



Use of Trenchless Technologies for a Comprehensive Asset Management of Culverts and Drainage Structures

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16. Abstract Due to an aging and rapidly deteriorating transportation infrastructure, agencies are facing the challenge of making quick and reliable decisions regarding the repair and renewal of their assets. While comprehensive asset management strategies have been developed for the visible components of the highway system, such as bridges and pavement, culverts and drainage structures are often neglected. The investigators recently completed an MRUTC project in which they have investigated the current culvert asset management practices of transportation agencies and also developed the inventory and inspection protocols necessary for establishing an effective culvert asset management program. This study builds upon the findings of the previous research project and focuses on the application of trenchless technologies for inspection, construction, repair and renewal of culverts. A literature search, a survey of departments of transportation and a survey of technology providers have been conducted to identify and characterize trenchless technology methods used for buried pipes. The limitations of trenchless technologies in terms of applicability to culverts are investigated. Steps of establishing a comprehensive culvert asset management strategy are identified. Based upon the findings a decision support system is developed which will help the decision makers identify the optimum repair/renewal procedures as a function of the condition of the culvert.			
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Executive Summary

Project Summary

Transportation agencies are facing a severe problem regarding the repair and renewal of their heavily deteriorated infrastructure. Wide geospatial distribution, environmental exposure, and budget and resource restrictions further complicate the management of these assets. Traditionally, the visible components of the roadway infrastructure, such as pavement and bridges, have been the main focus points of agencies developing their asset management programs. In contrast, less visible components, such as culverts and drainage structures, have often been neglected.

A comprehensive asset management program begins with the development of inventory and inspection procedures. These procedures enable the agencies to identify and record their assets and monitor the conditions of these assets through periodic inspections. This stage of the development of a comprehensive asset management strategy for culverts has been recently completed by the investigators in an MRUTC funded project entitled as “An Asset Management Approach for Drainage Infrastructures and Culverts”. The next step involves designing the proper decision support models for identifying the appropriate repair, rehabilitation and replacement procedures for culverts. This project focuses on developing a decision support system for use of trenchless technologies to properly repair, renew, manage and maintain these assets.

Trenchless technologies can be used to inspect, construct, repair, rehabilitate and replace buried pipes without disrupting the adjacent properties or public. These methods provide safer construction operations both for workers and commuters. Trenchless technology allows agencies to extend the life of their assets and improve their hydraulic characteristics with minimum

negative impact. However, there are numerous trenchless methods, some of which have only recently been introduced; and while viable, have little field performance history in application to culverts and transportation systems.

Each trenchless technique has its own capabilities and limitations. The methods have basically emerged from the buried infrastructure renewal market, and many state departments of transportation (DOTs) have started using them with no clear standard methodology. This study aims at identifying the characteristics of trenchless technologies which may be used on culverts and providing a decision support methodology which integrates the inspection procedures with such methods.

Background:

This research project is performed with the collaboration of University of Cincinnati, University of Texas at Arlington, Ohio Department of Transportation (ODOT), and Michigan Department of Transportation (MDOT) under the research program of Midwest Regional University Transportation Center (MRUTC). This project can be considered as the second phase of a previous MRUTC project entitled “An Asset Management Approach for Drainage Infrastructure and Culverts” in which the authors investigated the development of inventory and inspection procedures for culverts and developed a decision support platform in terms of identifying appropriate actions to be taken given the condition of the culvert. The present project is built upon the findings of the previous project. The usage of trenchless technologies is further investigated and a detailed methodology which will help the decision makers select a specific repair, rehabilitation or replacement method is developed.

Process:

The literature search for this project was conducted through a review of major civil engineering publications and databases such as provided by the American Society of Civil Engineers (ASCE), Federal Highway Administration (FHWA), Transportation Research Board (TRB) Records, American Association of State Highway and Transportation Officials (AASHTO) and the National Cooperative Highway Research Program (NCHRP).

A survey of state departments of transportation (DOTs) was conducted to obtain information regarding current culvert maintenance practices and trenchless repair and renewal methods. The questionnaire was sent to the state DOTs via the electronic mailing list provided by the Ohio Department of Transportation on three occasions.

A survey of technology providers was conducted in order to obtain additional information on the usage and characteristics of relevant trenchless technology methods. This survey was uploaded to a website and respondents submitted their responses either electronically or by fax.

The duration for this research project was 22 months.

Findings and Conclusions:

The participation rate of the departments of transportation to the survey was lower than expected. The probable reasons for this low response were that the majority of the state DOTs are not familiar with several trenchless technology methods and are relying upon the manufacturers' and contractors' experience and knowledge. Although the information gathered from the survey was somewhat limited in detail, it nonetheless provided an indication concerning the usage of trenchless technologies for application to culverts.

Twenty three responses were received from technology providers. These responses provided additional information regarding the usage of trenchless technologies for application to culverts.

Based upon the results of the surveys and literature review, the following tasks were completed:

- Development of an asset management strategy for culverts.
- Preparation of a table identifying the applicable sizes and other key characteristics of trenchless repair and renewal methods.
- Investigation of the limitations of trenchless technologies regarding their applicability to culverts.
- Creation of a database form to record the results and characteristics of individual trenchless repair and renewal projects.
- Development of a decision support system linking the inspection procedures of Ohio Department of Transportation's Culvert Management Manual with appropriate trenchless repair and renewal methods.

Recommendations for Further Action:

This research project focuses on the current trenchless technology methods and proposes a link between the inspection procedures of culverts with these methods. Due to technological improvements and new discoveries in material science, new methods of trenchless technologies are expected to be available in the future. As the urbanization and traffic volume increases, more agencies will prefer the use of trenchless technologies to open cut methods in order to prevent disruptions to other assets and public. The continuing development field of trenchless technology methods and associated experiences will therefore provide additional information in the future. The investigators suggest that researchers update the technologies and methodologies presented in this research project on an ongoing basis.

1. Introduction

1.1 Background of the study

Culverts and drainage structures constitute an important part of the highway system which are in need of periodic inspection, maintenance, repair procedures and timely rehabilitation or replacement. An increasing rate of deterioration, wide geospatial distribution and wide variation in environmental factors and the structural characteristics (such as material type, shape, backfill material) further complicate the effective management of these important highway components. A comprehensive culvert asset management strategy helps highway agencies maximize the values of these assets through their life cycle by establishing systematic inventory, inspection and decision making procedures.

The investigators of this study have recently completed another MRUTC project entitled “An Asset Management Approach for Drainage Infrastructures & Culverts”. The objectives of this study were to investigate current practices in culvert asset management procedures and factors affecting culvert performance and to provide a platform for a decision support system for culvert repair, rehabilitation, and replacement (rehabilitation and replacement can be collectively referred to as “renewal”). Based upon the results of this study, there is a lack of nationwide recognition of culvert management procedures. While management procedures and strategies are established for other important highway components, such as pavements and bridges, culverts are often neglected. As these structures have begun to fail, the costs of emergency repairs and the cost to the public (user costs) demonstrate the importance of establishing an effective culvert asset management. Ohio Department of Transportation’s Culvert Management Manual was referenced in this study as it provides procedures for detailed inspection and inventory of culverts. Culvert maintenance, repair, rehabilitation and replacement methods were investigated

and a decision platform, which would help the agencies to choose the best strategy given the overall condition of the culvert according to ODOT Culvert Management Manual Rating, was developed. As a part of this study, investigators also proposed new inventory and inspection procedures and performed pilot studies to validate these procedures.

The present project builds upon the previous project, described above, by exploring trenchless technologies in greater detail and incorporating them into a decision support system to effectively manage the culverts. Trenchless technologies allow inspection, construction, repair and renewal (rehabilitation and replacement) of a culvert with little or no excavation. Therefore these methods are not disruptive to the transportation systems and they provide safer construction operations for both workers and the general public. Trenchless technologies can provide a new design life to the existing culverts and simultaneously increase their hydraulic capacities. Basic trenchless renewal methods can be categorized into:

1. Cured-in-Place Pipe (CIPP)
2. Sliplining (SL)
3. In-Line Replacement (ILR)
4. Close-Fit Pipe (CFP)
5. Panel Lining (PL)
6. Point Source Repair (PSR)
7. Coatings and Linings (C&L)
8. Thermoformed Pipe (THP)

Several factors affect the selection of trenchless culvert renewal methods including type, length, shape, size, and alignment of the culvert, as well as the nature of the problem. The

absence of field performance history of these methods further complicates the decision making procedures.

1.2 Objectives and Tasks

The primary objectives of this study are to investigate and recommend potential trenchless technologies that can be used to repair and renew culverts and to develop a decision support system that will help ODOT and MDOT engineers select the best technologies for a specific culvert description and condition.

In order to accomplish these objectives, the following tasks have been identified and addressed:

Task 1: Review literature and case studies

Task 2: Review factors affecting culvert deterioration

Task 3: Review and survey existing trenchless technology methods with potential use for renewal of culverts and drainage structures and identify capabilities and limitations of each of these methods.

Task 4: Develop inspection, asset management and maintenance requirements of renewed culverts with trenchless technology methods.

Task 5: Develop modification requirements in existing trenchless technologies to be used in culverts and drainage structures.

Task 6: Collaborate with ODOT and MDOT to establish a database and decision support system for selection of appropriate trenchless technology methods

Task 7: Develop course modules for culvert asset management using trenchless technologies.

1.3 Outline of the report

Task 1 (review of literature and case studies) is primarily addressed in chapters 2 and 5. Chapter 2 presents the results of the literature review on the characteristics of culverts and the factors affecting their performance (task 2). Chapter 3 provides the detailed results of the national survey of state DOTs which was conducted in order to gain further information regarding the asset management efforts and their implementation of trenchless technology. Similarly, chapter 4 presents the results of the survey conducted to gain information from the technology providers regarding the usage and characteristics of trenchless technology methods. Trenchless technology methods as presently deployed for inspection, construction, repair and renewal of buried pipes are examined (task 3) in chapter 5. Task 5, the development of modification requirements in existing trenchless technologies for application to culverts and drainage structures, is also addressed in chapter 5. Chapter 6 focuses on the development of asset management strategies incorporating the trenchless technologies for inspection and renewal purposes, with current asset management practices for culverts (task 4). A decision support system designed to help users identify optimum trenchless renewal technology method(s), for specific culvert characteristics and condition is developed in Chapter 7 (task 6). Based upon the information and results of the presentation investigation, as described herein, a formal course module will be prepared to demonstrate culvert asset management using trenchless technologies (task 7).

2. Literature Review

According to the Ohio Department of Transportation's Culvert Management Manual a culvert is defined as, "a structure that conveys water or forms a passageway through an embankment and is designed to support a super-imposed earth load or other fill material plus live loads" (ODOT 2003) . Therefore a culvert has to both withstand the chemical and physical deterioration due to effluent and soil characteristics and also carry the earth load due to soil cover and live loads due to traffic on the roadway at the same time. In this chapter the factors which affect the deterioration of a culvert are going to be covered and a review of previous publications related to the culvert performance is going to be presented.

2.1 Factors affecting culvert deterioration

Performance of a culvert is directly proportional to its remaining design service life which is defined as the period of service without a need for major repairs (AASHTO 1999). For corrugated metal pipes (CMP), this will normally be the period in years from installation until deterioration reaches the point of either perforation of any point on the culvert or some specified percent of metal loss. Service life of a reinforced concrete pipe is the period from its installation until reinforcing steel is exposed, or a crack signifying severe distress develops. Service life of a plastic pipe may be considered as the time period until excessive cracking, perforation, or deflection has occurred.

Culverts require constant maintenance and can deteriorate due to several reasons. A comprehensive study performed by the Water Research Center (WRc), concludes that the concept of measuring the rate of deterioration of sewers is unrealistic, and deterioration is more influenced by random events in a sewer life span. Examples of random events include a heavy rain storm or a nearby excavation. Distress and collapse of a culvert are the results of the

complex interactions of various mechanisms that occur within and around the culvert. The impact of the deterioration depends upon the culvert size, complexity, topography, and service.

Culvert service life can also be affected by debris damage, erosion (caused by major storm events), and improper manufacturing or handling of the culvert. Major factors influencing the performance or service life of a culvert are:

Durability factors:

- Corrosion
- Abrasion
- Erosion

Loss of Structural Integrity:

- Joint Separation
- Misalignment
- Seam Defects
- Seam cracking
- Longitudinal cracks
- Transverse cracks

Environmental Factors:

- Scaling
- Delamination
- Spalling
- Efflorescence
- Honeycombs
- Popouts

Hydraulic:

- Insufficient capacity and Flooding

Operational Factors:

- Roots
- Debris blockage
- Maintenance procedures

2.1.1 Durability Factors

Durability is the property to resist erosion, material degradation, and subsequent loss of function due to environmental and/or other service conditions. Abrasion and corrosion are the most common durability problems for culverts. Proper attention must be given to these problems in the design phase. Field inspection of culverts existing on the same stream will prove valuable in assessing potential problems.

2.1.1.1 Corrosion

Corrosion specifically refers to any process involving the deterioration or degradation of metal components. Metal culverts or reinforcement in concrete culverts corrode on contact with water that has a low pH value, acids, bases, salts, oils, and chemicals which act as an electrolyte. Metal acts as an anode, cathode, and conductor. As electrons move from the anode to the cathode, metal ions are released into solution, with characteristic pitting at the anode. The culvert will typically serve as both the anode and the cathode. Similar processes can occur to the cement in concrete pipe if subjected to highly alkaline soils or to other pipe materials if subjected to extremely harsh environments. Upon initiation, the corrosion process is self-sustaining, resulting in the formation of pits at the outer surface of the culvert, with various depths and widths. Different culvert materials have different characteristics in terms of their reaction to corrosion.

For instance, sulfate corrosion is produced as a result of sewer gases, excessive hydraulic flows, structural failures, leaks and infiltrations, and erosion. Furthermore, bacteria converts the sulfates to hydrogen sulfides which, when released into the culvert air space, become oxidized to form sulfuric acid. Sulfuric acid is reactive to some pipe materials leading to corrosion. Severe corrosion can jeopardize the structural integrity of a culvert and may lead to a collapse.

Corrosion is the process of metals returning to their native state of oxides or salts. Figure 2.1 shows corrosion in a metal culvert. Corrosion of culverts may also occur in the presence of soils and water containing acids, alkalis, dissolved salts, and organic industrial wastes.



Figure 2.1 Corrosion in Culverts (Najafi et. al. 2008)

The risk of interior corrosion of a culvert depends upon the susceptibility of the culvert material to corrosion and the amount of corrosive chemicals in the water. Interior culvert corrosion typically occurs from the formation and release of hydrogen sulfide. Hydrogen sulfide is formed in anaerobic conditions, such as debris piles, or pools caused by sagging lines. It is assumed that anaerobic conditions exist in open channel flow at the wetted perimeter, and therefore, a small amount of hydrogen sulfide is generated and some corrosion can occur if the conditions allow for release (ASCE, 1994). Hydrogen sulfide gas is released in turbulent conditions. Such conditions occur at culvert outlets, drop structures greater than 2ft, slope changes, and during high water velocities.

Acidic soils or groundwater attack unprotected cementitious or metal culvert materials. Stray currents in the ground cause a galvanic corrosion in metal or metal reinforced culverts.

2.1.1.2 Abrasion

Abrasion is the gradual wearing away of the culvert wall due to the impingement of bedload and suspended material. Abrasion will almost always manifest itself first in the invert of the culvert. Similar to corrosion, abrasiveness is also a function of several factors, such as culvert material, frequency and velocity of flow in the culvert, and composition of the bedload. The effect of abrasion can be seen in the pipe invert where exposure is most severe. It can result in loss of pipe strength or reduction in hydraulic quality as it gradually removes wall material. Abrasion is a precursor to accelerated corrosion.



Figure 2.2 Deterioration due to Abrasion (Caltrans 2003)

By far, bedload is the leading cause of culvert abrasion. Critical factors in evaluating the potential of bedload material in terms of abrasiveness are the size, shape, and hardness of the bedload material and the velocity and frequency of flow in the culvert. Generally, flow velocities less than 1.5 m/s (5 ft/s) are not considered to be abrasive, even if bedload material is present in the flow. Velocities in excess of 4.5 m/s (15 ft/s), which carry a bedload, are considered to be very abrasive and some modifications to protect the culvert should be considered. To date, there has not been extensive testing conducted for velocities exceeding 4.5 m/s (15 ft/s), and

extrapolation of existing test data to very high velocities is not recommended. Attempts to compare laboratory testing to field conditions to estimate the effects of bedload abrasion must be carefully considered. Designers should not use peak flow rate velocities in service life calculations.

It is very difficult to provide an absolute determination of how a culvert will be affected from bedload abrasion by just considering its material type. Perhaps the most useful method of making a reasonable determination is to look at the various types of culvert materials and make relative comparisons. Tests performed on concrete pipe have generally shown excellent wear characteristics. Although high-velocity flow will induce abrasion regardless of the size of bedload particles, tests performed on concrete pipe have shown that cobble and larger sizes (over 75-mm (3-in.) diameter) will induce higher wear rates than sands and gravels. Larger rocks may cause an impact on the pipe wall which with sufficient power will break away minute particles of the wall. The use of high-quality aggregate (i.e., aggregate that is harder than the anticipated bedload hardness) in the concrete mix can greatly enhance the wearability of the concrete. Likewise, manufacturing methods that lead to a denser concrete mix, such as roller compacted or spun concrete, or to a higher compressive strength concrete can exhibit increased wearability. Where velocities are known to be high, and a bedload is present, many entities recommend additional concrete cover over the reinforcing steel. The presence of a very high or very low pH environment will accelerate the abrasive effects of any bedload conditions. Steel culverts are the most susceptible to the dual action of abrasion and corrosion, particularly where thinner walled pipes are used. Once the thin protective coating on a steel pipe is worn away, whether it is zinc or other substance, exposure to low resistivity and/or low pH environments can dramatically shorten the life of a steel culvert. Although aluminum culverts are occasionally specified to

combat corrosion, plain aluminum is typically not recommended for abrasive environments since tests indicate that aluminum can abrade at a rate as much as three times the rate of abrasion of steel. Abrasive effects are typically countered in metal pipes by the use of:

- Protective coatings,
- Invert paving
- Added metal thickness
- Or a combination of these measures.

Plastic culvert materials (both polyvinyl chloride and high-density polyethylene) exhibit good abrasion resistance. Since plastic is not subject to corrosion, it does not experience the dual action of corrosion and abrasion. Plastic pipes, like metal pipes, have relatively thin walls and thus the rate of wear must be carefully evaluated by measuring the material thickness. The documented abrasive resisting capabilities of plastic pipe is primarily based upon tests using small aggregate sizes (gravels and sands) flowing at velocities in the range of 0.6 to 2.1 m/s (2 to 7 ft/s). The effects of large bedload particles (cobbles and larger) and/or high velocity flows are not well defined due to limited data. Additionally, due to the more recent emergence of application of plastic pipes as culvert products, specific rehabilitation methods have generally not been developed yet. Some of the more popular current strategies (e.g., invert paving) are not effective with plastic pipes due to the difficulty of achieving a satisfactory bond with the smooth surface of the plastic pipes.

2.1.1.3 Erosion

Erosion or scour at culvert ends can occur due to inadequate energy dissipation, headcutting that reaches a culvert, improper entrance or exit alignment and design, high watertable (above culvert level), frequent and high magnitude of hydraulic surcharge, and soil

types (silts, silty fine sands, and fine sands). Regardless of the cause, the removal of structural backfill from around the culvert eliminates the ability of the pipe to support loading. Loss of side support will allow the sides of the culvert to move outward when loaded vertically, and collapse will likely occur once the culvert deformation exceeds 10 percent. Uneven loading of culverts because of joint displacement also accelerates the pipe deterioration process. Erosive effects at culvert ends or the erosive effects of piping may lead to the ultimate failure of the culvert therefore precautionary measures should be taken as a part of routine design practice.

Erosion may also take place if a defined approach channel is not aligned with the culvert axis. If the culvert is not aligned with the channel and the channel is modified to bend into the culvert, erosion can occur at the bend in the channel. Erosion of the embankment at inlet may be reduced by constructing the culvert into the fill slope and retaining the fill by headwall and wingwalls. Good compaction of backfill material is essential to reduce the possibility of erosion. Where soils are fairly erosive, special impervious bedding and backfill materials should be placed for a short distance at the culvert entrance. Scouring is a problem that can be encountered at the culvert outlet. Local scour is the result of high-velocity flow at the culvert outlet, but its effect extends only a limited distance downstream as the velocity transitions to outlet channel conditions. Long, smooth-barrel culverts on steep slopes will produce the highest velocities causing highest erosion at outlet. A common mitigation measure for small culverts is to provide riprap aprons. If the flow velocity is very high and is not controllable by riprap aprons then energy dissipaters should be provided.

2.1.2 Loss of Structural Integrity

Although generally unpredictable from a design standpoint, there are other physical factors besides corrosion and abrasion that can shorten the life of drainage culverts. The loss of

structural integrity can sometimes be traced to a defect in the manufacturing process of the pipe, improper construction techniques or the effects of a large storm event. More commonly, though, the loss of structural integrity occurs over several years and is related to such factors as piping, seepage, soil movement, scour, and backfill soil loss. These processes can gradually reduce the culvert strength and make it susceptible to catastrophic events such as floods. The agencies are unable to predict when or how a particular drainage facility might be affected by one of these factors. Therefore, it is important to establish a program of routine inspections to identify the progression of a problem before damage to the roadway occurs.

Structural deterioration is hypothesized to be influenced by a set of installation and construction factors, including pipe design, pipe size, buried depth, and site factors such as soil type, moisture index and tree root intrusion (Tran et al. 2006). Structural defect failure mechanisms include cracks and fractures in the pipeline material that are caused by a change in the forces around a pipeline or a change in the ability of the pipe material to resist existing forces. The infiltration of groundwater through existing structural defects creates voids or increases the size of existing voids as the infiltrating water carries particles from the soil into the pipeline. The weakening of the soil makes the strata above the pipe vulnerable to surface collapse. The effects of infiltration on void formation are made worse by the process of exfiltration. Exfiltration occurs when water leaves the pipeline through structural defects during periods of hydraulic surcharge. Surcharge waste water can scour or loosen more fine material at the perimeter of the voids.

Common defects found in any culvert type are going to be discussed in the following sections:

2.1.2.1 Joint Separation

Allowable joint separation depends upon the type of joint being used. Joints with an external sleeve (as used for most corrugated metal pipes and corrugated high-density polyethylene) can allow a limited amount of axial separation between abutted pipe ends since the external sleeve will typically maintain joint integrity and limit infiltration/ exfiltration. For bell-and-spigot-type joints, there is no allowable separation; instead, some minimum amount of overlap at the joint corresponding depending on the pipe diameter is usually specified. This minimum amount of overlap at the joint becomes particularly important for pipes installed on a curved alignment. While the portion of the pipe joint on the inside of the curve may have no problem with meeting the minimum overlap, most specifications will call special attention to that portion of the pipe on the outside of the curve and require specially manufactured curved or angled pipe sections if the minimum overlap cannot be attained. There can be numerous causes of joint separation or insufficient overlap, with the most common being inadequate quality control during construction. Construction related problems can be due to uneven bedding, uneven or poorly compacted backfilling material, or unexpected settlement. Joint problems are also common when culverts are installed under existing roadways by constructing half the width at a time. This usually is accomplished by closing half of the roadway width while the other half is still open to traffic. The half section is then constructed in an open trench operation. The same procedure is then repeated on the other half of the roadway. Adequate backfill compaction and alignment at the point where the two halves meet is very difficult and proper joining may not occur. In addition to problems related to construction, natural forces can lead to joint separation and/or inadequate overlap. Earthquakes and landslides can easily shift culvert positions as can frost heave. Pipes laid on steep slopes, particularly downdrains that are often laid on the surface of the slope, are subject to joint separation. Anchorage and/or higher strength joint connections

are often specified. Culverts should be inspected for movement after any major natural event that could result in a shifting of culvert position.



Figure 2.3 Culvert Pipe showing Cracks and Joint Separation (Najafi et. al 2008)

The main function of culvert joints is to provide connections between pipe segments that are watertight, durable, and resistant to root intrusion. Joint failures are due to leaks where pipe joints become separated or rubber ring is improperly sealed. Joint type is an important issue since the type of joint will influence the susceptibility of the pipe to specific failures. A large portion of joint problems may be related to the amount of flexibility and lateral constraint the joint provides, as well as the culvert joint's actual strength and its ability to resist corrosion.

2.1.2.2 Misalignment

Almost all of the problems that cause joint separation can also lead to misalignment. Minor deviations from the planned alignment are typically not harmful. Minor amounts of deflection (or pull) at successive joints are occasionally planned in the design to create a curve in the alignment. Segmental construction, where portions of a single pipe run are constructed at separate times, will often lead to misalignment due to differing settlement rates and the difficulty in maintaining constant grade through the area of segment connection. For these reasons, it is generally preferable to construct an entire run of pipe in a single sequence.

2.1.2.3 Seam Defects

Seam defects are the result of poor manufacturing or improper handling. Defects of this type are typically realized prior to installation but, if undetected, may lead to culvert failure. Proper inspection during the construction phase, and obtaining pipe material specifications, are necessary to limit these potential problems.

The longitudinal seams in steel structures are bolted with high strength bolts in crests and valleys of the corrugations. These are bearing type connections and are not dependent on the minimum clamping force of bolt tension to develop interface friction between the plates. Fasteners must be checked for their tightness, as any loose or missing fasteners may lead to collapse of the structure. The lapped and bolted longitudinal seams affect the shape and curvature of the structure. Improper erection or fabrication can result in cocked or cusped seams. Cusped seams alter the structure's shape, appearance, and dimensions from the original design. A cocked seam can result in loss of backfill and may reduce the ultimate ring compression strength of the seam.

2.1.2.4 Seam Cracking

This type of defect is developed along the boltholes of longitudinal seams. As cracking progresses, the structure may lose ring compression capability of the seam and this could result in deformation of the culvert or possible failure. Longitudinal cracks are dangerous when accompanied by significant deflection, distortion, and other conditions indicative of backfill or soil problems. Cracking may be caused by improper erection practices such as using bolting force to lay down a badly cocked seam.

Bolted seams develop their ultimate strength under compression. Bolt tipping occurs when the plates slip. As the plates begin to slip, the bolt shank plastically elongates the bolts tip,

and the boltholes. Excessive compression on a seam could result in plate deformations around the tipped bolts and failure is reached when the bolts are pulled through the plates.

Pipe wall damages such as dents, bulges, creases, and cracks are found when the defects are extensive. They impair the integrity of the barrel in ring compression or permit infiltration of backfill. When the deformation type damages are critical, they result in distorted cross-sectional shapes.

2.1.2.5 Longitudinal Cracks

Concrete is strong in compression and weak in tension. Reinforcing steel is provided to handle the tensile stresses. Hairline longitudinal cracks in the crown or invert indicate that steel has received part of the load. Longitudinal cracking in excess of 0.1 inch in width may indicate overloading or poor bedding. If the pipe is placed on hard material and backfill is not adequately compacted around the pipe or under the haunches of the pipe, loads will be concentrated along the bottom of the pipe and may result in flexure or shear cracking as shown in the Figure 2.4.



Figure 2.4 Longitudinal Crack in a Culvert Pipe

(Source: National Research Council Canada, 2006)

2.1.2.6 Transverse Cracks

Poor bedding, as shown in Figure 2.5, causes transverse cracks or circumferential cracks. Cracks occur across the bottom or crown of the pipe when it is supported at the ends of each section. This is the result of poor installation practices, such as failing to provide sufficient depth of suitable bedding material.



Figure 2.5 Transverse Cracks in a Culvert Pipe (Najafi et. al. 2008)

2.1.3 Environmental Factors (Caltrans 2003)

2.1.3.1 Scaling

Scaling is the gradual and continuing loss of aggregate over an area due to the chemical breakdown of the cement bond. It starts as a localized small patch, which merges and extends to expose large areas. Light scaling does not expose the coarse aggregate whereas moderate scaling exposes coarse aggregate and may involve loss up to 1/8 to 3/8 inch of the surface mortar. In severe scaling, more surfaces will be lost (NRMCA 1998).



Figure 2.6 Scaling exposed on Concrete Surface.

(Source: Photomac Construction industries 2008)

2.1.3.2 Delamination

Delamination is the sub surface separation of concrete into layers. It is caused by corrosion and internal expansion. The extent of deterioration in delamination is often unknown until the delamination is opened up.



Figure 2.7 Delamination on a Concrete Surface.

(Source: Concrete Restoration and Construction 2007)

2.1.3.3 Spalling

Spalling is a depression in concrete caused by a separation of a portion of the surface concrete where the topping is popping or peeling off. This is due to the action of weak top surface, overworking of the concrete, low entrainment, excessive water, and freeze thaw cycling.



Figure 2.8 Spalling on a Concrete Surface.

(Source: Caltrans 2003)

2.1.3.4 Efflorescence

Efflorescence is a combination of calcium carbonate leached out of the cement paste and other recrystallized carbonate and chloride compounds. It is a white crystalline or powdery deposit on the surface of the concrete surface and is caused by water seeping through the culvert wall. The water dissolves salts inside the concrete surface, while moving through it, and then evaporates leaving the salts on the surface. Figure 2.9 shows efflorescence of the concrete surface.



Figure 2.9 Formation of Efflorescence on a Concrete Surface.

(Source: House Check 2007)

2.1.3.5 Honeycombs

Honeycombs (Figure 2.10) are coarse aggregates on the surface without any mortar covering or surrounding the aggregate particles. The honeycombing may extend deep inside the concrete and are caused by a poorly graded concrete mix or by insufficient vibration at the time of placement. Honeycombing must be repaired when noticed to prevent further deterioration of the concrete surface.



Figure 2.10 Honeycombing on a concrete surface.

(Source: Department of Architectural Engineering 2006)

2.1.3.6 Popouts

Popouts are conical fragments that break out of the surface of the concrete leaving small holes as shown in Figure 2.11. Popouts occur because the concrete has been overworked, allowing the aggregates to drift upward toward the surface.



Figure 2.11 Pop-outs in a Concrete Structure.

(Source: Concrete Sealers, Specialty Coatings and Consulting 2006)

2.1.4 Hydraulic Factors

When the performance of a culvert is reduced due to hydraulic factors, safety of the commuters, financial condition of the agency, and environment may be affected adversely. These impacts can be due to the flooding of adjacent properties or downstream areas from unexpected headwater depths. An inadequate hydraulic performance of a culvert may also damage the embankment or culvert because of erosion (FHWA 1986). Hydraulic factors that deteriorate culverts include but are not limited to the following:

2.1.4.1 Insufficient Capacity and Flooding

Flooding can cause overtopping of the roadway and, in extreme cases, failure of the culvert and the roadway above. In addition, flooding can damage property adjacent to the structure as well as property both upstream and downstream of the culvert. Flooding will cause incurrence of costs to the agency, the motorists, and to the owners of adjacent properties (FHWA 1986). Flooding of major urban or rural areas can be caused by insufficient culvert capacity. Insufficient capacity may result from faulty designs, debris blockage, etc. In a recent case (June 19th, 2008) covered by the Daily Courier (Connellsville, PA), a backed-up culvert ditch overflowed during two sudden, heavy rainfalls. It was reported that the culvert which traveled under a road, railroad tracks and into the river, was blocked by an illegally dumped tire.

2.1.5 Operational Factors

The failure mechanism due to operational defects originates from an increase in demand and a decrease in capacity. Infiltration and inflow are the two types of demand on a pipe system. Infiltration increases the demand as the number of structural defects grows. Inflow is the demand on the system from service connections or storm waters or both (ASCE 1994; EPA 1991). A decrease in capacity is the result of a decrease in the effective diameter of the pipeline and an increase in the roughness coefficient. The effective diameter is reduced by structural defects such as open and offset joints, broken pipe sections, root masses, grease, or collected debris.

2.1.5.1 Debris Blockage

Debris carried by stormwater can be a destructive element for culverts. However, this destructive potential is primarily related to clogging of the culvert with the accompanying effects of overtopping and erosion or a single impact from a large piece of debris that causes immediate damage to the culvert. Large volumes of debris can, however, add to the effects of bedload abrasion. The potential for debris to cause abrasion will depend primarily upon the relative hardness of the debris and the culvert material. The most common types of debris that lead to major damage are boulders, trees and shrubs, and ice although, during major storm events, anything movable by storm water can be transported to culvert locations. Figure 2.12 shows the debris accumulated in a culvert. Types of areas that have proven troublesome are drainage areas with unstable hillsides, heavily forested areas subject to fire, streams that support beaver activities, and cold weather sites where ice accumulation can block or otherwise damage drainage structures. Whenever debris is likely to pose a problem, appropriate debris control structures should be considered for installation.



Figure 2.12 Debris at the Opening of the Culvert (Najafi et. al. 2008)

The countermeasures that mitigate the effects of debris on culverts were examined and published by the Federal Highway Association (2005). Structural measures to mitigate debris blockage in culverts are:

- Debris Deflectors
- Debris Racks
- Debris Risers
- Debris Cribs
- Debris Fins
- Debris Dams and Basins
- Or a combination of two or more devices

There may be occasions in which it is almost impossible to mitigate the blockages by debris. One example of such an occasion would be hydraulic capacity reductions due to dams built by beavers at either one of the openings of a culvert or inside the culvert. Agencies are advised to carry out inspections and clean the culverts in a pre-determined span of time where beaver population is high. Figure 2.13 illustrates a debris blockage by a beaver dam.



Figure 2.13 Beaver Dam inside a Culvert (Patenaude 2003)

2.1.6 Other Factors

Other factors which influence the performance or service life of a culvert are as follows: (Information provided in this section is excerpted from “Trenchless Technologies” (Najafi 2004)).

Culvert Size

Several authors have investigated the relationship between pipe size and structural stability. Studies indicate that there is a decreasing trend in pipe failure rate with increasing diameter and this trend is directly attributed to the increasing wall thickness and joint reliability with increase in pipe diameter. Larger wall thickness provides the pipe with better structural integrity and improved resistance to corrosion failures.

Although longitudinal bending stresses increase with increasing pipe diameter, the rate is slower than the increase in pipe's section modulus, hence pipes, which have high length-to-diameter ratios, are more likely to suffer from excessive bending stresses. Despite the fact that the above issue is well documented within the literature, there is little evidence of any numerical or statistical investigation of the effect of high pipe length-to-diameter ratios in regard to the mode of failure.

Culvert Gradient

The slope of a gravity pipe is found to have an impact on the condition of the pipe. Under same conditions, a pipe with a steeper slope has a higher risk in terms of deterioration of its segments. The probable reason of this situation is due to the fact that steeper pipe segments cause faster flow rates, resulting in greater risk for abrasion, erosion and surface wear on the inside walls, invert sections or joints of pipe segments. Generation of deteriorating gases or movement of debris may also increase deterioration rates.

Culvert Depth

While investigating the effect of depth on structural condition of pipes, it was found that defect rate steadily decreases up to a depth of 18 ft, below which the defect rate begins increasing with depth. It was suggested that the first pattern probably reflected the decreasing influence of surface factors such as road traffic and utility or surface maintenance activity. The second occurrence or pattern was explained by the increasing effect of overburden pressure. Jones (1984) has suggested that, in shallow pipes, the effect of seasonal moisture variations in the soil surrounding might be significant. In an analysis of over 4400 pipe failures, Anderson and Cullen (1982) reported that 65 percent of all incidents occurred at a depth of 6.5 ft or less and 25 percent from 6.5 to 13 ft deep, although no indication of overall pipe depth distribution is provided. Changes in cover depth may also be important in determining a pipe's structural stability. (Najafi 2004)

Frost Heave

Frost heave is defined as the vertical expansion of soil caused by soil freezing and ice lens formation. All underground structures require the consideration of frost heave effects due to possible displacement of portions of the entire underground structure.

Differential heave causes sections of pipe to experience non-uniform displacements, and this situation may result in strong flexural stress. Uniform heaving may also prove to be a problem under certain circumstances where pipe joints are not subject to movement. Under this scenario, the pipe experiences stresses similar to a simple beam loading, in which the pipe will experience bending stresses. Failure of pipe joints may occur as a result of the frost heave process. This may be a function of the type of connection and the type of fill material used between joints.

The conditions for frost heave require the presence of a frost-susceptible soil, the presence of a sufficient water source, and a ground temperature below the freezing point.

With all of the above factors present, there is a potential for damage due to frost heave. The tendency of a soil to be affected by frost heave under freezing conditions is affected by properties such as grain size, rate of freezing, the availability of water, and by applied loads.

Frost Load

The failure of pipes during winter could be attributed to frost load which presents an increased earth load on the buried pipes. In a trench, the frost load develops primarily as a consequence of different frost susceptibilities of the backfill and the sidewalls of the trench and the interaction at the trench backfill-sidewall interface. Trench width, differences in frost susceptibilities of backfill and trench sidewall materials, stiffness of the medium below the freezing front, and shear stiffness and backfill-sidewall interface play important roles in the generation of frost loads. Thus, it is preferable to use a backfill material that has equal or lower frost susceptibility than that of the sidewall in order to minimize the development of excessive differential frost loads.

Soil-culvert Interaction

Soil-culvert interaction is among the possible causes of pipe deterioration. The resistance of the soil-to-pipe union is important because the shear strength of the interaction can affect the degree of mobility of the pipeline and hence its ability to displace. In cold temperatures, the bond between the soil and pipe restrains the pipe to shrink axially. A high soil-pipeline interaction will not allow the pipe to contract, and consequently the axial stress in the pipe will increase. A strong bond between an iron pipe and soil may cause excessive soil-pipe interface shear which may result in the abrasion of the pipe coating. This abrasion may lead to premature corrosion of the pipe exterior.

Pipe Wall Temperature Gradients

For longitudinal failures, a failure mechanism might be formed when a high temperature gradient occurs across the pipe wall. This temperature gradient can lead to unusually high hoop stresses and subsequently cause failure.

Differential culvert temperature

Some sources in literature speculate that a high differential temperature between the internal and external pipe wall can produce high temperature gradients. Under such conditions the inner and outer fibers will be subject to different temperature drops, resulting in differential strains and circumferential stresses.

Soil Type

The significance of the type of soil cannot be overlooked, as it is one of the most important factors, having effects on almost all of the above mechanisms. Its effects on frost heave, strength of soil-pipeline interaction, and external corrosion can be important for many failure mechanisms.

The type of soil the pipe is located in is also important in terms of differential heaving and thaw settlement. It has been shown that if a pipe is located at the interface of two different soil types, each type of soil will experience an uneven amount of frost heaving, and therefore have an influence on the amount of strain experienced by the pipe. In the same manner, thaw settlement will lead to differential stress distributions on the pipeline.

Soil corrosivity is a soil characteristic that must be considered for external corrosion predictions. Physical characteristics (particle size, friability, uniformity, organic content, color, etc.) may reflect corrosivity, based on observations and testing. Soil uniformity is important because of the possible development of localized corrosion cells. Corrosion cells may be caused by a difference in potential between unlike soil types, with both soils being in contact with the pipe. If the approximate uniformity coefficient for a particular soil class can be estimated, then the possibility of corrosion can also be estimated.

Groundwater Level

Soil water content is an important parameter in several aspects. As mentioned earlier, the rate of frost heave is controlled by the availability of free water. This parameter is also important in terms of external corrosion.

From the perspective of external corrosion, soil corrosion aggressiveness has been related to moisture content. Soils with moisture content above 20 percent are considered to be particularly corrosive (Jarvis and Hedges 1994). Studies substantiate that moisture content is a factor contributing to soil aggressiveness.

Overburden Pressure

Overburden pressure is considered to be important because of its ability to help characterize frost heaving and soil-pipeline resistance. It can be characterized by the depth of

cover and soil density. Literature indicates that the overburden pressure is important for the rate of heaving.

From the perspective of soil-pipeline interaction, it has been demonstrated that the frictional soil resistance is affected by pipe diameter and depth (Rajani et al. 1995). Also, from the perspective of failure modes, larger pipes are more susceptible to crushing type of failure than smaller pipes. This is due to depth, or the external loadings (i.e., roadways, large structures, and the like) to which the pipe is subjected (O'Day 1982).

Temperature

The effects of temperature on pipe breakage rates have been observed and reported by many researchers. Newport (1981) analyzed circumferential pipe breakage data and found that increased breakage rates coincided with cumulative degree-frost (usually referred to as freezing index in North America and expressed as degree-days) in the winter as well as with very dry weather in the summer. Newport attributed the increase in winter breakage rates to the increase in earth loads because of frost penetration, that is, frost loads, and the summer breakage rates to the increase in shear stress exerted on the pipe by soil shrinkage in a dry summer. Newport also observed that when two consecutive cold periods occurred, the breakage rates (in terms of breaks per degree-frost) in the first one exceeded those of the second one and rationalized that the early frost purged the system of its weakest pipes, causing the later frost to encounter a more robust system.

Precipitation (Snow or Rain)

Snow cover is indicative of the insulating effect on ground temperature, as the snow allows for the entrapment of heat into the ground. The amount of rainfall coupled with the soil type may be indicative of moisture content or hydraulic conductivity if these parameters are not

measured regularly. Some literature indicates that corrosion resistance is enhanced during dry periods of the year (Smith 1968). Therefore, inclusion of this parameter may be necessary to help characterize climatic changes as well as to infer adjustments to soil parameters.

Hydrogen Ion Concentration (pH)

In order to characterize external corrosion, it is necessary to find parameters which indicate the corrosivity of the soil. Soil pH is a good indicator of external corrosion because certain pH ranges allow for different corrosion mechanisms to occur. It has also been found that resistivity is a function of pH. For that reason, only one of the two may be required for characterization.

pH is a measure of the acidity or alkalinity of a solution. Generally soil or water pH levels between 5.5 and 8.5 are not harmful. The water is acidic if the pH is less than 5.5 and alkaline when pH is greater than 8.5. Presence of oxygen at the metal surface is necessary for corrosion to occur. The lowest pH levels (most acidic) are typically seen in areas that have received high rainfall over many centuries. The runoff and percolation will leach the soluble salts, with the resultant soil becoming acidic. Milder acids can be found in runoff from marshy areas, which contain humic acid, and mountain runoff that often contains carbonic acid. Conversely, arid areas are much more likely to be alkaline due to soluble salts contained in groundwater.

Soil Resistivity

Resistivity of soil is a measure of the soil's ability to conduct electrical current. It is affected primarily by the nature, concentration of dissolved salts, temperature, moisture content, compactness, and the presence of inert materials such as stones and gravel. The greater the resistivity of the soil, the less capable the soil is of conducting electricity and thus, the corrosion

potential is lower. The measurement unit for resistivity is ohm-centimeters or, more precisely, the electrical resistance between opposite faces of a one-centimeter cube. Resistivity values in excess of about 5000 ohm-cm are considered to present limited corrosion potential. Soils with resistivity values below the range of 1000 to 3000 ohm-cm will usually require some level of pipe protection, depending on the corresponding pH level (e.g., if $\text{pH} < 5.0$, enhanced pipe protection may be needed for resistivity values below 3000 ohm-cm; if $\text{pH} > 6.5$, enhanced pipe protection may not be needed unless resistivity values are below 1500). As a comparative measure, resistivity of seawater is in the range of 25 ohm-cm, clay soils' resistivity range from approximately 750 to 2000 ohm-cm, and loams' resistivity range from 3000 to 10000 ohm-cm. Soils that are of a more granular nature exhibit even higher resistivity values. Some entities use the reciprocal of resistivity, conductivity, as the criterion for corrosive potential.

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

Chlorides

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

and the reinforcing steel in concrete culverts if concrete cover is inadequate, cracked, or highly permeable.

Sulfates

Sulfates can occur naturally or may be a product of human activities, most notably mine wastes. Sulfates, in the form of hydrogen sulfide, can also be created from biological activity, which is more common in wastewater or sanitary sewers, and can combine with oxygen and water to form sulfuric acid. Although high concentrations can lower pH and be of concern to metal culverts, sulfates are typically more damaging to concrete. Typically, the sulfate in one or more various forms combines with the lime in cement to form calcium sulfate, which is structurally weak. Concrete pipe is normally sufficient to withstand sulfate concentrations of 1000 parts per million (ppm) or less. For higher concentrations of sulfates, higher strength concrete, concrete with lower amounts of calcium aluminate (under 5 percent) or special coatings may be necessary.

Industrial Effluents

Industrial effluents may contain compounds that are extremely destructive to pipe materials. Waste streams from most industries are sufficiently regulated therefore raise limited concern to the highway engineer. However, tailings from mining operations, livestock operations or illegal connections from residential or small commercial lots can be a source of highly acidic runoff. Potentially corrosive runoff can also be of concern at locations known for a high probability of accidental spills (e.g., runaway truck escape ramps). An assessment of the constituents and their possible concentrations in the streamflow should be performed whenever industrial effluents are suspected. If the source can be identified, corrective action can usually be taken.

