%
36" - 60"	Crack	Minor	IG	5	75.8%
			OC	5	24.2%
		Moderate	IG	5	52.7%
			SL	15	12.2%
			CIPP	5	35.1%
			OC	10	0%
		Major	SL	5	47.1%
			CIPP	5	52.9%
			OC	10	0.0%
	JM	Minor	Ignorance	-	-
		Moderate	CIPP	15	50%
			OC	15	50%
		Major	OC	5	100%
60" - 120"	Crack	Minor	IG	5	75.8%
			OC	5	24.2%
		Moderate	IG	15	60.8%
			SL	5	39.2%
			OC	10	0%
		Major	SL	15	100%
			OC	5	0%
	JM	Minor	Ignorance	-	-
		Moderate - major	OC	20	100%

Appendix B

Real-world Case Studies

Tables B.1, B.2 and B.3 present the details of various real-world case studies that were synthesized for validating CREST.

Table B.1 Case studies for RCP

Case	Year	Owner	Contractor	Location	Shape	Size (in)	Length (ft)	Major defect	Actual technique selection	References
1	Unknown	UDOT	Unknown	Unknown	Circular	24	18	Crack	SL	Contech, 2016
2	2014	Lakehurst Naval Air Station	Sequoia Construction & Heitkamp Inc.	Unknown	Circular	48	786	ID	SWL	Contech, 2014a
3	2014	Lakehurst Naval Air Station	Sequoia Construction & Heitkamp Inc.	Unknown	Circular	54	703	ID	SWL	Contech, 2014a
4	2012	WDOT	Michels Corporation	Mitchell Interchange on I-94, Wisconsin	Circular	54	300	Crack	SL	Contech, 2012a
5	2010	VAOT	Morrill Construction	Interstates 89 and 91, Vermont	Circular	96	500	ID	SL	Contech, 2010
6	2012	Bradford County	Florida Engineered Lining	Bradford County, Pennsylvania	Box	120	80	ID	SL	Contech, 2012b
7	2013	IDOT	Brandt Construction Co.	I-74 and I-80 in Moline, Illinois	Circular	144	360*2	ID	SL	Contech, 2013
8	2012	NHDOT	Weaver Brothers Construction Co Inc.	Route 123, New Hampshire	Circular	72	Unknown	Multiple	SL	Contech, 2012c
9	2014	MEDOT	Prock Marine Company	U.S. Route 1, Maine	Circular	96	42	Multiple (ID, Crack)	SL	Contech, 2014b
10	2014	Mobile Regional Airport	John G. Walton, Inc. Indiana Reline, Inc.	Mobile Regional Airport, Alabama	Circular	120	1500	Multiple (ID, Crack)	SL	Contech, 2014c

Table B.2 Case studies for CMP (1)

Case	Year	Owner	Contractor	Location	Shape	Size (in)	Length (ft)	Major defect	Actual technique selection	References
11	2010	Transportation of Quebec	Insituform	Highway 640 in Boisbriand, Québec	Circular	36	160	Corrosion	CIPP	Insituform, 2010
12	2010	Transportation of Quebec	Insituform	Highway 640 in Boisbriand, Québec	Circular	36	160	Corrosion	CIPP	Insituform, 2010
13	2010	MnDOT District 6 Wabasha, MN	Unknown	Unknown	Circular	36	80	Corrosion	CCCP	MDOT, 2012
14	2013	UDOT	Dennis Lierd Construction	State Route 201, Utah	Circular	45	550	Corrosion	SWL	MDOT, 2012
15	2010	Transportation of Quebec	Insituform	Highway 640 in Boisbriand, Québec	Circular	48	260	Corrosion	CIPP	Insituform, 2010
16	2010	Transportation of Quebec	Insituform	Highway 640 in Boisbriand, Québec	Circular	48	260	Corrosion	CIPP	Insituform, 2010
17	Unknown	Keowee Key Golf Course & Country Club	Milliken	Keowee Key Golf Course and Country Club, SC	Circular	60	220	Corrosion	CCCP	Milliken, 2015a
18	2013	Henrico County Virginia	Milliken	Byrdhill Rd, Virginia	Circular	66	25	Corrosion	CCCP	Milliken, 2013
19	2015	Alabama & Gulf Coast Railway	Chase Plumbing & Mechanical, Inc.	Alabama & Gulf Coast Railway, Alabama	Circular	132	106	Corrosion	SL	Contech, 2015a

Table B.3 Case studies for CMP (2)