2.2 Modes of Culvert Deterioration

As explained at the beginning of the chapter, culvert deterioration is a complex process; which is affected by many factors such as structural failure, hydraulic factors, environmental factors, functional factors, age of the pipe, quality of initial construction, etc. The intensity of structural failures depends on the size of the defect, soil type, interior hydraulic regime, groundwater level and fluctuation, corrosion, method of construction, and loading on the pipe. Figure 2.14 illustrates various kinds of internal and external forces acting on a pipe. The modes of failure depend on the type of environment and pipeline material.

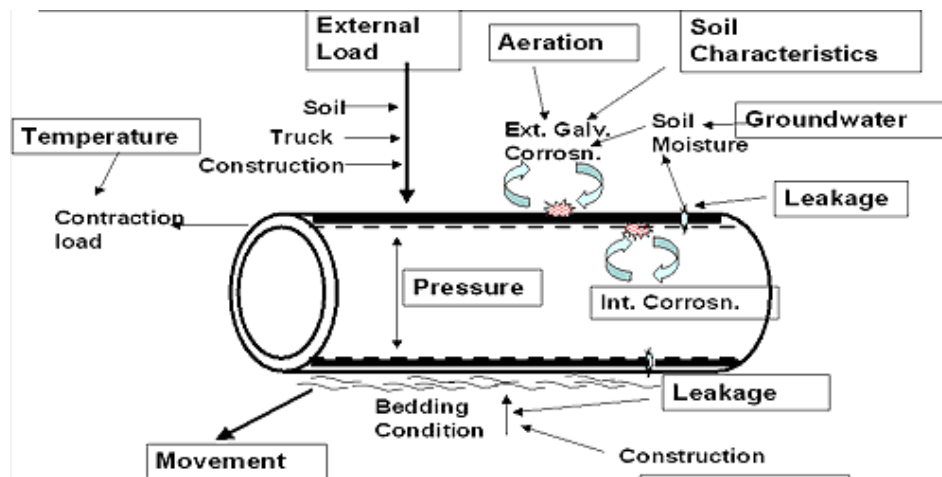


Figure 2.14 Pipeline and Culvert interactions leading to failure (O'Day et al., 1986)

Culvert breakage is likely to occur on pipes whose structural integrity has been compromised by corrosion, degradation, inadequate installation, or manufacturing defects.

A classical survival function relating the age of the pipeline to the failure rate is denoted by a bathtub curve as shown in Figure 2.15. The early part of the curve shows infantile failure which is representative of failure due to human factors in the actual laying of the pipe (manufacturing faults, tend to appear during that part). It is commonly assumed that the older the pipes, the poorer the pipe condition; however, this is not always the case and young pipes collapse, resulting in a reduced level of serviceability (Trans et al, 2006). A period of the time

follows in which failure rate is generally low. When failure does occur it may depend on many factors, such as presence of excessive loads for which the structure is not originally designed for, or settlement. As the pipes tend toward the end of their useful life the failure rate increases exponentially. This classic survival profile is known as the bathtub curve. The bathtub curve can be applied to an individual pipe, a group of pipes with similar characteristics, or the whole population of a pipe network.

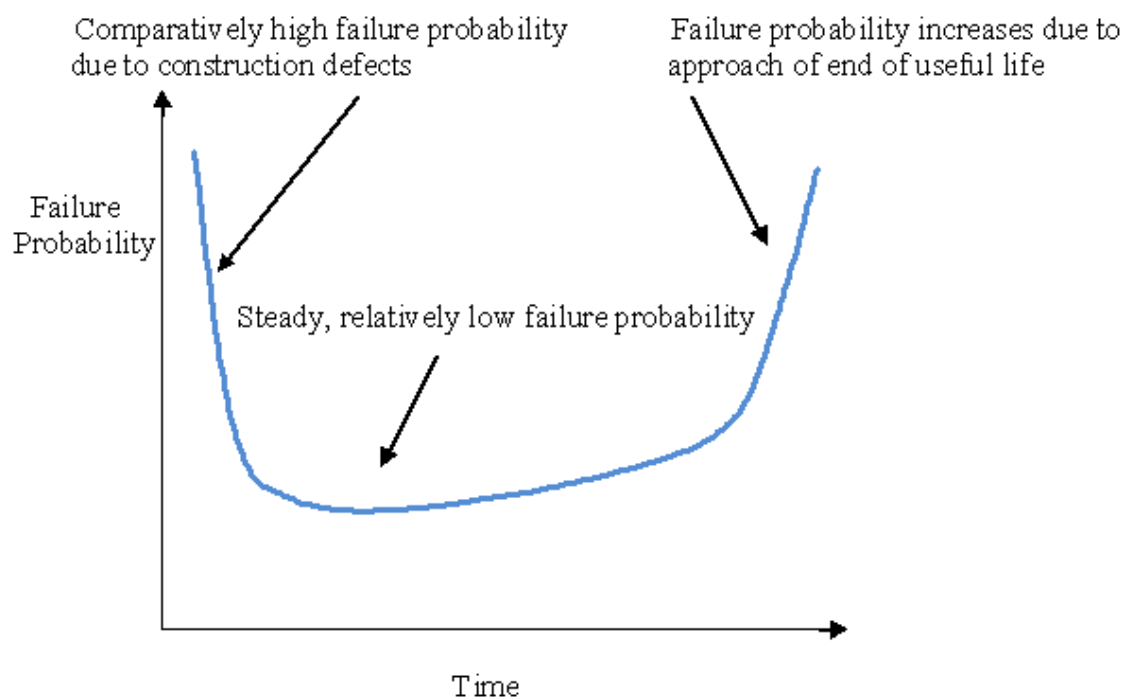


Figure 2.15 Bathtub curve of a pipe and culvert performance with age. (Najafi 2004)

2.3 Previous Research on Culvert Performance

Culvert durability and various factors affecting culvert performance have been focus points of researchers for a long time. Several culvert types have been examined under several different environmental conditions. These publications offer very important information in order to understand the behavior of culverts. In this section of the report culverts are going to be

divided into 4 different groups according to their material types and some of the important publications will be addressed in each group.

2.3.1 Corrugated Metal Culverts

Corrugated metal culverts have been in service for more than 60 years in the United States. Long range of selection for thickness and size and the ability of modification to increase the durability made this material preferable for many sites. George W. Ring has cited a letter written by Kent Allemeier in his paper “Culvert Durability: Where are we?” in 1984. According to Allemeier, the following are the advantages of Corrugated Steel Pipes:

- They are ideal for shipping due to their lightweight.
- Their sizes and shapes vary in a large range.
- The thickness of the sheets and also the corrugations can be selected from a wide range in order to obtain the required strength.
- Easy for the working crew to assemble and install.

Allemeier also mentioned the disadvantages of the Corrugated Steel Pipes as follows:

- Corrugation roughness decreases the rate of flow except for the smooth-lines pipes.
- Due to presence of sand and/or rock in a high velocity stream, abrasion may cause loss of metal.
- High sensitivity to high or low soil pH or water pH, and soil or water resistivity, which may end up with corrosion.
- Backfill operations must be handled with care due to the importance of soil support for load bearing.

According to Bednar (1989) the most important factors affecting the durability of galvanized steel pipes are the pH, dissolved salts, hardness, alkalinity, abrasiveness and time of

water contact. The rate of corrosion is affected negatively as the difference between acidity and chloride/sulfate salts and hardness and alkalinity salts increases and with the presence of abrasion. The author also adds that usually the rate of waterside corrosion is more rapid than the soil side corrosion therefore controlling factor is water side corrosion but not the soil side corrosion.

The disadvantages of corrugated metal pipes due to their sensitivity to abrasion and corrosion have been recognized by the transportation authorities and therefore several different protective coatings have been applied to the invert sections of the corrugated metal pipes where abrasion and corrosion was considered as a problem. Some of the studies investigating the durability and structural problems of corrugated metal culverts and the coating types are discussed in the following section:

One of the most thorough studies related to the durability of culverts is the “Ohio Culvert Durability” (Meacham et. al., 1982). In this particular project, 1616 culverts, which consisted of reinforced concrete pipes and galvanized corrugated steel pipes, were inspected in total. The total number of inspected culverts, 1616, corresponds to twenty percent of the total number of culverts with a diameter of 42” and higher gathered in the inventory database created in 1971. According to the predetermined breakdown of structures to be inspected, 67% of the 1616 culverts were metal and 33% concrete. Percentage of the metal culverts was higher than the percentage of the concrete culverts due to their higher variety. Corrugated metal culverts involved structural plate pipes and corrugated metal pipes. Selection of the culverts to be inspected also involved an age criteria, making the sample equally divided between 10 years of intervals. Following table (Table 2.1) was given to summarize the total number of the culverts in the inventory and the number of culverts inspected:

Material Type	Inventory	Inspected	% Inspected
Concrete	4170	545	13
Corrugated Metal	2193	685	31
Sectional Plate	1600	386	24
Total	7963	1616	20

Table 2.1: Breakdown of culverts inspected by Meacham et. al. (1982)

A visual rating system was used in order to evaluate the conditions of the culverts. According to this system 5 different classifications namely, excellent, very good, good, fair and poor, were used.

According to the statistical analysis authors conducted, the most important factor affecting the metal culvert rating was determined as the age of the culvert, which was defined as the time in years that the metal itself was exposed to the flow. Other significant parameters were determined as the pH of the water and abrasion. The acidity of the flow was shown to have a negative impact on the culvert condition. Abrasion was found to be detrimental for the flows with high pH flows. Four different equations were provided relating these significant variables to the metal loss for corrugated metal pipes with and without abrasion and for structural plates with and without abrasion respectively. Those equations yielded R-squared values in the range of 0.694 to 0.815.

Conventional Bituminous Protection was also analyzed in this study. Bituminous protection was divided into two groups: First group was the bituminous coating; second group was the bituminous coating with paved inverts. For the bituminous coating age was found to be the only factor with a statistically significant effect. The correlation between the age and protection rating was too low to reach to a conclusion about the service life of the protection. Therefore authors followed another strategy, which involved performing regression analysis to the protection rating and the percent of culverts rated as “not poor”. This strategy yielded a good correlation and the service life was estimated as 3.16 years. For the bituminous coating with

paved invert type of protection, age (very large negative effect), sum of sediment depth and flow depth (large negative effect) and abrasion (minor negative effect) was shown to have statistically significant effects. Correlation coefficient was found to be somewhat larger than the bituminous coating but still it was not satisfactory to reach a conclusion about the service life. The same strategy was used for the bituminous coating with paved invert type of protection and this strategy yielded 25 years of service life for the case where dry weather flow was within the paved section and 12 years of service life where dry weather flow overtopped the paved portion. Authors highlighted the difference between these two values and reached to the conclusion that the level of dry weather flow played a very important role on the service life of this particular protection.

A similar study is recently completed in May 2005 by Ohio Research Institute for Transportation and Environment (Mitchell et. al., 2005). In this study authors inspected a total number of 60 culverts with the objectives of verifying and modifying the inspection procedures of Ohio Culvert Management Manual and determining the significant parameters for culvert durability. The breakdown of these 60 culverts was determined as 25 concrete culverts, 25 metal culverts and 10 thermoplastic culverts. Some of the characteristics of the 25 metal culverts are given in Table 2.2

Description	Reading	Characteristics
Shape	7 out of 25	Pipe-arch
	18 out of 25	Circular
Age	14 out of 25	25 to 50 years old
	3 out of 25	50 to 75 years old
	8 out of 25	Unknown
Span	7 out of 25	2 to 5 ft.
	14 out of 25	5 to 8 ft. span
	4 out of 25	Larger than 8 ft span
Soil Cover	11 out of 25	0 to 5 ft
	5 out of 25	5 to 10 ft

Description	Reading	Characteristics
	3 out of 25	10 to 20 ft
	1 out of 25	10 to 20 ft
	5 out of 25	More than 30 ft
Road Type	4 out of 25	Interstate
	1 out of 25	U.S. Highway
	20 out of 25	State Highway
Annual Daily Traffic	3 out of 25	Less than 1000
	11 out of 25	1000 to 4000
	5 out of 25	4000 to 10000
	3 out of 25	10000 to 30000
	3 out of 25	more than 30000
pH	2 out of 25	less than 6
	22 out of 25	6 to 8
	1 out of 25	more than 8
Abrasiveness	12 out of 25	abrasive
	13 out of 25	not abrasive

Table 2.2: Characteristics of metal culverts inspected by Mitchell et. al. (2005)

Authors believed that the selected culverts represented a good sample in order to reach valid results in terms of identifying significant variables affecting the durability of culverts.

According to the results of the inspections, the authors determined the maximum service life of metal culverts as 60 to 65 years and they have found that culvert type (whether a corrugated metal pipe or a structural steel plate), pH, abrasiveness, flow velocity, age and rise were the significant parameters which affected the culvert rating. Authors observed that perforation at the invert and the flow line, scour at the inlet and outlet and concrete headwall movement were the most frequently encountered problems whereas culvert alignment was not a problem in most of the metal culvert sites and stress cracks were not observed at the bolt lines of any of the metal culverts. Invert region was determined to be more sensitive to material deterioration compared to other regions. However, crown corrosion can also represent a problem for some metal culverts due to the seepage of groundwater containing road salts. Hurd and

Sargand (1988) drew attention to the crown corrosion on metal culverts after examining 10 corrugated steel rib stiffened box culverts.

Another major study was conducted, that focused on the structural plate corrugated metal pipe structures of the arch-pipe configuration, by Degler et. al in 1988. This is an important study since the authors indicate that at the time of study approximately half of the structural plate corrugate metal pipes in Ohio were of pipe-arch configuration and all 12 districts of Ohio were involved in the study, therefore the resulting number of pipes inspected was as high as 890. According to the statistical analysis of the field data conducted by the authors, the durability of the structure was found to have a linear relationship up to 35 years and after 35 years the deterioration rate was found to be increasing. The durability of the corrugated metal structures was determined to be affected by the presence of high abrasive streams and low pH values in the Southeastern Ohio. The most frequently mode of failure encountered by the authors was corrosion and pitting of the multiplate structure, and seepage and corrosion of the bolted joints.

Transportation authorities applied different types of protective coatings to the corrugated metal pipes in order to increase the durability. Bituminous coating was examined in the “Ohio Culvert Durability” study and it was given as a summary in this report. Following section gives further information on other types of protective coatings:

Hurd, investigated the protective linings in Ohio in his paper, “Field Performance of Protective Linings for Concrete and Corrugated Steel Pipe Culverts” (Hurd 1984). Epoxy-coated concrete pipe, polymeric-coated corrugated steel pipe, and asbestos-bonded bituminous-coated and paved corrugated steel pipes located at the corrosive and abrasive sites of Ohio, Indiana and Kentucky were monitored. The results for the concrete pipe are going to be given in the “Concrete Culverts” section. Number of polymeric-coated pipes monitored was 57, and number

of asbestos-bonded bituminous-coated and paved culverts was 38. The major factor affecting the durability of the polymeric coating was determined as abrasiveness. The pH of the flow was not found to be effective on the coating; however it was found that it had an adverse effect on the pipe where the coating was worn away by the abrasive flow. Polymeric coating was found to be satisfactory at low pH sites with nonabrasive flow. Asbestos bonding was also found out to be affected by the abrasiveness. The adherence of bituminous coating was observed to be increasing with the presence of asbestos bonding. Asbestos-bonded bituminous coating with invert paving was shown to provide satisfactory results at low pH sites, with up to moderate abrasiveness.

In a similar study, Pyskadlo and Renfrew (1984) investigated the polymer coating for corrugated steel pipes in New York. Their findings support the study of Hurd (1984). Abrasiveness was found to affect the durability of the polymeric coating therefore authors suggested using a stilling basin to increase the durability of the polymeric coating. Renfrew (1984) further investigated the durability of Asphalt Coating and Paving on Corrugated Steel Culverts in New York. According to the author's findings round pipes had better coating durability than the arches and the coating on the round pipes added 30 years of life whereas the coating on the arches added only 20 years of life to the structure.

Another form of protective measures for steel pipes is using Aluminum instead of Zinc and obtaining an aluminized steel pipe. Morris and Bednar (1984) investigated the performance of aluminized steel and compared it to the galvanized steel at 54 test sites. According to the results of their investigation aluminized steel was found to show a significantly better performance compared galvanized steel in terms of corrosion and perforation. Stavros (1984) investigated the combined effect of zinc and aluminum on steel pipe improvement. The combined coating of zinc and aluminum with steel is sold with the trade name of Galvalume. As

a result of the tests, galvalume demonstrated the best performance compared to galvanized and aluminum coated pipes.

Apart from abrasion and corrosion, corrugated metal pipes are also affected by the backfill operations. Improper choice of backfill material selection, presence of groundwater, level of compaction and compaction equipment used during construction have very significant effects on the structural performance of corrugated metal pipes. For example, Sehn and Duncan (1984) investigated a replaced corrugated metal culvert due to excessive deformations. According to their findings, silty soil is found to be significantly affected by the vibratory loading during the compaction of the backfill. The strains were determined to be much higher in vibratory loading. Another example can be found in a study by Cowherd and Corda (1994). In this study, data from some of the failed metal culverts were compared with the data from the study of Degler et. al. (1988) Suggestions were made due to the percentage of midordinate reduction and depth of cover. Effects of different types of backfill material with different levels of compaction were graphed.

Structural failures of metal culverts may be frequently attributed to corrosion and abrasion related durability problems. However, excessive deflections during the installation and backfilling procedures may pose an important hazard to the structural integrity of the culvert as well.

In sum, most common problems associated with the corrugated metal culverts are their sensitivity to abrasion and corrosion and improper installation. Abrasion and corrosion may lead to severe durability problems and in some cases these may cause structural failures. Improper installation techniques may lead to severe shape distortions, joint or seam problems and misalignment. Corrosion can be eliminated or at least lessened by using appropriate types of

protection. Abrasion can be eliminated by using stilling basins. Structural problems can be eliminated by following the specifications and design guidelines and by proper application on the field.

2.3.2 Concrete Culverts

Concrete is one of the oldest materials used in the construction industry and as the usage of precast concrete increased in construction, agencies started using precast concrete sections in drainage infrastructures as well. Being more rigid compared to metal, concrete culverts are more resistant to the backfill loading, corrosion and abrasion. Allemeier states the advantages and disadvantages of concrete culverts as follows (Ring, 1984):

Advantages of concrete culverts:

- Their sizes and shapes vary in a large range
- The thickness and strength of the concrete, amount and configuration of reinforcement vary in a large range, making it possible to design appropriately for a specific site.
- Resistant to corrosion and abrasion in normal installations
- The flow has better characteristics due to the smoother surface compared to corrugations
- Rigidity of concrete makes it better in resisting loadings during compaction.

The disadvantages of concrete can be listed as follows:

- Heavy weight compared to metals, makes it difficult for shipping
- Installation or casting is more difficult and time consuming compared to metals.

Bealey (1984) explains the effects of different environmental conditions on concrete culverts. The author states that presence of abrasion and erosion, sulfate soils, chlorides and acids and freeze-thaw are the most important factors that determine the durability of concrete culverts whereas for precast concrete culverts acid attack is the only significant harmful attack.

The author also compares cast-in-place concrete culverts with precast concrete culverts and reaches the conclusion that precast concrete culverts can withstand the most aggressive environments if they are designed accordingly.

As it was mentioned in the “Metal Culverts” section, one of the most comprehensive concrete culvert evaluations was made in the “Ohio Culvert Durability Study” (Meacham et. al., 1982). In this study a total of 545 concrete culverts were inspected and statistical analysis for those inspected culverts was performed. According to the observations and results given in this report, concrete culverts were found to have different behaviors depending on the pH level. For water pH larger than 7, the age of the culvert was shown to be the only significant variable where slope, flow velocity and abrasion also showed significant but minor effects on the concrete rating. For water pH smaller than 7 (acidic flow), pH was determined as the highest significant effect. As the acidity increased (pH got smaller), the concrete rating was found to be decreasing with an increasing rate, beyond the pH level of 4.5, protection was suggested for the concrete culverts. Other significant variables were determined as pipe slope, sediment depth (positive) and age (negative). Regression equations relating these significant variables with the concrete rating was found to yield an R-squared value of 0.82

Some of the protection types for concrete culverts were also inspected during this project. According to the inspections of the authors, vitrified clay liner plates were observed to perform very well in extremely acidic conditions. Concrete field paving, was found to be successful in extending the life of the pipe in acidic conditions however the paving deterioration rate was observed to be faster than the pipe itself. Coal tar pitch coating was applied in some concrete culverts in Ohio but according to the investigations of the authors this type of coating performed poorly and did not last longer than 5 years in any of the sites.

ORITE has inspected 25 concrete culverts in Ohio in a same manner as it was mentioned in the “Metal Culverts” Section (Mitchell et.al., 2005). Some of the characteristics of the 25 concrete culverts are given in table 2.3:

Description	Reading	Characteristics
Shape	2 out of 25	horizontal ellipse
	4 out of 25	slab on top
	5 out of 25	circular
	14 out of 25	box
Age	1 out of 25	less than 25 year old
	7 out of 25	25 to 50 years old
	6 out of 25	50 to 75 years old
	5 out of 25	more than 75 years old
	6 out of 25	unknown
Span	9 out of 25	2 to 5 ft
	5 out of 25	5 to 8 ft. span
	1 out of 25	larger than 8 ft span
Soil Cover	22 out of 25	0 to 5 ft
	1 out of 25	5 to 10 ft
	1 out of 25	10 to 20 ft
Road Type	2 out of 25	interstate
	2 out of 25	U.S. Highway
	21 out of 25	State Highway
Annual Daily Traffic	7 out of 25	less than 1000
	13 out of 25	1000 to 4000
	2 out of 25	4000 to 10000
	3 out of 25	more than 30000
pH	1 out of 25	less than 6
	22 out of 25	6 to 8
	2 out of 25	more than 8
Abrasiveness	18 out of 25	abrasive
	7 out of 25	not abrasive

Table 2.3: Characteristics of concrete culverts inspected by Mitchell et. al. (2005)

According to the results of the inspections, the service life was determined as 70 to 80 years. The authors determined that age, pH and abrasiveness were significant parameters which were affecting the culvert rating. The regression equations generated in this study had an R-

squared value of 0.53. Authors state that deteriorated headwalls, crown region/top slab deterioration and transverse shear cracks were the most common problems in the inspected concrete culverts however there were no serious alignment problems for concrete culverts and there was no problem on the roadway surface passing over the culverts. Authors also added that cast-in-place box culverts and reinforced concrete circular/elliptical pipe culverts had exhibited similar performances.

Hurd (1991) investigated the performance of pre-cast reinforced box concrete culverts in Ohio between 1988 and 1990. A total number of 133 culverts were inspected in this study. According to the results, all of the culvert inverts had an excellent condition; however nine of the culverts had deteriorations on the top slab of the end sections. The probable reason of this deterioration was stated as exposure to roadway deicing salts. It was suggested to place a surface sealer on the external top slab of culverts having less than 3 ft of cover height.

In order to extend the service life of concrete culverts some protection methods are used. Hurd (1984) evaluated one of these protection methods in his paper titled as “Field performance of protective linings for concrete and corrugated steel pipe culverts”. The results for the corrugated steel pipes are given in the previous section. The method of protection investigated for concrete culverts was the epoxy-coating. In this study it is stated that epoxy-coating is used in Ohio for corrosive culvert sites since 1973 and it was initially used for sites where vitrified-clay protection was not available. Authors inspected a total number of 26 culverts where only one of the culverts was rated as poor, and the rest being either excellent or very good. The reason for the poor rating was explained as the detrimental effect of long-term sunlight exposure and/or poor bonding between the coating and concrete during the manufacture process. As a result it was

concluded that epoxy coating gives satisfactory protection if it is properly applied at acidic sites with nonabrasive to moderately abrasive flows.

Concrete culverts usually do not face structural problems due to their rigidity if they are designed according to the specifications however the soil conditions adjacent to the concrete pipes can create problems. For example, Heger and Selig (1994) investigated two case studies in rigid pipe installation failures. According to the results of their investigation soft soil adjacent to the pipe under high fills can cause increased earth loads on the structure and they suggested that soft soils should be removed from each side of the culvert for a distance of at least one diameter.

In sum, according to the studies presented, the performance of concrete culverts depend on the pH of the flow, age of the culvert, sediment depth, slope, the presence of roadway deicing salts and the soil strata next to the culvert. Concrete culverts may be considered more durable than metal culverts but they are heavier and the installation process is harder. Corrosion and abrasion may still be a major problem in some of the extremely corrosive environments. This condition may lead to durability problems, slabbing, spalling and joint problems in precast concrete culverts.

2.3.3 Plastic Culverts

Technological improvements in materials science enabled pipe manufacturers to produce lightweight and durable pipes from polymers. Several DOTs started using plastic pipes instead of conventional pipes where conditions were appropriate. Even though they are expected to perform better than conventional pipes, still some durability and structural problems arise.

ORITE has inspected 10 thermoplastic pipes in Ohio for the project “Risk Assessment and Update of Inspection Procedure for Culverts” (Mitchell et. al., 2005). Some of the characteristics of the 10 thermoplastic culverts are given in table 2.4:

Description	Inventory	Characteristics
Material	6 out of 10	High Density Polyethylene (Circular)
	4 out of 10	PVC (Circular)
Age	9 out of 10	less than 10 year old
	1 out of 10	20 to 30 years old
Diameter	5 out of 10	2 to 3 ft.
	4 out of 10	3 to 4 ft
	1 out of 10	larger than 4 ft
Soil Cover	4 out of 10	0 to 5 ft.
	1 out of 10	5 to 10 ft
	4 out of 10	10 to 20 ft
	1 out of 10	larger than 20 ft
Road Type	3 out of 10	U.S. Highway
	4 out of 10	State Highway
	3 out of 10	Others
pH	10 out of 10	6 to 8
Abrasive	9 out of 10	abrasive
	1 out of 10	not abrasive

Table 2.4: Characteristics of plastic culverts inspected by Mitchell et. al. (2005)

According to the results of the inspections authors indicate that the most frequently observed problems were the deflection of the pipes for more than 7.5%, followed by the localized buckling, and followed by the misalignment problems at joints. Authors further stated that one of the thermoplastic pipes installed at a site with severe environmental conditions proved that, with proper design and installation, these pipes could be in service for at least 20 years.

Another study carried out by Gassman et. al (2002) shows that a majority of the high density polyethylene (HDPE) pipes were deflected less than 5% in South Carolina. As a part of this study 45 HDPE pipes were selected to represent the HDPE pipes in South Carolina. Visual inspections and measurements were carried out with respect to AASHTO and ASTM specifications. According to those inspections, it was observed that 36% percent of the pipes exhibited minor cracks, punctures or bulges however pipes were still in the circular shape. The

reason of these deflections and cracks were explained as improper installation techniques such as poor bedding of soils and inadequate backfilling.

Sargand et al. (2002) studied the long term behavior of profile-wall High Density Polyethylene Pipes under deep soil cover. Two pipes with diameters of 1050 mm located under 20 ft and 40 ft cover were monitored in this study. According to the results of the paper, both pipes were found to have a satisfactory performance and the sandy soil with a 96% relative compaction was determined as good as the crushed limestone with the same compaction level.

A similar study is performed by Adams et. al. (1989) in which 24 in. diameter corrugated Polyethylene pipe was placed under 95 ft of fill. According to the results of this study the pipe was observed to remain in its circular shape and the vertical diameter decrease was observed around 4 percent whereas the horizontal diameter increase was observed around 0.4 percent. The earth pressure was also measured at the crown section of the pipe and it was determined to be only 20 percent of the vertical embankment pressure. This study shows the significance of soil-pipe interaction.

To sum up, plastic pipes can be manufactured with the desired durability to withstand the effects of corrosion and abrasion however installation and backfilling procedures have to be handled with care. Similar to the other flexible culvert types, plastic culverts also depend on the soil–structure interaction in terms of structural stability. Improper design and/or installation techniques may lead to deflections and misalignments in plastic culverts.

2.3.4 Aluminum Culverts:

Aluminum has been used as a construction material for drainage structures for approximately 50 years in the United States. Having a better corrosion resistance compared to

metal culverts made aluminum culverts the choice of designers in many sites. Allemeier gives the advantages and disadvantages of aluminum as follows (Ring, 1984):

Advantages of Aluminum:

- They are ideal for shipping due to their very light weight.
- Their sizes and shapes vary in a large range.
- The thickness of the sheets and also the corrugations can be selected from a wide range in order to obtain the required strength.
- Easy and fast assembling and installation procedures.
- They have better resistance against corrosion than steel pipes in salty water.

Disadvantages of aluminum are listed as follows:

- Corrugation roughness decreases the rate of flow except for the smooth-lines pipes.
- In case of significant amount of presence of sand and/or rock in a high velocity stream, abrasion may cause loss of material.
- They are generally more expensive than steel pipes.
- Installation procedures have to be handled more carefully compared to steel pipes due to higher flexibility.
- They are more sensitive to the live and dead loads compared to the steel pipes due to higher flexibility.

Summerson (1984), explains the high corrosion resistance of aluminum pipes with the oxide films produced by the chemical reactions on the surface of the pipe. The author states that this very thin layer of oxide film is extremely stable and therefore does not show any reaction over a wide range of conditions and even in a case of mechanical damage such as abrasion the film refreshes itself instantly. The author further states that corrosion may be a problem on some

defective areas on the pipe where the oxide film has some micro defects due to the metallurgical properties however; this corrosion takes place locally as a form of pitting therefore it does not affect the overall durability of the pipe drastically. Summerson does field inspections and laboratory tests in California in order to prove the theoretical corrosion resistance of aluminum culverts. According to the results of the inspection, when aluminum pipes are used at the sites where pH values are within the specifications (between 4 and 9) and the minimum resistivities are 500 ohm-cm aluminum pipes show excellent performance.

Bellair and Ewing (1984) investigated and compared the metal-loss rates observed in uncoated steel and aluminum culverts in New York. The field survey included 190 galvanized steel culverts and 35 aluminum culverts. According to their findings, aluminum culverts showed significantly better performance than uncoated steel culverts throughout the state and with the application of statistical analysis to the field data they have reached to the conclusion that 35 mil thickness of material was satisfactory for a 70-year design life, which was already within the minimum thickness requirement.

Hurd et. al. (1991), investigated the structural performance of an aluminum box culvert during the installation and live load application on the structure. The culvert selected for investigation was a corrugated aluminum box culvert with a span of 14 ft 10 in, a rise of 4 ft 10 in. and a length of 42 ft. Deflections and strains along the culvert were recorded and results were analyzed with computer programs and a finite element analysis was made. As a result of the analysis it was concluded that the structural performance of the aluminum culvert was satisfactory and finite element analysis was proved to be beneficial in analyzing and designing these structures. Some criticism about the computer program CANDE was made after comparing the actual measurements and computer outputs.

To sum up, aluminum culverts and aluminum coated culverts can be considered to have better corrosion resistance compared to steel culverts if they are used on the sites within the design limits; however, installation and backfilling procedures should be handled with a greater care due to the higher flexibility.

2.4 Culvert Asset Management

Culvert asset management provides the ability to show how, when, and why culvert resources were/are committed. Transportation officials are highly accountable for all transportation assets. Even though, periodic inspections and preventive repairs may appear to cause an added economic burden, the transportation agencies, will obtain tremendous cost savings by lowering the emergency repair costs due to reduced number of failures. The traveling public will benefit from culvert asset management because user delays are minimized. Asset management practices also improve efficiency and increase the value of services to transportation users.

Some of the benefits to DOTs from asset management practices are (Perrin, 2004):

- Accountability to the public
- Increased budget demands
- Rational approach to resource allocation
- Defense against politicizing the program

The American Association of State Highway and Transportation Officials (AASHTO) and Federal Highway Association (FHWA) recommend that asset management is a better way to do business. They provide national leadership and guidance to states for implementing and developing asset management in all states (Perrin, 2004). The culvert management system allows

the transportation agency to have an inventory of culverts, and to develop a short and long-term plan for maintenance and renewal (FHWA, 2001).

3. National Survey

One of the objectives of this project is to conduct a national survey among the departments of transportation (DOTs) in the United States in order to develop a database of trenchless technology methods that are being used to repair and renew culverts. The outcome of this survey would provide valuable detailed information regarding the use of trenchless technologies such as frequency, advantages and disadvantages of each method employed as well as the DOTs' insights of these methods.

The survey was prepared by the researchers after performing the literature review on the trenchless repair and renewal methods. It was structured as 3 parts. First part consisted questions regarding the contact information of the respondent. Second part focused on culvert asset management issues and the last part focused on culvert repair and renewal methods and usage of trenchless technologies. A copy of the survey form can be seen in Appendix 1.

The survey was conducted electronically through the mailing list of ODOT and sent to the DOTs on three occasions. The first round of survey was conducted in March 2008 and it was re-conducted due to low number of responses in April and May 2008 for the second and third times respectively. Ohio, Texas, Minnesota, Missouri, West Virginia, Maryland, New York, and California State DOTs responded to the questionnaire. One of respondents indicated that they are not aware of any trenchless technologies used for the renewal of culverts in their state and preferred not to fill out the survey form. Therefore the outcomes of this questionnaire are going to be presented in the following sections according to the responses of seven state DOT officials. Due to the low number of responses statistical analysis of the results is not performed.

Investigators believe that the low number of responses were due to the fact that majority of the state DOTs are not yet familiar with several trenchless technology methods and state

DOTs are relying on the manufacturers' and contractors' experience and knowledge. Although information gathered from the survey was limited in detail, it provided an insight about the application of trenchless technologies to culverts by state departments of transportation.

3.1 Results of the Survey

The survey consisted of 22 questions in total. First part of the questions, (questions from 1 to 9) address culvert asset management strategies of DOTs, second part of the questions (questions from 10 to 22) address culvert repair and renewal procedures and usage of trenchless technologies. The results of the survey are going to be presented under these two groups.

3.1.1 Culvert Asset Management

Question 1: What is the definition of a culvert in your agency?

The responses to this question are given in Table 3.1. The primary purpose of a culvert, that is carrying live and dead loads due to roadway and forming a passageway for water, is common in the answers. The maximum size of a culvert which differentiates it from a bridge varies from state to state. 4 states indicated that if a culvert is larger than 20 ft then it is categorized as a bridge whereas 1 of respondents indicated that culverts larger than 10 ft are classified as bridges in their state.

Question 2: What is the approximate breakdown of culverts with respect to their material type in your state?

The responses to this question are given in Table 3.2. For the states who responded to the questionnaire, concrete and metal culverts constitute approximately 95% of overall culverts. Concrete is the dominant material of choice for culverts among respondents.

Respondent	Definition of a culvert
Respondent 1	An open-ended structure which is typically designed hydraulically to take advantage of submergence at the inlet to increase hydraulic capacity. It is a structure used to convey surface runoff through embankments. It is a structure, as distinguished from a bridge, which is usually covered with embankment and is composed of structural material around the entire perimeter, although some are supported on spread footings with the stream bed serving as the bottom of the culvert.
Respondent 2	A culvert is a structure under a roadway, usually for drainage. It is a bridge-class culvert if it has a clear opening of 20 feet or more measured along the centerline of the roadway between extreme ends of the openings for multiple boxes or multiple pipes that are 60 inches or more in diameter.
Respondent 3	A culvert is defined as a structure sized hydraulically to convey surface water runoff under a highway, railroad or other embankment. Pipes with a span of 10 feet or greater are classified as a bridge for inspection and management.
Respondent 4	A structure not classified as a bridge (i.e. less than 20 ft. span), that provides an opening under any portion of a roadway. Rigid Pipe Culverts have been specified since 2004 in three Groups A, B and C. Group A is Concrete and Vitrified Clay Pipe, Pipe, Group B is those in A plus Polymer Coated Corrugated Metal, Aluminum Alloy, Polyethylene, PVC and Aluminum Coated Steel pipe, Group c is all in A & B plus Bituminous Coated Corrugated Metal AND Zinc-Coated Steel pipe.
Respondent 5	< 20' span
Respondent 6	Pipes, battery of pipes and box culverts 5' to 20'. In addition we inventory similar structures from 3' to 5 feet provided the amount of fill is less than or equal to their span length.
Respondent 7	A culvert is pipe that conveys water, and has an end treatment at either side. An end treatment is a physical break in the continuity of the culvert such as drop inlets and manholes

Table 3.1: Responses to Question #1

.	Percentage of Overall						
Material Type	Respondent 1	Respondent 2	Respondent 3	Respondent 4 ⁽²⁾	Respondent 5	Respondent 6	Respondent 7
Concrete	62	95	71	15.3	Unknown	52.24	27
Metal	32	5	26	82.3	Unknown	44.42	58
Plastic	4	<<1	3	1.7	Unknown	0.19	4
Aluminum	1	<<1	0	0.1	Unknown	0.15	Counted under metal
Other	1	<<1 ⁽¹⁾	0	0.6 ⁽³⁾	Unknown	0	11 ⁽⁴⁾

(1): Fiber Reinforced Concrete Pipe

(2): Percentage of pipes installed as of year 2000 on supplementary roads. Percentage of concrete pipes is much higher when primary and interstate roads are considered.

(3): Vitrified Clay

(4): 10% of the culvert material types are unknown. Masonry is 0.3%.

Table 3.2: Responses to Question #2

Question 3: Does your DOT have standardized inventory guidelines for culverts?

The responses to this question are shown in table 3.3 along with responses to question 4. 2 states had no inventory guidelines and 2 states stated that they used the national bridge inspection standards as their inventory guidelines. The remaining 3 states indicated that they had a standardized culvert inventory guideline.

Question 4: Does your DOT have standardized inventory guidelines for culverts?

The responses to this question are shown in table 3.3 along with responses to question 3. 1 state had no standardized inspection guidelines for culverts and 2 states stated that they used the national bridge inspection standards as their inspection guidelines. The remaining 4 states indicated that they had a standardized culvert inspection guideline however 1 of these 4 states has inspection guidelines for only culverts larger than 10 ft in size.

	Yes	No	Use NBIS
Inventory Guidelines	3 out of 7	2 out of 7	2 out of 7 ⁽²⁾
Inspection Guidelines	4 out of 7 ⁽¹⁾	1 out of 7	2 out of 7 ⁽²⁾

(1): One of the respondents indicated they have inspection guidelines for culverts 10' or greater in size.

(2): One of the respondents indicated they use NBIS for culverts 20' or greater in size for inventory and inspection purposes.

Table 3.3: Responses to Questions #3 and #4

Question 5: What are the major factors that are considered while inspecting culverts?

The responses to this question are given in table 3.4. According to the results, corrosion, abrasion, shape, wall thickness, alignment and joint failures are the most common factors considered while inspecting metal culverts. Cracking, alignment, joint failures, abrasion, shape, and corrosion are among the most common factors considered while inspecting concrete culverts. Shape, alignment and joint failures are among the most common factors considered while inspecting plastic culverts.

Factor	Metal			Concrete			Plastic			Other ⁽¹⁾		
	Yes	No	No Answer	Yes	No	No Answer	Yes	No	No Answer	Yes	No	No Answer
Corrosion	7			5	1	1	2	3	2	1		6
Abrasion	6	1		6	1		4	2	1	1		6
Shape	7			5	2		6		1	1		6
Wall Thickness	5	2		2	5		2	4	1		1	6
Alignment	7			7			6		1	1		6
Cracking	4	3		7			4	2	1	1		6
Joint Failures	6	1		7			5	1	1	1		6
Hydraulic Capacity	3	3	1	3	3	1	4	2	1	1		6
Other ⁽²⁾	2		5	2		5	2		5	1		6

Table 3.4: Responses to Question #5

(1): Respondent 7 indicated masonry and unknown under the “other” category of material types for culverts in question #2.

(2): Two respondents indicated that they consider other factors while inspecting culverts as summarized in the following table (3.5):

Respondent	Factors
Respondent 3	Holes, Piping, Infiltration, Inslope Cavitation, Roads Voids or Stress, Erosion
Respondent 7	Stream/channel flowing into or out of culverts, Roadway as it is interacting with the culvert, End treatments (end treatments are any structure that breaks the continuity of a culvert such as drainage inlets and manholes), Embankment around the end treatment

Table 3.5: Other Factors Considered While Inspecting Culverts

Question 6: How often does your agency inspect culverts located under state highways and interstate highways?

The responses to this question can be found on table 3.6. The inspection frequency depends on the size of the culvert for some of respondents. If the culvert size is large enough to be classified as a bridge-culvert it is inspected according to the bridge inspection requirements. For some other states the culvert size is not considered while determining the inspection frequency.

Question 7: Does your DOT have a computer database to store the culvert inventory information?

The responses to this question are given along with responses to question 8 and 9 in table 3.7. According to the results it can be seen that some of states do not have a computerized database to store the culvert inventory information. One of the respondents indicated they have the database for only culverts that are larger than 20 ft.

Respondent	Inspection Frequency
Respondent 1	Every 5 years
Respondent 2	24 - 48 months
Respondent 3	No required inspection frequency for pipes smaller than 10 ft. Culverts 10 feet and greater are designated as bridges and follow bridge management inspection frequency 1 to 2 years.
Respondent 4	Box culverts are inspected every 5 years. Pipe culverts are inspected only as needed.
Respondent 5	5 years for culverts 10 feet or greater
Respondent 6	4 years
Respondent 7	Currently still on the first cycle of our complete condition survey, with revisits done on an as needed basis

Table 3.6: Responses to Question #6

Question 8: Is there a model or formula that your agency uses in order to determine the remaining service life of culverts depending on the inspection results?

The responses to this question are given along with responses to question 7 and 9 in table 3.7. Only one respondent indicated that they use have a formula to calculate the remaining service life of a culvert depending on the inspection result. The respondent provided a copy of the project report in which a comprehensive examination of culverts was performed and researchers reached service life equations for metal and concrete culverts in 1982.

Question 9: Does your DOT have a decision support system which integrates the culvert inventory, condition assessment and repair/renewal method selection?

The responses to this question are given along with responses to question 7 and 8 in table 3.7. Three (3) respondents indicated that they have a decision support system which integrates inventory, inspection and repair/renewal method selection. One of these three respondents added

that this was a part of their bridge management system therefore it can be concluded that it is only applicable to large culverts which can be classified under the bridge category.

Questions 7, 8, and 9	Yes	No
Computer database for culvert inventory	5 ⁽¹⁾	2
Formula to determine remaining service life	1	6
DSS integrating inventory, inspection and renewal procedures	3 ⁽²⁾	4

(1): One of the respondents indicated they have a computer database for culverts larger than 20 feet.

(2): One of the respondents indicated that the decision support system is a part of their overall bridge management program.

Table 3.7: Responses to Questions #7, #8, and #9

3.1.2 Culvert Renewal and Usage of Trenchless Technologies

Question 10: How does your inspector overcome the confined space problems?

The responses to this question are given in table 3.8. One of the respondents indicated that they follow the OSHA approved confined space entry procedures while majority of the remaining respondents indicated that they inspect inlet and outlet of culverts. 4 respondents further stated they also use CCTV.

Method	Used by
CCTV	4 out of 7 respondents
Inspecting inlet and outlet	5 out of 7 respondents
Other	2 respondents ⁽¹⁾

(1): One of the respondents indicated they follow OSHA approved confined space entry procedures. The other respondent indicated they do not enter all the culverts, they decide according to their engineering judgment

Table 3.8: Responses to Questions #10

Question 11: What are the major structural or hydraulic culvert problems in your state?

The responses to this question are given in table 3.9. According to the responses deterioration is the major problem faced with culverts. The hydraulic performance of a culvert is affected by the presence of debris and sediment accumulation. Improper installation and the resultant joint problems are also along the problems faced by DOTs.

Respondent	Major structural or hydraulic culvert problems
Respondent 1	Structural: Proper Installation Hydraulic: No major problems
Respondent 2	Structural deterioration, debris and sediment accumulation
Respondent 3	Joint separation in concrete pipes and holes in metal pipes
Respondent 4	Use of materials other than reinforced concrete pipe under roadways with over 7500 ADT in order to reduce costs Rusting out of metal culverts within 5 years of installation in mining areas.
Respondent 5	Abrasive soils and acidic water
Respondent 6	Rusted inverts
Respondent 7	Debris and corroded inverts, End of service life

Table 3.9: Responses to Questions #11

Question 12: What are the most common maintenance / repair methods in your state?

The responses to this question are given in table 3.10. It can be seen that paving the inverts of culverts is among the most common repair methods used by DOTs. One of the respondents also indicated that they use internal sleeves to repair joints. Repairing the concrete inslope sections of culverts is also mentioned by one of the respondents.

Respondent	Most common maintenance / repair methods
Respondent 1	Paved Invert, Joint Repair with expandable internal sleeve
Respondent 2	Reconstruction of short pipe lengths is very uncommon.
Respondent 3	Resetting concrete sections at inslope
Respondent 4	Replacing ends of pipe as problems reach the shoulder line. Sometimes when rusted out, paving inverts with concrete or HMA
Respondent 5	Reconstruction of partial length
Respondent 6	Grout line the inverts
Respondent 7	Culvert lining

Table 3.10: Responses to Questions #12

Question 13: What are the most common rehabilitation or replacement methods in your state?

The responses to this question are given in table 3.11. According to the responses rehabilitating existing culverts with liners is a commonly employed method. It can be seen that open cut replacement is the main method of replacing culverts among the respondents.

Respondent	Most common rehabilitation or replacement methods
Respondent 1	Reline
Respondent 2	Replacing CIPP and sliplining with HDPE once or twice each year for the past several years.
Respondent 3	Lining Replace in conjunction with road rehabilitation or reconstruction project, typically open trench installation.
Respondent 4	PVC and HDPE liners Insituform thermally formed liners
Respondent 5	Open cut trenches with replacement Boring or jacking
Respondent 6	Grout line the inverts
Respondent 7	CIPP, culvert lining, and invert lining or paving

Table 3.11: Responses to Questions #13

Question 14: Which of these factors are considered while repairing or replacing the existing culverts?

The responses to this question are given in table 3.12. Almost all of the respondents indicated that they consider inspection results and structural problems of the culvert while repairing or replacing procedures. Hydraulic capacity, traffic volume and cost are also considered by almost all of the respondents. The age of the culvert was considered by four of the respondents and the roadway surface and embankment condition was considered by only three of the respondents and (out of 7 respondents).

Factor	Yes	No	No Answer
Inspection Results	6	1	
Structural Problems	6	1	
Age of the culvert	4	3	
Hydraulic Capacity	5	2	
Traffic Volume	5	2	
Roadway Surface	3	4	
Embankment Condition	3	4	
Cost	5	2	
Other ⁽¹⁾	1	1	5

(1): One of the respondents indicated that they also consider the following factors: access to pipe such as right of way to do repair or replace technique, scheduled road project, cover, size and, shape (round, arch, box) of pipe, rocks in soil (can be problem with jacking)

Table 3.12: Responses to Questions #14

Question 15: What are the trenchless renewal methods employed in your state and what is the frequency of use for each method on the average per year?

The responses to this question are given in table 3.13. According to the results sliplining, grouting, and cured-in-place pipe methods are the trenchless methods employed by the highest number of respondents. Among these methods, sliplining seems to have the highest frequency of use and cured-in-place seems to have the lowest frequency of use.

Method	Yes	No	No Answer	Frequency
Cured-in-Place Pipe	4	2	1	No answer ⁽¹⁾ , 2-4 ⁽²⁾ , 10% ⁽³⁾ , Frequent ⁽⁷⁾
Sliplining	6	1		Used most often ⁽¹⁾ , 20 ⁽²⁾ , 90% ⁽³⁾ , 1-2 ⁽⁴⁾ , No answer ⁽⁵⁾ , Frequent ⁽⁷⁾
Pipe Bursting	1	4	2	Tested Once ⁽³⁾
Pipe Reaming		5	2	N/A
Pipe Eating		5	2	N/A
Pipe Ejection/Extraction		5	2	N/A
Close-Fit Pipe		5	2	N/A
Panel Lining	1	4	2	1 or 2 ⁽⁵⁾
Robotic Repair		5	2	N/A
Grouting	5	1	1	Occasional ⁽³⁾ , 20 ⁽⁴⁾ , 10 ⁽⁵⁾ , no answer ⁽⁶⁾ , Rarely ⁽⁷⁾
Internal Seal	2	3	2	Occasional ^(3,7)
Point CIPP	1	4	2	Occasional ⁽³⁾
Cement Mortar Lining	2	3	2	Occasional ⁽³⁾ , Rarely ⁽⁷⁾
Epoxy Coating	1	4	2	Once or twice ⁽⁷⁾
Thermoformed Pipe	1	4	2	1 or 2 only ⁽⁴⁾
Other	1 ^(*)		6	A few times ⁽⁷⁾

(*): One of the respondents indicated they used Spiral Wound PVC Lining

(1): Frequency reported by respondent 1.

- (2): Frequency reported by respondent 2.
- (3): Frequency reported by respondent 3.
- (4): Frequency reported by respondent 4.
- (5): Frequency reported by respondent 5.
- (6): Frequency reported by respondent 6.
- (7): Frequency reported by respondent 7.

Table 3.13: Responses to Questions #15

Question 16: For each of the trenchless methods employed before what are the critical pre-construction, construction and post-construction issues?

The responses to this question are given in table 3.14. The critical issues while employing the three common trenchless repair and renewal procedures (sliplining, cured-in-place pipe and grouting) are as follows: According to the results the pipe to be sliplined needs to be free of debris, excessive misalignment and deformations prior to the start of renewal procedures. The opening in the existing pipe should not restrict the insertion of the lining pipe. During the sliplining process it is important to pay attention to the grouting procedure to avoid floating and/or bulging of the liner pipe. Providing a staging area is also important during sliplining. During grouting procedure the pipe size should be checked against whether it allows access or not. During the cured-in-place pipe applications the existing pipe should be cleaned and the surface of the pipe should be prepared to prevent any irregularities in the finished CIPP and to provide a tight fit of the liner with the pipe. The cured-in-place pipe procedure also requires adequate curing procedures.

Method	Respondent	Pre-Construction	Construction	Post-Constru ction
Cured-in-Place Pipe	Respondent 1	Debris clean out, Access	No Answer	
	Respondent 2	Used infrequently, Rely on Manufacturer's recommendations		
	Respondent 3	Cost/ Benefit, Traffic, Use with Asbestos Bonded	Grout road voids, let contract with multiple cipp liners	No answer

Method	Respondent	Pre-Construction	Construction	Post-Construction
	Respondent 7	Pipe deformation and cross section	Adequacy of cure	No Answer
Sliplining	Respondent 1	Debris Clean Out, Access	Maximum opening, grouting	No Answer
	Respondent 2	Used infrequently, Rely on Manufacturer's recommendations		
	Respondent 3	No deformation or misalignment in existing pipe, hydraulic capacity	Staging area required, grouting voids can cause bulged pipe	No answer
	Respondent 4	No answer	Room to insert liner	No answer
	Respondent 5	Unknown conditions	Grouting	No answer
	Respondent 7	Cross section, available space for insertion	Annulus grouting pressure	No Answer
Pipe Bursting	Respondent 3	Rocks	No Answer	
Panel Lining	Respondent 6	No answer		
Grouting	Respondent 3	Access - pipe size	No Answer	
	Respondent 4	No answer		
	Respondent 5	No answer		
	Respondent 6	No answer		
	Respondent 7	No answer		
Internal Seal	Respondent 3	Access - pipe size	No answer	
	Respondent 7	Pipe stability, working space	Achieving water tight seal and testing	No Answer
Point CIPP	Respondent 3	No answer		
Cement Mortar Lining	Respondent 3	Access - pipe size, pipe strength	No Answer	
	Respondent 7	Use of fibers for reinforcing vs WWM	No Answer	
Epoxy Coating	Respondent 7	Toxicity of material	Bond strength	No Answer
Thermofomed Pipe	Respondent 4	Clean Pipe	Inspection	Inspection

Method	Respondent	Pre-Construction	Construction	Post-Construction
Spiral Wound Pipe	Respondent 7	No answer		

Table 3.14: Responses to Questions #16

Question 17: For each of the trenchless methods employed before what are the minimum and maximum culvert sizes in inches?

The responses to this question are given in table 3.15. Sliplining method has been employed in various ranges among states. The minimum and maximum sizes reported among the respondents were 12 inches and 144 inches respectively. Cured-in place pipe method has been employed for pipes with similar sizes among the three respondents. The minimum and maximum sizes reported among the respondents were 12 inches and 48 inches respectively. Thermoformed pipe method was employed by one of the respondents and it was indicated that this method was used to renew pipes within the range of 10 inches and 30 inches.

Method	Respondent	Minimum (in)	Maximum (in)
Cured-in-Place Pipe	Respondent 1	15	36
	Respondent 2	18	48
	Respondent 3	Unknown	
	Respondent 7	12	48
Sliplining	Respondent 1	54	144
	Respondent 2	18	48
	Respondent 3	Unknown	
	Respondent 4	12	36
	Respondent 5	15	42
	Respondent 7	18	60
Pipe Bursting	Respondent 3	Unknown	
Panel Lining	Respondent 6	No restrictions	
Grouting	Respondent 3	Unknown	
	Respondent 4	No answer	
	Respondent 5	No answer	
	Respondent 6	No restrictions	

Method	Respondent	Minimum (in)	Maximum (in)
	Respondent 7	48	Unknown
Internal Seal	Respondent 3	Unknown	
	Respondent 7	30	72
Point CIPP	Respondent 3	Unknown	
Cement Mortar Lining	Respondent 3	Unknown	
	Respondent 7	36	96
Epoxy Coating	Respondent 7	6' x 8' box	Unknown
Thermoformed Pipe	Respondent 4	10	30
Spiral Wound Pipe	Respondent 7	No answer	

Table 3.15: Responses to Questions #17

Question 18: For each of the trenchless methods employed before what is the average construction cost/linear feet/per inch of diameter?

The responses to this question are given in table 3.16. The majority of the respondents were unable to indicate a cost figure for the trenchless methods they employed.

Method	Respondent	Average Cost
Cured-in-Place Pipe	Respondent 1	No tracking mechanism
	Respondent 2	\$5.00 - \$10.00
	Respondent 3	Unknown
	Respondent 7	No data
Sliplining	Respondent 1	No tracking mechanism
	Respondent 2	No answer
	Respondent 3	Unknown
	Respondent 4	Cost of PVC or HDPE pipe - do with own crews
	Respondent 5	Unknown
	Respondent 7	No data
Pipe Bursting	Respondent 3	Unknown
Panel Lining	Respondent 6	No Answer
Grouting	Respondent 3	Unknown
	Respondent 4	No answer
	Respondent 5	Unknown
	Respondent 6	\$50 / LF for invert paving
	Respondent 7	No data
Internal Seal	Respondent 3	Unknown
	Respondent 7	No answer

Method	Respondent	Average Cost
Point CIPP	Respondent 3	Unknown
Cement Mortar Lining	Respondent 3	Unknown
	Respondent 7	No data
Epoxy Coating	Respondent 7	No data
Thermoformed Pipe	Respondent 4	Unknown
Spiral Wound Pipe	Respondent 7	No answer

Table 3.16: Responses to Questions #18

Question 19: What are the advantages and limitations of the trenchless methods used by your agency before?

The responses to this question are given in table 3.17. According to the results sliplining method offers the advantages of cost savings and limited traffic disruption. Another important advantage of the sliplining method is the availability of the equipments needed for this type of renewal. Limitations of sliplining are given as staging requirement, pipe condition, size, loss of diameter and potential accessibility problems. Cured-in-place pipe method offers the advantages of hydraulic capacity improvement, structural strength improvement, and little traffic disruption. The limitations of cured-in-place pipe are given as the cost of the method, size, pipe condition, diameter loss and potential accessibility problems. Pipe bursting method was reported to have limitations due to rocks and directional control of the method. Grouting and internal seal methods were reported to have limitations due to the pipe size. Point cured-in-place pipe method offers the advantages of improved hydraulic efficiency and little traffic disruption however it has a limitation due to its high cost. Thermoformed pipe was also reported to have a limitation due to its high cost.

Method	Respondent	Advantages	Limitations
Cured-in-Place Pipe	Respondent 1	Cost Savings, Limited Traffic Disruption	Size, pipe condition, accessibility, height of cover
	Respondent 2	Being able to repair pipe in place	Unknowns associated with new technologies, some loss of inside

Method	Respondent	Advantages	Limitations
			diameter
	Respondent 3	Hydraulic capacity, expected lifespan, structural strength, little traffic disruption	Cost- requires contract with multiple pipes for efficiency
	Respondent 7	Small footprint, minimum impact on pipe cross section	No answer
Sliplining	Respondent 1	Cost Savings, Limited Traffic Disruption	Size, pipe condition, accessibility, height of cover
	Respondent 2	Being able to repair pipe in place	Unknowns associated with new technologies, some loss of inside diameter
	Respondent 3	Maintenance forces have equipment and can slipline, little traffic disruption	Staging area required
	Respondent 4	No excavation	Cost
	Respondent 5	No answer	
	Respondent 7	Many contractors, relatively cheap	Need lots of space for construction, takes large amount of host pipe cross section
Pipe Bursting	Respondent 3	No answer	Rocks and directional control
Panel Lining	Respondent 6	No answer	
Grouting	Respondent 3	Speed, low cost, little traffic disruption	Pipe size minimum for access
	Respondent 4	No answer	
	Respondent 5	No answer	
	Respondent 6	Does not affect traffic	Working room
	Respondent 7	No answer	Limited durability of chemical grouts
Internal Seal	Respondent 3	Speed, low cost, little traffic disruption	Pipe size minimum for access
	Respondent 7	Cheap	Only works for certain joint defects
Point CIPP	Respondent 3	Hydraulic capacity, little traffic disruption	Cost, must let contract with multiple pipes for cost efficiency
Cement Mortar	Respondent 3	No answer	

Method	Respondent	Advantages	Limitations
Lining	Respondent 7	Relatively inexpensive	Ineffective for most abrasion problems
Epoxy Coating	Respondent 7	No answer	
Thermofomed Pipe	Respondent 4	No excavation	Cost
Spiral Wound Pipe	Respondent 7	No answer	

Table 3.17: Responses to Questions #19

Question 20: What are the future maintenance requirements of culverts renewed by the following trenchless methods?

The responses to this question are given in table 3.18. According to the results future maintenance of the trenchless renewal methods are not specifically formulated. Basically same maintenance requirements are used for renewed culverts and existing culverts.

Method	Respondent	Future Maintenance Requirements
Cured-in-Place Pipe	Respondent 1	No change in practice
	Respondent 2	Unknown
	Respondent 3	Unknown
	Respondent 7	Unknown
Sliplining	Respondent 1	No change in practice
	Respondent 2	Unknown
	Respondent 3	Unknown
	Respondent 4	Make sure pipe does not flout out
	Respondent 5	No answer
	Respondent 7	Unknown
Pipe Bursting	Respondent 3	Unknown
Panel Lining	Respondent 6	No answer
Grouting	Respondent 3	Unknown
	Respondent 4	No answer
	Respondent 5	No answer
	Respondent 6	None
	Respondent 7	Unknown

Method	Respondent	Future Maintenance Requirements
Internal Seal	Respondent 3	Unknown
	Respondent 7	Unknown
Point CIPP	Respondent 3	Unknown
Cement Mortar Lining	Respondent 3	Unknown
	Respondent 7	Unknown
Epoxy Coating	Respondent 7	Unknown
Thermoformed Pipe	Respondent 4	None
Spiral Wound Pipe	Respondent 7	Unknown

Table 3.18: Responses to Questions #20

Question 21: What are the inspection frequencies of culverts renewed by the following trenchless methods?

The responses to this question are given in table 3.19. According to the results, inspection frequency of the culverts renewed by trenchless renewal methods is not specifically defined. Basically same inspection frequency is used for renewed culverts and existing culverts.

Method	Respondent	Inspection Frequency
Cured-in-Place Pipe	Respondent 1	5 years
	Respondent 2	Same as other culverts
	Respondent 3	Unknown
	Respondent 7	Unknown
Sliplining	Respondent 1	5 years
	Respondent 2	Same as other culverts
	Respondent 3	Unknown
	Respondent 4	N/A
	Respondent 5	No answer
	Respondent 7	Unknown
Pipe Bursting	Respondent 3	Unknown
Panel Lining	Respondent 6	no answer
Grouting	Respondent 3	Unknown
	Respondent 4	N/A
	Respondent 5	No answer
	Respondent 6	Maintain a 4 year cycle
	Respondent 7	Unknown
Internal Seal	Respondent 3	Unknown

Method	Respondent	Inspection Frequency
	Respondent 7	Unknown
Point CIPP	Respondent 3	Unknown
Cement Mortar Lining	Respondent 3	Unknown
	Respondent 7	Unknown
Epoxy Coating	Respondent 7	Unknown
Thermoformed Pipe	Respondent 4	N/A
Spiral Wound Pipe	Respondent 7	Unknown

Table 3.19: Responses to Questions #21

Question 22: What are the important factors which influence the decision making procedure on whether to employ an open-cut (traditional) replacement or to use trenchless renewal methods?

The responses to this question are given in table 3.20. Almost all of the respondents indicated that traffic volume and detour availability were considered while deciding on whether to employ an open-cut (traditional) replacement or to use a trenchless renewal method. Location and depth of cover was considered by 5 respondents (out of 7 respondents). Another important factor, whether the repair/replacement could be included in a road project or not, was indicated by one of the respondents. One of respondents indicated that they consider cost and obstructions while deciding on whether to employ an open-cut replacement or trenchless repair and renewal.

Factor	Yes	No	No Answer
Location	5		2
Traffic Volume	6		1
Detour Availability	6		1
Depth of Cover	5		2
Other	2		5

Table 3.20: Responses to Questions #22

4. Survey of Technology Providers

In order to further investigate the trenchless technology methods a survey was planned, and distributed among all the technology providers known. This survey was divided into three major parts:

Part1. Contact Information: Respondent identifies himself/herself by filling 11 spaces with the necessary information.

Part 2. Culvert Asset Management: Respondent was asked to answer nineteen (19) questions. Question types involved “Fill in the blanks, Yes/No and alternative ranking”.

Part 3. Culvert Construction, Repair, Renovation, Replacement (Renewal) and Usage of Trenchless Technologies: Respondent was asked to select the types of trenchless methods used and identify some key characteristics and limitations when using those methods

The survey was developed by the research team and uploaded to a website. The surveyed companies had the option to submit their responses either electronically or by fax. The survey form can be seen in Appendix 2. This chapter has the intention to show the results of the survey in a dynamic and comprehensive manner.

4.1 Results and Analysis

Question 1: Does your company work on culverts?

The survey had 23 responses, out of which 13 companies or 57 percent replied to be capable to work on culverts; this question must be interpreted as work on renewal purposes by trenchless methods. It should be noticed that these numbers represent the industry average in the US. Results can be seen on Figure 4.1

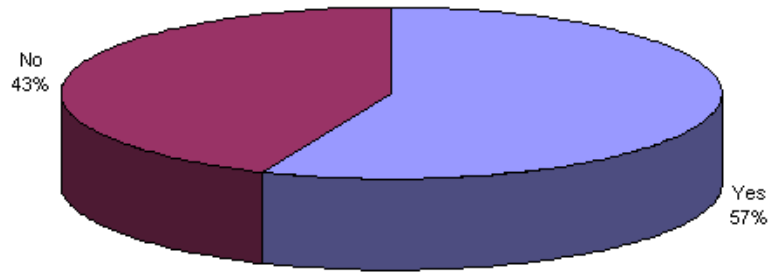


Figure 4.1 Responses to Question #1

Question 2: Does your company provide Culvert Inspection Services?

A total of 8 companies or 35 percent of the 23 companies provide culvert inspection services, inspection services can include but are not limited to the following: Closed-Circuit television (CCTV), radar, laser, etc. (see Figure 4.2).

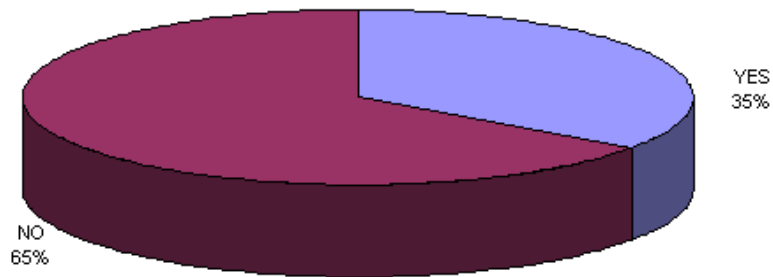


Figure 4.2 Responses to Question #2

Question 3: Does your company have or use any Standard Inspection Services?

Out of the 8 companies which provide culvert inspections, 3 companies (about 13 percent of overall respondents of the survey) indicated that they use standards for the inspection of culverts. Respondents indicated that they use ASTM, PCAP and NASSCO standards without specifying the exact standard number. (See Figure 4.3).

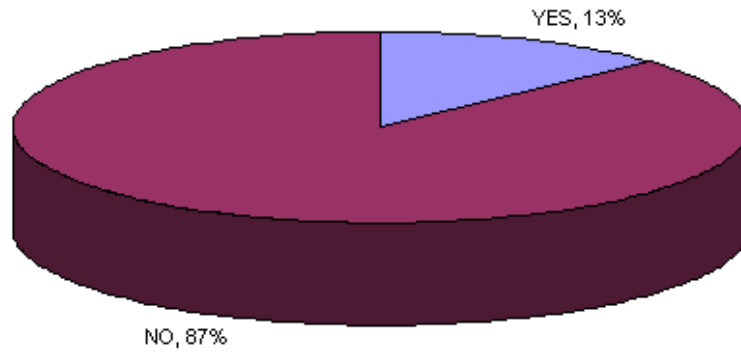


Figure 4.3 Responses to Question #3

Question 4: Rank the major problems responsible for failure of culverts.

Question 4 solicited the respondents to rank the major problems affecting metal, concrete, and plastic culverts. According to the experience of the companies, corrosion and abrasion ranked as the major problems affecting metal culverts; for concrete culverts, joint failure and cracking ranked as the major ones; and deflection and joint failure ranked as the major problems suffered by plastic culverts. According to the results, corrosion was not taken into account as a factor for plastic culverts (see Figure 4.4). It is also noteworthy that wall thickness and hydraulic capacity remained as factors that have less influence on culvert failure for any type of culvert material (metal, concrete and plastic). Another type of problem encountered by the surveyed companies is sedimentation with a rank of 3 out of 7. For illustration purposes number “7” was given to the factor that affects the most and number “0” to the factor that affects the least (see Figure 4.4).

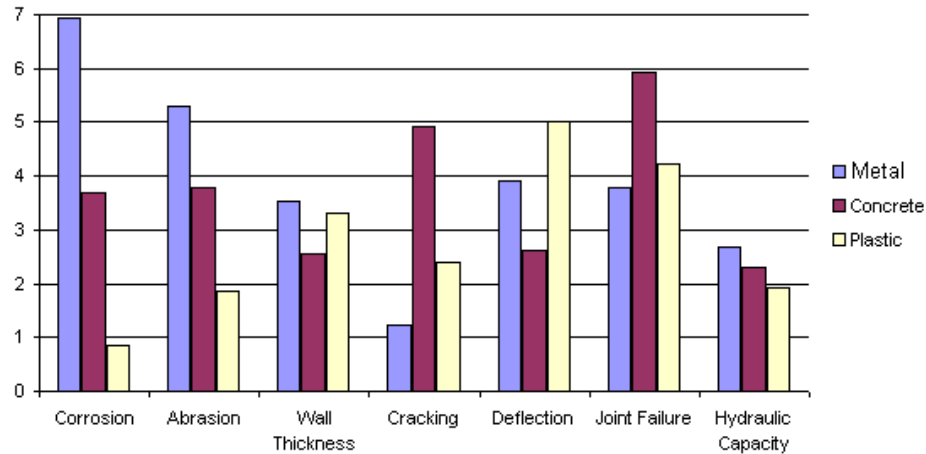


Figure 4.4 Responses to Question #4

Question 5: Circle the Culvert Materials which your company renews more.

According to the responses from the industry and technology providers metal culverts are renewed the most, followed by concrete and plastic culverts (see Figure 4.5). This tendency may be explained due to the higher number of corrugated pipe culverts placed below the roads several decades ago which nowadays are deteriorating due to completion of their design life accompanied by the effects of corrosion and abrasion over a long period of time. According to the survey, other types of renewed culvert materials are wood and clay pipes. For illustration purposes number “3” was given to the factor that affects the most and number “0” to the factor that affects the least.

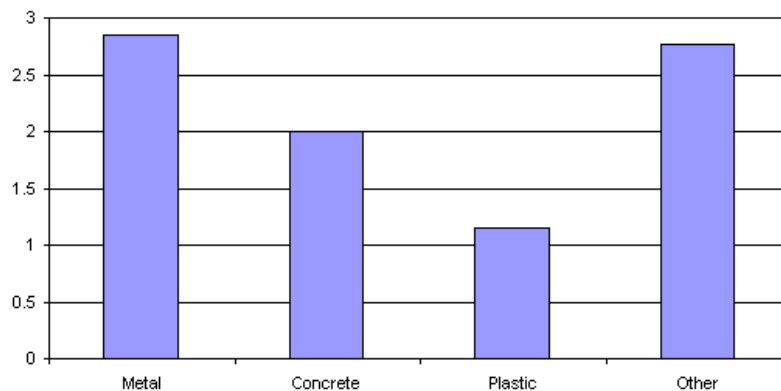


Figure 4.5 Responses to Question #5

Question 6: Which Trenchless Renewal Methods does your company carry out?

According to the findings of the survey, sliplining, pipe bursting and CIPP methods represent almost 45 percent of all the trenchless renewal methods used by companies. The use of the sliplining method (20 percent) is comparable to the summation of the use of grouting, panel lining, close-fit pipe and polymer coating. (see Figure 4.6)

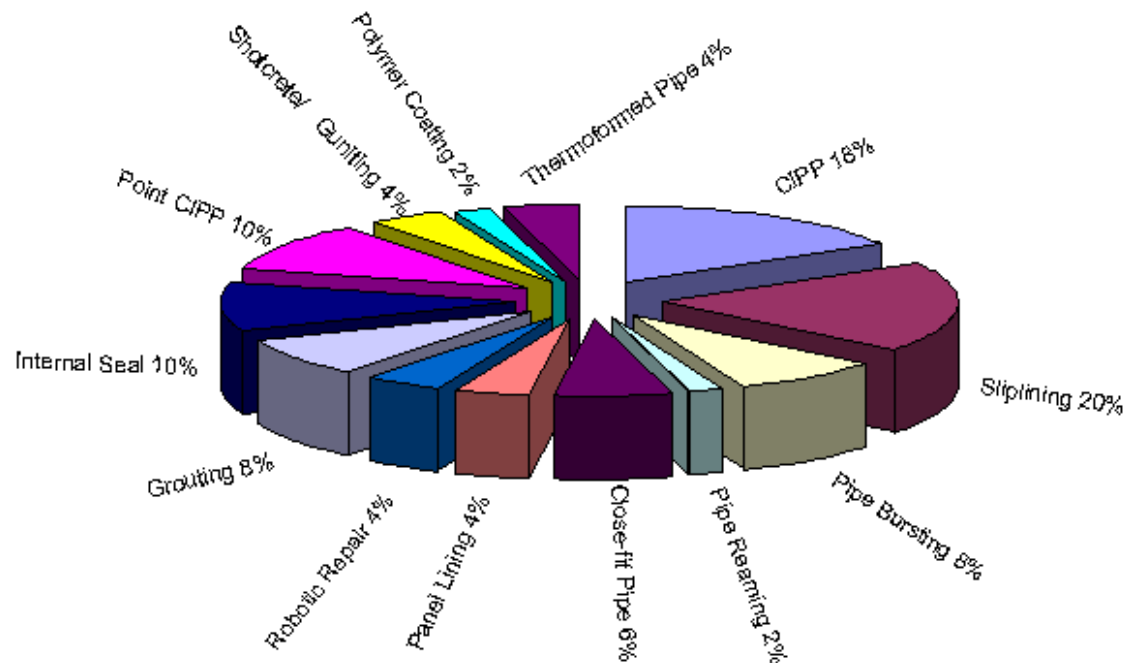


Figure 4.6 Responses to Question #6

Question 7: Rank the factors which govern the selection of a particular type of trenchless renewal method according to their importance.

Cost of repair versus cost of replacement, as well as the condition of the existing culvert ranked as the two most influential factors when selecting a trenchless method for renewing a culvert. According to the survey findings aesthetics might not be a crucial issue. Figure 4.7 shows a number of factors that influences the selection of a trenchless renewal project. For illustration purposes number “13” was given to the factor that affects the most and number “0” to the factor that affects the least.

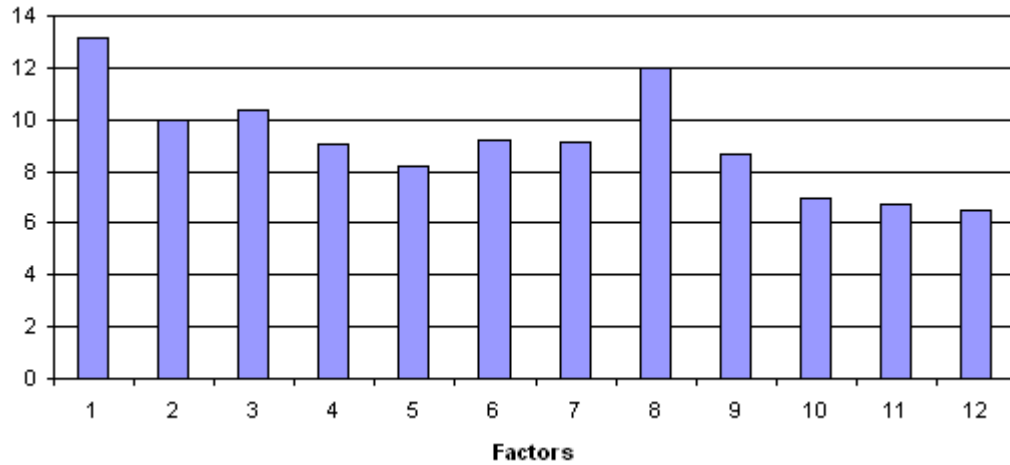


Figure 4.7 Responses to Question #7

List of Factors

1. Condition of the existing culvert and its suitability for renewal.
2. Capacity, alignment, and other characteristics of the culvert.
3. Site conditions.
4. Funding availability.
5. Availability and expertise of in-house forces.
6. User cost or time out of service.
7. Current and future needs of the area served by the culvert.
8. Cost of repair versus cost of replacement.
9. Effluent characteristics.
10. Availability and expertise of local contractors.
11. Availability and cost of materials and specialized equipment.
12. Aesthetics.

Question 8: Rank the critical pre-construction issues that play a wide role during planning phase on the following Trenchless Renewal Methods.

According to the responses, the existing condition of a culvert plays a big role during planning phase of using a Trenchless Renewal Method (See Figure 4.8). It is also important to note that the diameter, shape and material of the culvert become critical factors when renewing culverts via trenchless methods. On the other hand, the type of flow is the factor that less influences pre-construction phase among all the trenchless methods listed in Figure 4.8. For illustration purposes number “7” was given to the factor that affects the most and number “0” to the factor that affects the least (see Figure 4.8).

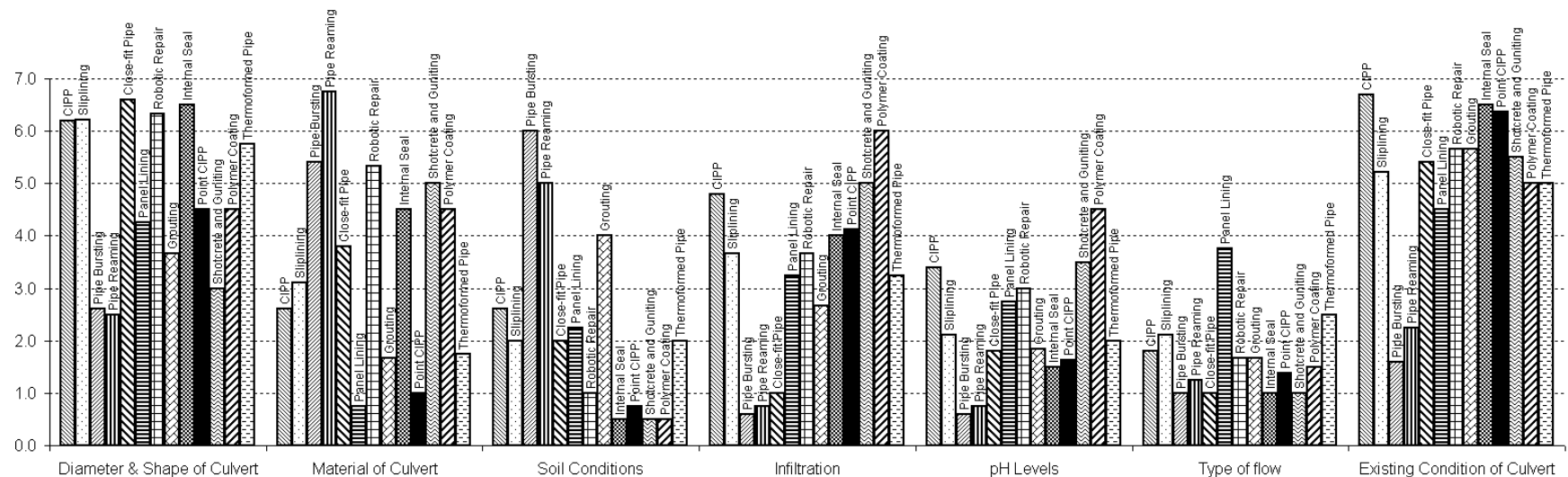


Figure 4.8 Responses to Question #8

Question 9: Rank the critical construction issues which are very important during installation of the following renewal methods.

In the construction process of a trenchless renewal technique the issues encountered were more diverse in their rank. As expected, shotcrete/guniting, polymer coating and internal seal methods that require worker entry ranked this particular factor as close to critical, moreover, the study also found that safety and flow diversion may become a greater issue in this stage. It is also notable that, in average ground stability was ranked as a “not extremely critical construction issue” for the Trenchless Renewal Methods listed below. For illustration purposes number “7” was given to the factor that affects the most and number “0” to the factor that affects the least (see Figure 4.9).

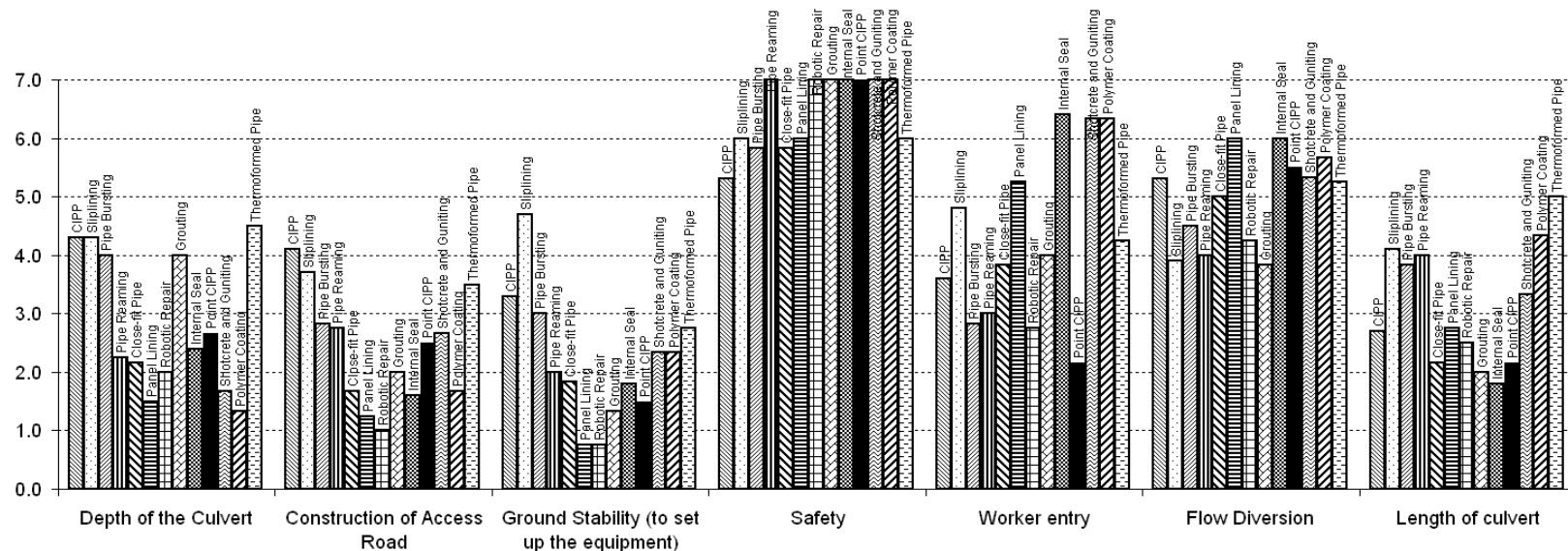


Figure 4.9 Responses to Question #9

Question 10: Rank the critical Post-Construction issues that are important following installation of the following renewal methods.

In the post-construction phase, regular inspections and maintenance factors ranked as semi-critical factors followed by the length of service. For illustration purposes number “3” was given to the factor that affects the most and number “0” to the factor that affects the least (see Figure 4.10).

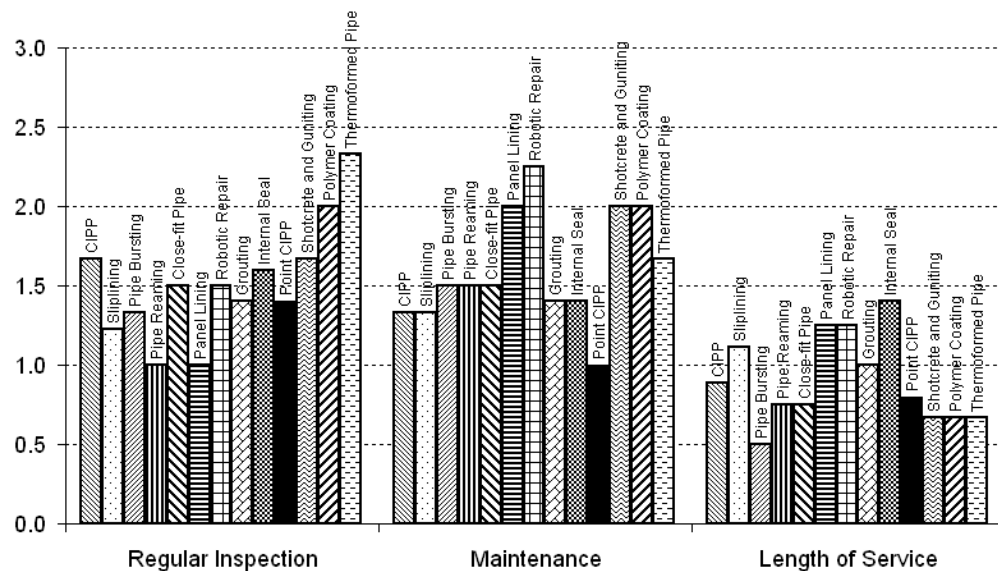


Figure 4.10 Responses to Question #10

Question 11: What are the important factors in order to decide on whether to do an open-cut (traditional) replacement or to use trenchless renewal methods? (yes/no)

When asked about if depth of cover, location, and traffic volume were critical factors while deciding whether to perform an open-cut or trenchless renewal process, all respondents indicated “yes” to all of them. This situation shows that these factors deserve an important consideration during the decision making process. However 8% of the companies believe that detour availability might not represent an important factor when deciding to use trenchless renewal methods.

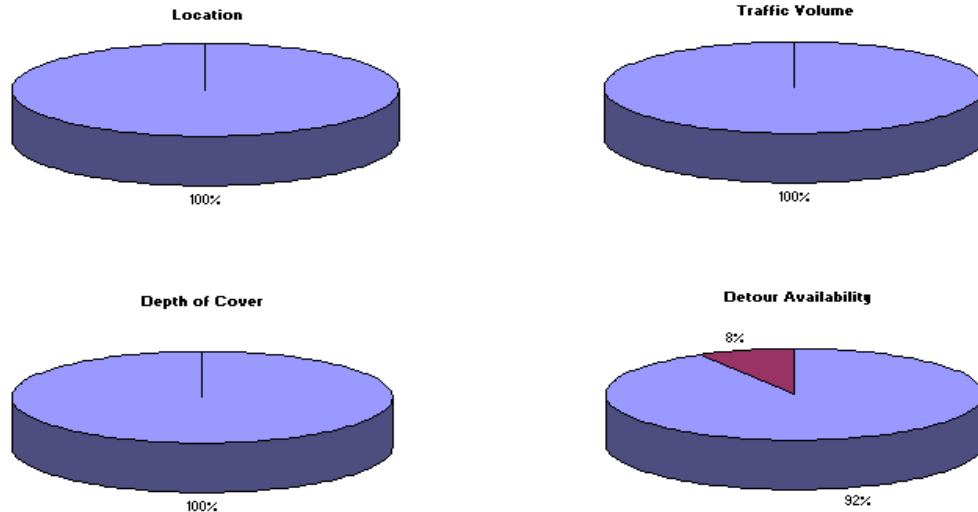


Figure 4.11 Responses to Question #11

Question 12: Provide the minimum and maximum culverts sizes your company has employed for the following Trenchless Renewal Methods in inches. Also specify the Maximum size of the culvert that you think can be installed by the following methods.

The outcome values for this question vary widely; however, the lowest minimum value, the highest maximum size and the highest accepted size among all the surveyed is given below (Table 4.1):

Method	Minimum Size in Inches	Maximum Size in Inches	Maximum Accepted Size in Inches
Cured-in-Place Pipe (CIPP)	4 in.	120 in.	120 in.
Sliplining	4 in.	96 in.	63 in.
Pipe Bursting	3 in.	36 in.	30 in.
Pipe Reaming	6 in.	30 in.	48 in.
Close-fit pipe	8 in.	24 in.	48 in.
Panel Lining	10 in.	Unlimited	Unlimited
Robotic Repair	6 in.	36 in.	36 in.
Grouting	6 in.	120 in.	120 in.
Internal Seal	24 in.	66 in.	144 in.
Point CIPP	6 in.	48 in.	120 in.
Shotcrete/Guniting	48 in.	77 in.	144 in.
Polymer Coating	48 in.	96 in.	144 in.
Thermoformed Pipe	10 in.	30 in.	30 in.

Table 4.1: Responses to Question #12

Question 13: What are the limitations for the following Trenchless Renewal Methods?

When the survey turned its focus to the limitations of the trenchless renewal methods, some important findings appear. All the companies believe that bypassing is needed when using panel lining, shotcrete/guniting, polymer coating and thermoformed pipe. It is notable as expected, that the bypassing represents an important problem among all the other methods listed in Figure 4.12. For the sliplining method it is unavoidable to observe that the seals liner ends are treated as a great limitation of that trenchless method. The importance of the need for worker entry for the shotcrete/guniting and for the polymer coating methods should also be noticed.

Question 14: How many years of additional life can be provided to a deteriorated culvert after it is being renewed by the following methods?

Any renewal method explained in this report has the intention to extend the operational life of a culvert. Almost 60 years can be added to a culvert when pipe bursting is used to renew it. Point CIPP, polymer coating, shotcrete and guniting, robotic repair, sliplining, close-fit pipe and pipe reaming also provide an additional life to a culvert with an average of 50 years, however it should be noticed that point CIPP offers a local design improvement thus it will not improve the total length of the culvert. Grouting does not necessarily increase the operational life of a culvert as shown in Figure 4.13. It is also important to express, these additional operational life values can only be achieved by the use of good construction means and methods.