Case	Year	Owner	Contractor	Location	Shape	Size (in)	Length (ft)	Major defect	Actual technique selection	References
20	2014	Sheboygan County	Sheboygan County	Lakeshore Road and Najacht Road, Wisconsin	Circular	74	38*2	ID	SL	Contech, 2014e
21	2014	Scott Air Force Base	Davinroy Mechanical Contractors Inc	St. Clair County, Illinois	Ellipse	72	2208	ID	SL	Contech, 2015b
22	Unknown	community of Walden on Lake Conroe	Milliken	Walden on Lake Conroe, Texas	Circular	66	130	Multiple (Corrosion, ID)	CCCP	Milliken, 2015c
23	Unknown	City of Rock Springs	Milliken	Unknown	Arch	72	700	Multiple (ID, JI)	CCCP	Milliken, 2015d
24	2012	City of Campbell River	Upland Excavating Ltd.	Coast of British Columbia, Canada	Circular	120	86	Multiple	SL	Contech, 2012d
25	2013	UDOT	Dennis Lierd Construction	State Route 201, Utah	Circular	18~36	6000	Corrosion	SL	Contech, 2014d
26	Unknown	McAllen Texas	Milliken	Rio Grande, Texas	Circular	120	300	JI	CCCP	Milliken, 2015b

REFERENCES

Al-Barqawi, H., and Zayed, T. (2008). “Infrastructure Management: Integrated AHP/ANN Model to Evaluate Municipal Water Mains’ Performance.” *Journal of Infrastructure Systems*, 14 (4), 305–318.

Ariaratnam, S.T. and Sihabuddin, S.S. (2009). “Comparison of Emitted Emissions Between Trenchless Pipe Replacement and Open Cut Utility Construction.” *Journal of Green Building*, 4(2), 126-140.

Ariaratnam, S.T., Piratla, K., Cohen, A. and Olson, M. (2013). “Quantification of Sustainability Index for Underground Utility Infrastructure Projects.” *Journal of Construction Engineering and Management*, 139(12), p.A4013002.

Ballinger, C. A., and Drake, P. G. (1995). “Culvert Repair Practices Manual: Volume1.” *RD-94-096, Federal Highway Administration, Mclean, VA.*

Caltrans. (2003). “General Culvert Barrel Rehabilitation Techniques.” <www.dot.ca.gov/hq/oppd/dib/dib83-01-6.htm>.

Caltrans. (2013). “Design Information Bulletin No. 83 - 03Caltrans Supplement to FHWA Culvert Repair Practices Manual.” <http://www.dot.ca.gov/hq/oppd/dib/dib83-03.pdf>.

Centripipe. (2016a). “Centripipe- The Proven, Engineered CCCP System.” <http://permaform.net/Products/Centripipe/tabid/94/Default.aspx>.

Centripipe. (2016b). “How It Works.” <http://www.centripipe.com/CentriPipe/HowitWorks/tabid/99/Default.aspx>.

Construction Specification Institute (CSI). (2009). “Construction Specification 33 – Shotcrete.” *210–VI–NEH, January 2009.*

Contech. (2010). “I-89 Relines, Quimby Mountain Rd & Exit 2.” <http://www.conteches.com/KnowledgeCenter/CaseStudies/CaseStudyDetails?articleId=674>.

Contech. (2012a). “I-94 Reline at Mitchell Interchange.” < http://www.conteches.com/knowledge-center/case-studies/case-study-details/articleid/678/i-94-reline-at-mitchell-interchange>.

Contech. (2012b). “Bradford County Reline.” <http://www.conteches.com/KnowledgeCenter/CaseStudies/CaseStudyDetails?articleId=443>.

Contech. (2012c). “NHDOT State Route 123.” <http://www.conteches.com/KnowledgeCenter/CaseStudies/CaseStudyDetails?articleId=828>.

Contech. (2012d). “Galerno Road over Simms Creek Reline.” <http://www.conteches.com/KnowledgeCenter/CaseStudies/CaseStudyDetails?articleId=978>.

Contech. (2013). “Henry County – IDOT I-74/280 Reline.” <http://www.conteches.com/KnowledgeCenter/CaseStudies/CaseStudyDetails?articleId=1146>.

Contech. (2014a). “Lakehurst Naval Air Station – Reline.” <http://www.conteches.com/KnowledgeCenter/CaseStudies/CaseStudyDetails?articleId=1136>.

Contech. (2014b). “US Route 1 - Warren, Maine Culvert Replacement.” <http://www.conteches.com/KnowledgeCenter/CaseStudies/CaseStudyDetails?articleId=1310>.