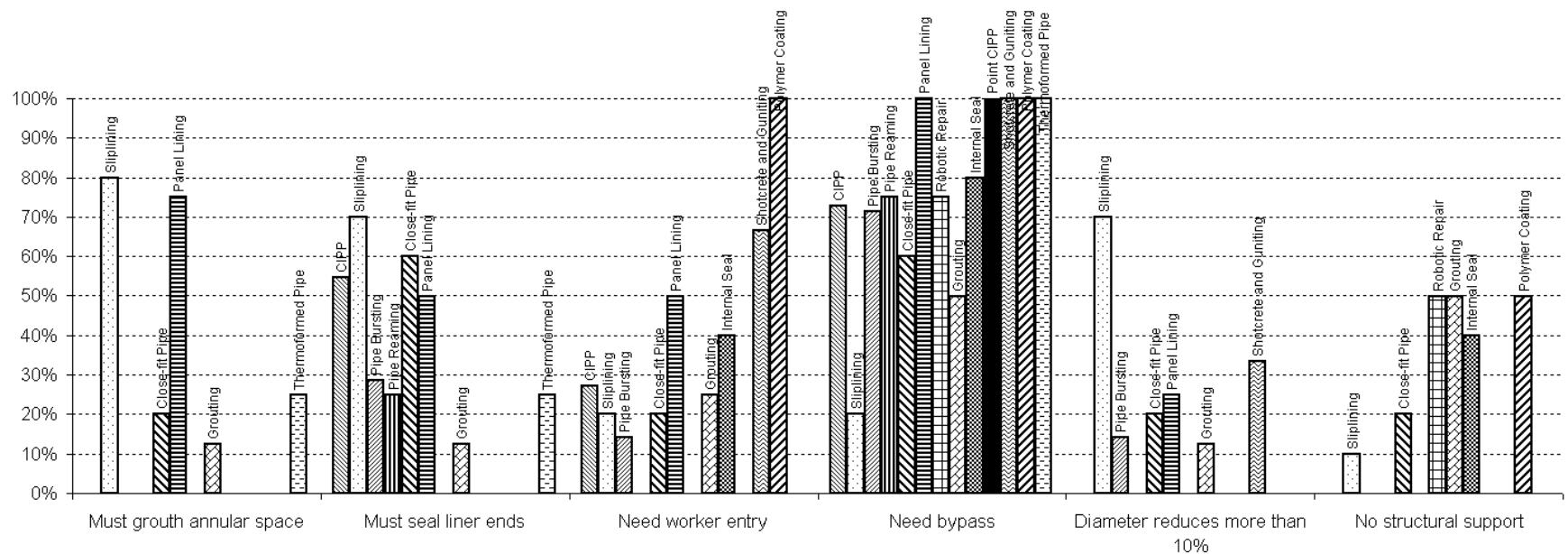


Figure 4.12 Responses to Question #13

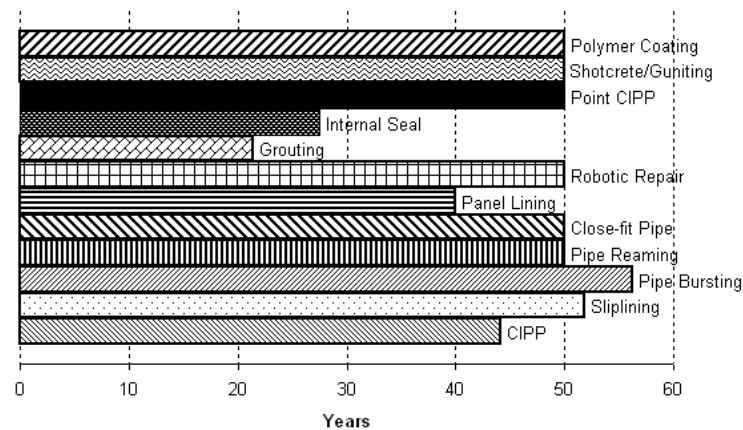


Figure 4.13 Responses to Question #14

Question 15: Does your company typically perform any test on the renewal methods after they are being applied to the existing deteriorated culvert?

Tests on the trenchless renewal methods are frequently used by companies as a quality control measure. Some of the respondents indicated that they do not carry out any type of tests, however the reader must take into account that the test might be carried out by other subcontracted companies. Another surveyed company, indicated that they use several techniques, such as: physical properties, hydraulic tests and Closed Circuit Television (CCTV) for the Cured-in-Place Pipe, hydraulic tests and CCTV for sliplining as well for pipe bursting; air tests and CCTV for grouting and CCTV for point CIPP.

Question 16: Which of the trenchless renewal methods are suitable for the following problems executed in the culvert?

One of the main focuses of this report is to suggest a method to renew culvert and storm sewers given a set of problems. This question inquires the surveyed companies to suggest a Trenchless Renewal Method to be used in a summarized list of problems. On average, companies believe that pipe bursting and robotic repair methods are suitable to renew culverts with all the defects given in the list below. The survey also found that for a culvert which is affected by seam defects and scalling the use of internal seal is highly suitable. A highlighted finding in this question is that; CIPP and sliplining techniques is not suitable for renewing culverts affected by misalignment / joint separation problems.

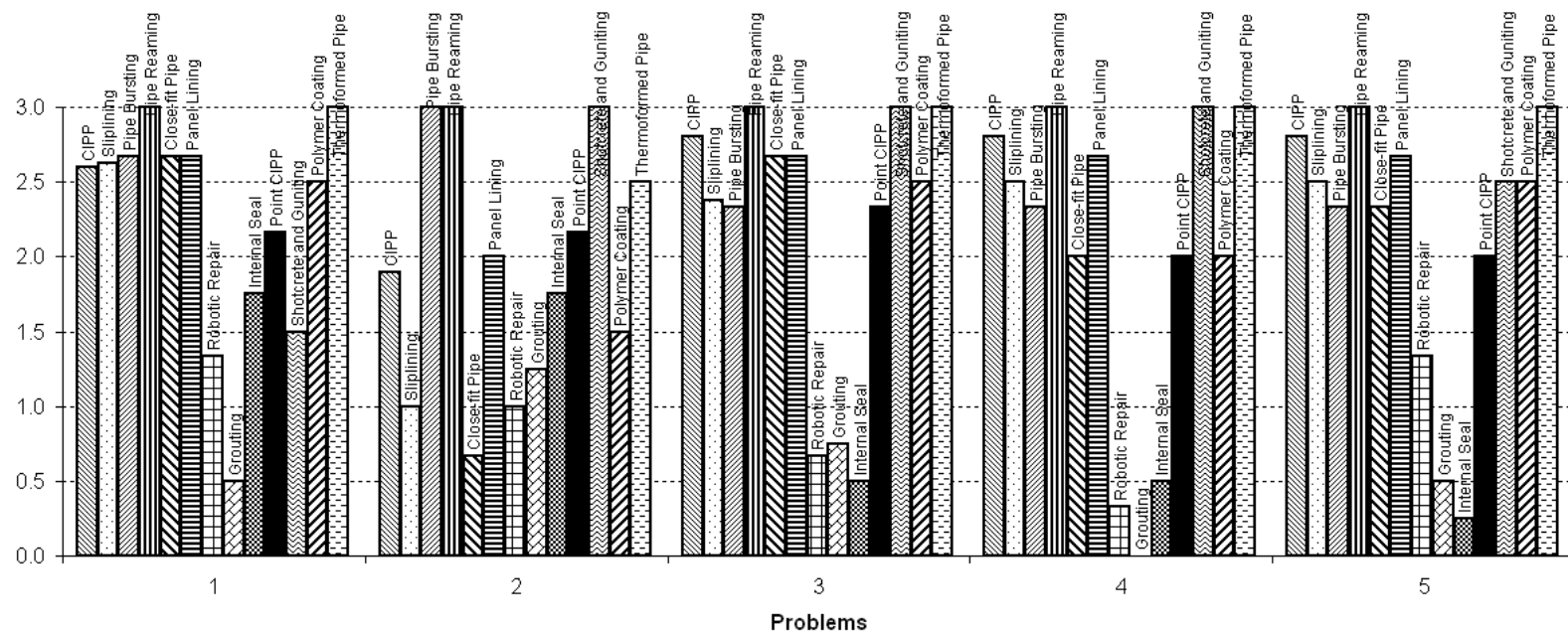


Figure 4.14 Responses to Question #16

List of the problems:

1. Corrosion & abrasion
2. Misalignment & joint separation
3. Seam defects & scalling
4. Delamination & efflorescence
5. Spalling & honey combing

Question 17: Is there any relation between the existing culvert material and the trenchless renewal method?

Question 17 mainly focused on the suitability of the trenchless renewal methods for a given existing culvert material. According to the findings of the survey most of the renewal methods are suitable for concrete pipes; it is also notable that the grouting technique is more suitable for concrete culverts compared to other type of materials. The results of the survey also show that close fit pipe is highly suitable for concrete pipes and plastic pipes and the corrugated formations inside the steel pipe and the aluminum pipe tend to discourage the use of close-fit pipe in renewal of culverts. For illustration purposes, number 3 was given to the most suitable method and number 0 to the least suitable method. Figure 4.15 summarizes the outcomes of this question.

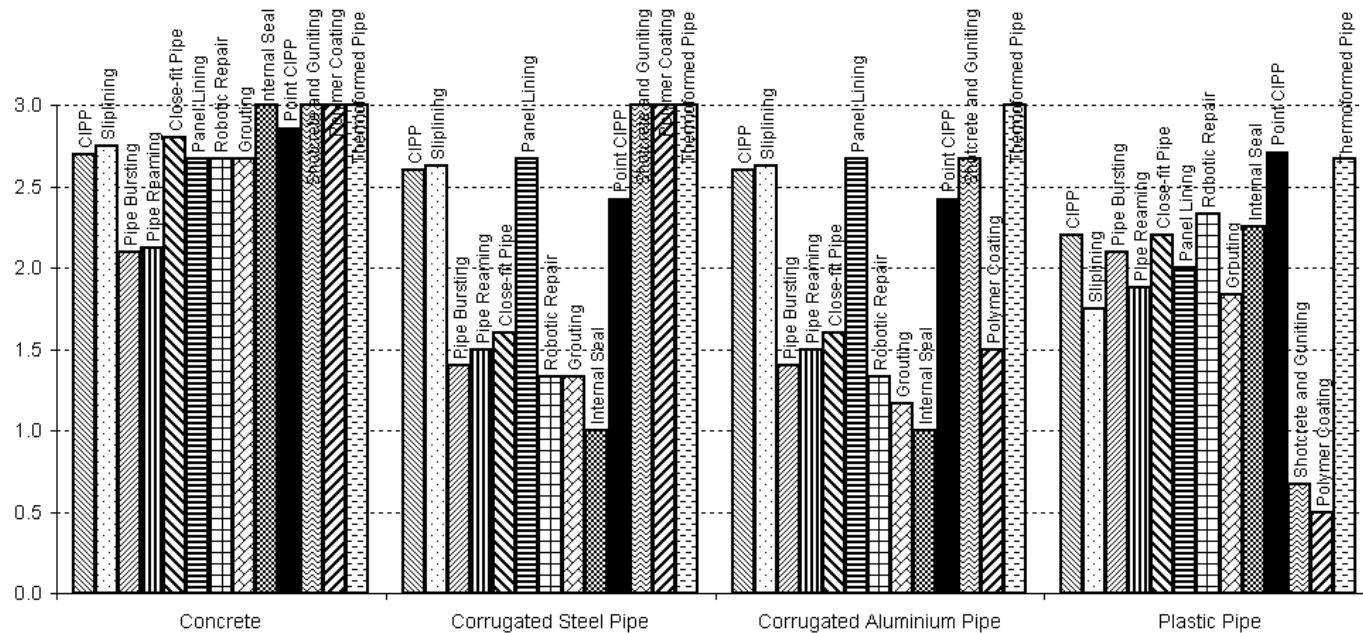


Figure 4.15 Responses to Question #17

Question 18: What specification and Material does your company use for Trenchless Renewal Methods specifically for culvert applications?

This open answer question had a wide variety of responses; however, a general summary will be provided in the following paragraphs:

Specifications:

- The study found that the industry standard “ASTM F1216” is used by companies to renew culverts when using point CIPP and CIPP techniques.
- Previous company projects and the standard “AASHTO M326” are the specifications used by companies to renew culverts when using Sliplining techniques.
- Previous company projects are commonly used as guideline specifications when renewing culverts using pipe bursting.
- NASSCO standards are used in the Grouting renewal method.

Materials:

- For sliplining and pipe bursting, HDPE is widely used.
- PVC pipes are also used in sliplining renewal projects.
- When companies use CIPP or point CIPP techniques, they tend to use polyester (PE) materials and combination of resin/felt as well.
- For the grouting renewal method, concrete is the material of choice.

Question 19: Please use this space additional information to be considered in our study. Also please explain if your company uses any other type of Trenchless Technology.

From all the responses there was not a worthwhile response to this question.

5. Trenchless Technology Methods

Construction and renewal (rehabilitation and replacement) of buried pipes have been performed traditionally by the open-cut method. This method generally involves excavation of a trench for the whole length of pipe, dewatering, placing bedding material, placing the pipe, and finally backfilling and compaction. This method causes construction and renewal procedures to be very expensive especially where the depth of excavation is high and in congested areas due to managing the traffic by providing detours. Other costs of open-cut construction and renewal of buried pipes involve items such as the costs due to damage to the existing pavement (and other buried infrastructure if present), user costs due to the waiting time and detour traveling, potential accident costs due to work-zones, and environmental damage.

Trenchless technology methods offer alternative methods for construction and renewal of buried pipes in which construction of trenches and thereby problems associated with the open-cut method are reduced if not eliminated. Some of the trenchless technology methods such as tunneling, and pipe jacking have been used in construction of buried structures for over a century however with the technological advancements in computer science, material science, and mechanical improvements in construction equipments during the last two decades new trenchless technology methods have been revealed to inspect, construct, repair and renew the existing buried structures in a cost effective manner without disrupting the environment and users. (Najafi 2004)

Since the design and construction of highway infrastructure network, the number of vehicles has increased tremendously and majority of these highway infrastructure elements are on the verge of completing their design lives. Therefore construction of new buried conduits and renewal of the existing ones are among the top priorities of highway agencies. Trenchless

technology methods for inspection, construction, repair and renewal of buried pipes are the most powerful tools of managing these highway assets which eliminate the problems associated with open-cut methods. In this section trenchless technology methods used for inspection, construction, repair and renewal of buried pipes are going to be examined in more detail.

5.1 Trenchless Inspection

Inspecting buried pipes for assessing their current conditions is one of the most important duties of highway and/or utility agencies since it affects the accuracy of the decisions made regarding the renewal of the pipe. Depending on the inspection results the agency decides whether to do nothing, or to perform point repairs, or to rehabilitate the whole length of the pipe, or to completely replace the existing pipe. Therefore the accuracy of the inspection results directly affects the accuracy of the decisions made.

Inspecting culverts manually by worker entry may not always be possible due to the size of the culverts or due to the dangers associated with entering into the particular culvert. In these situations relying on the outcomes of inspections made from inlets and outlets may result in taking a wrong course of action due to some of the defects unforeseen by the inspector. Trenchless inspection methods examined in this section help to assess the condition of buried pipes for which the entry of the inspector is not possible or dangerous.

5.1.1 Closed-Circuit Television (CCTV) (Najafi 2004)

CCTV technique is the most commonly used technique to inspect the inner surface of gravity sewer pipes. In order to use this method the existing flow within the pipe should be less than 25 to 30 percent. CCTV provides the inspectors a video record of the pipe surface which can be stored and viewed in the future. The history of using CCTV can be dated back to the 1950s (ISTT, 1990). With the technological advancements in the electronic devices during 1980s

the cameras used in CCTV applications became more durable and capable of providing detailed data. Today there are two major methods of using CCTV to inspect sewers. First one is the use of stationary cameras which are mounted at the manholes. This method can be used to detect whether a mobile CCTV application is needed or not. The defects closer to the manhole are detected easier compared to the ones farther away from the manhole. This process does not require cleaning of the pipe to insert the camera therefore may cost less than mobile CCTV however it is not effective in determining the defects behind obstructions. This method can be used in sewers up to 24 ft long and 36 inches in diameter. Second CCTV method is the mobile CCTV. This method involves inserting a camera mounted tractor in the sewer pipe. The tractor is operated by an expert above ground. Mobile CCTV equipment can detect defects on the pipe wall with pan and tilt or zoom capabilities however it cannot detect the defects below the existing flow level. CCTV method helps identifying problems related to cracks, infiltration, deformation, collapsed sections and missing bricks.

5.1.2 Ultrasonic Inspection (Najafi 2004)

Ultrasonic inspection (Sonar) is a method used to detect defects on the pipe surface when the existing flow restricts the use of video inspection methods. It is mostly effective for the pipes with flows greater than 75%. The theory behind this method is that; sound wave is sent to the surface of the pipe and the reflecting wave is different if there is a change in the density of the surface. This method is useful to detect cracks, voids and pits. Sonar devices can be attached to CCTV equipment to complement its functions.

5.1.3 Totally integrated Sonar and CCTV System (Najafi 2004)

This method combines the advantages of CCTV and Sonar methods. Sonar device is added to the bottom portion of the CCTV equipment to enable the inspector to detect the

problems under the flow level. This method is applicable for pipes having a flow level between 25% to 75% and greater than 24 inches in diameter.

5.1.4 Laser Based Scanning Systems (Najafi 2004)

Laser-Based Scanning Systems are useful to detect problems above the flow level. This method is useful to examine the shape of the pipe and the defects on the pipe wall. This method produces more detailed results compared to CCTV. Another advantage of laser-based scanning compared to CCTV is that; the output of inspection is recorded and analyzed by a computer automatically. Therefore human error associated with this method is less than the human error associated with CCTV.

5.1.5 Sewer Scanner and Evaluation Technology (SSET) (Najafi 2004)

SSET is designed to overcome the limitations of CCTV. The main advantages of SSET is the incorporation of side scan and position data to the forward view. Side scan enables the inspector to examine the whole pipe wall with the same light and angle settings, thereby eliminates the interpretation error of the operator. The side scan and forward view can be combined to create a three dimensional profile of the pipe wall. The position data enables accurate mapping data of the camera.

During the field data acquisition stage the camera does not need to be stopped to record the defects encountered during inspection. The operator is only responsible for ensuring the proper operation of the inspection gadget. Data analysis and interpretation can be managed by using computer softwares.

5.1.6. Ground Penetrating Radar (Najafi 2004)

Ground Penetrating Radar (GPR) is used to detect the soil conditions behind the pipe wall. Presence of voids or water behind the pipe wall due to infiltration or exfiltration may create

problems for the structural integrity of the buried pipes such as loss of soil support or differential settlement. In this method radio waves are sent to the surrounding soil either from above the ground or from within the pipe. When the waves hit an object with different conductivity and dielectric constant some portion of these waves is reflected while the rest simply maintains its original direction. This method is more effective in dry sand compared to wet sand and clays.

5.1.7 Wall Microdeflections and Natural Frequency of Vibration (Makar 1999)

These methods are used to identify the overall conditions of brick sewers. In the wall microdeflections method a microdeflection is created on the wall surface and pressure is applied to deform it. The deformation is examined for the change of position. If the microdeflection shows one directional change or if the direction of deformation shows rapid changes then the concrete or brick wall is damaged. Identifying the correct magnitude of the pressure is a major difficulty of this method. This method is only applicable to rigid pipes.

Natural frequency of vibration method is also used to determine whether the pipe has the required mechanical characteristics. The wall of the pipe is vibrated and the natural frequencies are examined. A good wall should show a certain predetermined type of natural frequency. The amount of water within the pipe and surrounding the pipe and the characteristics of the soil around the pipe may affect the vibrations.

5.1.8 Impact Echo / Spectral Analysis of Surface Waves (SASW) (Makar 1999)

These methods are employed to examine large concrete and brick pipes. An object is dropped on the pipe or a pneumatic hammer is used to create a controlled impact and the generated surface waves are detected by the geophones placed on the pipe wall. Spectral analysis of surface waves provides a more detailed examination by the use of additional sensors with

different frequencies. The limitations of this method are that, it is only applicable to man entry sized structures and the pipe wall probably needs to be cleaned before employing this method.

Makar (1999) summarizes the advantages and disadvantages of these methods in the following table (Table 5.1):

Technique	Advantages	Disadvantages
Mobile CCTV	• Standard technique • Considerable body of knowledge available to aid in interpreting results • Relatively cheap • Evaluates entire length of sewer	• Substantial operator interpretation of results • Difficult to accurately compare two evaluations of the same sewer conducted at different times • May miss defects hidden behind obstructions or under water
Stationary CCTV	• Cheaper than mobile CCTV • Possibly useful as screening mechanism for other techniques	• In addition to those listed above: • Only examines the sewer near man holes • Long brick sewers are likely to be incorrectly classified as undamaged
Light line CCTV	• As for conventional CCTV, except better estimation of sewer deformation	• As for conventional CCTV, except greater expense than conventional CCTV
Computer aided CCTV	• As for conventional CCTV, except: System reduces operator errors • Inspection time is reduced • Sewer defects are more precisely determined	• As for conventional CCTV, except: Considerable data processing time required • More expensive • Very recently introduced to North American market • Currently only available for small diameter sewers

Technique	Advantages	Disadvantages
Laser scanning	• Very accurate defect and geometry measurements • Computer based analysis • Digital data storage • Technique allows for accurate comparison between evaluations conducted at different times Multiple evaluations would allow rates of damage to sewers to be determined • Evaluates entire length of sewer	• Not yet commercially available for use in large diameter sewers • Only works above water line • More expensive than conventional CCTV
Ultrasound	• Capable of measuring defects above and below water line • Can store data directly on computer • Computer based analysis can be used to eliminate operator error • Accurate comparisons between evaluations at different times can be made • Multiple evaluations would allow rates of damage to sewers to be determined • Evaluates entire length of sewer	• Very difficult to identify areas of cracking • Thorough cleaning of sewer necessary for accurate measurements • Somewhat more expensive than conventional CCTV
Microdeflections	• Not affected by bedding condition • Can be used to evaluate entire length of sewer line • Provides direct measure of pipes structural integrity • Available in mobile form for entry in 600 x 900-mm sewers	• Rigid pipes only • More expensive than CCTV • Will not necessarily locate individual defects
Natural vibrations	• Can produce evaluation of structural condition of sewer • Can be used to evaluate entire length of sewer line • Possible able to give condition of section of sewer without travelling its entire length • Available in mobile form for entry in 600 x 900-mm sewers	• Effect of water inside pipe unknown • Effect of bedding condition unknown • Effect of specific defects unknown • More expensive than CCTV • Will not necessarily locate individual defects • May require thorough cleaning

Technique	Advantages	Disadvantages
Impact echo	• Can produce evaluation of structural condition of sewer • May detect voids behind sewers • Known to work in brick, concrete water lines • Can be used to evaluate entire length of sewer	• Results likely to combine pipe wall and bedding behaviors • Currently only available in form of manually operated equipment • More expensive than CCTV • Will not necessarily locate individual defects • May require thorough cleaning
SASW	• As impact echo, except frequency analysis allows separation of response from pipe wall and bedding	• Currently only available in form of manually operated equipment • More expensive than CCTV • Will not necessarily locate individual defects • May require thorough cleaning
GPR from surface	• Does not require entry into sewer • Theoretically capable of detecting voids near sewers	• Highly dependent on soil conditions • No evidence of consistent ability to detect voids • Tests have produced false positive results • Substantial operator interpretation of results is necessary
GPR from inside pipe	• Detection of voids, rocks, and other objects in bedding • Detection of exfiltration • Can detect delaminations in pipe walls • Otherwise not influenced by sewer condition	• More expensive than CCTV • Field tests required to prove technique • Substantial operator interpretation of results is necessary

Table 5.1 Advantage and Disadvantages of Inspection Methods (Makar 1999)

5.2 Trenchless Construction

Trenchless construction of buried pipelines under roadways includes procedures in which the pipe is installed without constructing large trenches which disrupt the traffic, pavement and environment. Excavation may be required only to construct the access shafts and reception shafts in order to install the pipes whereas in some methods the procedure may be performed above the ground without the need of constructing shafts.

According to the NCHRP Synthesis of Highway Practice No.242, *Trenchless Installation of Conduits Beneath Roadways*, trenchless construction methods can be divided into two major categories as techniques that do not require personnel entry (horizontal earth boring) and as techniques that require personnel entry during construction (pipe jacking and utility jacking) (Iseley and Gokhale 1997). There are several different methods which fall under these two categories. Table 5.2 which is taken from this NCHRP Synthesis of Highway Practice (No.242) summarizes the descriptions of each method. These methods are further going to be examined in detail in the following sections.

Method Type	Method Description
1. Techniques Not Requiring Personnel Entry - Horizontal Earth Boring	
Auger Boring	A technique that forms a bore hole from a drive shaft to a reception shaft by means of a rotating cutting head. Spoil is transported back to the drive shaft by helical wound auger flights rotating inside a steel casing that is being jacked in place simultaneously. Auger Boring may provide limited tracking and steering capability. It does not provide continuous support to the excavation face. Auger boring is typically a 2-stage process (i.e., casing installation and product pipe installation).
Slurry Boring	A technique that forms a bore hole from a drive shaft to a reception shaft by means of a drill bit and drill tubing (stem). A drilling fluid (i.e., bentonite slurry, water, or air pressure) is used to facilitate the drilling process by keeping the drill bit clean and aiding with spoil removal. It is a 2-stage process. Typically, an unsupported horizontal hole is produced in the first stage. The pipe is installed in the second stage.
Microtunneling	A remotely controlled, guided pipe jacking process that provides continuous support to the excavation face. The guidance system usually consists of a laser mounted in the drive shaft communicating a reference line to a target mounted

Method Type	Method Description
	inside the microtunneling machine's articulated steering head. The microtunneling process provides ability to control excavation face stability by applying mechanical or fluid pressure to counterbalance the earth and hydrostatic pressures.
Horizontal Directional Drilling	A 2-stage process that consists of drilling a small diameter pilot directional hole along a predetermined path and then developing the pilot hole into a suitable bore hole that will accommodate the desired utility and then pulling the utility into place. The horizontal directional drilling process provides the ability to track the location of the drill bit and steer it during the drilling process. The vertical profile of the bore hole is typically in the shape of an arc entrapping drilling fluid to form a slurry pathway rather than an open hole. This entrapped slurry provides continuous support to bore hole.
Pipe Ramming	A technique for installing steel casing from a drive shaft to a reception shaft utilizing the dynamic energy from a percussion hammer attached to the end of the pipe. A continuous casing support is provided and over excavation or water is not required. This is a 2-stage process.
Soil Compaction	This method consists of several techniques for forming a bore hole by in-situ soil displacement using a compacting device. The compacting device is forced through the soil, typically from a drive shaft to a reception shaft, by applying a static thrust force, rotary force and/or dynamic impact energy. The soil along the alignment is simply displaced rather than being removed. This is a 2-stage process.
2. Techniques Requiring Personnel Entry	
Pipe Jacking	A pipe is horizontally jacked through the ground from the drive shaft to the reception shaft. People are required inside the pipe to perform the excavation and/or spoil removal. The excavation can be accomplished manually or mechanically.
Utility Jacking	A 2-stage process in which a temporary ground support system is constructed to permit the installation of a product pipe. The temporary tunnel liner is installed as the tunnel is constructed. The temporary ground support system can be steel or concrete tunnel liner plates, steel ribs with wood lagging, or an all wood box culvert. People are required inside the tunnel to perform the excavation and/or spoil removal. The excavation can be accomplished manually or mechanically.

Table 5.2 Trenchless Construction Methods (Iseley and Gokhale 1997)

5.2.1 Horizontal Auger Boring (Iseley and Gokhale 1997)

Horizontal auger boring is a commonly used method for installing conduits under railways or roads. Augers and cutting head are placed inside a casing and an auger boring machine is used to rotate the augers and cutting head and to push the casing into the bore hole at the same time. The augers transport the displaced soil back to the driving shaft. The cutting head

can be adjusted for vertical alignment by using a water level. However it is harder to control the horizontal alignment and special components are needed for this purpose. There are two main types of horizontal auger boring. First type is the track type. In this method the auger boring machine is placed on tracks in the driving shaft. As the cutting head progresses through the soil the auger boring machine moves forward and pushes the casing forward. After insertion of a segment boring machine stops and moves backwards. Another segment of auger is connected and a new casing segment is welded to the existing ones. Due to limited vertical and horizontal alignment control the correct placement of the tracks on a solid foundation is extremely important. The jacking forces are transmitted from the boring machine to the tracks. The tracks further transmit this force to the thrust block located on the opposite wall of the shaft behind the boring machine. It is important to design this thrust block to withstand the jacking forces and to distribute these forces equally to the soil. Once the casing is installed within the soil the carrier pipe can be placed within the casing and the annular space can be filled with an appropriate type of grout. The second type of horizontal auger boring is the cradle type. In this method the auger boring machine is held in place by using a crane or similar equipment. Casing segments are welded before insertion therefore larger working space is needed for this type of auger boring.

Horizontal auger boring can be used in various types of soil including boulders as large as one-third of the casing diameter. The characteristics of horizontal auger boring method are given in Table 5.3:

Method	Diameter (in)	Length (ft)	Pipe	Application	Accuracy
Auger boring	4 – 60	600	Steel	Railway and road crossing	±1% of length
Auger boring steered on grade and on line grade	4 – 60	600	Steel	Railway and road crossing	± 12 inch

Table 5.3 Characteristics of Auger Boring (Najafi 2004)

The major advantages and limitations of this method are as follows (Najafi 2004): This method allows for immediate casing of the bored space in the soil and it can be applied to various types of soils. However purchasing several different sized cutting heads and augers may be expensive. Unstable soil conditions and working below water table can adversely affect the success of this method.

5.2.2 Pipe Ramming (*Iseley and Gokhale 1997*)

Pipe ramming is similar to a pile driving operation in which percussive action is used to insert a steel casing to soil. The vertical and horizontal control of the system is limited therefore adjusting the direction of pipe ramming machine is critical for the success of insertion. For small sized pipe (smaller than 8 inches in diameter) installations a cone shaped head part is connected to the steel casing. This method is referred to as the close-face pipe ramming method. For larger sized pipe installations a steel band is connected to the outer and/or inner edge of the casing. This method is referred to as open-face ramming method. This band both decreases the friction and strengthens the casing. The casing is inserted into the soil by the percussive action of a rammer connected to it. Casing can be installed either in a single drive if site conditions allow constructing a large shaft to accommodate the casing or in multiple drives by inserting one segment, removing the ramming machine from casing, welding next segment to the previous one and repeating the process. The last portion of the installation process is to remove the cone from the casing if close-faced method is used or to remove the soil from the casing if open-face method is used. Once the installation is complete the installation shaft is restored to its original condition. The characteristics of pipe ramming method are given in the table 5.4:

The major advantages and limitations of this method are as follows (Najafi 2004): Pipe ramming can be used to install pipes in various soil conditions. Different sizes of pipes can be

installed by using same ramming equipment. However, the horizontal and vertical control of the insertion process is difficult. The soil profile should be carefully analyzed to avoid misalignment of the casing due to presence of obstructions.

Method	Diameter (in)	Length (ft)	Pipe	Application	Accuracy
Pipe Ramming	Up to 120	400	Steel	Railway and road crossing	Dependent on setup

Table 5.4 Characteristics of Pipe Ramming (Najafi 2004))

5.2.3 Horizontal Directional Drilling (HDD) (Iseley and Gokhale 1997)

Horizontal directional drilling enables utility owners and contractors to install new utility lines underground with a desired path through the steering capability of the system. HDD can be divided into three major categories depending on the size of the application, maxi-HDD, midi-HDD and small-HDD. Characteristics of these methods are summarized in the table 5.5:

Method	Diameter (in)	Depth (ft)	Length (ft)	Material	Application	Accuracy
Maxi-HDD	24 – 48	200	6,000	PE, Steel	Pressure pipe	Varies
Midi-HDD	12 – 24	75	1000	PE, Steel, ductile iron	Pressure pipe	Varies
Mini-HDD	2- 12	15	600	PE, Steel, PVC, Clay, FRP	Pressure pipe, cable	Varies

Table 5.5 Characteristics of Horizontal Directional Drilling (Najafi 2004)

This procedure involves first drilling a pilot hole and then enlarging this pilot hole to install the pipeline. The pilot hole is drilled by using a rig which is operated from the ground surface. Therefore this method eliminates the need to construct a driving shaft. The drill rod is inserted to the ground with an angle of 5 to 30 degrees. Drilling may be accomplished by fluid-assisted mechanical drilling or high-pressure fluid jetting. The steering capability is accomplished by using offset jets or a special steerable head. The location of the drilling rod can be tracked by using transmitter and receivers. Once the pilot hole is drilled, reamer and pipeline

is connected to the rod and pullback procedure starts. As Reamer expands the bore hole pipeline is placed simultaneously. Due to high stresses applied to the pipe during installation steel pipes are commonly used for HDD applications along with polyethylene pipes.

The major advantages and limitations of this method are as follows (Najafi 2004): The steering capability is the major advantage of this method. Also construction of driving shafts is not necessary which may lower the construction costs. The major limitation of this method may be a potential danger of ground movement due to usage of pressurized fluids during drilling.

5.2.4 Microtunneling (Najafi 2004)

Microtunneling is a method of trenchless construction in which a remote controlled microtunneling boring machine (MTBM) is used to cut the soil and a jacking system is used to push the segments of the pipe and machine forward. A system for transporting the spoil and a laser guidance system are the other important components of the microtunneling process. An access shaft needs to be constructed in which the jacking system will be placed. Once the jacking system is MTBM is lowered and placed on the jacking system. The MTBM starts cutting the soil and the spoil is transported by a slurry mixture. The slurry is recycled once the spoil is removed in the separation unit. Once the MTBM is jacked into the soil the jacks are retrieved and the new segment of the pipe is lowered into the access shaft. The new segment is connected to the previous one and the process continues until the MTBM reaches the receiving shaft. Once the excavation and installation of the pipe is complete the MTBM is taken out of the receiving shaft. The annular space between the excavated surface and the outer diameter of the pipe is grouted. The characteristics of microtunneling method can be found in the Table 5.6:

Microtunneling method offers highly accurate installations of pipeline in any depth and various difficult ground conditions. The disadvantage of microtunneling is the high initial cost of

the microtunnel boring machines. Microtunneling is not appropriate for low strength pipe due to the jacking procedures involved. Obstructions in the soil profile may cause problems during the cutting procedure.

Method	Diameter (in)	Length (ft)	Material	Application	Accuracy
Microtunneling	10 – 136	500 - 1500	RCP, GRP, VCP, DIP, Steel, PCP	Gravity pipe	± 1 in

Table 5.6 Characteristics of Microtunneling (Najafi 2004)

5.2.5 Pipe Jacking and Utility Tunneling (Najafi 2004)

Pipe jacking and utility tunneling methods are similar to microtunneling except that these methods require the worker to be involved in the installation procedure. Therefore these methods are suitable for installing large diameter pipelines. Excavation can be performed by workers or mechanical cutting devices inside a shield or tunnel boring machines. The procedure involves construction an access shaft, lowering jacking equipment and inserting the cutting head and pipe segments by jacking. The difference between the utility tunneling and pipe jacking methods is that, in utility tunneling a liner is installed after excavation whereas pipe jacking the new pipeline is installed to the excavated space. The main features of pipe jacking and utility tunneling are summarized in the table 5.7:

Method	Diameter (in)	Length (ft)	Material	Application	Accuracy
Pipe jacking and utility lining	42 and up	1500	RCP, GRP, Steel	Pressure and Gravity pipe	± 1 in

Table 5.7 Characteristics of Pipe Jacking and Utility Lining (Najafi 2004)

Some of the major advantages and limitations of pipe jacking are given as follows: This method is applicable to almost any type of soil with a high accuracy. Due to the presence of workers immediate corrective actions can be taken. The limitations of this method include

requirement of high level of planning and coordination. The selected pipe material must be resistant to the high jacking forces.

5.2.6 Soil Compaction Methods (Iseley and Gokhale 1997)

Soil compaction methods involve inserting a compacting tool to the soil and displacing it rather than removing it. The compacting tool can be inserted into the soil by the application of a static force or impact energy. Once the compacting head reaches the reception shaft it is replaced with a swivel and the utility line is pulled. The characteristics of the soil such as compressibility, grain size and gradation should be carefully examined to use this method. Compaction method is typically used to install small sized utility lines such as telecommunication lines.

Main features of this method are given in table 5.8:

Method	Diameter (in)	Length (ft)	Material	Application	Accuracy
Compaction Methods	Less than 8 inches	250	Any	Pipe or cable	± 1 % of bore length

Table 5.8 Characteristics of Soil Compaction Methods (Najafi 2004)

By examining table 5.8 the major disadvantage of this type of method can be determined as the limited diameter range. This method is only applicable to construct small sized utility pipelines.

5.2.7 Pilot Tube Microtunneling (Najafi 2004)

Pilot tube microtunneling can be thought of as a combination of microtunneling, directional drilling and auger-boring. This method is mainly used for installing small diameter pipes with a high accuracy. Installation procedure involves inserting a pilot tube and enlarging this pilot bore by reamer and augers within a casing. Once the pilot bore is enlarged the pipe segments are connected to the last segment of casing and jacked by replacing the casings.

Main features of pilot tube microtunneling are given in table 5.9:

Method	Diameter (in)	Length (ft)	Material	Application	Accuracy
Pilot Tube Microtunneling	6 – 10	300	RCP, GRP, VCP, DIP, Steel, PCP	Small diameter gravity pipe	± 1 in

Table 5.9 Characteristics of Pilot Tube Microtunneling (Najafi 2004)

The major advantage and limitation of this method is given as follows: Pilot tube microtunneling offers very accurate installation of small diameter pipelines. However, this method is applicable for installing pipelines in soft soil conditions since the pilot tube needs to be inserted without replacing the soil.

5.3 Trenchless Repair and Renewal

Trenchless technologies can be used to repair, rehabilitate or to replace the existing buried structures in a cost effective manner and without disrupting the users, pavement and environment. In this report, renewal is used as a term to encompass rehabilitation and replacement activities which are used to provide a new service life to the culvert.

Trenchless repair activities are those activities which do not provide a new design life to the overall structure. They may be used to provide both structural and non-structural solutions for the defected portions of the pipeline. In this chapter the repair activities are going to be examined under the heading of “Point Source Repair” and “Invert Paving”.

Trenchless renewal activities provide a new design life to the pipeline by improving the condition of the whole portion of the pipeline. Rehabilitation activities involve relining of the pipelines or forming a new pipeline within the existing one. Cured-in-place pipe, sliplining, close-fit pipe, thermoformed pipe, panel lining, underground coatings and linings, spiral wound pipe and formed-in-place pipe are the trenchless rehabilitation methods which are going to be covered in the following sections.

Trenchless replacement activities involve destruction of the existing pipe and installation of a new pipeline with a same or greater diameter size to the same location of the existing one. Pipe bursting and pipe removal are the trenchless replacement methods which are going to be covered in the following sections.

5.3.1 Point Source Repair

Point source repair methods are used when a localized problem occurs in a buried pipe which is structurally in good condition when the overall structure is considered. These methods do not increase the design life of the structure however they offer structural and non structural solution (depending on the method) to eliminate certain problems which may prevent the structure from functioning with full capacity. Some of the common problems that may be addressed by local repairs are joint problems, cracks, misalignment, etc.

Sometimes a buried pipe may exhibit several localized problems. In these cases it is important to make economically feasible decisions whether to perform localized repairs or a renewal method which will be applied to the whole pipe and extend its design life. Life cycle cost analysis should be used by including any future maintenance costs associated with local repairs and it should be compared with the cost of a more comprehensive renewal method. Future plans regarding the location and surrounding area of the pipe should be kept in mind as well. According to a practical rule localized repairs can be used if the pipe has defects on 25 percent or less of its length (Najafi, 2004). In the following sections some of the common point source repairs will be examined in detail:

5.3.1.1 Robotic Repairs:

Robotic repair is mainly used to eliminate infiltration and cracks in gravity pipelines. The robot first grinds and prepares the area of repair and then fills the area with epoxy mortar (Najafi

2004). The robot is controlled from above the ground using a remote control system and a CCTV camera. Characteristics of the robotic repairs can be seen in table 5.10:

Method	Diameter (in.)	Length (ft)	Material	Pipe type
Robotic Repair	8 – 30	NA	Epoxy Resin, Cement Mortar	Gravity

Table 5.10 Characteristics of Robotic Repairs (Najafi 2004)

Advantages of robotic repair:

Advantages of robotic repair are as follows (Najafi 2004):

- Point repair of the pipe is handled with good precision.
- Repair method provides a better infiltration barrier and helps in restoring the structural integrity of the existing pipe.

Limitations of robotic repair:

Limitations of robotic repair are as follows (Najafi 2004):

- Robotic repair cannot be used to repair elliptical pipes.
- Defects larger than 2 inches cannot be repaired by robotic repair.
- Equipments used in robotic repair are expensive.

5.3.1.2 Grouting:

Grouting is a repair method which is mainly used to stop infiltration by applying a chemical mixture through defected joints. Once the grout hardens, it fills the voids in the pipe joint and prevents the groundwater from infiltrating the pipe. Grout can also be used to form a stable medium around the pipe.

It is important to analyze the physical properties of the surrounding soil and the level of groundwater to determine the correct composition of the grouting material. Acrylamide, acrylic and urethane based compositions are commonly used in the repairs of sewers as well as epoxy

resin and cement grouts (Najafi 2004). Pipes with small diameters which do not allow worker entry may be repaired with remote controlled machines similar to the robotic repair. As an advantage, grouting can effectively eliminate infiltration and exfiltration problems. As a limitation this method should not be viewed as a structural solution and it should be considered as a repair procedure for a pipe in good structural condition. The durability of the grout may be considered as another limitation. The characteristics of grouting are summarized in Table 5.11.

Method	Diameter (in.)	Length (ft)	Material	Pipe type
Grouting	NA	NA	Chemical gel grouts, cement based grouts	Any

Table 5.11 Characteristics of Grouting (Najafi 2004)

Advantages of Grouting:

Advantages of grouting are as follows:

- Low cost.
- Infiltration and exfiltration problems can be eliminated with this method.

Limitations of Grouting:

Limitations of grouting are as follows:

- This method does not enhance the structural condition of the whole pipe.
- Durability of the grout is usually limited.

Grouting is a widely employed method to tackle infiltration problems in sewers. In the following section some of the previous research studies and some case studies in which grouting is chosen as a repair method will be covered:

Residents living in the southern New Castle County of Delaware were facing sewer backup problems due to high level of infiltration in the SP-24 sewershed (Neidig and Shelton 2006). Test and seal method was used to repair joints and reduce infiltration. In this method,

joints are isolated and tested for leakage by using air pressure. If a joint fails the air test then grout is applied to the joint to seal it. In this project a total of 67 pipe segments were tested and sealed. The pipe sections had a diameter of 8 inches and they were made of PVC and VCP. Characteristics of test and seal method are also discussed in this study. A comparison between CIPP and test-and-seal method is presented. Test and seal method should be employed to prevent infiltration in structurally sound structures. It is stated that if this method is applied properly it can typically reduce the infiltration for a period of 10 years.

Grouting was used to repair the East Main Storm Sewer Pipe in the city of Woodland, CA (Khan and Barnes 2004). The storm sewer was constructed in 1990 and it was made of 60 inch and 84 inch diameter unreinforced cast in place concrete pipe. Excessive infiltration through the circumferential cracks caused roadway failures and expensive pipe repairs. Several different trenchless renewals methods were also suggested for different segments of the pipe. CCTV inspection and physical inspections were carried out. The cracks in the pipe were divided into three categories depending on their severity. The effectiveness of the grout was tested on 5 circumferential cracks before finalizing the design. During the test it was determined that sealing one crack affected other cracks which were not sealed yet. It was decided to perform a second round of grouting. Sealing of cracks was performed by applying polyurethane based chemical grout with hand held nozzles. The repair procedure started from upstream and continued toward downstream. This project showed that it is important to inspect the pipe after sealing the cracks since formation of new infiltration points due to the changes in groundwater level is possible.

5.3.1.3 Internal Seal:

Internal seal method offers structural solutions where a segment of the pipe or a pipe joint fails. It can be used for both nonworker entry pipes as small as 6 inches and worker entry pipes

as large as 110 inches (Najafi, 2004). It is important to prepare the surface of the damaged area to ensure proper adhesion with the sealing sleeve. The main characteristics of the internal seal procedure can be seen in Table 5.12.

Method	Diameter (in.)	Length (ft)	Material	Pipe type
Internal Seal	6 - 110	NA	Special Sleeves	Any

Table 5.12 Characteristics of Internal Seal (Najafi 2004)

Advantages of Internal Sealing:

Internal sealing method offers the following advantages (Najafi 2004):

- This method offers structural solutions.
- This method can be applied to solve problems such as pipe breakage, joint settlement and longitudinal cracks.
- Gravity sewers, culverts, and pressure pipes can be repaired without excavation.

Limitations of Internal Sealing:

Internal sealing method has the following limitations (Najafi 2004):

- Internal sleeve may cause a hydraulic loss due to decreased cross sectional area.
- This method is applicable to circular pipes.

5.3.1.4 Point Cured-in-place-pipe (CIPP):

Point CIPP method provides a structural solution to repair a failed section of a pipe. The methodology of point CIPP is similar to the CIPP renewal method in which the whole pipe is being renewed. The lining material is applied to the desired location by the use of an inflatable packer and cured by the use of hot water or steam. (Najafi 2004) The liner should not be heated before it is pressured to the surface of the existing pipe. The main characteristics of Point CIPP method is given in Table 5.13.

Method	Diameter (in.)	Length (ft)	Material	Pipe type
Point CIPP	4 -60	50	Fiberglass, polyester, etc.	Gravity

Table 5.13 Characteristics of Point CIPP (Najafi 2004)

Advantages of Point CIPP:

Point CIPP method offers the following advantages (Najafi 2004):

- Defected pipe sections between 3 ft and 50 ft of length with diameters up to 60 inches can be repaired.
- Point CIPP adheres to the existing pipe tightly and eliminates infiltration.
- The repair procedure may usually be performed without diverting the existing flow.
- This method offers structural solution to the defected pipe segment.
- Lining does not obscure the flow due to tapered smooth ends.

Limitations of Point CIPP:

Point CIPP method has the following limitations (Najafi 2004):

- This method does not improve the structural condition of the pipe as a whole.
- Point CIPP method may be more expensive than other point source repairs.
- Hydraulic capacity may be slightly decreased due to lining.

5.3.2 Invert Paving

Invert paving is a common procedure to protect deteriorated inverts of culverts from further deterioration due to corrosion and abrasion. If the deterioration has reached to a point where the loss of material from the invert section is endangering the structural integrity of the culvert, reinforcing steel should be welded while paving the invert. Various concrete types such as Portland cement concrete, steel fiber reinforced concrete, high strength concrete...etc can be used for invert paving procedures.

The detailed explanation of invert paving procedure can be found in FHWA's Culvert Repair Practices Manual Volume 2 (1995). According to this manual, the procedure starts with diverting the flow. Water flow to the culvert should not be allowed until the concrete cures for 48 hours. The culvert should be cleaned thoroughly and the reinforcing steel should be placed on the culvert. The amount of the reinforcing steel to be placed should be adequate to restore the structural strength of the culvert. Concrete should be placed on the invert covering an adequate percentage of the cross sectional area depending on the geometry of the culvert. Finally the surface of the pavement should be smoothened and concrete should be properly cured before returning it to the service.

The main characteristics of the invert paving procedure can be found in Table 5.14:

Method	Diameter (in.)	Length (ft)	Material	Pipe type
Invert Paving	More than 48 in.	NA	Concrete (Portland Cement, steel fiber reinforced concrete, etc.)	Gravity

Table 5.14 Characteristics of Invert Paving

Advantages of Invert Paving:

The advantages of invert paving procedures are as follows:

- Cost of repair is low.
- No need for special equipment.

Limitation of Invert Paving:

The durability of the paved section is usually limited.

5.3.3 Cured in Place Pipe (CIPP)

Cured in Place Pipe (CIPP) is one of the most commonly employed buried pipe renewal methods. It was developed by Insituform in 1971 in the United Kingdom and brought to the U.S. market in 1977 (Najafi 2004). This method is applicable to a very wide range of pipe types

including pipes with non circular shapes, bends and varying vertical alignments. CIPP offers both structural and nonstructural solutions. CIPP must be designed according to the needs of the renewal site at hand. Each job site should be handled separately and the design specifications should be prepared and ordered after examining the original deteriorated pipe. Details of the cured-in-place pipe renewal procedure can be found in ASTM F1216 07b (installation by inversion) and ASTM F1743-96 (installation by pulling in place) standards.

Thermosetting resin and the fabric tube constitutes the major parts of the cured in place pipe. The resin provides the necessary structural strength to the pipe. Unsaturated polyester, vinyl ester and epoxy are among the most commonly used materials for CIPP resins (Najafi 2004). The fabric tube is used to hold the resin during the installation process. Summary of the characteristics of CIPP method is given in Table 5.15:

Method	Diameter (in)	Max. length (ft)	Liner	Applications
Inverted in place	4 – 108	3000	Thermoset resin / fabric composite	Gravity and pressure pipelines
Winched in place	4 – 108	1500	Thermoset resin / fabric composite	Gravity and pressure pipelines

Table 5.15 Characteristics of Cured-in-Place-Pipe (Najafi 2004)

As of 2008, a large majority of CIPP installed has used the hydraulic pressure of water to install the CIPP tube and heated water to cure heat-initiated resin. During the hot water cure cycle, small amounts of organic chemicals such as styrene can leach into the cure water. This hot water cure process is generally acceptable in sanitary sewers because the waste process water can safely be discharged to the sanitary sewer system when cooled. However, this waste process water should not be discharged to the environment. Thus, if water is used to install and cure CIPP for culverts or storm sewers, the waste process water must either be pumped to an adjacent

sanitary sewer system or hauled to a suitable disposal site. Depending on the project location and logistics, this process can be cost prohibitive. Many rural culverts are long distances from water sources and suitable cure water disposal sites. As a result, water must be hauled to the job site, used during the installation, and then collected and hauled away from the job site to a suitable disposal location. These additional costs can yield a project not cost-effective.

CIPP Procedure:

The steps of cured in place pipe renewal method are as follows:

- Cleaning the existing pipe
- Preparing the CIPP
- Installing CIPP
- Curing

Cleaning the existing pipe:

In this step the existing pipe should be cleaned completely in order to prevent irregularities in the finished CIPP and ascertain that the new pipe will fit tightly to the existing pipe in the installation step. During the cleaning procedure the characteristics of the new CIPP, such as the diameter, length, and thickness, should be determined accurately by examining the existing pipe.

Preparing the CIPP:

Once the design of the CIPP is completed it should be prepared for installation. This preparation includes saturating also called impregnating the flexible tube with the thermosetting resin. This step is crucial in achieving a successful renewal since if the CIPP is not saturated properly, the new pipe will not have a tight fit to the existing pipe.

Installing CIPP:

The impregnated tube can be installed by either water inversion, compressed air inversion or the winch method. Water inversion and compressed air inversion methods force the impregnated tube to be inverted inside out through the length of the pipe to be renewed. The winch method involves pulling the CIPP liner into its place and inflating the liner to fit into the existing pipe. During the installation process care must be given to ensure a tight fit with the existing pipe and liner is not damaged.

Pull-in and Invert Through is a method of installing CIPP which combines the two types of installation. Wall thickness design and installation of CIPP utilizing the pull-in and invert-through process is described in ASTM F 1743 (ASTM 2003). Two CIPP tubes are required for this process. Once the host pipeline has been cleaned and prepared, the CIPP tubes are saturated with liquid thermosetting polyester resin or wet out. Typically the bulk of the finished wall thickness, and, thus, resin is placed in the tube that is pulled-in (Tube A). The inverted tube (Tube B) may include a thin layer of fabric to be wet out. Or, it can simply be a bladder material with no fabric, requiring no wet out (ASCE 2008)

First, Tube A is pulled into place. Tube B is then inverted with air through Tube A. This process inflates Tube A and holds it in place tight against the host pipeline. Steam is then introduced to cure the resin. If Tube B included a fabric material that was wet out, Tube A and Tube B cure together forming one laminate. If Tube B is simply a bladder material with no wet out fabric, it is typically extracted and discarded. With this process the resin is contained between an outer and inner membrane or coating during the cure process thus minimizing the chance that any liquid resin will escape into the environment.

This process is advantageous for difficult to access locations. Tube A which has a larger wall thickness can be lowered in with a crane and pulled-in with a cable and winch. Air inverting

smaller sized Tube B is much easier and does not require the large set-up area when compared to inverting only one tube that has the desired wall thickness (Thickness of Tube A plus thickness of Tube B).

Curing:

Once the CIPP liner is installed into the existing pipe, it needs to be cured by water, steam or UV light. During water and steam curing controlling the temperature is important to achieve a successful renewal. Sudden drops in temperatures should be avoided. Once the new CIPP is cured and cooled, the ends of the pipe can be opened. The interior of the new pipe should be examined for any installation problems.

Quality Assurance and Quality Control

The contractor installing the CIPP should take quality assurance measures during the installation process to ensure that quality controls listed in the contract documents are met. This process is more easily accomplished if the contractor has a permanent quality program in place.

The testing requirements to determine if the installed CIPP meets the performance requirements of the contract documents are typically listed in the technical specifications. Also, the basic testing requirements outlined in ASTM F 1216, ASTM F 1743 and ASTM D 5813 are applicable to storm sewers and culverts. These include:

- **Workmanship:** This includes a visual inspection for dry spots, lifts, delaminations or other defects. This inspection is by closed-circuit-television (CCTV) for small pipes or a walk-through on larger storm sewers or culverts.
- **Flexural Properties:** Flexural strength and flexural modulus are determined from a CIPP sample collected at the jobsite. These values should meet or exceed the values specified.

- **Wall Thickness:** The in-place wall thickness should meet or exceed the specified minimum wall thickness including any +/- tolerances.
- **Chemical Resistance:** Although chemical resistance properties are not as important in a storm sewer or culvert as compared to a sanitary sewer, the materials installed should meet the requirements of the chemical resistance test in ASTM F 1216.
- **Tensile Strength:** Tensile strength testing is not required for CIPP used to renew storm sewers, culverts or sanitary sewers. Tensile testing is required only for pressure CIPP.

Conformance to performance-based requirements is a true indication of the installed CIPP's ability to perform satisfactorily over the expected design life of the project. Strict means and methods specifications can be restrictive and exclusive because there are several types of CIPP installation methods and numerous CIPP installers in the marketplace.

Inspector's qualifications and responsibilities also determine how the final CIPP installation is performed. The inspector must become thoroughly familiar with the contract documents for the project and most importantly the detailed specifications. The detailed specifications guide the inspector to the areas where the trenchless project must be inspected, recorded, documented, tested and otherwise verified to ensure that the product is being installed as specified (NASSCO 2007).

Among some of the quality control procedures, it is recommended by the ASTM D5813 that for each inversion designated by the owner, a specified number of CIPP samples must be required. The sample should be cut from a section of the CIPP at the termination point that has been inverted through. If the CIPP is used to repair large diameter culverts, the sample should be fabricated from material taken from the tube and the resin/catalyst system used and cured in a

clamped mold placed in the tube when circulating heated water is used and in the silencer when steam is used (NASSCO 2007).

The finished CIPP should be continuous over the entire length of the culvert and be free of dry spots, lift, and de-lamination. If these conditions are present, the CIPP will be evaluated for its ability to meet the applicable requirements of the contract documents. Where the CIPP does not meet the requirements of the contract documents or specifically stated requirements of the specifications, the affected portions of CIPP should be removed and replaced with an equivalent repair (NASSCO 2007).

Advantages of CIPP:

The CIPP method offers the following advantages (Najafi 2004):

- CIPP eliminates the need for grouting due to the tight fit with the existing pipe.
- CIPP offers an improved flow capacity due to its smooth interior
- Pipes with noncircular shapes can be renewed without decreasing the flow capacity.
- CIPP can be used in renewal of pipes with bends and deformations.

Limitations of CIPP:

Some of the limitations of the CIPP method are as follows (Najafi 2004):

- The lining material must be specially designed for each project.
- The existing flow must be diverted.
- Liner pipe ends or lateral connections may have to be prevented against infiltration by sealing.
- Monitoring, inspecting and testing of the curing process must be handled with great care.
- Removing the curing water from the job site may be a problem if pipe to be renewed is not a sanitary sewer pipe.

- Lining can be affected by obstructions

Previous Research and Case Studies Related to CIPP

There have been several research studies related to the installation and performance of CIPP due to the wide usage of the technique. In this section some of these important studies will be discussed:

The Vallejo Sanitation and Flood Control District (VCFCD) chose the CIPP method to renew the “North Interceptor” which was a 48-inch diameter reinforced concrete main sanitary sewer pipe located 15 feet deep (Nelson et al. 2005). The interior pipe wall was seriously deteriorated. Among the alternatives of open-cut replacement, sliplining, pipe bursting, microtunneling and cured in place pipe (CIPP), CIPP was selected as the proper renewal method. Open cut replacement was not suitable due to the site conditions and cost. Sliplining was not suitable due to the decrease in cross section area. Pipe bursting was not feasible for the type and size of the existing sewer pipe. Constructing a parallel line by microtunneling was not suitable due to the cost and complexity. CIPP was selected as the best option due to minimum bypassing time, and improved flow capacity. The execution of the project involved diverting the flow by installing pumps, cleaning the pipe (high velocity water jet), inverting the liner (water inversion), curing the liner (water curing), trimming the ends of the liner, and inspecting the finished product. As a result this project is reported as a success due to the short project duration and cost-effectiveness offered by the CIPP method.

Another CIPP application was performed during the renewal of Franklin-Main Interceptor Sewer in the city of Columbus, Ohio (Siegfried and Coffey 2004). The three segments of the sewer which have been renewed by using CIPP were made of 24” diameter clay pipe in 1913. The depth of flow for segment 1 was between 3’ and 15’ with a total length of

1,867'. Segments 2 and 3 were 5,737' in length. The section of segments 2 and 3 where the sewer interceptor was passing below a river presented problems. The river water could wash away the resin and affect the curing process due to its cold temperature. Grouting was thought as a remedy to stop river infiltration but the high velocity of the infiltrating water made this option impossible. Finally, it was decided to install pre-liner to prevent river water from infiltrating and a thicker liner was chosen. The resin was also changed to improve its reaction time to curing. In this project CIP manhole lining was utilized as well.

The city of San Jose used the CIPP method to renew a 42 inch diameter interceptor line which was made of unlined reinforced concrete pipe (Ho and Pamintuan 2003). The CIPP method was selected due to the presence of bends and the heavy traffic above the pipe and also to minimize the capacity reduction of the renewed pipe. In some sections of the finished pipe uplifts of the liner were observed. The reason of these uplifts was explained as the presence of water pressure during the installation (inversion) of the liner. The flow was diverted at an upstream location since the CIPP method does not allow renewing a pipe without fully diverting the flow.

Another CIPP application was performed in Boston, Massachusetts while renewing the South Charles River Valley Sewer (Pescatore 2007). This sewer line was constructed in 1895 and it had an oval shape with 54 inches width and 61.5 inches of height. Due to the populated area and the existing utilities around the job site a trenchless method had to be selected. The renewal was completed in three runs from two access points. First run started from the first access point and it was 1550 ft long, second run started from the second access point and it was 2350 ft long in the backward direction, third run started from the second access point and it was 1550 ft long. Water inversion was used in this particular project. There were difficulties in terms

of controlling the temperature of the CIPP liner. Due to hot weather the liner hardened before reaching the final destination.

A steam cured CIPP application was used to renew a 300 linear feet vitrified clay sewer pipe in Portland, Oregon (Snyder 2004). The vertical alignment of the sewer pipe showed great fluctuations, averaging 22% which lowered the number of replacement alternatives. As a result CIPP lining with steam curing option was selected as the best available option. The final product showed minor wrinkles at points where the vertical alignment changed however the steep slope and smoother interior would eliminate this problem in terms of flow capacity.

Utility agencies may gain precious time by employing the CIPP method to renew a buried pipe as in the case of the emergency renewal of a 30 inch diameter sewer pipe in the City of Reno (Ablin and Stram 2005). The location of this highly deteriorated sewer pipe was very sensitive against a potential spill due to the collapse of the pipe. The water inversion and water curing of the CIPP lining enabled the renewal of the sewer pipe in only three weeks from identifying the problem and completing the renewal.

The brick sewers in Newark, New Jersey are under an evaluation and rehabilitation program since 1990. (Pennington et al. 2005). Water inverted and cured CIPP liners were used extensively to restore the structural condition of these old and large sewers. Water inverted linings were preferred due to higher quality achieved compared to the winch method and easier installation around bends. Before the lining procedure started the voids were filled and any ground water infiltration was stopped by injected acrylamide gel. The importance of the smooth connection of laterals to the renewed sewer line was emphasized and application of rapid setting epoxy mortar to achieve this connection was suggested.

Apart from the sewer pipes the CIPP method has also been employed to renew the water distribution pipes. The city of Longueuil, QC, Canada is among the cities that select CIPP as a convenient method to renew their water distribution network due to the following advantages: (Fortin and Loiacono 2006)

- CIPP offers structural solutions while improving hydraulic capacity.
- CIPP can be applied for the renewal of water mains which are situated in urban environments due to lesser amount of excavation needed.
- The installation procedure enables a quick return to normal operation of the water main.
- The CIPP method is cost effective compared to traditional methods.
- Social costs to the public are kept at a lower amount.

The water main pipe renewal is different than the renewal of a sewer pipe in terms of the testing of the final product for hydrostatic pressure and disinfecting the pipe before it is reopened for use.

The CIPP method has been applied successfully to structurally renew non circular, rectangular box culverts (Tingberg 2007). One of the biggest advantages of CIPP over renewal methods such as sliplining was given as the elimination of grouting the space between the new pipe and the host pipe. Poor quality grouting procedures may cause piping and eventually loss of soil support to the renewed structure. Working crew's previous experience, preparation of the host pipe, accurate examination of the project site and testing the renewal material were listed as important factors which influence the success of the renewal project. The CIPP liners can be impregnated in the factory or on the job site depending on the transportation requirements of the liner to the jobsite. Some of the large rectangular culverts were converted into elliptical culverts by using fillets in the corners. This was performed to ensure a full contact between the host pipe

and the CIPP liner. Even though this practice resulted in a decrease of the cross sectional area the flow capacity was not affected to the smoother interior surface provided by CIPP liner. The testing of the final product is important in terms of proving the resin was adequately impregnated and the curing process was accomplished in accordance to the plans. The finished pipe should also be tested against any voids behind the liner and fins on the surface of the liner. If any voids are present the voids can be filled in by using curing resin, or epoxy or these sections of the finished pipe can be cut and a point repair can be performed. The fins on the surface of the liner may be eliminated by sanding.

In order to achieve long lasting renewal solutions by using CIPP owners should play attention to several parameters (Kampbell 2005). These parameters can be divided into three categories as the design phase, bidding phase and the construction phase. In the design phase the condition of the existing pipe (whether it is partially deteriorated or fully deteriorated) and the ground water level should be determined accurately as these factors influence the thickness of the liner. During the bidding phase the experience of the bidders should be examined carefully. During the construction phase the liner should be installed tightly to the existing pipe. The ground water infiltration should be eliminated by stabilizing the surrounding soil. The thickness of the finished product should be tested against the thickness in the plans.

It is very important to take samples from the field appropriately after the installation of the CIPP liner (Lee and Ferry 2007). Relying on the results of specimens prepared in a laboratory may not provide accurate results for a pipe installed and cured on the site. It may not be a good strategy to rely on the manufacturer's information neither. Therefore adequate number of samples with appropriate lengths should be taken from the job site and tested in a laboratory in order to justify the long term behavior of the renewed CIPP pipe.

The quality assurance and control practices play an important role in the long term behavior of the CIPP liners. The mechanical properties of the liners can be affected by the amount of moisture absorbed from the environment surrounding the liner. (Bakeer et al. 2004)

The city of Portland has been using the CIPP method to renew their buried pipes for about 39 years (Braun 2006). According to their experience the method gave poor results under certain circumstances. These circumstances were related to the presence of unexpected levels of groundwater on the jobsite, faults in curing method and issues regarding the lateral reconnection. These problems should be eliminated by proper design and installation procedures to have a successful renewal project and to improve the quality of the final product.

Ground water infiltration may cause the bottom section of the CIPP liners to be lifted up and also may cause the formation of ribs along the liner (Khan 2005). To eliminate these problems a pre-liner may be installed. The boiler unit should be selected according to the requirements of the job site. If the capacity of the boiler is not sufficient smaller sections of CIPP liner should be installed. If the shape of the liner and the host pipe does not have a good match fins and wrinkles may form on the liner. Fins can be grinded and coated with epoxy. Wrinkles should be checked whether they are causing any structural deficiencies.

The problems associated with faulty CIPP applications may be categorized under three groups: Aesthetic defects, operational defects and structural defects (Larsen et al. 2006). Small irregularities on the surface of the liner such as small bumps and ribs which do not affect the flow can be considered as aesthetic defects. These problems usually do not need to be corrected and can be eliminated by using appropriately sized liners in the future. Larger bumps, ridges or ribs which affect the flow can be considered as operational defects. Improper sizing and installation, errors in lateral restoration or in grouting may cause operational defects. The liner

should be reinstalled partially or as a whole to correct operational defects. Problems such as bulging and insufficient strength or thickness of the liner are among the structural defects which may cause the failure of the liner. The liner has to be reinstalled partially or as a whole to correct structural problems.

In the majority of the applications of CIPP styrene is emitted to the environment (Bauer and McCartney 2004). Styrene is used in CIPP liners since it shortens the reaction time and it is cost effective however it can also have adverse effects on the workers and public. Therefore a program to eliminate the odor problem due to the styrene present in the liner would be beneficial. National Association of Sewer Service Companies (NASSCO) has recently published a guideline in which the use of styrene in CIPP pipe renewal was examined (2008). According to the findings presented in this guideline styrene has not caused any serious health problems during the timeframe it has been used in CIPP application. Since styrene can be detected even at very low concentrations and due to lack of definitive documentation, speculations arose regarding its effects on workers, public and environment arose. According to the guideline, typical CIPP applications, in which styrene is used, emits 0.5 ppm styrene which is a low figure when compared to the voluntary industry standard value of 50 ppm. Styrene has found to cause reversible effects on central nervous systems at levels above 50 ppm. The guideline also provides information on the proper procedures related to receiving and storing chemicals, handling resins, and installation procedures for CIPP applications that contain styrene.

The renewal of large pipes by using CIPP method may be difficult due to the space requirements of the equipment and liner during installation. Fiber-reinforced sandwich technology can be used in the renewal of large pipes in order to decrease the thickness of the liner and space requirements of the equipment in the installation process (Hahn 2007). Three

large culverts were renewed by the fiber reinforced CIPP method in Chesterfield County, Virginia. The project was a success and the large culverts were renewed with a lighter and durable material.

5.3.4 Sliplining

Sliplining is a simple renewal technique which involves inserting a new pipe into an existing pipe and filling the annular space by grouting. Due to its simplicity it has been one of the oldest trenchless renewal techniques. It offers both structural and nonstructural renewal of the host pipe in gravity and pressure pipelines without diverting the flow. However renewing a pipeline with several bends may be difficult by using sliplining. Capacity of the renewed pipeline may also decrease due to the smaller cross-sectional area of the new pipe therefore a smoother pipe should be selected where the capacity of the pipeline is important. Details of the sliplining renewal procedure can be found in ASTM F585-94. Summary of the main characteristics of sliplining is given in Table 5.16:

Method	Diameter (in)	Maximum Length (ft.)	Liner	Application
Segmental	24 – 160	1000	PE, PP, PVC, GRP (-EP and –UP)	Gravity and pressure
Continuous	4 – 63	1000	PE, PP, PE/EPDM, PVC	Gravity and pressure

Table 5.16 Characteristics of Sliplining (Najafi 2004)

Sliplining Procedure:

The steps of renewing a pipeline by using sliplining are as follows:

- Constructing an insertion pit and accessing the pipe
- Cleaning the existing pipe
- Testing the host pipe for any obstructions by using a mandrel
- Placing the new pipe into the existing pipe

- Establishing the connection to the laterals
- Grouting the annular space
- Closing the pits

Constructing an insertion pit and accessing the pipe:

An insertion pit with an appropriate size should be excavated over the existing pipe. The size of the insertion pit may depend on the depth of the pipe and the flexibility of the liner material. The insertion pit for a sliplining procedure where a long segment of fused PE pipe is used as a liner would have a larger size compared to the insertion pit required for a sliplining procedure where small segments of the liner is connected to each other in the insertion pit. The insertion pit should be water tight in order to reduce the exfiltration of the flow to the surrounding soil once the existing pipe is accessed.

Cleaning the existing pipe:

The existing pipe should be cleared of any debris and obstruction in order to provide a pathway for the liner pipe.

Testing the host pipe for any obstructions by using a mandrel

A mandrel which has the same exact size with the liner material should be inserted into the existing pipe in order to test the pathway for the liner.

Placing the new pipe into the existing pipe

Once the preparation of the host pipe is finished the new liner should be placed inside the host pipe before the formation of debris and accumulation which may obstruct the insertion of the new pipe. The new pipe can be pushed or pulled into the existing pipe. Care must be given not to damage the liner by applying excessive pressure.

Establishing the connection to the laterals

The laterals should be connected to the main pipe before grouting the annular space by excavating and installing the connector segments.

Grouting the annular space:

The annular space between the new liner and existing pipeline should be grouted by using an appropriate strength grout. The grout selection depends on the design of the new pipeline system. If a bond is needed between the host pipe and the new liner is not capable of withstanding the structural loading then using a cementitious grout would be appropriate. If the grout is used only to transfer loads from the host pipe to the liner then a grout with strength of stiff clay would be appropriate (Najafi 2004).

The floating of the liner should be avoided during the grouting process. The existing flow escapes from the annular space with the application of the grout.

Quality Assurance and Quality Control:

- Verify liner pipe is undamaged from insertion and grouting by inspection via walk through or video.
- Verify all joints are fully assembled by inspection via walk through or video.
- Verify liner pipe deflection is $\leq 5\%$ (if some distortion is noticeable).
- If required, leakage test the installed by infiltration, exfiltration or air testing.

Advantages of Sliplining:

The Sliplining method offers the following advantages (Najafi 2004):

- Special expensive equipments are not needed.
- It is a simple method applicable to both gravity and pressure pipelines.
- It offers both structural and nonstructural solutions.
- This method allows for renewal without diverting the actual flow.

Limitations of Sliplining:

Some of the limitations of the Sliplining method are as follows (Najafi 2004):

- Pipe diameter is reduced as a result of sliplining
- A pit needs to be constructed.
- Laterals need to be connected by using open cut installation.
- The annular space generally needs to be closed by grouting.

Previous Research and Case Studies Related to Sliplining

There have been several research studies related to the sliplining renewal method due to the simplicity and wide usage of this technique. In this section some of these important studies will be discussed:

In Framingham, MA sliplining method was used to rehabilitate a 200 ft. long sewer pipe located in the downtown area under a railroad (Wells and Cahill 2007). The presence of a rock entering the pipeline from the surrounding soil further complicated the rehabilitation of the pipeline. Using CIPP was eliminated since the presence of rock was a threat to the structural properties of the CIPP liner. Pushing the rock outside was not possible since a remotely controlled hydraulic jack would be expensive and could risk the structural properties of the pipe. The rock could not be removed by excavation since it was located underneath the railroad tracks. Pipe bursting was not possible for this rehabilitation project since the location of the pipe restricted the size of the access pit that could be constructed. As a part of this rehabilitation project a permanent by pass was constructed therefore the reduction in the cross sectional area did not present any capacity problems and there were no lateral connections present on the sewer pipe. Therefore sliplining the 18-inch sewer pipe with a 12-inch HDPE pipe was suitable for this rehabilitation project. In order to decrease the size of the access pit it was decided to connect

pipe segments in the access pit before inserting them to the host pipe. The pipe segments were ordered after measuring the size of the manhole from which the insertion would be performed. A mandrel was run through the host pipe in order to assure the inserted pipe would fit in the host pipe even in the presence of the rock. Pipe segments were lowered into the manhole and connected to each other by using a chain wrench. The connected pipe segment was hydraulically pushed inside the host pipe. Once the insertion was completed the annular space was filled. The rehabilitation project was successful with no disruption to the public for a little cost.

Another sliplining project took place in the City of Los Angeles to rehabilitate a 3,200 feet long 42 inch brick sewer pipe (Jenson et al. 2003). The sliplining method was chosen since it was not possible to divert the flow in the main line. In the pipe selection stage it was important to choose a pipe with a large inner diameter and a small outside diameter in order to maximize the flow capacity of the renewed pipe without risking the insertion procedure of the new pipe. The pipe selected for this rehabilitation project was a CCFRPM pipe with an inner diameter of 36 inches and an outside diameter of 39 inches. The access pit was constructed with a size of 10 foot by 30 foot. The host pipe was cleaned by using winches and a sled. The cleaned pipe was not tested by using a mandrel on this project however the sled used to clean the pipe was the same size with the pipe to be inserted. The pipe was inserted while blocking a section of the roadway at night time. Once the new pipe was inserted the laterals and chimneys were connected to the main line and the annular space between the host pipe and the new pipe was grouted. As the grout was injected to the annular space the water was pushed out. Therefore the sewer line was rehabilitated without diverting or by passing the existing flow.

The City of San Jose decided to renew the 48-inch diameter reinforced concrete Forest Rosa supplemental interceptor line with the sliplining method (Ho and Pamintuan 2003). The

new pipe was selected as a closed profile wall PVC. The insertion pit used for the sliplining method was 20 feet (width) by 30 ft. (length). During the insertion process more sharp bends were found than anticipated. The difficulty of inserting a new pipe in some of these sections was overcome by building new manholes and using smaller segments of pipe. However for some of the sections these solutions did not work and these sections were left for a future rehabilitation project. The laterals were connected to the main line by using a trenchless method, namely the top hat procedure wherever the open cut excavation was not possible.

The City of Gatineau, Quebec has used the sliplining method to renew 220 meters of corrugated steel sewer pipe (Tardif 2003) located underneath a boulevard and also crossing a railroad track. Two different types of pipes were selected for this project. A profile wall HDPE pipe was used to renew 163 meters of the pipe and a solid wall HDPE pipe was used to renew the remaining 57 meters of the pipe. The profile wall HDPE pipe had an inner diameter of 1200 mm. and the solid wall HDPE pipe had an external diameter of 1350 mm. The existing pipe had a bituminous coating when it was built but due to the abrasion of the flow the coating was damaged. The cleaning process involved removing the any remaining coating from the existing pipe. A mandrel was prepared to test the opening in the existing pipe. Skis which were made out of cut portions from the new pipe were placed on the insertion pipe. Access pits were constructed over the existing pipe. A fusion machine was used to connect two solid wall HDPE pipe segments and the insertion was performed by using a shovel and a crane. The profile wall HDPE pipe segments were lowered into the access pits and they were connected to each other by using slings. The segments were inserted into the pipe one by one. The lateral connections were performed by open cut excavation. The annular space between the new pipe and the old pipe was

grouted through the grouting holes every 3 meters. The skis kept the new pipe in place and eliminated floating.

The city of Los Angeles used sliplining method to renew a 5,700 feet long tile lined concrete sewer in Crenshaw District (Cho et al. 2003). The sewer line had a diameter of 75 inches and it was renewed by inserting a new pipe which had a diameter of 66 inches. The sliplining method was selected since it was impossible to divert the flow within the pipe at any time. Access pits were constructed where there were bends and angles. The existing pipe was cleaned by using a steel cable and cylinders attached to winches. Once the cleaning was complete the pipe was tested for obstruction by using three different mandrels. One of the mandrels had the same external diameter with the new pipe and the others were 1 inch bigger and smaller in external diameter respectively. An insertion machine was used to push the segments of the CCFRPM pipe which were lowered into the access pit by a crane. The lateral connections were established with the new pipe and the annular space between the old pipe and the new pipe was grouted. The sliplining method presented some challenges to the public due to the access pits constructed on narrow streets and odor problems however the public relations were handled with care to eliminate complaints.

The city of Portland has been using sliplining as a renewal method since about 1990 (Braun, 2006). According to their experience sliplining can cause problems when the size of the new pipe is not determined accurately, when there are excessive number of service lateral connections and when the grouting place is not handled with care. If the size of the pipe to be inserted into the existing pipe is close to the diameter of the existing pipe, the obstructions on the existing pipe due to joint offsets may affect the sliplining process. Excessive number of service lateral connection may cause the construction cost to increase due to the need of open cut

excavation and connection of lateral service lines. The grouting process may cause hydrostatic pressure and damage on the existing pipe and the new pipe. The grouting procedure also may cause flotation of the pipe and damage the lateral connections.

Sliplining was also used in the renewal of a storm drain in the city of Los Angeles (Pickering et al. 2003). The storm drain renewed in this study was a 470 feet long arched corrugated metal pipe. Due to an angle present along the drain the project was performed in two parts. Downstream of the angle was renewed by man-entry installation and epoxy connection of 3ft long sections followed by grouting annular space. The first part of the project was renewed by sliplining 6 ft long sections. Once all the sections were connected to each other by using rubber gasket and gasket spigot and placed within the existing pipe the annular space was grouted.

Minnesota Department of Transportation performed a study about sliplining deteriorated culverts with a variety of materials in order to compare their constructability and costs with open-cut methods (Johnson and Zollars 1992). The findings of this study are as follows:

- Smooth Polyethylene pipes had debonding problems due to differences in coefficients of thermal expansion and due to the completion of grouting process in only one step (which caused floating of the liner)
- Spiral Ribbed Polyvinyl Chloride had an inexpensive material cost but pushing ribbed liner through the culvert was difficult. PVC exhibited brittle behavior in cold weather.
- Fiberglass liners had high material costs. Even though the installation was smooth, pushing through corrugated metal exhibited problems. Fiberglass liners are quite heavy which makes it difficult to handle compared to other liners.

- Installation of a Spiral Ribbed Coated Steel Arch was the most difficult and time consuming. Ribs on the liner were caught on the rivets and corrugation on the older culvert. Although it was the hardest to install, spiral ribbed coated steel arch provided the least capacity loss.

5.3.5 Close-Fit Pipe

Close-fit pipe renewal method involves inserting a polyethylene pipe which has a modified cross sectional area into a deteriorated pipe and returning the polyethylene pipe into its original shape by pressurization. This method is generally employed in the renewal of pressurized pipelines. There are two methods of close-fit renewal: mechanically folded liners (MFP) and reduced diameter pipes (RDP) (Najafi 2004). In MFP process, the new polyethylene pipe the cross section of the new pipe is changed into a U-shape by using a mechanical shaper and temporary bands are used to keep the pipe in this shape until it is filled with water and pressurized. In the RDP method the cross sectional area of the new pipe is modified either mechanically by using mechanical rollers or thermally by using heat. Characteristics of close-fit pipe renewal method are given in Table 5.17:

Method	Diameter (in.)	Length (ft)	Material	Pipe type
Close-fit Structural	3 – 24	1000	HDPE, MDPE	Pressure, gravity
Close-fit Nonstructural	3 - 63	1000	HDPE, MDPE	Pressure, gravity

Table 5.17: Characteristics of Close-fit Pipe (Najafi 2004)

Close-Fit Pipe Renewal Procedure:

The steps of close-fit renewal method are as follows:

- Cleaning the existing pipe
- Modifying the cross section of butt fused polyethylene pipes
- Inserting the modified polyethylene pipe

- Rerounding the polyethylene pipe

Cleaning the existing pipe:

In this step any accumulation and deposit in the existing pipe should be removed. The existing pipe should also be inspected for any groundwater infiltration. If infiltration is present it should be stopped by appropriate point repair options.

Modifying the cross section of butt fused polyethylene pipes:

Depending on the method of choice, MFP or RDP, the new polyethylene pipe should be modified in cross section either mechanically or thermally. If MFP is used temporary bands should be used to keep the new pipe in its deformed shape.

Inserting the modified polyethylene pipe:

The polyethylene pipe should be inserted to the existing pipe immediately after modifying its cross sectional area. Excessive pulling forces may damage the new pipe during insertion therefore new pipe should be lubricated whenever necessary.

Rerounding the polyethylene pipe:

Once the new pipe is inserted into the existing pipe the ends of the pipe should be temporarily sealed and the new pipe should be filled with water. Once the pipe is filled with water, the pipe should be rerounded by applying pressure. To achieve a successful fit between the existing pipe and the new pipe the pressure should be maintained for the predetermined amount of time.

Quality Assurance and Quality Control

- A final quality review should be performed to compare the completed renewal work with the requirements of technical specifications and contract documents. A final review

would expose any variations of changes between the contract documents and the work of the contractor.

- When a renewal project is completed, the contractor should provide the pipeline owner with documentation of the quality of the work performed. In this respect, it is important that requirements for such documentation be included in the bid documents. The documentation should include the following:
 - Information on the products and the installation method used.
 - Pre and postinspection results.
 - Test results
 - Any changes or deviations from contract documents and possible corrective work performed
 - Information on service lateral reinstatements and pipe ends or manhole connections and possible grouting process performed.
 - Recommendations for future inspections, cleaning, maintenance, and other renewal works to be completed as part of a comprehensive renewal work.
 - Survey of residents, businesses and customers about the renewal project.

Advantages of Close-Fit Pipe:

The Close-fit pipe method offers the following advantages (Najafi 2004):

- The new polyethylene pipe used in renewing the existing pipe is produced in a controlled environment.
- The cross sectional loss is minimal.
- This method is useful in eliminating internal corrosion problems.
- Pipes with bends up to 45 degrees can be renewed by MFP.

- Installations can be performed up to 1000 ft.
- It is possible to establish the lateral connections internally.

Limitations of Close-Fit Pipe:

Some of the limitations of the Close-fit Pipe method are as follows (Najafi 2004):

- Diameter range and length of installation are limited.
- The new butt-fused polyethylene pipe occupies a large space.
- Pipes with varying cross sectional area and large bends are not appropriate for this method.
- In general, an insertion pit needs to be constructed.
- Usually the existing flow needs to be diverted.
- Valves and connections may require excavation.

Previous Case Study Related to Close-Fit Pipe

Close-Fit Pipe renewal method was employed during the renewal of a 600 meter long pressure sewer pipe in Berlin, Germany (Singer 2006). Cold swage lining method was preferred to renew the particular pressure sewer pipe. The renewal work was performed in two sections which were 322 meters and 216 meters long. Before installing the liner, old pipe was cleaned by using high pressure jet-cleaning and inspected by using CCTV. It is indicated that it is not necessary to obtain a smooth metallic surface however any obstacles which would affect the installation process should be eliminated. The lining pipe is selected with a 3% excess diameter size compared to the inner diameter of the old pipe in order to obtain a close-fit. The selected lining pipe is transported to the job site and reduced in size by using a “swage lining die”. The tension in the liner pipe is maintained by using a special pulling rig however a winch and cables can also be used for this purpose. Once the whole liner is placed inside the old pipe the pressure

is slowly released. The ends of the liner pipe are welded with sockets to complete the installation. Pressure tests and CCTV inspection are used to check the quality of the finished product.

5.3.6 Thermoformed Pipe

Thermoformed Pipe is a rehabilitation method in which the existing pipe is lined with an HDPE or PVC pipe that initially has a reduced and modified cross sectional area and returned to its original state within the existing pipe after insertion. Thermoformed pipe renewal method can be applied in three different options, namely fold and formed, deformed and reformed, and fused and expanded (Najafi 2004). PVC pipes are used in fold and formed, and fused and expanded methods whereas high-density polyethylene (HDPE) pipes are used in deformed and reformed method. The difference between these methods lies in the procedures followed before insertion to the existing pipeline. In fold and formed method the PVC pipe is flattened in the factory and brought to the field in this situation. The flattened pipe is folded before insertion in the field. The liner pipe may require heating to increase its flexibility. In deformed and reformed method HDPE pipes are brought into a U-shape in the factory and the pipe is inserted into the pipe without any further deformations. In fused and expanded method, PVC pipe sections are fused to each other in the field and inserted into the existing pipe afterwards. Once the liner is in place the liner is heated and pressurized to restore its original cross sectional and to obtain a tight fit between the liner and the existing pipe. Fold and formed method is applicable to renew pipes with diameters up to 24 in. and bends up to 60 to 90 degrees depending on the diameter of the liner. Deformed and reformed method also offers renewal of pipes with diameters up to 24 in., however pipes with bends up to 22.5 degrees can be renewed with this method. Fused and expanded method has been used in renewal of pipes with sizes larger than 30 in. (Najafi 2004).

The details of deformed and reformed type of renewal can be found in the ASTM F1606-05 standard and the details of the fold and formed type of renewal can be found in the ASTM F1867-98 standard.

Characteristics of thermoformed pipe method can be summarized in Table 5.18:

Method	Diameter (in.)	Length (ft)	Material	Pipe type
Thermoformed Pipe	4 – 30	1500	HDPE, PVC	Pressure, gravity

Table 5.18: Characteristics of Thermoformed Pipe (Najafi 2004)

The PVC materials have a material Manning's coefficient of approximately 0.009, although the effective Manning's coefficient is expected to be higher due to conformance to the host pipe geometry. The enhanced surface smoothness after lining can significantly increase the flow speed, thus reducing future debris and silts deposition. Although the pipeline will slightly reduce the culvert inside diameter the increase in flow rate will result in no loss of flow capacity. Even though it is generally not the primary reason for culvert lining, the increased flow rate resulting from lining can be significant. As a result, project engineers should be cautious to consider the prospects of downstream scouring after lining and to include additional outlet modifications as needed (ASCE 2008). The installation of Folded Thermoplastic Pipe liners is generally not precluded by steep slopes or narrow catch basins; such site conditions do not alter any of the design properties of a Folded Thermoplastic Pipeline.

Thermoformed Pipe Procedure:

The steps of thermoformed pipe renewal method are as follows:

- Cleaning and preparing existing pipe
- Inserting the liner
- Returning the liner to the original shape

Cleaning and preparing existing pipe:

Existing pipe should be cleaned thoroughly to ensure that the thermoformed pipe has a close fit. Any obstacles or intrusions within the existing pipe need to be removed during cleaning. If groundwater is infiltrating to the existing pipe sealing or grouting should be used to ensure that water does not adversely affect the rerounding process of the liner.

Inserting the liner:

The thoroughly cleaning process of the existing pipe helps determining the exact size of the liner and hence the design of the liner. Depending on the method employed the liner should be inserted and pulled inside the existing pipe with the help of a winch. If fold and formed method is used the liner should be heated otherwise it can be inserted at an ambient temperature. Liner should not be damaged during the insertion process.

Returning the liner to the original shape:

Once the liner is placed within the pipe, it is returned to its original shape by heating and pressurizing. Steam or liquid can be used for this process. The pressure required for fold and formed method is usually lower than the deformed and reformed method. The highest pressure is usually needed in fused and expanded method. Pressure should be lowered after cooling of the liner.

Quality Assurance and Quality Control

- Folded Thermoplastic Pipeliners are pre-manufactured. The required quality control protocols of the ASTM product standards verify the pipeliner's compliance with wall thickness, material modulus, corrosion resistance, and other long-term structural design requirements within the controlled environment of the manufacturing facilities. The field installation process, including variable field conditions and crew decisions, does not and can not influence the structural design compliance of a Folded Thermoplastic Pipeliner.

Compound suppliers, manufacturers, and technology providers perform essential roles in the QA/QC of Folded Thermoplastic Pipeliners. The construction crews have a negligible influence upon the pre-manufactured pipeliner's design properties and can do very little to subvert quality assurance.

- The compound supplier is responsible for testing every blended “lot” of compound for either the flexural modulus and flexural strength or the tensile modulus and tensile strength according to the referenced ASTM standards.
- The technology supplier's production request to the manufacturer should include the following information:
 - Confirmation #
 - Customer (Installation Contractor)
 - Project Manager/Project Engineer (Consultant/Agency)
 - End-User (Agency/Owner)
 - Manhole or Access Point #
 - Nominal Size of the pipeliner
 - Extruded O.D. (sleeve size) of the pipeliner
 - Nominal Wall Thickness (the wall thickness after expansion to the nominal size)
- The manufacturer, in order to comply with the applicable specifications and standards, is generally required to clearly mark the following information at 5ft intervals or less:
 - “Brand Name”
 - Date
 - Shift
 - Nominal Pipe Size

- o Cell Classification
 - o The legend “DRXX Folded Pipe” (where XX designates the nominal DR)
 - o The designated ASTM specification to which the material complies
 - o The approximate coil length
- The following information should be recorded during production:
 - o Operator’s Name
 - o Resin Batch # and Production Lot #
 - o Shift
 - o Date and Time
 - o Pipe Diameter Measurements (ASTM D 2122)
 - o Additional comments by the operator
- The following information should be gathered and recorded by the QA/QC personnel:
 - o Wall Thickness measurements at the end of the reel
 - o Internal Cosmetics
 - o External Cosmetics
 - o Additional Comments
 - o Overall (pass or fail)
- Samples should be collected from the beginning and end of every reel produced. From a portion of these samples the following tests should be run, in order to comply with the applicable specifications and standards:
 - o Impact resistance (ASTM D256 & D 2444)
 - o Flattening to 60% (ASTM D 2412)
 - o Pipe Stiffness at 5% Deflection (ASTM D 2412)

- o Acetone Immersion (ASTM D 2152)
- o Heat Reversion (ASTM F 1057)
- o Tensile Strength (ASTM D 638)
- o Flexural Modulus (ASTM D 790)
- o Overall (pass or fail)
- o Signature of QA/QC Inspector

Advantages of Thermoformed Pipe:

The thermoformed pipe method offers the following advantages (Najafi 2004):

- This method offers fast installation due to the factory manufacturing of the liner pipe.
- Quality of the finished product is high since the liner is manufactured in a controlled environment.
- This method does not involve discharge of harmful chemicals to the environment
- Excavation risk is lower due to start/stop capability of many thermoformed pipe methods.
- Minimal reduction in cross section area
- Problems due to corrosion and infiltration can be corrected.
- This method offers structural solutions and new design life up to 100 years.
- The installation can be performed through a manhole or insertion pit.
- Pipes with large bends can be renewed with this method.
- Installation lengths up to 1500 ft are possible which provides smooth and jointless pipes between manholes.
- Lateral connections can be made internally.