Contech. (2014c). “Mobile Regional Airport - Runway 14/32.” <http://www.conteches.com/KnowledgeCenter/CaseStudies/CaseStudyDetails?articleId=1148>.

Contech. (2014d). “UDOT SR201 and I-80 Reline.” <http://www.conteches.com/KnowledgeCenter/CaseStudies/CaseStudyDetails?articleId=1460> .

Contech. (2014e). “Lakeshore & Najacht Road Reline.” <http://www.conteches.com/KnowledgeCenter/CaseStudies/CaseStudyDetails?articleId=1496>.

Contech. (2015a). “Alabama & Gulf Coast Railway Reline.” <http://www.conteches.com/KnowledgeCenter/CaseStudies/CaseStudyDetails?articleId=1496>.

Contech. (2015b). “Scott Air Force Base Drainage Improvements.” <http://www.conteches.com/KnowledgeCenter/CaseStudies/CaseStudyDetails?articleId=1179>.

Contech. (2016). “Cornia Drive.” <http://www.conteches.com/KnowledgeCenter/CaseStudies/CaseStudyDetails?articleId=520>.

Creswell, J. W., and Miller, D.L. (2000). “Determining Validity in Qualitative Inquiry.” *Theory into practice*, 39(3), 124-130.

Davies, D., and Dodd, J., (2002). “Qualitative Research and the Question of Rigor.” *Qualitative health research*, 12(2), 279-289.

FHWA. (2005). “Highway & Rail Transit Tunnel Maintenance & Rehabilitation Manual.” <https://www.fhwa.dot.gov/bridge/tunnel/maintman04.cfm>.

Golafshani, N. (2003). “Understanding Reliability and Validity in Qualitative Research.” *The Qualitative Report*, 8(4), 597-606.

Hollingshead, T., and Tullis, B. P. (2009). “In-Situ Culvert Rehabilitation: Synthesis Study and Field Evaluation.” *Report No. UT-09.16, Utah Department of Transportation, Salt Lake, Utah.*

Hunt, J. H., Zerges, S. M., Roberts, B. C., and Bergendahl, B. (2010). “Culvert Assessment and Decision-Making Procedures Manual for Federal Lands Highway.” *Publication No. FHWA-CFL/TD-10-005, Federal Highway Administration Central Federal Lands Highway Division, Lakewood, CO.*

Insituform. (2010). “MTQ Rehabilitates Highway Culverts.” <http://www.insituform.com/AboutUs/CaseStudies/NACaseStudies/Canadian-Culvert-Rehab>.

Johns, R. C. (1995). “Chemical Grouting.” *Department of the Army U.S. Army Corps of Engineers Washington, DC 20314.*

Lincoln, Y. S., and Guba, E.G. (1985). *Naturalistic Inquiry* (Vol. 75). Beverly Hills, CA: Sage.

Ludwig Huber. (1998). “Validation of Analytical Methods and Procedures.” <http://www.labcompliance.com/tutorial/methods/default.aspx>.

Matthews, J. C., Simicevic, J., Kestler, M. A., and Piehl, R. (2012). “Decision Analysis Guide for Corrugated Metal Culvert Rehabilitation and Replacement Using Trenchless Technology.” *1177 1810-STDDC, United States Department of Agriculture, Washington, D.C.*

MCAA. (2016). “Cold Weather Mortar and Grout Mixing Solution.” <http://www.masoncontractors.org/2011/01/07/cold-weather-mortar-and-grout-mixing-solution/>.

Meegoda, J. N., Juliano, T. M., and Tang, C., (2009). “Culvert Information Management System – Demonstration Project.” *FHWA-NJ-2009-017, New Jersey Department of Transportation, Trenton, NJ.*

Minesota Department of Transportation (MDOT). (2012). “Culvert Repair Best Practices, Specifications, and Special Provisions: Task C Research Synthesis.” *Minesota Department of Transportation, Minesota.*

Milliken. (2013). “Geospray® Geopolymer: Culvert Relining.” <http://infrastructure.milliken.com/pages/case-studies/detail/0/22/>.

Milliken. (2015a). “Geospray® Geopolymer: Culvert Rehabilitation.” <http://infrastructure.milliken.com/pages/case-studies/detail/0/23/>.

Milliken. (2015b). “Geospray® Geopolymer: Storm Water Rehab.” <http://infrastructure.milliken.com/geospray-storm-water-rehab-case-study/>.