Limitations of Thermoformed Pipe:

Some of the limitations of the Thermoformed Pipe method are as follows (Najafi 2004):

- This method is applicable to a small range of pipes in size.
- Drive lengths are smaller in larger sized pipes.
- In fused and expanded method the liner pipe requires a large working space before insertion.
- Existing flow should be diverted in most of the cases.
- Valves and connections generally require excavation in the renewal of water mains.

Previous Research and Case Studies Related to Thermoformed Pipe

In this section some of case studies in which thermoformed pipe renewal method was used to renew buried pipes are going to be covered.

Fold and formed type thermoformed renewal method was employed during the renewal of pipes with sizes between 6 inches to 12 inches in the Brick Township on the Jersey Shore, New Jersey (Rohan 2006). This method was selected due to reasons such as previous experience, the capability of structurally renewing the pipes, high quality of the pipe, less disruption to public and trained installers. The steps of fold and formed type renewal were given as inspection of the existing pipe with closed circuit television (CCTV), preparing the pipe, placing the liner, inspection of the renewed pipe with CCTV and re-establishing lateral connections. The existing pipe was inspected with CCTV in order to determine the location of lateral connections and any obstructions in the pipe. Pipe was prepared by removing roots and other obstructions such as service taps, and performing local repairs such as applying patches to the necessary locations. The necessity of eliminating groundwater elimination is also mentioned in this study. Pipe was cleaned by using water jet. Before insertion the folded pipe was heated inside the truck. The stress on the liner due to the pulling force was eliminated by the application of hot steam. Once the placement of the liner was completed it was formed by following the manufacturer's

guideline. The lateral connections were established after the pipe was cooled. The renewal procedure was successful in terms of renewing a structurally deteriorated pipe without disruption to public and traffic.

Deformed reformed type of thermoformed pipe renewal method was employed during the renewal of a 16" carbon steel water pipeline in the city of Morelia, Michoacan, Mexico. (Crabtree 2005). This method was chosen due to its lower cost compared to other alternatives, applicability to water pipes and higher hydraulic capacity. The first step of renewal is the inspection and cleaning step. Once the pipe is prepared the liner is inserted into the pipe. Steam is used to reform the liner within the existing pipe. Both temperature and pressure is used while the reforming step. When the reforming of the liner is complete the temperature is lowered by application of air and then water. The pressure in the liner is maintained during the cooling step. The finished liner was tested by application of a pressure test whereas camera inspection was also given as an option. Service connections can be made by fused or mechanically joint adapters. The renewal project was completed without disrupting the pavement or other adjacent utilities for a lower relative cost.

5.3.7 Panel Lining

Panel lining renewal method is a man-entry procedure in which segments of the new lining pipe are connected inside the existing pipe and the annular space between the new pipe and the existing pipe is grouted. According to WRc's sewerage rehabilitation manual there are three design types of panel lining method. (WRc 1990). Type I design focuses on the interaction between the existing pipe, grout and the new lining pipe. The grout used in the type I design must have sufficient strength in order to transfer the external loads to the new lining. The groundwater in the surrounding area is not a part of the design process. Type II design does not

focus on the interaction between the existing pipe, grout and the lining pipe. The lining pipe design according to a type II design is capable of withstanding the hydrostatic pressure by itself. Some designs may incorporate the properties of both type I designs and type II designs. These panel linings are capable of both resisting hydrostatic pressure and the road and overburden loadings at the same time. This type of design can be referred to as type II design using type I design as a check. Type III design is mainly used for nonstructural rehabilitation purposes where groundwater is not present. Characteristics of panel lining method are summarized in Table 5.19:

Method	Diameter (in.)	Length (ft)	Material	Pipe type
Panel Lining	More than 48 inches	Varies	GRP, PE, PVC, PP, PVDM	Gravity Pipelines

Table 5.19: Characteristics of Panel Lining (Najafi 2004)

Panel Lining Procedure:

The steps of panel lining renewal method are as follows:

- Cleaning the pipe and performing local repairs where necessary
- Lowering and installing the panel segments
- Grouting

Cleaning the pipe and performing local repairs where necessary

This step involves the activities to prepare the existing pipe for renewal. Any debris or accumulation in the pipe should be removed by thoroughly cleaning the existing pipe. Flow in the pipe does not always have to be diverted however for the safety of the workers in the pipe the flow should be restricted and monitored at all times. Apart from cleaning if infiltration is an issue local repairs should be performed to reduce or eliminate the infiltration.

Lowering and installing the panel segments:

Once the existing pipe is prepared for renewal the panel segments can be lowered to the existing pipe by using a crane. Workers manually position the segments of the new lining pipe

inside the existing pipe. The segments are connected to each other with sealed joints. Bends and cross-sectional changes are lined with modified panels to fit to the geometry of the existing pipe.

Grouting:

In this step, the annular space between the existing pipe and the newly installed pipe is grouted with the appropriate grout according to the design type of the panel lining. Grouting pressure should be monitored to avoid excessive pressure and floating of the new lining pipe.

Quality Assurance and Quality Control

- During the installation, certain safety and quality requirements should be met. OSHA's safety regulations for confined-space entry must be addressed by a competent person. After installation it is often necessary to carry out the completion work by conducting a final inspection and leak testing. Also notifying residents and businesses about work completion and conducting a public survey for improvements in future projects is usual.

Advantages of Panel Lining:

The panel lining method offers the following advantages (Najafi 2004):

- Panel lining can be used to renew any shape drainage structure which allows for worker-entry
- Panel lining offers both structural solutions and nonstructural solution.
- Existing flow does not have to be diverted in many cases. Restricting the flow is sufficient.
- Culverts can be renewed by panel lining.
- Long-drive lengths are possible where access is difficult.
- Panels having a diameter up to 21 ft. can be manufactured.
- Hydraulic capacity of the pipe can be increased by using smoother lining material.

- Liner offers resistance to abrasion and corrosion.

Limitations of Panel Lining:

Some of the limitations of the panel lining method are as follows (Najafi 2004):

- Only worker entry pipes can be renewed by panel lining.
- Cross-sectional area can be reduced significantly.
- In some cases access shafts need to be constructed.
- The annular space between the existing pipe and the new liner must to be grouted.

Previous Research and Case Studies Related to Panel Lining

There have been several research studies related to the installation and performance of panel lining. In this section some of these important studies will be discussed:

A box shaped concrete storm sewer and a circular CSP storm sewer was renewed by using the type 1 design panel lining method in Toronto, Ontario in 2003 (Doherty et al. 2005). The box shaped concrete storm sewer having a length of 714 m. (2,342 ft) was located in the downtown area of Toronto. The dimensions of the storm sewer varied throughout its length. According to the results of the design analysis two different panel configurations were found to be satisfactory to carry the flow after renewal. A plywood form was passed through the existing sewer to verify the panels would not be stuck during renewal procedure. Sewer was cleaned and prepared for renewal. The existing flow was not bypassed. The GRP panels were lowered into the sewer from two access points and a self-propelled carrier was used to move the panels within the sewer. The grouting process was the challenging part of the renewal procedure due to the distortion of the panels. The problem was solved by grouting with a higher number of separate lifts. Another type 1 design panel lining project was addressed in the same study. This project involved renewal of a 359 m (1,178 ft) long 1650 mm (66”) diameter CSP storm sewer at the

Pearson International Airport, Toronto. The pipe had a deflection at one location and the diameter of the pipe at that location was measured as 53". Therefore the GRP panels used in this project had an outside diameter of 52". A panel length of 1.5 m (5 ft) was used in order to negotiate bends. Flow was not diverted in this project. Same contractor who worked in the renewal of the box concrete storm sewer was selected in this project. Therefore contractor knew that the grouting step of the renewal procedure would be critical in order to avoid delays in the project. A computer application which would help in determining the key steps of grouting procedure, such as number and height of lifts and volume of grout per lift, was generated. This project did not suffer from the grouting challenges which were faced in the previous project and the renewal of the pipe was completed successfully.

Another panel lining renewal project was performed in the renewal of a 4 mile long 7 ft - 8ft vertical diameter arch sewer in Chicago, IL (Pearson and Khamanian 2004). 4 access shafts were constructed as a part of the renewal project. The interceptor was completely cleaned before the panel installation. 8 ft long panels were manufactured in England and shipped to the job site in two-pieces. In order to expedite the construction the segments were connected to each other before placing them inside the existing pipe. Access shafts were constructed at a larger size than planned and a pipe loader and tracks were used to move the panels within the existing pipe. All these efforts resulted in approximately double installation rate. The renewal project was successful and it was completed before the contract deadline.

Glass-reinforced Plastic (GRP) panels were also used to rehabilitate a large combined sewer in Chicago, IL (Osborn 2005). 1,100 feet of the combined sewer had a diameter of 9 ft and 340 feet of the sewer had a diameter of 10.5 ft. The panels used to line the sewer had a diameter of 8 ft for the 9 ft sections and 9.5 ft for the 10.5 ft sections. Panels were manufactured at 4 ft, 6

ft, and 8 ft of length. Each panel section was manufactured in a semi circular shape. The flow in the sewer was diverted to a parallel line by using sand bags. Two access shafts were used to lower the panels to the existing pipe. The semi circular panel sections were jointed together and bonded to their places by using epoxy. The annular space was grouted with a cementitious grout after the service connections were established. The renewal project was completed successfully. In the same study another panel lining renewal project to renew 2 sections of a 72 inch diameter brick sewer in Fort Wayne, IN is also discussed. The first section of the project had a total length of 40 feet and this section was to be reached through passing a 90 degree bend. The second section of the project had a total length of 100 feet and the 90 degree bend was a part of this section. Therefore panels were constructed in 180 degree segments and were jointed and bonded to each other inside the existing sewer. The panel sections which corresponded to the 90 degree bend section were custom manufactured and checked for alignment before being delivered to the job site. After placing all the panel sections and constructing the lateral connections the annular space was grouted.

5.3.8 Underground Coatings and Linings

Buried pipes can be coated with various materials such as polymeric materials and cementitious materials to improve their durability against corrosion and abrasion. Coating with cementitious materials involves procedures of applying cast-in-place concrete, shotcrete, or gunite with or without reinforcing depending on the structural condition of the existing pipe. (Najafi 2004) Admixtures may also be added to the cementitious mixture to further improve the characteristics of the finished product. Shotcrete and gunite procedures involve application of concrete mixtures under high velocities thereby achieving low porosity and high compaction. Cementitious coating protects the existing pipe by increasing the alkalinity (Najafi 2004).

Cementitious coating of water mains is selected as a renewal method due to corrosion protection and improved flow characteristics of the finished product. This method differs from the invert paving repair method since the whole pipe is renewed with this method whereas in invert paving only the invert section of the pipe is repaired. Coating with polymeric materials involves structural or nonstructural enhancement of existing pipes by using rapid setting materials such as epoxies and polyesters. Coatings can be applied to renew both small diameter pipes by using spraying machines and larger diameter pipes by man entry procedures. However, structural improvement of a small diameter pipe coated by using a spraying machine may be limited (Najafi 2004). Characteristics of underground coatings are summarized in Table 5.20:

Method	Diameter (in.)	Length (ft)	Material	Pipe type
Underground coatings and linings	3 – 180	1000	Epoxy. Polyester, silicone, vinyl ester, polyurethane, cementitious	Pressure, gravity

Table 5.20: Characteristics of Underground Coatings and Linings (Najafi 2004)

Moisture can weaken a coating's curing processes as well as its ability to bond to the existing structure. Although moisture is relatively easy to mitigate in above-surface structures, it cannot be completely avoided below grade, especially in concrete and masonry structures. Therefore, a coating with high moisture tolerance offers an adhesion advantage for below-grade coatings projects. Epoxies can generally be formulated to offer the best moisture tolerance, although some urethanes and urea also offer moderate tolerance or require the use of an epoxy primer. Other attributes to analyze include structural enhancement, permeability and chemical resistance, quick return-to service, maintenance and visibility.

Underground Coating Procedure

The steps of underground coating renewal method are as follows (Najafi 2004):

- Preparing the pipe
- Performing local repairs where necessary
- Coating

Preparing the pipe

The procedure for applying an underground coating to renew an existing pipeline starts with preparing the pipe for coating. The pipe surface should be cleaned thoroughly and should not have any unwanted materials which will cause inadequate adhesion of the coating. The cleaning procedure may be performed by water jetting or mechanical tools.

Performing local repairs where necessary

Any infiltration present in the existing pipe should be eliminated as it adversely affects the coating process. Voids on the surface of the concrete pipes should be filled with appropriate filling materials. Steel pipes should be reinforced with appropriate materials wherever the wall thickness is not adequate.

Coating:

Once the pipe surface is prepared the coating can be applied. If the pipe to be coated does not allow worker entry spraying machines can be used. Spraying machine should be placed in the center of the pipe and it should be moved along the pipe at a constant speed to obtain a uniform coating thickness. If the pipe size is adequate for man entry the coating is applied by using hand held nozzles.

Quality Assurance and Quality Control

Visual inspection and project documentation should be carried out at a minimum by the project inspector. The inspector should entirely know the products used and their installation process. Any deficiencies in the finished coating should be marked and repaired according to the

coating or lining manufacturer's recommendations. For non-worker entry culverts a Closed Circuit TV or CCTV equipment can be used to address this topic; nevertheless, the inspector should be careful that the CCTV equipment can be used after the curing process has finished.

For cementitious and epoxy coatings, thickness of the applied coating should be randomly checked prior to the setting of the coating. Cementitious products generally will use a depth gauge to measure the applied thickness.

Spark testing or holiday detection can be used to detect holidays or pinholes in a polymer coating and inadequately welded seams in sheet liners. After the protective coating has set hard to the touch or after welding has been completed the system can be inspected with high-voltage holiday detection equipment. Surfaces should first be dry, and induced holiday is then be made on to the coated concrete surface and serves to determine the minimum or maximum voltage to be used to test the coating for holidays at that particular area.

Bond strength of polymer coatings can be measured in accordance with ASTM D4541. Any areas detected to have inadequate bond strength should be evaluated by the project engineer. Further bond tests may be performed in that area to determine the extent of potentially deficient bonded area and repairs made in accordance with the manufacturer's recommendations. An understanding between the owner and installer should be made prior to testing takes place regarding inadequate adhesion. There are many variables that play a part in analyzing the results of an adhesion test. Adhesion testing is a destructive test and consideration should be made as to the extent of testing in a structure in which the objective is to provide a monolithic coating

Advantages of Cementitious Coating of Man-Entry Pipelines

The advantages of using cementitious coating in the renewal of man entry sized pipelines are as follows (Najafi 2004):

- Connecting laterals is handled easily.
- Pipes of any size can be renewed.
- Cross sectional area changes can be handled easily.
- Cementitious coating is not expensive.

Limitations of Cementitious Coating of Man-Entry Pipelines

The limitations of using cementitious coating in the renewal of man entry sized pipelines are as follows (Najafi 2004):

- Safe working environment for the workers inside the pipe should be present.
- Highly skilled operators are required.
- The coating material is sensitive to the water pH
- Installation speed is relatively low compared to epoxy coating.

Advantages of Epoxy Coating Using Spraying Machine

The advantages of using epoxy coating in the renewal of nonworker-entry sized pipelines are as follows (Najafi 2004):

- The coating is not affected by the pH of the water.
- The finished product provides higher flow capacity compared to cementitious coating.
- The epoxy coating is more wear resistant compared to the cementitious coating.
- Reconnection of lateral service lines is not required.
- Cross sectional area changes can be handled easily.
- Installation speed is higher compared to cementitious coating.

Limitations of Epoxy Coating Using Spraying Machine

The limitations of using epoxy coating in the renewal of nonworker-entry sized pipelines are as follows (Najafi 2004):

- Coating is not structurally integrated with the existing pipe.
- Epoxy coating is slightly more expensive than the cementitious coating.
- Infiltration should be eliminated.

Previous Research and Case Studies Related to Underground Coatings and Linings

There have been several research studies related to the renewal of buried pipes using underground coating and lining. In this section some of these important studies will be discussed:

The city of Waterloo, Ontario, Canada had problems related to the water quality in 1998 (Amyot et al 2003). During the analysis of water transmission lines it was discovered that the reason of discoloration was due to the internal corrosion and scaling in the iron water mains. The structural condition of the water pipes was determined to be good due to low break frequency and visual observations. The 24 kms of iron water mains was chosen to be renewed by non-structural lining in order to solve the problem in 2002/2003. Properties of cement mortar lining and epoxy lining were presented in the same study. The protection mechanism of cement mortar lining is explained by formation of a thin, oxide layer raising the pH level. The lining does not depend on a high quality control as it can heal any defects itself. Furthermore, the cleaning procedure of the existing pipe is not critical as the lining does not require a bond with the existing pipe. The lining does not have to cover the complete pipe. Cement mortar lining is effective in renewing water mains with an alkalinity level of at least 55 mg/l CaCO_3 and pH of at most 9.5. The protection mechanism of epoxy lining is explained by formation of an impermeable layer which prevents water from reaching the iron. A high quality control is essential for an epoxy lining to be successful therefore existing pipe should be cleaned and dried before application. Epoxy lining has a smaller thickness compared to cement mortar lining and it does not have the ability to restore protection in areas where the lining is defected. Cement

mortar lining requires more curing time compared to the epoxy lining however it is generally less expensive and can be applied to renew larger diameter pipes as well as small diameter pipes. The size range of the pipes which can be renewed by cement mortar lining is taken from the ANSI / AWWA Standard for Cement Mortar Lining of Water Pipelines and is given as 100 mm to 9.2 m. The range of thickness of the lining is taken from the same source and is given as 4 mm (small pipes) to 12 mm (large pipes). The size range of the pipes which can be renewed by epoxy lining is taken from the WRc Source Document for the Water Main Rehabilitation Manual and is given as 75 mm to 800 mm. The range of thickness of the lining is taken from the same source and is given as 1 mm to 4 mm. The city of Waterloo decided to choose cement mortar lining to renew the 24 kms of water mains with cement mortar lining due to lower cost, experience with this type of lining lower quality requirements and the hardness of water.

Application of shotcrete with steel reinforcement was demonstrated during the renewal of a section of the Old Stony Brook Conduit in Boston, MA (Shea 2007). The Old Stony Brook conduit was being used as a storm drain at the time of renewal and had an arch shape with a concave floor. The section to be renewed was 1500 feet long with a cross section of 132" x 90" and was exhibiting large cracks on the crown section which were deep enough to reach the soil. The shallow depth of cover over the conduit and formation of cracks on the street above the conduit were also adding to the criticality of the situation. According to the hydraulic analysis the reduction in the diameter of the conduit was limited to 8 inches. Epoxy coating with pressure grout, and localized grouting and sealing with concrete methods were eliminated since they did not offer structural renewal of the conduit. Sliplining was not selected as the reduction in diameter was larger than 8 inches. Spiral wound PVC was also eliminated due to the geometry of the conduit. Cured in place pipe was eliminated due to shape and size of the conduit. Finally it

was decided to renew the conduit by applying 8 inch thick shotcrete with steel reinforcement. The existing flow was diverted and reinforcing steel was placed. After inspecting the reinforcement for quality purposes shotcrete was applied in several layers. Samples were taken from each layer and project was successfully completed in 65 days with a cost of \$840 per linear foot.

The basic properties of nonstructural lining materials used to renew water mains differ from each other tremendously and each material has advantages and limitations of its own (Oram 2004). The materials used for nonstructural water main renewal can be divided into three categories, namely cement mortar lining, epoxy lining and rapid setting linings. Large pipes which allow worker entry are usually renewed by cement mortar lining method. For smaller pipes it is difficult to identify one point better compared to others. UK had led the way in terms of developing lining materials which needs less curing time since during the renewal of water mains a temporary water service is not supplied. Cement mortar lining has a proven history in the US and building temporary water mains is a key component of a water main renewal process in the US. Therefore epoxy lining and rapid setting materials have not been widely used in the US market compared to UK. Furthermore cement mortar lining is more flexible in terms of quality control during the installation process compared to epoxy and rapid setting materials. Epoxy linings and rapid setting materials depend heavily on the pipe preparation and application procedures. However cement mortar lining suffers in durability when the water alkalinity is high and cement mortar lining is thicker compared to epoxy coating. Epoxy coating does not block flow to service lines. Author also suggests that nonstructural lining should not be used to prevent leakage even though it may reduce leakage in the short term. The reduction in the pipe diameter can be compensated by the smooth profile of the lining in all three methods.

Rapid setting polymeric lining was used in to eliminate perchloroethylene in the potable water supply in the Sandwich Water District, Sandwich, MA in 2002 (Derr 2004). The original pipe was constructed of asbestos cement ranging in diameter from 6 to 12 inches in 1970s and it had a vinyl lining which was the source of percholoroethylene. To test the effectiveness of rapid setting polymeric material pipe samples were taken from the site and lined in a test environment. Test was successful and it was decided to renew 8,500 ft of the pipe with the rapid setting material and return the pipe to service on the same day. Despite some difficulties renewal was accomplished with an approximate cost of \$46 per foot and it was returned to service in 8 hours. The water samples were determined to be clean and boiling notice lasted for only 24 hours.

It is possible to change the composition of cementitious linings by adding fibers. In a study Luk investigated the effects of adding oxidation resistant steel fibers into the cement lining mixture. (Luk 2001). 5 different pipe types, namely old cast iron, new cast iron, cement mortar lined, epoxy lined and fiber-reinforced mortar lined, were tested with still water (both disturbed and undisturbed) in terms of pipe friction, water quality and structural strength. Epoxy coating had the lowest pipe friction value, cement mortar lining and fiber-reinforced mortar lining had similar friction values both higher than epoxy coating. In terms of water quality (pH level, iron content, turbidity, total alkalinity), fiber-reinforced cement mortar lining had better results compared to cement mortar lining especially with respect to total alkalinity. Epoxy coating had better pH level and total alkalinity value compared to the cement based linings. Fiber-reinforced cement mortar lining also increased comprehensive strength and rupture pressure values of cement mortar lining.

Geopolymer concrete and zeolite are among the advanced cementitious materials which have outstanding mechanical and chemical properties. Coating buried pipes with these materials are among the subjects of current researchers (Allouche et al. 2007).

5.3.9 Spiral Wound Pipe

In spiral wound pipe method, a special winding machine is used to form a PVC pipe inside the existing pipe. PVC profiles are fed to the machine and the machine forms a continuous pipe by welding the PVC profiles. This method can be used both for structural purposes and nonstructural purposes. Once the PVC pipe is placed within the existing pipe, the annular space is grouted by an appropriate strength grout depending on the nature of the renewal. Details of the spirally wound pipe renewal method can be found in ASTM F1698-02 standard. Characteristics of Spiral Wound Pipe method are given in Table 5.21:

Method	Diameter (in.)	Length (ft)	Material	Pipe type
Spiral Wound Pipe	6 – 108	1000	PE, PVC, PP, PVDM	Gravity

Table 5.21: Characteristics of Spiral Wound Pipe (Najafi 2004)

Depending on the condition of the host pipe, the design of the Spiral Wound Liner Pipe is carried out based on either a Partially Deteriorated Host Pipe Design or a Fully Deteriorated Host Pipe Design.

In a partially deteriorated pipe design the host pipe is assumed able to support the soil and surcharge loads throughout the design life of the rehabilitated pipe with the soil adjacent to the existing pipe providing the required side support and bedding. The spiral wound pipe should be designed to withstand ground water hydrostatic pressure without buckling.

In a fully deteriorated pipe design the Spiral Wound Liner Pipe is designed to support all hydraulic, soil and live loads specified in the project specifications (with safety factor). Two

distinctive design theories are used in the design of Fully Structural Spiral Wound Liner Pipe. The first design theory looks at rigid plastic pipe design theory that utilizes the rigidity/stiffness of the plastic profile combined with the supporting modulus of soil reaction to determine the maximum external pressure allowed before the Spiral Wound Liner Pipe buckles. The second design theory looks at the composite structure of Spiral Wound Liner Pipe, Grout, and any Residual Structural Capability of Existing Host Pipe as one structural unit. The design of this particular theory is either based on Reinforced Concrete Pipe Design or on WRc Type I Design. It is noted that without accurate empirical test data which proves that composite action between the grout and the host pipe occurs, most owners are reluctant to consider the residual structural capability of the host pipe and therefore the resulting in an overdesigned Fully Structural Spiral Wound Liner Pipe.

Each manufacturer of the Spiral Wound Lining System has undertaken testing to determine the durability of their product for a 50 year design life. This includes the testing of plastic's short and long term tensile and bending stresses, the flexural modulus, etc to make sure that the structural capability of the plastic is sustained over 50 years. Also, the design of the water way thickness is such that the final spiral wound liner pipe will resist a minimum of 50 year abrasion from sand and other solid item that might be flowing through the pipe.

Some unevenness in wall roughness can be found in all commercially available pipes. In spirally wound liner pipe, there is also irregularity of surface due to the spiral wound joint connecting each successive profile wrap. However, documented testing by the spiral wound pipe manufacturers has shown little difference in roughness coefficient exists between regular PVC pipe and the spiral wound pipe.

Modifications for culvert applications using a Spiral Wound Lining System are minimal. When rehabilitating corrugated metal pipe, additional bottom railing may be needed to guide the wound liner pipe into the host pipe so that it does not get caught by the corrugations within the host pipe.

Also, unlike sanitary sewer, the defects observed on storm sewer and culverts usually occur on the bottom of the host pipe instead of the top. If the bottom of the storm sewer and/or culvert is severely corroded, the bottom needs to be repaired prior to the installation of the spiral wound liner pipe.

Spiral Wound Pipe Procedure:

The typical steps of spiral wound pipe renewal method are as follows:

- Placing the winding machine inside the pipe
- Feeding the PVC profiles into the machine
- Grouting the annular space

Placing the winding machine inside the pipe

This step involves positioning the special winding machine which continuously welds the PVC strips to form the lining pipe. The winding machine can be stationary or traveling. If the pipe to be rehabilitated is a sewer pipe, the machine can be lowered from an existing manhole.

Feeding the PVC profiles into the machine:

This step involves forming the actual liner by feeding the PVC profiles into the machine. The profiles can be placed above the ground and fed through the machine.

Grouting the annular space:

The liner formed by the machine has a smaller cross sectional area compared to the host pipe. The annular space left between the liner and the host pipe should be filled with an appropriate strength grout.

Quality Assurance and Quality Control

- The plastic profile used in the Spiral Wound Lining System should be distinctly marked on its surface at appropriate intervals with a code number identifying the manufacturer, plant, date of manufacture and profile designation.
- When structural grout is required by the design, the grout should be sampled and tested as designated by the owner. The properties that should be tested may include compression strength test, bleed test, shrinkage test, flowability test, etc.
- After the completion of installation, the Spiral Wound Liner Pipe should be inspected either by physical visual inspection or by closed circuit television.
- The spiral wound pipe shall be wound continuously over the entire length of the host pipe and be free from defects such as foreign inclusions, holes, cuts, tears, and grout voids. Any splices or grout holes should be repaired by manufacturer recommended material, and no infiltration of ground water through the spiral wound liner pipe shall be observed. All service connections should be accounted for and unobstructed.
- Any defect which will, or potentially could affect the structural integrity or performance of the renewed conduit shall be repaired using means and method approved by the owner before the final acceptance of the product.

Advantages of Spiral Wound Pipe:

The advantages of spiral wound pipe method are as follows (Najafi 2004):

- The lining pipe is formed by combining strips of PVC segments therefore large working and storage space is not required.
- Mobilization costs are low.
- Bends with large radius can be negotiated with this method.
- Lining can be formed in various diameter sizes within the range of the winding machine.
- Overall costs are low-to-moderate.

Limitations of Spiral Wound Pipe:

Some of the limitations of the spiral wound pipe method are as follows (Najafi 2004):

- Skilled and trained personnel are needed to operate the winding equipment.
- Hydraulic capacity of the renewed pipe can be reduced significantly.
- Grouting is required to fill the annular space.
- The PVC strips have to be continuously welded, fused or mechanically joined together to form a continuous joint.

Previous Research and Case Studies Related to Spiral Wound Pipe

Due to its advantages such as applicability to noncircular buried pipes and little working space requirement, spiral wound pipe is becoming a popular method of renewal among the world. In this section some of the case studies in which this renewal method was employed will be covered:

A Japanese company developed a renewal method called Sewage Pipe Renewal (SPR) in 1986 in which a winding machine is used to form a rigid PVC pipe within existing buried pipes (Morioka et al. 2003). Since then the company further improved this method to rehabilitate large and noncircular pipes. The principles of SPR method is the same as the spiral wound pipe method where a PVC strip is fed to the winding machine and once the liner is formed the annular

space is grouted. While renewing noncircular pipes “steel enhancements” are added to the PVC profile in order to prevent the PVC from returning into a circular shape. The grouting procedure can cause floating and deformation of the liner therefore profiles used in the renewal of large pipes are selected as stiffer profiles and “support jacks” are installed with predefined intervals along the pipeline. The company developed a method called the “New SPR Method” in which the grouting process is performed simultaneously as the winding machine proceeds with the liner formation. This method eliminates the use of support jacks and results in a faster renewal procedure with improved flow characteristics compared to the conventional SPR method. The fracture strength of the SPR method was tested on specimens of renewed standard box culverts and box culverts with wall reduction of 25 mm with top reinforcing bars missing. According to the results it was stated that the renewed pipe regained 2 to 3 times of the strength of the standard culvert and regained an equal amount of strength in the case of renewal of a culvert with wall reduction of 25 mm and missing top reinforcing steel bars. The compressive strength and flow characteristics of renewed pipes by using new SPR method were also investigated. According to the results the compression strength of the renewed was better than the original pipe and the flow capacity was improved by 20%. Case studies in which a rectangular box culvert (with dimensions 2750 mm by 1850 mm) was renewed by using the SPR method and a circular water pipeline (with a diameter of 1800 mm) was renewed by using the new SPR method were presented. In case of the box culvert the liner had dimensions of 2630 mm by 1730 mm and in case of the circular pipe the liner had a diameter of 1750 mm. Both projects were completed successfully and the pipes were back in service within a short amount of time.

SPR method was also used for the renewal of rectangular box culvert in Sapporo New Chitose Airport, Sapporo, Japan (Nakamura et al. 2004). The box culvert had dimensions of

3000mm by 4500 mm and a total length of 779 m. The renewed section of the culvert had a length of 209.5 m. and dimensions of 2790 mm. by 4330 mm. The renewal was performed with the existing flow which had a depth between 25cm and 50 cm. The renewal project was completed successfully without disruption of the flow and airport operations.

The SPR method was employed to construct a corrosion barrier during the renewal of the Emergency Bypass Channel in the city of Los Angeles (Hanks et al. 2005). The structural repair of the structure was performed by conventional methods. The winding machine had the capability of negotiating curves however for this project the curves exceeded the capacity of the machine. Therefore segments of lining were fabricated above the ground and placed within the pipeline. The grouting was successful in terms of penetration behind the liner. According to the conclusion of this study it was determined that SPR method could be employed in the future and the grout could be considered as a structural element.

5.3.10 Formed-in-Place Pipe (FIPP)

Formed-in-place pipe method involves insertion of two or more high density polyethylene (HDPE) sheets to the existing structure and filling the space between these sheets with an appropriate grout (Najafi 2004). The studs located on the outer surface of the inner HDPE sheet create the space between the liners. When the grout hardens a rigid pipe forms which fits closely to the existing pipe. FIPP method can be applied to renew structures with both circular and non-circular shapes. The characteristics of this method are given in Table 5.22:

Method	Diameter (in.)	Length (ft)	Material	Pipe type
Formed-in-Place Pipe	8 – 144	Varies	PVC, HDPE	Gravity

Table 5.22: Characteristics of Formed-in-Place Pipe (Najafi 2004)

The portion of the HDPE panels exposed at the ends of the culvert must contain UV protection such as carbon black. The translucent panels typically used for sanitary sewer rehabilitation do not provide suitable UV protection for the exposed ends of culvert applications, and if they are to be used, will require the application of additional UV protection measures at the culvert ends.

Formed-in-Place Pipe Procedure:

The steps of formed-in-place pipe renewal method are as follows (Najafi 2004):

- Preparing the liners
- Installing the liners
- Grouting

Preparing the liners

This step involves fabrication of the HDPE liners specifically for the pipe to be renewed. After fabrication these liners are transported to the job site in rolls and folded just before insertion.

Installing the liners

This step involves inserting the folded liners into the pipe by pulling from the downstream end. Once the liner is placed within the pipe it is returned to its original shape with the application of pressure. The remaining liners are also placed within the pipe and pressurized to obtain several lining pipes placed one after the other. The liners are forced to the host pipe with the application of water pressure.

For culverts larger than 80in. in diameter, or of irregular geometry, the use of formworks, instead of pressurization, is generally required for various constructability reasons. Where form works prove to be advantageous, the technique can be used in any man-entry diameter pipe

(generally 42in. and larger). The form works must be structurally sufficient to withstand all short-term loads including the grout. Although grouting in lifts has increased labor and installation time disadvantages, there can be cost advantages from the reduced structural requirements for the form works. Such considerations must be weighed on a case by case basis (ASCE 2008).

The use of formworks avoids the use of high volumes of pressurization water, which is frequently not readily accessible at remote culverts, or is prospectively environmentally unacceptable. The use of form works has the added advantage of potentially reducing the duration of by-pass pumping. On the other hand, forming the pipeline by pressurization has the advantage of eliminating or at least reducing the need for man-entry and also significantly reducing set-up labor costs and overall time of construction. Once again, such considerations must be weighed on a case by case basis.

Grouting the annular space:

The last step involves grouting the space between the liners with an appropriate strength grout. In order to avoid trapping air, the grout is generally introduced by gravity column and allowed to flow from the lower end of the culvert upwards. The length which the grout can be applied will be influenced by the slope of the culvert, the volume of grout that can be mixed and injected during the allotted grout flow period, and the diameter of the pipeline. The water pressure should be maintained while performing the grouting operation and should be released after sufficient time (12 hours) is passed according to the manufacturer's specifications.

Quality Assurance and Quality Control

The wall thickness and corrosion resistance of HDPE FIPP is unalterably established during the pre-manufacturing of the HDPE pipeliner panels. However, the FIPP culvert

rehabilitation technique is still largely a field manufacturing process, which is inevitably subject to variables which may affect the quality of constructed culvert pipeliner. Besides the QA/QC procedures at the manufacturing facilities of the HDPE panels and the grout, QA/QC at the construction site is essential to control the influence of field variables and to provide the customer with the best quality product as constructed.

The following inherent technology advantages facilitate the QA/QC of FIPP pipeliner:

- The minimum thickness of the pipeliner is the height of the embedded anchors and is unalterable by field conditions or by construction crew decisions.
- The grout is injected into the sealed annulus between the layers of the pipeliner using a gravity column, instead of pumping; this tends to preclude the creation of grout voids inside the pipeliner.
- The required volume of grout necessary to achieve the structural wall thickness requirements is established and controlled by the fixed, sealed annulus between the layers of the pipeliner.
- The application of the preliner prevents the grout from escaping, washing away, or losing strength due to dilution by ground water.
- The weld quality and the water-tightness of the HDPE FIPP are confirmed during the installation process.

Since critical structural design properties of a HDPE FIPP are established during field manufacturing, additional field quality tests are essential before and during the grouting process to ensure that design values are being achieved under varying field conditions. With HDPE FIPP, design compliance is monitorable and confirmable during installation. Required field quality

tests of the structural grout include: viscosity, weight, water-cement ratio, temperature, and material expansion (ASCE 2008).

Since temperature, humidity, and other field conditions routinely vary as the installation progresses, the field crews are required to make adjustments to maintain the water-cement ratio of the grout in order to maintain specification compliance. By maintaining tolerances throughout the installation process, the specification compliance and consistency of the HDPE FIPP can be confirmed down the full length of the installed pipeliner. Conformance of these material property requirements during field manufacturing should also ensure that the post-construction strength tests of grout beam samples will also comply with the specification requirements and be reliably representative of the full length of the as-constructed HDPE FIPP.

Voids are not known to form with such low viscosity grout (prior to curing it flows like milk) which is injected by gravity column from the low end to the high end of the culvert. With the translucent HDPE panels, an internal visual inspection, even by CCTV, can confirm the lack of voids in the grout. For man-entry sizes, a “tapping test” can confirm the lack of voids behind an opaque HDPE panel.

Advantages of FIPP

The advantages of FIPP method are as follows (Najafi 2004):

- FIPP method can be applied to renew any shape drainage structure up to 12 ft in diameter.
- This method offers both structural solutions and corrosion control.
- Culverts can be renewed with FIPP method.
- This method can be applied in long drive-lengths.
- Hydraulic capacity can be improved due to using a smoother lining material.

- The liner installed is resistant to abrasion and chemicals.

Limitations of FIPP

The limitations of FIPP method are as follows (Najafi 2004):

- Cross sectional area can be reduced significantly.
- Construction of access shafts may be required.
- Grouting must be used to fill the annular space between lining sheets.

Previous Case Study Related to FIPP

Formed in Place Pipe Method was used to renew 520 meter long brick sewer pipeline in Bielefeld, Germany (Kirste 2007). The commercial name for the method used is Trolining. In this specific project the preliner was not used, therefore the outer wall of the lining pipe was actually the host pipe itself. The grouting procedure in this renewal project helped repair the joint problems of the host pipe. The project started by diverting the existing flow and preparing the old sewer line for the insertion of liners. The liners were inserted through the manholes located above the sewer. The liner ends were sealed and egg-shaped packers were installed. Water was pumped to obtain the required hydrostatic pressure. The annular spaces between the liners and the host pipe and the liner were grouted by using special grouts. The outer annular space was grouted first and then the inner annular space was grouted afterwards. After curing the pressure was released. Finally the service connections were established.

5.3.11 In-Line Replacement

In-line replacement of buried pipes involves trenchless procedures in which the deteriorated pipe is replaced with a new pipe having the same or a larger diameter. In-line replacement can be performed either by fracturing and splitting the existing pipe and inserting a

new pipe, namely by pipe bursting, or by destroying and removing the existing pipe, namely by pipe removal (Najafi 2004).

Pipe Bursting procedure:

The procedure for pipe bursting in general includes inserting a cone to the existing pipe which is connected to a winch at the downstream pit and pulling this cone to fracture the existing pipe. While the cone advances through the deteriorated pipe a new pipe, which is connected to the cone, replaces the fractured parts simultaneously. Depending on the type of force applied to the existing pipe the pipe bursting can be divided into static pipe bursting, hydraulic pipe bursting or pneumatic pipe bursting. If the pipe material is not brittle a different type of cone, which first cuts the pipe and then splits the pipe, should be used.

As a general rule, the pipe bursting project is subdivided into sections or lengths so that the specific bursting equipment can perform bursting based on the geometry and layout of the total length of culvert being replaced. The length of the culvert that can be replaced in a section is dependent on the type of pipe being burst, degree of upsize, soil conditions, geometry of the original installation, and the type of bursting equipment and method used. In addition, the new pipe, whether it is continuous or sectional, will dictate the type of equipment required and the pit setup (Lueke & Ariaratnam 2001).

The maximum size of a pipe which can be renewed pipe bursting is given as 48 in. however larger sized pipes were renewed by using this method. Larger energy need and ground disturbance are the factors which limit the maximum size of the pipe bursting method (Najafi 2004). The characteristics of pipe bursting are given in table 5.23.

Pipe Removal Procedure:

The procedure for pipe removal involves the removal of the existing pipe rather than pushing it to the surrounding soil as in pipe bursting. Pipe reaming is a pipe removal technique in which horizontal directional drilling procedures are employed to remove the existing pipe in segments whereas in pipe eating microtunneling procedures are employed for the same purpose. In pipe extraction the whole pipe is pushed out and replaced by a new pipe (Najafi 2004). The characteristics of pipe removal are given in Table 5.23.

Method	Diameter (in.)	Length (ft)	Material	Pipe type
Pipe bursting	4 – 48	1500	PE, PP, PVC, GRP	Pressure and Gravity pipelines
Pipe removal	Up to 36 inches	300	PE, PVC, PP, GRP	Pressure and Gravity pipelines

Table 5.23: Characteristics of In-Line Replacement (Najafi 2004)

Quality Assurance and Quality Control

When assuring the quality of a project, guidelines should be followed where the potential for subsidence (loss of ground) and risks are high.

The amount of risk depends on the contractor's experience in addition to a number of factors that require engineering judgment such as: depth of cover, diameter of culvert, proposed methods, soil type (cohesionless sands, gravels, and cobbles or boulders below groundwater surface are probably the worst) and potential obstructions.

In house designs should consider the following four categories. Depending on the complexity, it may be necessary to hire a consultant to perform the design:

- i. Geotechnical investigation
- ii. Settlement, surface bump and bust, monitoring
- iii. Contractor submittals

iv. Contract inspection

Items 2 and 3 should be addressed in the plans and specifications and should be based on the results of item 1.

Advantages of In-Line Replacement Methods:

The in-line replacement methods offer the following advantages (Najafi 2004):

- In-Line replacement methods can be used to renew a wide range of pipe types.
- Diameter of the pipe can be increased.
- The renewed pipe has the same alignment with the existing pipe
- The existing pipe does not have to be disposed if pipe bursting is employed.

Limitations of the In-Line Replacement Methods:

Some of the limitations of the in-line replacement methods are as follows (Najafi 2004):

- Shafts may be required for insertion and reception.
- Construction equipment over the ground needs working space.
- Lateral service connections should be established by open cut excavation.
- The renewal should be performed while the flow is diverted.
- Nearby utilities and structures may be damaged if excessive ground movements and vibrations are present in the job site.

Previous Research and Case Studies Related to In-Line Replacement

There have been several research studies related to the installation and performance of in-line replacement techniques. In this section some of these important studies will be discussed:

Pipe bursting was selected as the proper replacement method to renew a 450 mm diameter clay tile combined sewer in the City of Edmonton, Alberta, Canada (Kwan and Chua 2005). The existing pipe was located at a depth of 6.6 meters to 7.4 meters. It was originally built

in 1914 and as a result of CCTV inspection it was determined that the pipe could collapse immediately. After conducting a cost estimate for alternative renewal options it was decided to perform pipe bursting for 85 meters of the deteriorated pipe, constructing a new manhole and relining the remaining 105 meters. The contractor suggested performing pipe bursting for the whole length of the pipe and it was accepted. However during the execution of the project the bursting head was broken half way through the renewal process. The portion of the pipe which was not renewed by pipe bursting was found out to be in good condition therefore the renewal process was finished and a new manhole was built. The reason for the breakage of the bursting head was due to the pipe bedding change into concrete encasement.

Pipe bursting was applied in the renewal of a 18-inch diameter 310 feet long clay sanitary sewer pipe on the campus of Michigan State University (Lee et al. 2007). 4 different open-cut replacement methods were compared with the pipe bursting. The open-cut options were, simple sloping, simple sloping with benches, combination of sloping and shielding, and shoring or shielding. The first two options were not included in the cost comparison due to the extensive excavation needed to perform simple sloping. In option 3 (combination of sloping and shielding) the amount of shielding was less than the one in option 4 (shoring or shielding) however replacing the pavement and restoring the backfill was more costly. The cost estimates for option 3 and option 4 were found out to be \$100,974 and \$137,298 respectively. The major portion of the open cut replacement cost estimate was due to the excavation, pipe installation and backfilling operations. The cost estimate for the pipe bursting process in which the new pipe was the same size with the original pipe was found out to be \$71,965. The actual cost of the renewal by pipe bursting was given as \$52,000 of which \$30,000 was due to the pipe bursting process itself. According to the findings of the study pipe bursting can be cost effective and faster

compared to open cut procedures. If the length of the pipe to be renewed increases pipe bursting becomes more efficient since the excavation and backfilling costs increase with a higher order compared to the linear nature of pipe bursting operation.

Lueke and Ariaratnam cite three case studies in which pipe bursting was employed in order to renew buried pipelines (2001). In the first case study a 450 mm diameter 300 meter long corrugated metal pipe was renewed in the city of Renton, WA. In order to break and split the corrugated metal pipe cutting fins were placed on the pulling rod, however these fins failed to cut the existing pipe after some time and made the bursting operations further complicated. Therefore another method in which a 1 meter long pipe with cutting wheels installed on it was used to burst the CMP. This method proved to be successful and the pipe was renewed by pipe bursting with the help of cutting wheels. In the second case study, pipe bursting method was used to renew a section of a 300 mm diameter clay sewer pipe in Calgary, Alberta. The difficulty of this project was due to the highly congested location of one of manholes which made the construction of an access pit impossible. To overcome this difficulty a smaller bursting machine which pulled the back side of a new segment of the new pipe was used simultaneously with a large bursting machine which was connected to the bursting head. A polymer lubricant was used to overcome difficulties due to the soil type. The contractor successfully renewed the clay pipe with a rigid polyethylene pipe having a 12.5 mm wall thickness. In the third case study, the surface heave problem due to the vertical misalignment of the new pipe during pipe bursting of a 56 meter long 600 mm diameter reinforced concrete pipe in the city of Phoenix is described. The vertical misalignment was due to the failure of bursting head to cut the invert of the existing pipe. In order to overcome this problem the bursting head was elongated on both sides which helped the bursting head to remain within the existing pipe. The invert of the existing pipe was

fractured by the addition of a cutting fin on the bursting head. The contractor was successful in the renewal of the pipe by using pipe bursting after employing these solutions.