Milliken. (2015c). “Geospray® Geopolymer: Corrugated Metal Storm Sewer.” <http://infrastructure.milliken.com/pages/case-studies/detail/0/20/>.

Milliken. (2015d). “Geospray® Geopolymer: Arched Storm Culvert.” <http://infrastructure.milliken.com/geospray-arched-storm-culvert-case-study/>.

Mitchell, G. F., Masada, T., Sargand, S. M., and Jobes Henderson & Associates, Inc. (2005). “Risk Assessment and Update of Inspection Procedures for Culverts.” *FHWA/OH-2005/002, Ohio Department of Transportation, Columbus, OH.*

Najafi, M., and Bhattachar, D. V. (2011). “Development of a Culvert Inventory and Inspection Framework for Asset Management of Road Structures.” *J. King Saud University Science*, 23(3), 243–254.

Najafi, M., Salem, S., Bhattachar, D., Salman, B., and Patil, R. (2008). “An Asset Management Approach for Drainage Infrastructure and Culverts.” *Midwest Regional University Transportation Center, University of Wisconsin-Madison, WI 53706*

National Cooperative Highway Research Program. (NCHRP). (2002). “Assessment and Rehabilitation of Existing Culverts,” *Rep. No. 303, Transportation Research Board, National Research Council, Washington, DC.*

PCA. (2015). “Shotcrete.” <http://www.cement.org/concrete-basics/concrete-homes/building-systems-for-every-need/shotcrete>.

Perrin Jr, J., & Jhaveri, C. S. (2004). “The Economic Costs of Culvert Failures.” *Transportation Research Board, 2004 Annual Meeting, Washington DC.*

ProjectMax. (2006). “Rehabilitation of Sewer Pipelines.” <file:///C:/Users/hjin/Downloads/Overview_of+Sewer_Rehabilitation_Techniques%20(3).pdf>.

Public works. (2013). “Three Trenchless Culvert-Rehab Solutions.” <http://www.pwmag.com/pipes/three-trenchless-culvert-rehab-solutions.aspx>.

Seale, C. (1999). “Quality in Qualitative Research.” *Qualitative Inquiry*, *5*(4), 465-478.

Stenbacka, C. (2001). “Qualitative Research Requires Quality Concepts of its Own.” *Management Decision*, 39(7), 551-556.

Syachrani, S., Jeong, H. S., Rai, V., Chae, M., and Iseley, T. (2010). “A Risk Management Approach to Safety Assessment of Trenchless Technologies for Culvert Rehabilitation.” *Tunneling and Underground Space Technology*, 25, 681–688.

Taylor, C. A. and Marr, J. (2014). “Culvert Repair Best Practices, Specifications and Special Provisions – Best Practices Guidelines.” *Minnesota Department of Transportation, St. Paul, MN.*

The City of Portland (COP). (2016). “Open Trench Excavation.” <https://www.portlandoregon.gov/bes/article/490269>.

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

Turner. (1997). “Grouting Materials and Methods.” *Applied Geotechnical Engineering, U.K.*

Utah State University (USU). (2015). “Culvert Rehabilitation Practices.” <https://www.udot.utah.gov/main/uconowner.gf?n=1128117589169310>.

Venner, M. and Venner Consulting . (2014). “Culvert and Storm Drain Management Case Study: Vermont, Oregon, Ohio, and Los Angeles County.” *Federal Highway Administration, Office of Asset Manage*

Wagener, B. D. and Leagjeld, E. E. (2014). “Culvert Repair Best Practices, Specifications and Special Provisions- Best Practices Guidelines,” *Rep. No. MN/RC 2014-01, Minnesota Department of Transportation, St. Paul, MN.*

Yang, C and Allouche, E. (2009). "Evaluation of Non-destructive Methods for Condition Assessment of Culverts and Their Embedment." *ICPTT 2009*, 361, 28-38

Yang, C. (2011). "Predicting Deterioration Rate of Culvert Structures Utilizing a Markov Model." *Doctoral Dissertation, College of Engineering and Science, Louisiana Tech University, Ruston, LA.*

Yazdekhasti, S., Piratla, K. R., Khan, A. and Atamturktur, S. (2014). "Analysis of Factors Influencing the Selection of Water Main Rehabilitation Methods," *NASTT No Dig 2014, Orlando, FL.*

Yoo, D., Kang, D, Jun, H, and Kim, J. (2014). "Rehabilitation Priority Determination of Water Pipes Based on Hydraulic Importance." *Water,* 6(12), 3864-3887.