5.4 Applicability of Trenchless Technologies for Culverts

The trenchless technologies presented in this section were mainly developed to be used in the management of water and sewer networks. Culverts can be considered as buried pipes or conduits located below the roadways. Therefore the methods applicable to water and sewer networks are also applicable for culverts. Waterlines need to have appropriate inner layers which will not affect the quality of the drinking water. This is not a concern for culverts since the water carried by culverts does not have to have a high quality as the water carried by waterlines. Furthermore the shape of waterlines is dominantly circular and these pipes operate under pressure whereas culverts can be constructed in a variety of shapes and they operate under gravity. Therefore culverts can be considered to have a resemblance with the sewer pipes, especially storm sewers, both in terms of shape, and operation or deterioration mechanisms.

The trenchless technology methods presented in this chapter may have some limitations which affect their applicability to be used for culverts. These limitations are going to be discussed in the following sections:

Trenchless Inspection Methods:

The trenchless inspection methods covered in this report and their possible limitations in terms of applicability to culverts are given in Table 5.24:

Inspection Method	Limitations to use with culverts
Closed Circuit Television (CCTV)	Applicable for low flow level (25%)
Ultrasonic Inspection	Applicable for high flow level (75%)
Totally Integrated Sonar and CCTV Inspection	Applicable for flow levels between 25% and 75%. Diameter should be greater than 24 inches.
Laser Based Scanning System	Applicable for low flow level
Sewer Scanner and Evaluation Technology	Applicable for low flow level

Inspection Method	Limitations to use with culverts
Ground Penetrating Radar	No limitation
Wall Microdeflections	Applicable to rigid pipes
Natural Frequency of Vibration	Applicable to rigid pipes Should be used in low flow level since the effect of water is unknown
Impact echo	Applicable for large rigid pipes. Individual defects are not located.
Spectral Analysis of Surface Waves	Applicable to man-entry sized pipes.

Table 5.24: Limitations of Inspection Methods for Culverts

These inspection methods should be modified and improved to eliminate their limitations in order to make them suitable for the inspection of culverts of any size and material.

Trenchless Construction Methods:

The trenchless construction methods covered in this report and their limitations in terms of applicability to culverts are given in Table 5.25:

Construction Method	Limitations to use with culverts
Horizontal Auger Boring	Small diameter range (4 to 60 inches) Pipe material is steel and due to the boring action with augers it cannot be coated. Installing another carrier pipe within the steel pipe further decreases the pipe diameter.
Pipe Ramming	Pipe material is steel. Installing another carrier pipe within the steel pipe further decreases the pipe diameter
Horizontal Directional Drilling	Maximum size of installation is 48 in.
Microtunneling	No limitation
Pipe Jacking and Utility Tunneling	Worker entry procedure. Size of installation is greater than 42 inches.
Soil Compaction Methods	Size of installation is less than 8 inches.
Pilot Tube Microtunneling	Size of installation is between 6 and 10 inches.

Table 5.25: Limitations of Trenchless Construction Methods for Culverts

Another major limitation to use trenchless construction technologies with culverts is that in general these technologies do not allow agencies to construct non-circular pipes. These construction methods should be modified and improved to eliminate their limitations in order to make them suitable for the construction of culverts of any size and material.

Trenchless Repair and Renewal Methods:

The trenchless repair and renewal methods covered in this report and their limitations in terms of applicability to culverts are given in Table 5.26.

Repair/Renewal Method	Limitations to use with culverts
Invert Paving	Limited durability of the paved section.
Robotic Repair	Limited diameter range (8 to 30 in.) Not applicable to noncircular pipes
Grouting	Durability of the grout
Internal Sealing	Applicable up to 110 inches in diameter. Not applicable to noncircular pipes
Point CIPP	Limited diameter range (4 to 8 in.)
Cured-in-place pipe	Applicable for pipes with diameters up to 108 in. Removal of the curing water from the site can be a problem
Sliplining	Continuous sliplining can be applied to pipes with diameters up to 63 inches Renewing culverts with excessive bends and deformations is not possible. Renewal of noncircular structures and pipes with varying cross sectional areas may cause very significant reductions in the hydraulic capacity. Large staging area is required
Close-Fit Pipe	Limited diameter range (Up to 24 inches for structural renewal and 63 inches for nonstructural). Requires large working area. This method cannot be used to renew pipes with bends, cross sectional variations and noncircular shapes.
Thermoformed Pipe	Limited diameter range (4 to 30 inches)
Panel Lining	Applicable for man entry buried sized pipes (Diameter larger than 48 in.) Hydraulic capacity can be reduced significantly.
Cement Mortar Lining	Prevents corrosion however does not offer structural solution
Epoxy Coating	Prevents corrosion however does not offer structural solution
Shotcrete / Gunite Lining	Applicable for man entry sized buried pipes. (Diameter larger than 48 in.) Hydraulic capacity can be reduced significantly.
Spiral Wound Pipe	Applicable to buried pipes with diameters up to 108 inches.
Formed in Place Pipe	No limitation
Pipe Bursting	Applicable to buried pipes with diameters up to 48 inches. May not be suitable for non brittle pipes.
Pipe Removal	Applicable to buried pipes with diameters up to 36 inches.

Table 5.26: Limitations of Trenchless Repair and Renewal Methods for Culverts

The repair and renewal methods should be modified and improved to eliminate their limitations in order to make them suitable for the renewal of culverts of any size and material.

6. Asset Management of Culverts

The majority of transportation infrastructure elements of the United States have reached to the end of their design lives. The aging infrastructure is forcing the transportation agency officials to make correct and fast decisions regarding the preservation of these assets. The necessity and importance of a systematic way of gathering information and decision making procedures is becoming more obvious as transportation assets are either failing or causing agencies to perform costly emergency repairs after failures. A comprehensive asset management strategy offers the solution to this complex problem by establishing the rules and protocols for information gathering and decision-making procedures.

The Governmental Accounting and Standards Board – Rule 34 (GASB-34) brought new rules for the state departments of transportation (DOTs) which required them to determine and document the conditions of their assets by implementing asset management procedures. Transportation elements such as pavements and bridges were among the important elements for transportation agencies however culverts and buried pipes were often neglected. Due to aging and accelerated deterioration rates, and high costs of emergency replacements or failures these elements are gaining more importance and agencies are searching for ways of implementing a comprehensive asset management strategy.

Federal Highway Administration (FHWA) defines asset management as “a systematic process of maintaining, upgrading, and operating physical assets cost-effectively”. It is also added that “it combines engineering principles with sound business practices and economic theory, and it provides tools to facilitate a more organized, logical approach to decision-making. Thus, asset management provides a framework for handling both short- and long-range planning.” (FHWA, 1999)

National Cooperative Highway Research Program also defines transportation asset management as “a set of concepts, principles, and techniques leading to a strategic approach to managing transportation infrastructure” (NCHRP, 2002).

In “Asset Management Primer”, Federal Highway Administration (FHWA) provides a generic asset management system as in Figure 6.1 (FHWA 1999)

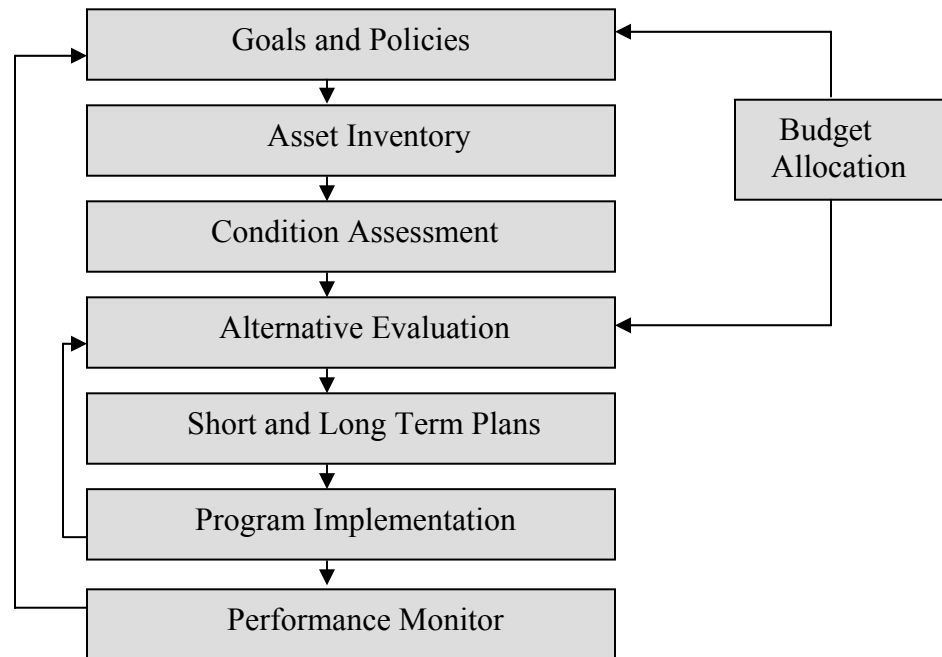


Figure 6.1: Asset Management System (FHWA 1999)

Implementing a culvert asset management strategy will provide the agencies with an overview of the current condition of their culverts and provide them a management strategy which will eliminate costly emergency repair and renewal procedures and also provide them more credibility and accountability. In order to implement this strategy a transportation agency may follow the steps shown in Figure 6.2:

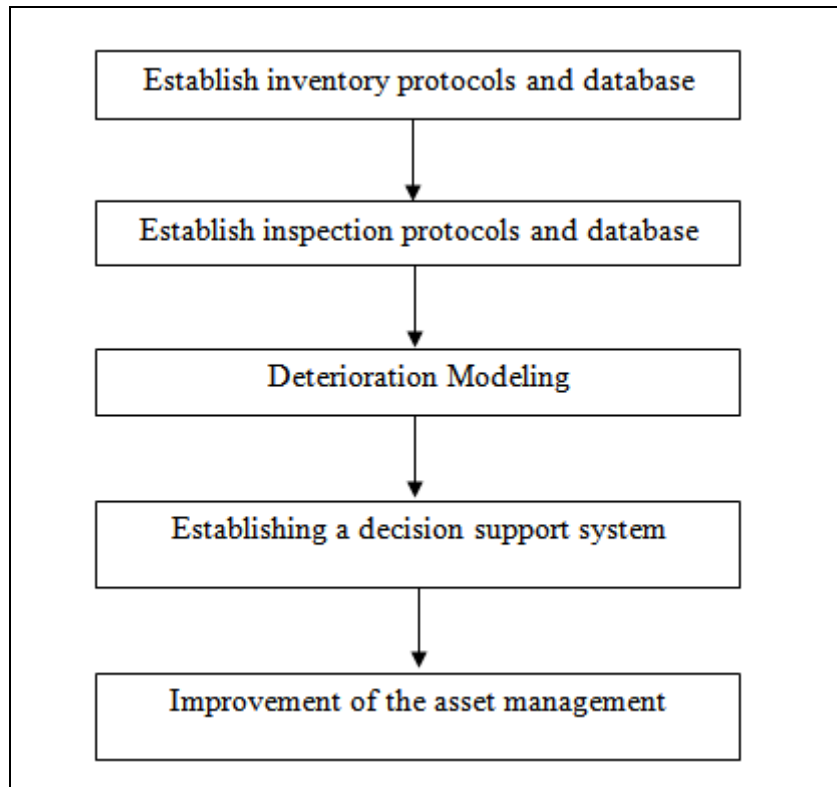


Figure 6.2: Steps of Implementing a Culvert Asset Management Program

Ohio Department of Transportation (ODOT) established their inventory and inspection procedures and published the “Ohio Department of Transportation Culvert Management Manual” in 2003. These procedures were covered in detail in a previous MRUTC research project entitled as “An Asset Management Approach for Drainage Infrastructure and Culverts” conducted by the investigators. Apart from the inspection and inventory procedures a decision support platform was also generated.

In this chapter the steps of a culvert asset management program and the potential use of trenchless technologies to improve this asset management strategy are going to be covered.

6.1 Establishing Inventory Protocols and Database

Establishing an inventory protocol and generating a computerized inventory database is the first step of implementing a culvert asset management program. The inventory database

provides valuable information such as the size, location, material, etc. of each culvert the agency is responsible of managing.

Ohio Department of Transportation (ODOT) uses the form CR-87 (see appendix 3) to record the inventory information for each culvert. This form is used to add a newly constructed culvert to the database or to remove a retiring culvert from the database or to modify the information on the database whenever changes have been made to the existing culvert.

The following items are addressed while filling the CR-87 form:

Culvert File Number

Item 1: Entry Class

Location and Route Information:

Item 2: District

Item 7: Longitude

Item 3: County

Item 8: Road ID

Item 4: Route

Item 9: Maintenance Responsibility

Item 5: Straight Line Mileage

Item 10: Feature Inspection

Item 6: Latitude

Culvert

Item 11: Year Built

Item 18: Gage / Wall Thickness

Item 12: Number of Cells

Item 19: Gage / Wall Thickness

Item 13: Shape

Item 20: Type of Protection

Item 14: Material

Item 21: Slope of Pipe (%)

Item 15: Span

Item 22: Skew

Item 16: Rise

Item 23: Inlet end treatment

Item 17: Length

Item 24: Outlet end treatment

Item 25: Maximum height of cover

Item 28: Modification Material

Item 26: Modification Type

Item 29: Modification Size

Item 27: Year Modified

Extension Inlet

Item 30: Year extended

Item 34: Rise

Item 31: Shape

Item 35: Gage / Wall Thickness

Item 32: Material

Item 36: Extension length

Item 33: Span

Extension Outlet

Item 37: Year extended

Item 41: Rise

Item 38: Shape

Item 42: Gage / Wall Thickness

Item 39: Material

Item 43: Extension length

Item 40: Span

Hydrology / Hydraulics

Item 44: Drainage area

Item 45: Design discharge

Item 46: Abrasive conditions

Item 47: pH

Item 48: Channel protection (inlet)

Item 49: Channel protection (outlet)

The detailed instructions on how to fill the CR-87 form are addressed in the previous research study of the investigators (An Asset Management Approach for Culverts and Drainage Structures) as well as the ODOT Culvert Management Manual (ODOT 2003).

6.2 Establishing Inspection Protocols and Database

The inspection procedures are generated in order to identify the current conditions of the culverts. The accuracy of the information obtained from inspection procedures affect the accuracy of the decisions made to perform timely renewals. Therefore the content of the inspection procedures should provide a clear picture of the actual condition of the culvert. Another important part of the inspection procedures is the standardization of the inspection procedures. The instructions and the distinctions between the visual ratings should be clear in order to eliminate judgmental differences between inspectors.

Ohio Department of Transportation (ODOT) uses the form CR-86 (see appendix 3) while inspecting culverts. This form is used to verify the current condition of the culvert and to make decisions on the necessary renewal procedures. The frequency of inspections is given in Table 6.1:

Description	Frequency of Inspection	Type of Inspections
12" ≤ Diameter / Span ≤ 120	5	Routine
Storm Sewers, Diameter ≥ 36"	5	Routine, storm sewer
Culverts and Storm Sewers with known defects	Determined by culvert inspection reviewer or bridge engineer	Damage, interim

Table 6.1: Frequency of Inspections (ODOT 2003)

According to the manual, the inspection procedure for a particular culvert should start with examining the available information. Required safety precautions should also be reviewed. The general overall condition of the culvert and the approach roadway should be examined. The

embankment, end treatment structures and the culvert barrel should be examined from the outlet and the procedure should be repeated for the inlet.

The manual defines the entry procedure while inspecting culverts according to the following flow chart (Figure 6.3):

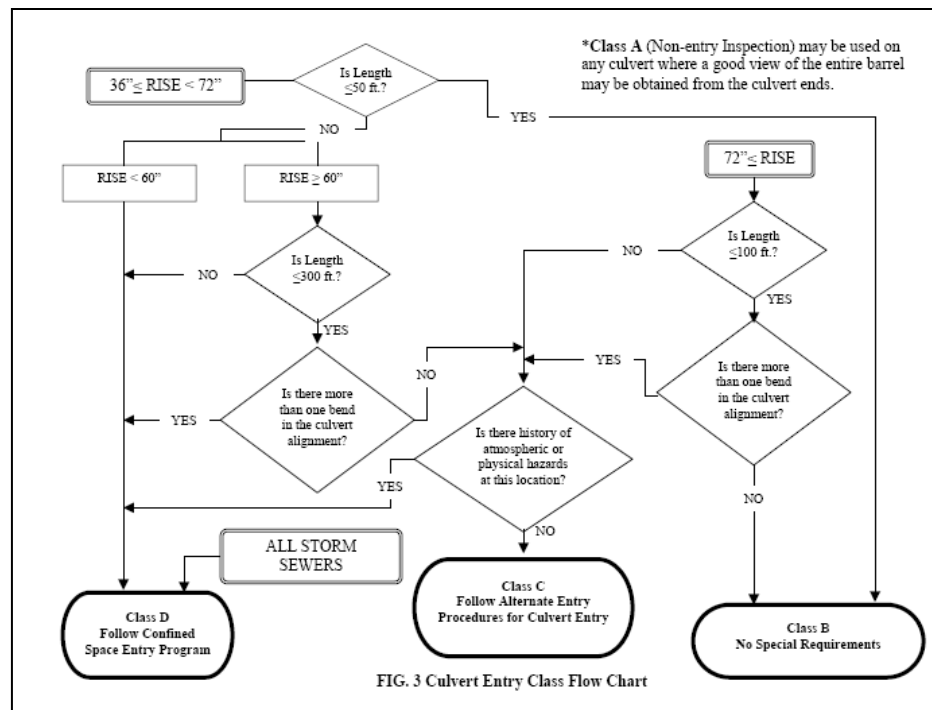


Figure 6.3 Culvert Entry Class (ODOT 2003)

Trenchless inspection methods such as closed circuit television (CCTV), ultrasound inspection or totally integrated sonar and CCTV can be implemented to the flow chart to replace the procedures for Class D and Class C entry type culverts. CCTV method is useful for inspecting pipes with 25% flow. The ultrasound inspection is useful for inspecting pipes with more than 75% flow. To inspect any pipe which has a flow level between 25% and 65% integrated ultrasound and CCTV methods can be used.

Some of the items of the inspection form (CR-86) provided in the ODOT Culvert Management Manual are as follows:

Culvert

Item 1: General

Item 5: Slab

Item 2: Culvert Alignment

Item 6: Abutments

Item 3: Shape

Item 7: Headwalls

Item 4: Seams or joints

Item 8: End Structure

Channel

Item 9: Channel Alignment

Item 11: Culvert Waterway Blockage

Item 10: Protection

Item 12: Scour

Approaches:

Item 13: Pavement

Item 15: Embankment

Item 14: Guardrail

Item 16: Level of Inspection

General Appraisal & Operational Status

The detailed instructions on how to fill the CR-87 form are addressed in the previous research study of the investigators (An Asset Management Approach for Culverts and Drainage Structures) as well as the ODOT Culvert Management Manual (ODOT 2003).

6.3 Deterioration Modeling:

The behavior of culverts under several different environmental conditions has been a study point for many researchers. However there is no exact formula which will give the remaining service life of a culvert under certain conditions. There are some factors which are known to affect the deterioration rate of a culvert. The deterioration modeling is used to explain the deterioration of a culvert in terms of these factors and to predict the remaining service life of the particular culvert under these circumstances. In order to have an accurate deterioration model

inspection results gathered over time need to be examined carefully and a statistical model which will fit closely to the actual deterioration characteristics should be generated.

6.4 Prioritizing the culverts:

According to the results of the deterioration modeling the remaining service life and rate of deterioration should be used to identify the culverts which need immediate attention in terms of renewal. The risk of failure and the cost of failure for each culvert should be determined and this information should be used in order to categorize the culverts in terms of risk levels. The highest risk category should involve culverts which need immediate attention in terms of renewal (repair, rehabilitation or replacement).

Prioritizing can be accomplished by using one of the following methods (Hudson et al. 1997):

- Ranking projects based on subjective judgment
- Ranking by using parameters such as level of service and condition
- Ranking by using parameters regarding the economic analysis
- Optimization on a year-by-year basis
- Near optimization by incorporating a marginal cost-effectiveness approach
- Comprehensive optimization taking into account “which, what and when”

6.5 Establishing a decision support system

The objective of implementing a culvert asset management strategy is to make accurate and justified decisions regarding the repair and renewal (rehabilitation and replacement) of the culverts. In order to accomplish this objective a systematic way of decision making procedures has to be generated. The inventory, inspection, deterioration modeling and prioritization procedures enable the decision maker to identify which culverts need immediate response and

which culverts are still within the safe operating conditions. Next step of the culvert asset management involves generating a decision support system which aids the decision maker in terms of providing available options for each risk category of the culvert database.

Repair procedures are used to solve the problems related to a portion of the culvert therefore they do not improve the condition of the culvert as a whole. Some of the common repair procedures involve invert paving, patching, grouting, internal sealing and point CIPP. Renewal procedures can be divided into rehabilitation and replacement. Rehabilitation of culverts involves procedures which improve the overall condition of the culvert without removing the existing pipe. Therefore rehabilitation methods involve lining methods which cover the whole length and circumference of the culvert. Replacement of a culvert involves either removing or destroying the existing culvert and placing a new one to the same alignment. Open cut method is the most commonly used method of culvert replacement. However trenchless replacement techniques such as pipe bursting and pipe removal are becoming more popular especially to replace buried pipes located under busy roadways and under high fill.

The trenchless repair and renewal methods were covered in detail in chapter 5. Some of the basic characteristics of these methods are summarized in table 6.2. (The comparative cost column is generated by using the information provided on “Trenchless Technology” (Najafi 2004). The actual values may differ depending on the region. This information is provided as a general reference.) Table 6.2 can be used to identify potential repair and renewal methods which suit the circumstances at hand. This table is generated to develop a database of trenchless repair and renewal options. A detailed decision support system which identifies the optimum repair or renewal procedure given the condition of the culvert depending on the Ohio Culvert Management Manual inspection procedures is provided in the next chapter.

	Method	Diameter Range		Solutions against			Significant Diameter Loss
		Minimum (in.)	Maximum (in.)	Structural problems	Corrosion	Infiltration from joints	
Repair	Invert Paving	48	-	Yes	Limited	Limited	Depends on the thickness
	Robotic Repair	8	30	No	No	Yes	No
	Grouting	3	180	No	No	Yes	No
	Internal Seal	6	110	Yes	Yes	Yes	No
	Point CIPP	4	48	Yes	Yes	Yes	Yes
Rehabilitation	Cured in Place Pipe	4	108	Yes	Yes	Yes	No
	Segmental Sliplining	24	160	Yes	Yes	Yes	Yes
	Continuous Sliplining	4	63	Yes	Yes	Yes	Yes
	Close-Fit Pipe (Structural)	3	24	Yes	Yes	Yes	No
	Close-Fit Pipe (Nonstructural)	3	63	No	Yes	Yes	No
	Thermoformed Pipe	4	30	Yes	Yes	Yes	No
	Formed-in-place	8	144	Yes	Yes	Yes	Depends on the design
	Panel Lining	48	-	Yes	Yes	Yes	Depends on the design
	Spiral Wound Pipe	6	108	Yes	Yes	Yes	No
	Cement Mortar Lining	3	180	No	Yes	Yes	No
	Epoxy Coating	3	24	No	Yes	Yes	No
	Shotcrete-Gunite Lining	48	180	Yes	Yes	Yes	Yes
Replacement	Pipe Bursting	4	48	Yes	Yes	Yes	No
	Pipe Removal	12	36	Yes	Yes	Yes	No

Table 6.2: Important Characteristics of Trenchless Repair and Renewal Procedures

6.6 Improvement of the asset management strategies:

This step involves modifying the previous steps of the asset management strategy, inventory procedures, inspection procedures, deterioration modeling, prioritization, and decision support system, according to the technological developments and experiences with some of the previous decisions.

The technological developments offer new trenchless renewal methods and at the same time improve the existing methods. These improvements should be a part of upgrading the available renewal options list.

Once a culvert is repaired or renewed (rehabilitated or replaced) the information regarding this culvert in the culvert inventory database should be updated. Items 26 through 29 of the Culvert Inventory Form (CR-87) of ODOT Culvert Management Manual covers important information regarding the modifications made to the existing culvert.

Inspection and maintenance procedures of a renewed culvert do not defer from these of an existing culvert. However if the culvert is repaired due to a defect the inspection frequency for this culvert should be shorter. Since repair procedures do not cover the whole length of the culvert but only a portion the same types of problems can be experienced in the rest of the culvert. Rehabilitated and replaced culverts typically have the same design life with a newly constructed culvert. Therefore the inspection requirements of rehabilitated and replaced do not differ from the newly constructed culverts. It is of utmost importance to inspect the renewed culvert during the renewal procedure and as soon as the renewal is completed. The procedures have to be performed according to the particular standards and design requirements. Samples from the field have to be taken and tested. For rehabilitation projects where a culvert is lined and a new pipe is formed within the existing pipe careful inspection of the final product is extremely

important. The renewed culvert should be inspected for any defects such as bulging, fins, deformations and if any problems are detected they should be corrected immediately.

7. Establishing a Database and a Decision Support System

Usage of trenchless technologies for renewal of buried pipes has offered a solution to manage these assets located under high fills and/or congested areas. Especially water and waste water agencies have been using these techniques whenever the site conditions dictated performing a structural or non-structural renewal of the system without disturbing the pavement, moving traffic and other utility lines located underground such as gas and communication lines. Culverts can be categorized as both buried pipes in small diameters with no access and worker entry and pipes in larger diameters with possibility of manual inspection and renewal. Trenchless technologies offer the same advantages of cost savings, safety, and non-disturbance of the surrounding facilities for culverts. However many DOTs have started using these technologies without clear standard methodology. Despite the increasing popularity of these methods there is still a lack of guidance and DOT-centered decision support systems on how to make the correct decisions regarding the selection of these methods. The aim of this section is to propose a methodology to develop a database of trenchless technologies used while managing culverts and a decision support system which will help the agencies to select the optimum trenchless technology given the condition of the culvert.

7.1 Database of Trenchless Technology Methods

The purpose of establishing a database of trenchless technology methods is to record all the information associated with the trenchless technology methods used to renew culverts such as cost, problems faced during pre-construction, construction and post-construction phases, advantages, limitations, future maintenance requirements etc. and make this information readily available in the future to generate guidelines for decision making and successful renewal of culverts. The proposed form can be seen in figure 7.1:

CULVERT TRENCHLESS RENEWAL REPORT

CULVERT FILE NUMBER: _____

SHAPE: _____ MATERIAL: _____ LENGTH: _____

MAX. HEIGHT OF COVER: _____ AADT: _____

LATITUDE: _____ LONGITUDE: _____

ENTRY CLASS: _____ NUMBER OF CELLS: _____

GENERAL APPRAISAL & OPERATIONAL STATUS BEFORE RENEWAL: _____

OBSERVED PROBLEMS	SIZE	RENEWAL METHOD	PRE- CONSTRUCTION ISSUES	CONSTRUCTION ISSUES	POST CONSTRUCTION ISSUES

COST / LN. FT.: _____ HYDRAULIC CAPACITY OF THE RENEWED CULVERT: _____

EXPECTED SERVICE LIFE OF THE RENEWED CULVERT: _____

GENERAL APPRAISAL & OPERATIONAL STATUS OF THE RENEWED CULVERT: _____

FUTURE MAINTENANCE REQUIREMENTS: _____

COMMENTS: _____

INSPECTED BY: _____ DATE: _____ REVIEWED BY: _____ DATE: _____

Figure 7.1: Trenchless Renewal Form

Culvert Trenchless Renewal Report starts with the section regarding the general information related to the particular culvert. This section involves the following items:

- Culvert File Number
- Shape
- Material
- Length
- Max. height of cover
- AADT (Annual Average Daily Traffic)
- Latitude
- Longitude
- Entry Class
- Number of Cells
- General Appraisal & Operational Status before renewal

Second section involves a table where the following items need to be filled:

- Observed Problems
- Size
- Renewal Method
- Pre-Construction Issues
- Construction Issues
- Post-Construction Issues

Final section involves the cost of the renewal project and characteristics of the culvert after the renewal procedures. This section includes the following items:

- Cost / Linear foot
- Hydraulic Capacity of the renewed culvert
- Expected Service Life of the renewed culvert
- General appraisal and operational status of the renewed culvert

- Future Maintenance Requirements

The item “The Hydraulic Capacity of the renewed culvert” should be filled in the form in terms of percentage of the culvert before the renewal.

The trenchless renewal report ends with the fields for additional comments, name of the inspector and date, name of the reviewer and date fields.

7.2 Decision Support System

Decision making procedure regarding the renewal of culverts is a complex issue which requires careful examination and evaluation of several factors such as sources of the problem, characteristics of the culvert such as material, shape, and length, availability of funds, hydraulic capacity, etc. Since each culvert is unique in terms of these factors it is not possible to generate a universal solution to the problem. Moreover, each alternative trenchless technology method has limitations and advantages over another. It is important to justify that the selected procedure fits to the given situation even though it has some limitations. Therefore it is of utmost importance to have a degree of flexibility in terms of adjusting the decision making procedure to the circumstances at hand. The decision support system proposed in this project addresses this issue by employing Analytical Hierarchy Process (AHP). The characteristics and procedure of AHP is going to be covered in the following section.

7.2.1 Analytical Hierarchy Process (AHP)

Analytical Hierarchy Process is a decision making procedure developed by Professor Thomas Saaty. The rationale behind the procedure involves constructing a hierarchy of the objective, factors, sub-factors and alternatives, determining the priorities and ranking the alternatives according to those priorities. The strength of this process comes from the ability of incorporating qualitative data coming from judgment and experience, with the quantitative data.

Detailed information regarding the analytical hierarchy process can be found in “Decision Making for Leaders: The Analytical Hierarchy Process for Decisions in a Complex World” (Saaty 1982).

The steps followed in using Analytical Hierarchy Process are as follows:

1. Building the hierarchy
2. Comparing each factor in terms of importance, preference or contribution under the higher level and show the comparisons using matrices.
3. Determining the priority vectors for all matrices.
4. Checking the matrices of pair-wise comparison in terms of consistency.
5. Determining the scores of alternatives and selecting the alternative with the highest score.

7.2.1.1 Building the hierarchy

Building the hierarchy involves 4 steps:

- Determining the overall objective
- Determining the factors which have an effect on achieving the objective
- Determining sub-factors under each factor
- Determining the alternatives

Once the objective, factors, sub-factors and alternatives are determined the hierarchy can be drawn as in Figure 7.2. The hierarchy in this figure consists of two major factors (Factor A and Factor B) and two sub-factors connected to each one of these major factors (Sub-Factors A-1, A-2 and Sub-Factors B-1, B-2). There are two alternatives in this sample hierarchy, namely Alt 1 and Alt 2.

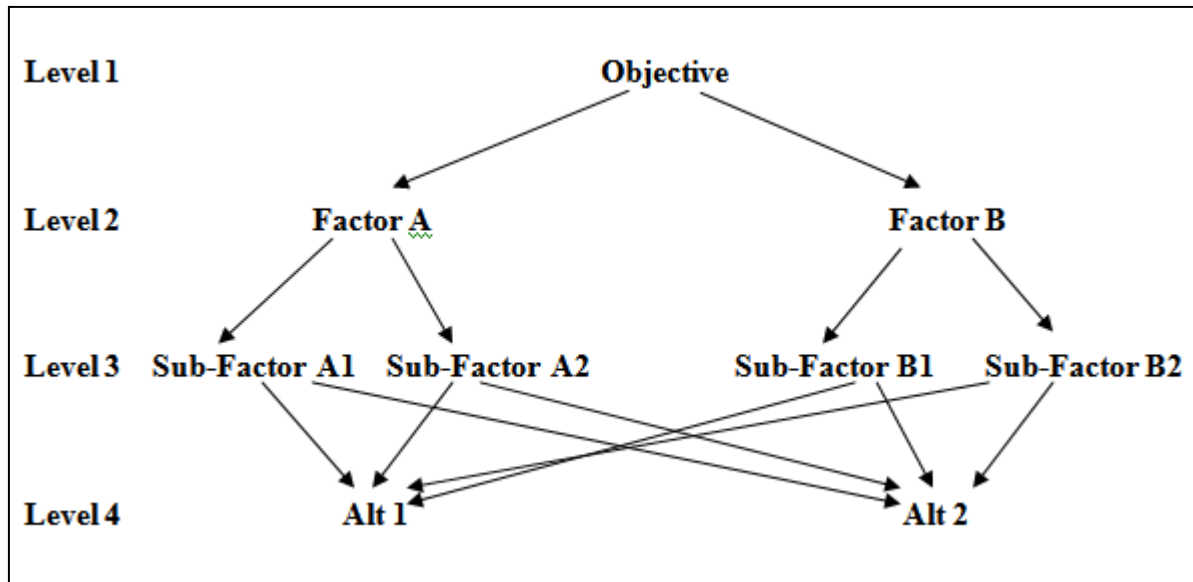


Figure 7.2: Sample Hierarchy

7.2.1.2 Comparison matrices

Comparison matrices are formed by comparing the importance, influence or contribution of factors or sub-factors which are located on the same level. Pair wise comparison is performed by listing all the items on the same level of the hierarchy on the rows and columns of the matrix and filling the matrix with the values according to the table 7.1:

Intensity of importance	Definition	Explanation
1	Equal importance of both elements	Two elements contribute equally to the property
3	Weak importance of one element over another	Experience and judgment slightly favor one element over another
5	Essential or strong importance of one element over another	Experience and judgment strongly favor one element over another
7	Demonstrated importance of one element over another	An element is strongly favored and its dominance is demonstrated in practice
9	Absolute importance of one element over another	The evidence favoring one element over another is of the highest possible order of affirmation

Intensity of importance	Definition	Explanation
2, 4, 6, 8	Intermediate values between two adjacent judgments	Compromise is needed between two judgments
Reciprocals	If activity i has one of the preceding numbers assigned to it when compared to activity j, then j has the reciprocal value when compared to i	

Table 7.1: Values to Fill Pairwise Comparison Matrices (Saaty 1982)

For example, the comparison matrices for the hierarchy given in Figure 7.2 would be as shown in Figures 7.3, 7.4, and 7.5.

Objective	Factor A	Factor B
Factor A	1	A / B
Factor B	B / A	1

Figure 7.3: Pairwise Comparison Matrix of Factors A and B

Factor A	Sub-Factor A1	Sub-Factor A2
Sub-Factor A1	1	A1 / A2
Sub-Factor A2	A2 / A1	1

Figure 7.4: Pairwise Comparison Matrix of Sub-Factors A1 and A2

Factor B	Sub-Factor B1	Sub-Factor B2
Sub-Factor B1	1	B1 / B2
Sub-Factor B2	B2 / B1	1

Figure 7.5: Pairwise Comparison Matrix of Sub-Factors B1 and B2

7.2.1.3 Determining the priority vectors

Priority vectors are determined in order to convert the pair-wise comparison matrices into the weight of each factor and sub-factor. Average of the normalized columns which is an approximate method of determining eigenvectors is going to be used in this study. This method involves the following steps:

- Summation of the values in each column of the matrix
- Dividing each value to the corresponding column total
- Taking the average of the values in each row

As an illustration the priority vector for the pair-wise comparison matrix given in Figure 7.6 is found as follows (see Figures 7.7 and 7.8):

Objective	Factor A	Factor B
Factor A	1	2
Factor B	1 / 2	1

Figure 7.6: Sample Pairwise Comparison Matrix of Factors A and B

Step 1: Calculating the column totals:

Objective	Factor A	Factor B
Factor A	1	2
Factor B	1 / 2	1
Total	1.5	3

Figure 7.7: Calculation of Priority Vectors for the Matrix Given in Figure 6.6 - Step 1

Step 2: Dividing each value to the corresponding column total:

Objective	Factor A	Factor B
Factor A	0.67	0.67
Factor B	0.33	0.33

Figure 7.8: Calculation of Priority Vectors for the Matrix Given in Figure 7.6 - Step 2

Step 3: Taking the average of values in each row:

Factor A: $(0.67 + 0.67) / 2 = 0.67$

Factor B: $(0.33 + 0.33) / 2 = 0.33$

0.67 and 0.33 form the priority vector of the two factors with respect to the objective. Same methodology should be applied to all the pair wise matrices constructed in the previous step.

7.2.1.4 Checking the consistency of pair-wise comparison matrices

In order to reach accurate decisions the pair-wise comparison matrices need to have a certain level of consistency. Comparison of quantitative elements usually result in consistent matrices however the situation may be different for qualitative comparison. If the comparison of factor A to factor B results in a value of 3 and the comparison of factor B to factor C results in a value of 2, the comparison of factor A to factor C should result in a value close to 6. The deviation from that expected value may generate inconsistency in the comparison matrices. This level of inconsistency can be measured by the consistency ratio. In order to find the consistency ratio, first consistency index has to be calculated according to the following formula:

Consistency Index: $(\lambda_{\max} - n) / (n - 1)$

Where $\lambda_{\max}$ is found by the following procedure:

- Multiply the elements of each column with the corresponding relative priority

- Sum the elements in each row of the resulting matrix.
- Divide the summation of each row with the corresponding relative priority
- Find the average of the resultant numbers from the last step.

Once the consistency index is found it should be divided by the random consistency number to find the consistency ratio. The values of random consistency numbers can be found in Saaty 1982. These values are given in table 7.2:

n	Random consistency
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

Table 7.2: Random Consistency Values (Saaty 1982)

If the consistency ratio is determined to be higher than 0.10, the inconsistency should be corrected.

7.2.1.5 Determining the scores of alternatives

In order to find the alternative which best suits the given hierarchy the weights of all the sub-factors which are linked to the alternatives should be calculated. This is performed by multiplying the relative priority of the higher factors with the relative priority of sub-factors which are connected to these factors. For example if Factor A is connected to sub-factors A1 and A2 and these sub-factors are connected to the alternatives x and y the weights of sub-factors A1 and A2 should be calculated by multiplying the relative priority of factor A with the relative priority of sub-factor A1 and with the relative priority of sub-factor A2 respectively. If factor A has a relative priority of 0.67 and sub-factor A1 has a relative priority of 0.33 and sub-factor A2

has a relative propriety of 0.67, the final relative priority of sub-factor A1 would be 0.67 multiplied by 0.33 and the final relative propriety of sub-factor A2 would be 0.67 multiplied by 0.67.

Once all the weights for all sub-factors are calculated the alternatives should be compared against each other in terms of satisfying each sub-factor. Pair-wise comparison matrices which involve the comparisons of alternatives with respect to each sub-factor should be created. The priority vectors of these matrices should be calculated.

The overall scores for all alternatives are calculated by multiplying the priority vector of alternatives with the transpose of sub-factor relative priorities. The alternative with the highest score satisfies the given conditions best and therefore selected as the best alternative.

7.2.2 Decision Support System Incorporating AHP and ODOT Inspection Procedures

In this section a decision support system which combines the analytical hierarchy process (AHP) with the Ohio Department of Transportation's Culvert Inspection Procedures is developed. The outline of the procedure is going to be presented and an illustrative example is going to be used to further explain each step. One of main reasons of selecting AHP is the flexibility of the method which enables the user to adjust it according to the site-specific conditions at hand. The factors, sub-factors and the alternatives among which a decision must be made may be different for each culvert therefore the example provided in this section only serves as an illustrative example. Decision makers should make the required modifications in order to use this method for the specific site conditions.

The steps of the proposed decision support system are as follows:

Step 1: Determine the structural condition of the culvert

Step 2: Identify the type of treatment required

Step 3: Generate the potential renewal alternatives

Step 4: Identify the site-specific factors and sub-factors

Step 5: Build the hierarchy

Step 6: Construct the comparison matrices

Step 7: Check the consistency of comparison matrices

Step 8: Find the priority vectors for all sub-factors

Step 9: Create pair-wise comparison matrices for alternatives and sub-factors

Step 10: Select the alternative with the highest score

Illustrative example:

An agency wishes to find the optimum way to renew their culvert which has serious problems associated with the structural components. Suppose that, the culvert to be renewed is a corrugated metal pipe under 12 ft depth of height and having a diameter of 65 inches. Culvert does not have misalignment or excessive deformations. The site specific factors are determined as cost, working space requirement, design life of the renewed culvert, previous experience with the method, hydraulic capacity of the renewed culvert and contractor availability.

Step 1: Determine the structural condition of the culvert

The condition of the culvert is the most important input variable of the decision support system since it dictates the kind of renewal that needs to be performed. The information regarding the structural condition of the culvert can be taken from the output of inspection procedures performed by following the Ohio Culvert Management Manual. The general appraisal item of the inspection form identifies the structural condition of the culvert according to table 7.3. This information is going to be used in the steps that follow in order to select the type of renewal that is required.

Code	Description
9	As built condition
8	Very good condition - no problems noted
7	Good condition - some minor problems
6	Satisfactory condition - structural elements show some deterioration
5	Fair condition - all primary structural elements are sound, but may have minor section loss
4	Poor condition - advanced section loss, deterioration, or spalling
3	Serious condition - loss of section, deterioration, or spalling have seriously affected primary structural components
2	Critical condition - advanced deterioration of primary structural elements. Culvert should be closed or closely monitored, until corrective action is taken
1	“Imminent” failure condition - major deterioration or section loss present on structural components. Culvert is closed to traffic.
0	Failed condition - out of service - beyond corrective action

Table 7.3: General Appraisal Score (ODOT 2003)

In our illustrative example, the culvert to be renewed can be classified with a general appraisal level of 3.

Step 2: Identify the type of treatment required

The term treatment is used to encompass repair, rehabilitation and replacement activities. Repair procedures are the procedures which do not extend the design life of the whole structure. These procedures are carried out to eliminate local defects in the culvert. Rehabilitation and replacement procedures result in the formation of a new pipeline and therefore these procedures provide a new design life. Rehabilitation procedures involve formation of the new pipeline within the existing pipe whereas the replacement procedures require eliminating the existing pipe completely. This step identifies the type of treatment required for the culvert at hand by examining its structural condition. The following table (Table 7.4) categorizes the culverts according to their structural condition and provides the type of treatment options to be considered in the following steps.

General Appraisal	Required action
9 and 8	No action required. Routine maintenance is sufficient
7 and 6	Repair procedure or Do Nothing
5	Combination of repair procedures or rehabilitation
4, 3, 2 and 1	Rehabilitation or replacement

Table 7.4: Categories of Culverts in Terms of Structural Condition and Required Action

According to this table the culvert in our illustrative example needs to be rehabilitated or replaced.

Step 3: Generate the potential treatment alternatives

Once it is determined what type of action is required to improve the condition of the culvert, it is necessary to generate a list of alternative procedures. Table 6.2 is generated to summarize the main characteristics of trenchless culvert repair and renewal techniques. This table is going to be revisited in this chapter as Table 7.5. Table 7.6 and Table 7.7 summarize the advantages and disadvantages of trenchless repair and renewal procedures respectively which were described in Chapter 5.

List of potential alternatives should be generated by eliminating the methods which do not satisfy the requirements of the specific renewal procedure in terms of size, presence of bends and excessive misalignment and whether the repair/renewal method needs to improve the structural condition of the culvert or not after examining Tables 7.5 through 7.7. (The comparative cost column in Table 7.5 is generated by using the information provided on “Trenchless Technology” (Najafi 2004). The actual values may differ depending on the region. This information is provided as a general reference.) The decision makers can use their judgment to eliminate any alternative which they believe is not possible to be employed at that time.

The potential methods of renewal for the culvert in our illustrative example are cured-in-place-pipe, sliplining, formed-in-place pipe, panel lining, spiral wound pipe, shotcrete-gunite lining.

	Method	Diameter Range		Solutions against			Significant Diameter Loss
		Minimum (in.)	Maximum (in.)	Structural problems	Corrosion	Infiltration from joints	
Repair	Invert Paving	48	-	Yes	Limited	Limited	Depends on the thickness
	Robotic Repair	8	30	No	No	Yes	No
	Grouting	3	180	No	No	Yes	No
	Internal Seal	6	110	Yes	Yes	Yes	No
	Point CIPP	4	48	Yes	Yes	Yes	Yes
Rehabilitation	Cured in Place Pipe	4	108	Yes	Yes	Yes	No
	Segmental Sliplining	24	160	Yes	Yes	Yes	Yes
	Continuous Sliplining	4	63	Yes	Yes	Yes	Yes
	Close-Fit Pipe (Structural)	3	24	Yes	Yes	Yes	No
	Close-Fit Pipe (Nonstructural)	3	63	No	Yes	Yes	No
	Thermoformed Pipe	4	30	Yes	Yes	Yes	No
	Formed-in-place	8	144	Yes	Yes	Yes	Depends on the design
	Panel Lining	48	-	Yes	Yes	Yes	Depends on the design
	Spiral Wound Pipe	6	108	Yes	Yes	Yes	No
	Cement Mortar Lining	3	180	No	Yes	Yes	No
	Epoxy Coating	3	24	No	Yes	Yes	No
	Shotcrete-Gunite Lining	48	180	Yes	Yes	Yes	Yes
Replacement	Pipe Bursting	4	48	Yes	Yes	Yes	No
	Pipe Removal	12	36	Yes	Yes	Yes	No

Table 7.5: Main Characteristics of Culvert Repair and Renewal Procedures

Method	Advantages	
Invert Paving	Cost of repair is low. No need for special equipment.	Limited Durability

Robotic Repair	Point repair of the pipe is handled with good precision. Repair method provides a better infiltration barrier and helps in restoring the structural integrity of the existing pipe.	Robotic repair cannot be used for large defects. Defects larger than 2 inches cannot be repaired. Equipments used in robotic repair are expensive.
Grouting	Low cost. Infiltration and exfiltration problems can be eliminated with this method.	This method does not enhance the structural integrity of the pipe. Durability of the grout is uncertain.
Internal Seal	This method offers structural solutions. This method can be applied to solve problems such as pipe breakage, joint settlement and longitudinal cracks. Gravity sewers, culverts, and pressure pipes can be repaired without excavation.	Internal sleeve may cause a reduction in flow capacity. This method is applicable to small defects.
Point CIPP	Point CIPP adheres to the existing pipe tightly and eliminates infiltration. The repair procedure may usually be performed without diverting the existing flow. This method offers structural solution to the defected pipe segment. Lining does not obscure the flow due to tapered smooth ends.	This method does not improve the structural integrity of the pipe. Point CIPP method may be used for small defects. Hydraulic capacity may be reduced.

Table 7.6: Advantages and Limitations of Trenchless Repair Procedures

Method	Advantages	Limitations
Cured in Place Pipe (CIPP)	CIPP eliminates the need for grouting due to the tight fit with the existing pipe. CIPP offers an improved flow capacity due to its smooth interior. Pipes with noncircular shapes can be renewed without decreasing the flow capacity. CIPP can be used in renewal of pipes with bends and deformations. Manholes can be used to access the existing pipe.	The lining material is expensive. The existing flow capacity may be reduced. Liner pipe ends or joints may be weak points. Monitoring, inspection and maintenance are difficult. Removing the cured lining is difficult. Lining can be affected by chemicals. CIPP can be more expensive than other methods.
Sliplining	Special expensive equipments are not needed. It is a simple method applicable to both gravity and pressure pipelines. It offers both structural and nonstructural solutions. This method allows for renewal without diverting the actual flow.	Pipe diameter is reduced. A pit needs to be dug at each end. Laterals need to be installed separately. The annular space may cause problems.
Close-Fit Pipe	The new polyethylene pipe used in renewing the existing pipe is produced in a controlled environment. The cross sectional loss is minimal. This method is useful in eliminating internal corrosion problems. Pipes with bends up to 45 degrees can be renewed by MFP. Installations can be performed up to 1000 ft. It is possible to establish the lateral connections internally.	Diameter range and length are limited. The new butt-fused joints may be weak points. Pipes with varying diameters cannot be renewed. In general, an inspection is required. Usually the existing pipe is not removed. Valves and connections are difficult to install.
Thermoformed Pipe	This method offers fast installation and high quality due to the factory manufacturing of the liner pipe. This method does not involve discharge of harmful chemicals to the environment. Excavation risk is lower due to start/stop capability of many thermoformed pipe methods.	This method is applicable to small defects. Drive lengths are short. In fused and expanded methods, the annular space may cause problems.

Method	Advantages	
	Minimal reduction in cross section area Problems due to corrosion and infiltration can be corrected. This method offers structural solutions and new design life up to 100 years. The installation can be performed through a manhole or insertion pit. Pipes with large bends can be renewed with this method. Installation lengths up to 1500 ft are possible which provides smooth and jointless pipes between manholes. Lateral connections can be made internally.	Existing flow should be maintained. Valves and connections can be renewed.
Formed-in-place	FIPP method can be applied to renew any shape drainage structure up to 12 ft in diameter. This method offers both structural solutions and corrosion control. Culverts can be renewed with FIPP method. This method can be applied in long drive-lengths. Hydraulic capacity can be improved due to using a smoother lining material. The liner installed is resistant to abrasion and chemicals.	Cross sectional area is maintained. Construction of access pits is required. Grouting must be done.
Panel Lining	Panel lining can be used to renew any shape drainage structure which allows for worker-entry Panel lining offers both structural solutions and nonstructural solution. Existing flow does not have to be diverted in many cases. Restricting the flow is sufficient. Long-drive lengths are possible where access is difficult. Panels having a diameter up to 21 ft. can be manufactured. Hydraulic capacity of the pipe can be increased by using smoother lining material. Liner offers resistance to abrasion and corrosion.	Only worker entry is required. Cross-sectional area is maintained. In some cases access pits are required. The annular space must be grouted.
Spiral Wound Pipe	Large working and storage space is not required. Mobilization costs are low. Bends with large radius can be negotiated with this method. Lining can be formed in various diameter sizes within the range of the winding machine. Overall costs are low-to-moderate.	Skilled and trained workers are required. Hydraulic capacity is maintained. Grouting is required. The PVC strips have a long life.
Cement Mortar Lining	Cement mortar coating is slightly less expensive than the epoxy coating.	The finished product is durable. The cement mortar lining is applied in a wet condition. This method does not require access pits.
Epoxy Coating	The coating is not affected by the pH of the water. The finished product provides higher flow capacity compared to cementitious coating. The epoxy coating is more wear resistant compared to the cementitious coating. Reconnection of lateral service lines is not required. Cross sectional area changes can be handled easily. Installation speed is higher compared to cementitious coating.	Coating is not structural. Infiltration should be avoided. Epoxy coating is sensitive to moisture. This method does not require access pits.

Method	Advantages	
Shotcrete-Gunite Lining	Connecting laterals is handled easily. Pipes of any size (for man-entry sized pipes) can be renewed. Cross sectional area changes can be handled easily. Cementitious coating is not expensive.	Safe working environment. Highly skilled operators. The coating material is durable. Installation speed is fast.
Pipe Bursting and Pipe Renewal	These methods can be used to renew a wide range of pipe types. Diameter of the pipe can be increased. The renewed pipe has the same alignment with the existing pipe. The existing pipe does not have to be disposed if pipe bursting is employed.	Shafts may be required. Construction equipment is expensive. Lateral service connections are difficult. The renewal should be done in a planned manner. Nearby utilities are not disturbed.

Table 7.7: Advantages and Limitations of Trenchless Renewal Procedures

Step 4: Identify the site-specific factors and sub-factors

This step involves identifying the factors which may affect the overall objective of repairing/renewing the culvert in the most efficient way. These factors can also consist of several other sub-factors which may have different weights compared to each other.

Factors affecting the decision in our illustrative example are cost, working space requirement, design life of the renewed culvert, previous experience, hydraulic capacity of the culvert, and contractor availability. Two sub-factors can be linked to the cost factor, as direct cost and user cost.

Hydraulic capacity is one of the most important factors which should be considered while renewing any pipe. The cross sectional area and the smoothness of the lining pipe are the critical elements which affect the hydraulic capacity of renewed pipes. While many relining methods cause a decrease in the cross sectional area the smoothness of the lining pipe may compensate for the loss in hydraulic capacity due to that decrease in the cross sectional area. However relining methods which result in smaller diameter pipes may also cause renewal problems in the future. It may not be possible to reline the same pipe in the future due to the small diameter. These factors should be considered in terms of hydraulic capacity of renewed pipes.

Step 5: Build the hierarchy

Building the hierarchy involves showing the objective, factors, sub-factors and alternatives in a hierarchy format. The objective is placed on top, then the factors and sub-factors and finally the alternatives are placed on the bottom level.

The hierarchy in our illustrative example can be built as in Figure 7.9:

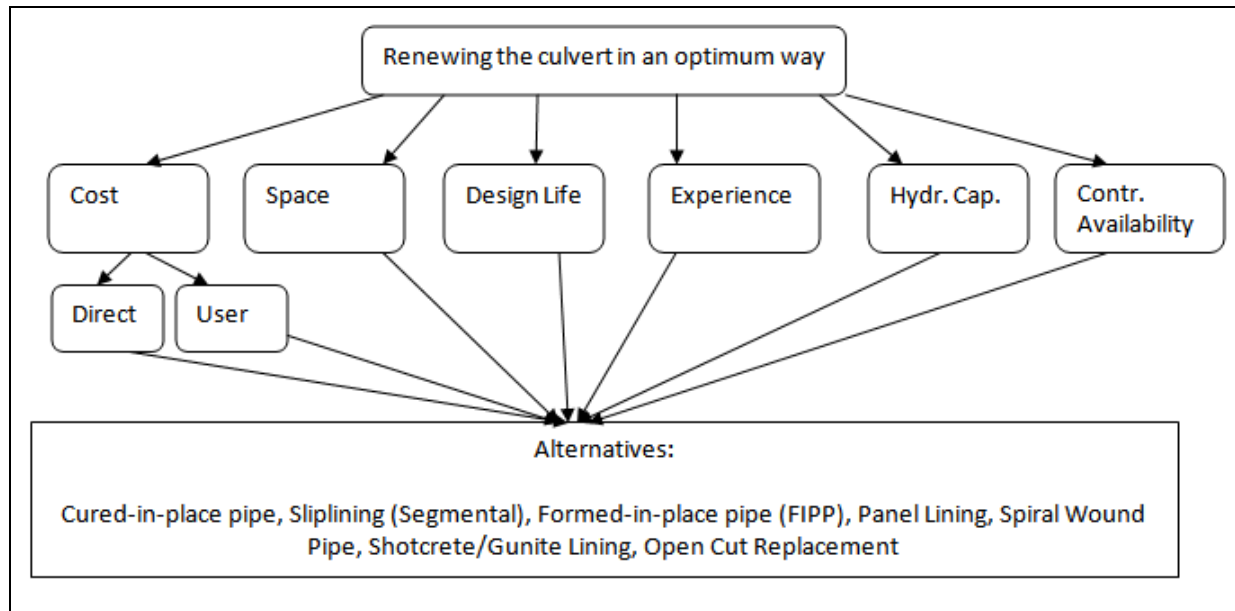


Figure 7.9: Hierarchy of the Illustrative Example

Step 6: Construct the comparison matrices and find the priority vectors

The comparison matrices are used to perform the pair wise comparisons between the items located on the same level. In our illustrative example the comparison matrices for the main factors and sub-factors related to cost are shown in Figures 7.10 and 7.11:

Objective	C	S	L	E	H	CA
C	1	2	1	3	1	3
S	0.5	1	0.5	1	0.5	0.5
L	1	2	1	3	1	3
E	0.333333	1	0.333333	1	0.333333	0.5
H	1	2	1	3	1	3
CA	0.333333	2	0.333333	2	0.333333	1

Figure 7.10: Pairwise Comparison Matrix of Factors

Where,

C: Cost

S: Working Space

L: Design Life

E: Previous Experience

H: Hydraulic capacity of the renewed culvert

CA: Contractor availability

Cost	Direct	User
Direct	1	1
User	1	1

Figure 7.11: Pairwise Comparison Matrix of Sub-Factors Direct Cost and Indirect Cost

The priority vectors are found with the average of normalized columns method. The sums of the columns are found and each element in the matrix is divided by the corresponding column total. Finally the average of each row is taken. The normalized comparison matrices and average values for each row can be seen in Figures 7.12 and 7.13.

Objective	C	S	L	E	H	CA	Averages
C	0.24	0.2	0.24	0.230769	0.24	0.272727	0.237249
S	0.12	0.1	0.12	0.076923	0.12	0.045455	0.097063
L	0.24	0.2	0.24	0.230769	0.24	0.272727	0.237249
E	0.08	0.1	0.08	0.076923	0.08	0.045455	0.077063
H	0.24	0.2	0.24	0.230769	0.24	0.272727	0.237249
CA	0.08	0.2	0.08	0.153846	0.08	0.090909	0.114126

Figure 7.12: Normalized Pairwise Comparison Matrix and Averages Values of Factors

Cost	Direct	User	Averages
Direct	0.5	0.5	0.5
User	0.5	0.5	0.5

Figure 7.13: Normalized Pairwise Comparison Matrix and Averages Values of Sub-Factors

Direct Cost and Indirect Cost

Step 7: Check the consistency of comparison matrices

The consistency ratio of the comparison matrices should be checked against the value of 0.10 as described under the AHP section. In our illustrative example the consistency ratio for the main factors is 0.026 which is below 0.10 therefore the pair-wise comparison matrix has the required consistency.

Step 8: Find the priority vectors for all sub-factors

In this step the priority vectors of the last elements before the alternatives in the hierarchy chart are calculated. In our illustrative example the final elements before the alternatives are direct cost, user cost, working space, design life, previous experience, and contractor availability. The final priority vector is found by multiplying the values of priority vectors for sub-factor and the factor: The results are shown in Table 7.8.

Sub-Factor/Factor	Priority vector
Cost-Direct	$0.5 * 0.24 = 0.12$
Cost - User	$0.5 * 0.24 = 0.12$
Working Space	0.1
Design Life	0.24
Previous Experience	0.08
Hydraulic Capacity	0.23
Contractor availability	0.11

Table 7.8: Priority Vectors for the Sub-Factors and Factors

Step 9: Create pair-wise comparison matrices for alternatives and sub-factors

This step involves creating the pair-wise comparison matrices for each sub-factor/factor in which the alternatives are compared against each other in terms of how well they perform under each sub-factor/factor. For our illustrative example the comparison matrices in Figures 7.14, 7.15, 7.16, 7.17, 7.18, 7.19, and 7.20 are created.

Direct Cost	CIPP	SL	FIPP	PL	SWP	S/G	Open Cut	Vector of Priorities
CIPP	1.00	0.33	0.50	0.33	0.50	0.33	1.00	0.07
SL	3.00	1.00	2.00	1.00	2.00	1.00	3.00	0.21
FIPP	2.00	0.50	1.00	0.50	0.50	0.50	2.00	0.11
PL	3.00	1.00	2.00	1.00	2.00	1.00	3.00	0.21
SWP	2.00	0.50	2.00	0.50	1.00	0.50	2.00	0.13
S/G	3.00	1.00	2.00	1.00	2.00	1.00	3.00	0.21
Open Cut	1.00	0.33	0.50	0.33	0.50	0.33	1.00	0.07
Consistency Ratio = 0.008954907								

Figure 7.14: Pairwise Comparison Matrix of Alternatives in Terms of Direct Cost

User Cost	CIPP	SL	FIPP	PL	SWP	S/G	Open Cut	Vector of Priorities
CIPP	1.00	1.00	1.00	1.00	1.00	1.00	5.00	0.16
SL	1.00	1.00	1.00	1.00	1.00	1.00	5.00	0.16
FIPP	1.00	1.00	1.00	1.00	1.00	1.00	5.00	0.16
PL	1.00	1.00	1.00	1.00	1.00	1.00	5.00	0.16
SWP	1.00	1.00	1.00	1.00	1.00	1.00	5.00	0.16
S/G	1.00	1.00	1.00	1.00	1.00	1.00	5.00	0.16
Open Cut	0.20	0.20	0.20	0.20	0.20	0.20	1.00	0.03
Consistency Ratio = 0								

Figure 7.15: Pairwise Comparison Matrix of Alternatives in Terms of User Cost

Working Space Requirement	CIPP	SL	FIPP	PL	SWP	S/G	Open Cut	Vector of Priorities
CIPP	1.00	3.00	2.00	3.00	1.00	1.00	5.00	0.22
SL	0.33	1.00	2.00	1.00	0.33	0.33	5.00	0.11
FIPP	0.50	0.50	1.00	0.50	0.50	0.50	5.00	0.10
PL	0.33	1.00	2.00	1.00	0.33	0.33	5.00	0.11
SWP	1.00	3.00	2.00	3.00	1.00	1.00	5.00	0.22
S/G	1.00	3.00	2.00	3.00	1.00	1.00	5.00	0.22
Open Cut	0.20	0.20	0.20	0.20	0.20	0.20	1.00	0.03
Consistency Ratio = 0.045517228								

Figure 7.16: Pairwise Comparison Matrix of Alternatives in Terms of Working Space

Requirement

Design Life	CIPP	SL	FIPP	PL	SWP	S/G	Open Cut	Vector of Priorities
CIPP	1.00	2.00	2.00	2.00	2.00	4.00	1.00	0.23
SL	0.50	1.00	1.00	1.00	1.00	3.00	0.50	0.12
FIPP	0.50	1.00	1.00	1.00	1.00	3.00	0.50	0.12
PL	0.50	1.00	1.00	1.00	1.00	3.00	0.50	0.12
SWP	0.50	1.00	1.00	1.00	1.00	3.00	0.50	0.12
S/G	0.25	0.33	0.33	0.33	0.33	1.00	0.25	0.05
Open Cut	1.00	2.00	2.00	2.00	2.00	4.00	1.00	0.23
Consistency Ratio = 0.003414465								

Figure 7.17: Pairwise Comparison Matrix of Alternatives in Terms of Design Life of the

Renewed Culvert

Experience	CIPP	SL	FIPP	PL	SWP	S/G	Open Cut	Vector of Priorities
CIPP	1.00	0.50	1.00	1.00	1.00	0.50	0.33	0.09
SL	2.00	1.00	2.00	2.00	2.00	1.00	1.00	0.19
FIPP	1.00	0.50	1.00	1.00	1.00	0.50	0.33	0.09
PL	1.00	0.50	1.00	1.00	1.00	0.50	0.33	0.09
SWP	1.00	0.50	1.00	1.00	1.00	0.50	0.33	0.09
S/G	2.00	1.00	2.00	2.00	2.00	1.00	0.33	0.17
Open Cut	3.00	1.00	3.00	3.00	3.00	3.00	1.00	0.28
Consistency Ratio = 0.010020185								

Figure 7.18: Pairwise Comparison Matrix of Alternatives in Terms of Previous Experience

Hydraulic Capacity	CIPP	SL	FIPP	PL	SWP	S/G	Open Cut	Vector of Priorities
CIPP	1.00	3.00	2.00	3.00	2.00	2.00	1.00	0.24
SL	0.33	1.00	0.50	1.00	0.50	0.50	0.33	0.07
FIPP	0.50	2.00	1.00	2.00	1.00	1.00	0.50	0.13
PL	0.33	1.00	0.50	1.00	0.50	0.50	0.33	0.07
SWP	0.50	2.00	1.00	2.00	1.00	1.00	0.50	0.13
S/G	0.50	2.00	1.00	2.00	1.00	1.00	0.50	0.13
Open Cut	1.00	3.00	2.00	3.00	2.00	2.00	1.00	0.24
Consistency Ratio = 0.002562957								

Figure 7.19: Pairwise Comparison Matrix of Alternatives in Terms of Hydraulic Capacity of the
Renewed Culvert

Contractor Availability	CIPP	SL	FIPP	PL	SWP	S/G	Open Cut	Vector of Priorities
CIPP	1.00	0.50	2.00	2.00	2.00	0.50	0.50	0.13
SL	2.00	1.00	3.00	3.00	3.00	1.00	1.00	0.22
FIPP	0.50	0.33	1.00	1.00	1.00	0.33	0.33	0.07
PL	0.50	0.33	1.00	1.00	1.00	0.33	0.33	0.07
SWP	0.50	0.33	1.00	1.00	1.00	0.33	0.33	0.07
S/G	2.00	1.00	3.00	3.00	3.00	1.00	1.00	0.22
Open Cut	2.00	1.00	3.00	3.00	3.00	1.00	1.00	0.22
Consistency Ratio = 0.001925753								

Figure 7.20: Pairwise Comparison Matrix of Alternatives in Terms of Contractor Availability

Step 10: Select the alternative with the highest score

In this final step the priority values of sub-factors are combined with the vector of priority values of each alternative by using the following formula:

Overall Score = Σ (Priority Vector of Each Sub-Factor) x (Priority Vector of Each Alternative in Terms of that Particular Sub-Factor)

The alternative with the highest score satisfies the most important criteria most adequately. In our illustrative example the overall priority values are obtained as shown in Table 7.9:

Alternative	Calculation of overall priority	Overall priority
CIPP	$(0.12 \times 0.07) + (0.12 \times 0.16) + (0.10 \times 0.22) + (0.24 \times 0.23) + (0.08 \times 0.09) + (0.23 \times 0.24) + (0.11 \times 0.13)$	0.18
SL	$(0.12 \times 0.21) + (0.12 \times 0.16) + (0.10 \times 0.11) + (0.24 \times 0.12) + (0.08 \times 0.19) + (0.23 \times 0.07) + (0.11 \times 0.22)$	0.14
FIPP	$(0.12 \times 0.11) + (0.12 \times 0.16) + (0.10 \times 0.10) + (0.24 \times 0.12) + (0.08 \times 0.09) + (0.23 \times 0.13) + (0.11 \times 0.07)$	0.12
PL	$(0.12 \times 0.21) + (0.12 \times 0.16) + (0.10 \times 0.11) + (0.24 \times 0.12) + (0.08 \times 0.09) + (0.23 \times 0.07) + (0.11 \times 0.07)$	0.12
SWP	$(0.12 \times 0.13) + (0.12 \times 0.16) + (0.10 \times 0.22) + (0.24 \times 0.12) + (0.08 \times 0.09) + (0.23 \times 0.13) + (0.11 \times 0.07)$	0.13
S/G	$(0.12 \times 0.21) + (0.12 \times 0.16) + (0.10 \times 0.22) + (0.24 \times 0.05) + (0.08 \times 0.17) + (0.23 \times 0.13) + (0.11 \times 0.22)$	0.14
Open Cut	$(0.12 \times 0.07) + (0.12 \times 0.03) + (0.10 \times 0.03) + (0.24 \times 0.23) + (0.08 \times 0.28) + (0.23 \times 0.24) + (0.11 \times 0.22)$	0.17

Table 7.9: Calculation of overall scores for each alternative

The priority value of each alternative under each sub-factor is multiplied by the priority value of the sub-factor and this calculation is carried out over all the sub-factors in the hierarchy. According to the calculations Cured-in-place-pipe method has the highest priority score therefore this alternative is the optimum alternative which satisfies the important factors.

Commerical software packages such as ExpertChoice can be used to simplify the calculation procedures presented in this chapter.

8. Conclusions and Recommendations

8.1 Conclusions

Trenchless technology methods offer both structural and non-structural solutions to buried pipe problems without incurring damage to adjacent utilities, infrastructure or pavement, and with minimal disruption or inconvenience to the public. Such techniques have been widely used for repair and renewal of sewer and water pipes. The present study focuses on the collection of information regarding the main characteristics of trenchless technologies including their advantages and limitations, and examines the applicability of these methods to culverts. The tasks performed in this study include:

Task 1: Review literature and case studies

Task 2: Review factors affecting culvert deteriorations

Task 3: Review and survey existing trenchless technology methods with potential use for renewal of culverts and drainage structures and identify capabilities and limitations of each of these methods.

Task 4: Develop inspection, asset management and maintenance requirements of renewed culverts with trenchless technology methods.

Task 5: Develop modification requirements in existing trenchless technologies to be used in culverts and drainage structures.

Task 6: Collaborate with ODOT and MDOT to establish a database and decision support system for selection of appropriate trenchless technology methods

Task 7: Develop course modules for culvert asset management using trenchless technologies.

As part of this study, an extensive literature review was performed examining major civil engineering publications and databases provided by the American Society of Civil Engineers (ASCE), Federal Highway Administration (FHWA), Transportation Research Board (TRB) Records, American Association of State Highway and Transportation Officials (AASHTO) and the National Cooperative Highway Research Program (NCHRP). A survey of state departments of transportation (DOTs) was conducted to obtain information regarding current culvert maintenance practices and trenchless repair and renewal methods. In addition, a survey of technology providers was prepared and conducted in order to gain more comprehensive information on the subject.

The collected information was used to develop an asset management strategy for culverts. The applicable characteristics and range of application of trenchless repair and renewal methods has been conveniently summarized in a table, and limitations of trenchless technologies in terms of applicability to culverts has been investigated. A database form was created to record the characteristics of any future trenchless repair and renewal job. A decision support system which links the inspection procedures of Ohio Department of Transportation's Culvert Management Manual to appropriate trenchless repair and renewal methods has also been developed.

The proposed decision system utilizes the Analytical Hierarchy Process (AHP) which provides the required flexibility to the user in terms of adjusting the procedure according to the situation at hand. Each culvert can be considered unique in terms of job site conditions and structural conditions. Therefore factors and alternatives for each jobsite should be evaluated before making decisions regarding the appropriate repair and renewal procedures for culverts. A method that may work well for one culvert situation may not be optimum or appropriate for another. For this reason, the decision support system contained in this report, provides a

methodology to the users that enables them to enter the factors and alternatives for each jobsite and to identify the optimum procedure(s) depending on these factors and alternatives.

8.2 Recommendations for future studies

It is to be expected that new and improved methods of trenchless technology will continue to evolve due to technological improvements and new discoveries in material science, accelerated by increasing demand as growing urbanization and traffic volume force agencies to employ non-disruptive trenchless technologies. The continuing development of trenchless technology methods and associated experiences will provide additional information in the future. The investigators suggest that researchers update the technologies and methodologies presented in this research project on an ongoing basis.

9. References

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10. Appendices

Appendix 1: Survey Form Sent to the State DOTs



Survey Form

“Use of Trenchless Technologies for a Comprehensive Asset Management of Culverts and Drainage Structures”

University of Cincinnati and The University of Texas at Arlington are collaborating on an important Midwest Regional University Transportation Center (MRUTC) project regarding the use of trenchless technologies for a comprehensive asset management of culverts and drainage infrastructures. The main objective of this project is to provide a comprehensive study and decision making procedures for the selection of appropriate trenchless technology methods for renewal, renovation, and maintenance of culverts and drainage infrastructures. This national survey is one of the most important tasks in order to fulfill this objective since it will provide valuable information regarding the asset management of culverts and use of trenchless technologies for culvert construction, renewal, renovation and maintenance.

This survey consists of 3 parts. First part is about the contact information of the respondent. Second part focuses on culvert asset management issues and the last part focuses on trenchless technologies used for culvert construction, renewal, renovation and maintenance. There are 22 questions in this survey and we estimate that it will take around 20-25 minutes to complete. There are no risks or individual benefits by associated with completing this survey. The deadline for submitting this survey is 03/31/2008.

If you have any questions regarding this survey or the project, please contact Dr. Sam Salem (osalem@uc.edu), Director, Infrastructure Systems and Management Program, University of Cincinnati (Tel: 513-556-3759) or Dr. Mohammad Najafi (najafi@uta.edu), Director, CUIRE, The University of Texas at Arlington (Tel: 817-272-0507).

Directions for the filling the survey form:

- Please type your answers in the blank fields provided.
- For Yes, No type of questions, please highlight the appropriate fields

Part 1. Contact Information:

Respondent's Name and Affiliation:

Respondent's Title:

Agency:

Address:

City:

State:

Zip:

Phone Number:

Fax Number:

E-mail:

Part 2. Culvert Asset Management:

Question 1: What is the definition of a culvert in your agency?

Question 2: What is the approximate breakdown of culverts with respect to their material type in your state?

Material Type	Percentage of overall
Concrete	
Metal	
Plastic	
Aluminum	
Other:	

Question 3: Does your DOT have standardized inventory guidelines for culverts?

- ☐ Yes
- ☐ No
- ☐ Do Not Know

If “Yes”, please provide a link to access the associated files via Web or attach a copy with this questionnaire.

Question 4: Does your DOT have standardized inspection guidelines for culverts?

- ☐ Yes
- ☐ No
- ☐ Do Not Know

If “Yes”, please provide a link to access the associated files via Web or attach a copy with this questionnaire.

Question 5: What are the major factors that are considered while inspecting culverts?

Factors	Metal	Concrete	Plastic	Other:
Corrosion	☐ Yes ☐ No	☐ Yes ☐ No	☐ Yes ☐ No	☐ Yes ☐ No
Abrasion	☐ Yes ☐ No	☐ Yes ☐ No	☐ Yes ☐ No	☐ Yes ☐ No
Shape	☐ Yes ☐ No	☐ Yes ☐ No	☐ Yes ☐ No	☐ Yes ☐ No
Wall Thickness	☐ Yes ☐ No	☐ Yes ☐ No	☐ Yes ☐ No	☐ Yes ☐ No
Alignment	☐ Yes ☐ No	☐ Yes ☐ No	☐ Yes ☐ No	☐ Yes ☐ No
Cracking	☐ Yes ☐ No	☐ Yes ☐ No	☐ Yes ☐ No	☐ Yes ☐ No
Joint Failures	☐ Yes ☐ No	☐ Yes ☐ No	☐ Yes ☐ No	☐ Yes ☐ No
Hydraulic Capacity	☐ Yes ☐ No	☐ Yes ☐ No	☐ Yes ☐ No	☐ Yes ☐ No
Other:	☐ Yes ☐ No	☐ Yes ☐ No	☐ Yes ☐ No	☐ Yes ☐ No

Question 6: How often does your agency inspect culverts located under state highways and interstate highways?

Question 7: Does your DOT have a computer database to store the culvert inventory information?

☐ Yes

☐ No

☐ Do Not Know

Question 8: Is there a model or formula that your agency uses in order to determine the remaining service life of culverts depending on the inspection results?

☐ Yes

☐ No

☐ Do Not Know

If “Yes”, please provide a link to access the associated files via Web or attach a copy with this questionnaire.

Question 9: Does your DOT have a decision support system which integrates the culvert inventory, condition assessment and repair/renewal method selection?

☐ Yes

☐ No

☐ Do Not Know

If “Yes”, please provide a link to access the associated files via Web or attach a copy with this questionnaire.

Part 3. Culver Repair, Rehabilitation, Replacement and Usage of Trenchless Technologies

Question 10: How does your inspector overcome the confined space problems?

- ☐ CCTV
- ☐ Just Inspects inlet and outlet
- ☐ Other

If "Other", please explain briefly.

Question 11: What are the major structural or hydraulic culvert problems in your state?

Question 12: What are the most common maintenance / repair methods in your state?

(Repair: Reconstruction of short pipe lengths, but not the reconstruction of the whole pipe line. Therefore a new design life is not provided.)

Question 13: What are the most common rehabilitation or replacement methods in your state?

(Rehabilitation: Renewal method in which the partially or fully deteriorated pipe is used as the host pipe and a new pipe is formed within this host pipe)

Question 14: Which of these factors are considered while repairing or replacing the existing culverts?

Factors	Considered?
Inspection Results	☐ Yes ☐ No
Structural Problems	☐ Yes ☐ No
Age of the culvert	☐ Yes ☐ No
Hydraulic Capacity	☐ Yes ☐ No
Traffic Volume	☐ Yes ☐ No
Roadway Surface	☐ Yes ☐ No
Embankment Condition	☐ Yes ☐ No
Cost	☐ Yes ☐ No
Other:	☐ Yes ☐ No

Question 15: What are the trenchless renewal methods employed in your state and what is the frequency of use for each method on the average per year?

Method	Employed?	Frequency
Cured-in-Place Pipe (CIPP)	☐ Yes ☐ No	
Sliplining	☐ Yes ☐ No	
Pipe Bursting	☐ Yes ☐ No	
Pipe Reaming	☐ Yes ☐ No	
Pipe Eating	☐ Yes ☐ No	
Pipe Ejection/Extraction	☐ Yes ☐ No	
Close-fit Pipe	☐ Yes ☐ No	
Panel Lining	☐ Yes ☐ No	

Robotic Repair	☐ Yes ☐ No	
Grouting	☐ Yes ☐ No	
Internal Seal	☐ Yes ☐ No	
Point CIPP	☐ Yes ☐ No	
Cement Mortar Lining	☐ Yes ☐ No	
Epoxy Coating	☐ Yes ☐ No	
Thermoformed Pipe	☐ Yes ☐ No	
Other:		

Question 16: For each of the trenchless methods employed before what are the critical pre-construction, construction and post-construction issues?

Method	Pre-Constr.	Construction	Post-Constr.
Cured-in-Place Pipe (CIPP)			
Sliplining			
Pipe Bursting			
Pipe Reaming			
Pipe Eating			
Pipe Ejection/Extraction			
Close-fit Pipe			
Panel Lining			
Robotic Repair			

Grouting			
Internal Seal			
Point CIPP			
Cement Mortar Lining			
Epoxy Coating			
Thermoformed Pipe			
Other:			

Question 17: For each of the trenchless methods employed before what are the minimum and maximum culvert sizes in inches?

Method	Minimum (in.)	Maximum (in.)
Cured-in-Place Pipe (CIPP)		
Sliplining		
Pipe Bursting		
Pipe Reaming		
Pipe Eating		
Pipe Ejection/Extraction		
Close-fit Pipe		
Panel Lining		
Robotic Repair		
Grouting		

Internal Seal		
Point CIPP		
Cement Mortar Lining		
Epoxy Coating		
Thermoformed Pipe		
Other:		

Question 18: For each of the trenchless methods employed before what is the average construction cost/linear feet/per inch of diameter?

Method	Average Cost/Linear Ft./per inch of diameter
Cured-in-Place Pipe (CIPP)	
Sliplining	
Pipe Bursting	
Pipe Reaming	
Pipe Eating	
Pipe Ejection/Extraction	
Close-fit Pipe	
Panel Lining	
Robotic Repair	
Grouting	

Internal Seal	
Point CIPP	
Cement Mortar Lining	
Epoxy Coating	
Thermoformed Pipe	
Other:	

Question 19: What are the advantages and limitations of the trenchless methods used by your agency before?

Method	Advantages	Limitations
Cured-in-Place Pipe (CIPP)		
Sliplining		
Pipe Bursting		
Pipe Reaming		
Pipe Eating		
Pipe Ejection/Extraction		
Close-fit Pipe		
Panel Lining		
Robotic Repair		
Grouting		

Internal Seal		
Point CIPP		
Cement Mortar Lining		
Epoxy Coating		
Thermoformed Pipe		
Other:		

Question 20: What are the future maintenance requirements of culverts renewed by the following trenchless methods?

Method	Maintenance requirements
Cured-in-Place Pipe (CIPP)	
Sliplining	
Pipe Bursting	
Pipe Reaming	
Pipe Eating	
Pipe Ejection/Extraction	
Close-fit Pipe	
Panel Lining	
Robotic Repair	
Grouting	

Internal Seal	
Point CIPP	
Cement Mortar Lining	
Epoxy Coating	
Thermoformed Pipe	
Other:	

Question 21: What are the inspection frequencies of culverts renewed by the following trenchless methods?

Method	Frequency of Inspection
Cured-in-Place Pipe (CIPP)	
Sliplining	
Pipe Bursting	
Pipe Reaming	
Pipe Eating	
Pipe Ejection/Extraction	
Close-fit Pipe	
Panel Lining	
Robotic Repair	
Grouting	
Internal Seal	

Point CIPP	
Cement Mortar Lining	
Epoxy Coating	
Thermoformed Pipe	
Other:	

Question 22: What are the important factors which influence the decision making procedure on whether to employ an open-cut (traditional) replacement or to use trenchless renewal methods?

Factor	Considered?
Location	☐ Yes ☐ No
Traffic Volume	☐ Yes ☐ No
Detour Availability	☐ Yes ☐ No
Depth of Cover	☐ Yes ☐ No
Other:	☐ Yes ☐ No

Appendix 2: Industry Survey Form

USE OF TRENCHLESS TECHNOLOGIES FOR A COMPREHENSIVE ASSET MANAGEMENT OF CULVERTS AND DRAINAGE INFRASTRUCTURES

SURVEY FORM

Part 1 Contact Information

NAME OF THE COMPANY:		WEBSITE:	
RESPONDENT'S NAME:		TITLE:	
ADDRESS COMPANY):			
CITY:		STATE:	
		ZIP CODE:	
PHONE:		FAX:	
		E-MAIL:	

Part 2 Culvert Asset Management

Definition of Culvert:

A structure of less than 6.1-m (20-ft) span as measured along the road centerline which is used as an underground drainage system for highways is classified as a culvert.

Question 1: Does your company work on Culvert? (Yes/No)

If yes, continue with the survey, if NO, Thank You for your time.

Question 2: Does your company provide Culvert Inspection Services? (Yes/No)

Question 3: Does your company have or use any Standard Inspection Guidelines? (Yes/No)

If yes, please provide what standard you use

Question 4: Rank the major problems responsible for failure of culverts. (Rank "1" for the factor which affects more and "8" to the problem which affects the least for the problems listed below).

Factors	Metal	Concrete	Plastic	Other (Specify) _____ _____
Corrosion*				
Abrasion*				
Wall Thickness				
Cracking*				
Deflection*				
Joint Failure*				
Hydraulic Capacity*				
Other (Specify) _____				

*The definitions of all the factors are explained in the Glossary section in the end of the form

Question 5: Rank the Culvert Materials which your company renews more in descending order. (Number "1" for culvert which is renewed most to Number "4" which your company has renewed least). If the material is not listed in the Drop down list then choose "other" and specify the material outside the table in the space given.

Material	Rank			
Metal	1	2	3	4
Concrete	1	2	3	4
Plastic	1	2	3	4
Other	1	2	3	4

Part 3 Culvert Construction, Repair, Renovation, Replacement (Renewal) and Usage of Trenchless Technologies

Question 6: Check the boxes for the **Trenchless Renewal Methods** which your company carry out? How many installations do your company carry out do every year?

Method		Installations/Year
Cured-in-Place Pipe (CIPP)*	☐	
Sliplining*	☐	
Pipe Bursting*	☐	
Pipe Reaming*	☐	
Close-fit Pipe*	☐	
Panel Lining*	☐	
Robotic Repair*	☐	
Grouting*	☐	
Internal Seal*	☐	
Point CIPP	☐	
Shotcrete and Guniting*	☐	
Polymer Coating*	☐	
Thermoformed Pipe*	☐	
Other (Specify)_____		

*The definitions of all the Trenchless Renewal Methods are explained in the Glossary section in the end of the form

Question 7: Rank the factors below which govern the selection of a particular type of Trenchless Renewal Methods according to their importance? (1 to be highest through 14 to be lowest)

- | | |
|---|--|
| _____ Condition of the existing culvert and its suitability for renewal | _____ Current and future needs of the area served by the culvert |
| _____ Capacity, alignment, and other characteristics of the culvert | _____ Cost of repair versus cost of replacement |
| _____ Site conditions | _____ Effluent characteristics |
| _____ Funding availability | _____ Availability and expertise of local contractors |
| _____ Availability and expertise of in-house forces | _____ Availability and cost of materials and specialized equipment |
| _____ User cost or time out of service | _____ Aesthetics |
| _____ Condition of the existing culvert and its suitability for renewal | |

Question 8: Rank the critical **pre-construction issues** that play a wide role during planning phase of the following Trenchless Renewal Methods. (1 to be highest through 8 to be lowest)

Methods	Diameter & Shape of Culvert	Material of Culvert	Soil Conditions	Infiltration	pH Levels	Type of Flow	Existing Condition of Culvert	Other (Specify)
Cured-in-Place Pipe (CIPP)*								
Sliplining*								
Pipe Bursting*								
Pipe Reaming*								
Close-fit Pipe*								
Panel Lining*								
Robotic Repair*								
Grouting*								
Internal Seal*								
Point CIPP*								
Shotcrete and Guniting*								
Polymer Coating*								
Thermoformed Pipe*								
Other (Specify)_____								

*The definitions of all the Trenchless Renewal Methods are explained in the Glossary section in the end of the form

Question 9: Rank the **critical construction issues** which are very important during installation of the following renewal methods? (1 to be highest through 8 to be lowest)

Methods	Depth of the Culvert	Construction of Access Road	Ground Stability (to set up the equipment)	Safety	Worker entry	Flow Diversion	Length of culvert	Other (Specify)
Cured-in-Place Pipe (CIPP)*								
Sliplining*								
Pipe Bursting*								
Pipe Reaming*								
Close-fit Pipe*								
Panel Lining*								
Robotic Repair*								
Grouting*								
Internal Seal*								
Point CIPP*								
Shotcrete and Guniting*								
Polymer Coating*								
Thermoformed Pipe*								
Other (Specify)_____								

*The definitions of all the Trenchless Renewal Methods are explained in the Glossary section in the end of the form

Question 10: Rank the critical **Post-construction issues** that are important following installation of the following renewal methods? (1 to be highest through 4 to be lowest)

Methods	Regular Inspection	Maintenance	Length of Service	Other (Specify) _____ _____
Cured-in-Place Pipe (CIPP)*				
Sliplining*				
Pipe Bursting*				
Pipe Reaming*				
Close-fit Pipe*				
Panel Lining*				
Robotic Repair*				
Grouting*				
Internal Seal*				
Point CIPP*				
Shotcrete and Guniting*				
Polymer Coating*				
Thermoformed Pipe*				
Other (Specify)_____				

*The definitions of all the Trenchless Renewal Methods are explained in the Glossary section in the end of the form

Question 11: What are the important factors in order to decide on whether to do an open-cut (traditional) replacement or to use trenchless renewal methods?

Factor	Considered?	
Location	☐ YES	☐ NO
Traffic Volume	☐ YES	☐ NO
Detour Availability	☐ YES	☐ NO
Depth of Cover	☐ YES	☐ NO
Other (Specify)_____	☐ YES	☐ NO

Question 12: Provide the minimum and maximum culverts sizes your company has employed for the following Trenchless Renewal Methods in inches. Also specify the Maximum size of the culvert that you think can be installed by the following methods.

Methods	Minimum Size in Inches	Maximum Size in Inches	Maximum Accepted Size in Inches
Cured-in-Place Pipe (CIPP)*			
Sliplining*			
Pipe Bursting*			
Pipe Reaming*			
Close-fit Pipe*			
Panel Lining*			
Robotic Repair*			
Grouting*			
Internal Seal*			
Point CIPP*			
Shotcrete and Guniting*			
Polymer Coating*			
Thermoformed Pipe*			
Other (Specify) _____			

*The definitions of all the Trenchless Renewal Methods are explained in the Glossary section in the end of the form

Question 13: What are the **limitations** for the following **Trenchless Renewal Methods**? If your company has encountered some more limitations during installing these methods please specify it in the space given below

Methods	Must Grout Annular Space	Must Seal Liner Ends	Need Worker entry	Need Bypass	Diameter Reduces More than 10%	No Structural Support	Other (Specify) _____
Cured-in-Place Pipe (CIPP)*	☐	☐	☐	☐	☐	☐	☐
Sliplining*	☐	☐	☐	☐	☐	☐	☐
Pipe Bursting*	☐	☐	☐	☐	☐	☐	☐
Pipe Reaming*	☐	☐	☐	☐	☐	☐	☐
Close-fit Pipe*	☐	☐	☐	☐	☐	☐	☐
Panel Lining*	☐	☐	☐	☐	☐	☐	☐
Robotic Repair*	☐	☐	☐	☐	☐	☐	☐
Grouting*	☐	☐	☐	☐	☐	☐	☐
Internal Seal*	☐	☐	☐	☐	☐	☐	☐
Point CIPP*	☐	☐	☐	☐	☐	☐	☐
Shotcrete and Guniting*	☐	☐	☐	☐	☐	☐	☐
Polymer Coating*	☐	☐	☐	☐	☐	☐	☐
Thermoformed Pipe*	☐	☐	☐	☐	☐	☐	☐
Other (Specify) _____	☐	☐	☐	☐	☐	☐	☐

*The definitions of all the Trenchless Renewal Methods are explained in the Glossary section in the end of the form

Question 14: According to your company how many years of **additional life** can be provided to a deteriorated culvert after it is being renewed by the following methods? Also provide approximate cost of installation per linear ft/in. of diameter.

Methods	Additional Life in Years	Average Cost/Linear ft/in. of diameter
Cured-in-Place Pipe (CIPP)*		
Sliplining*		
Pipe Bursting*		
Pipe Reaming*		
Close-fit Pipe*		
Panel Lining*		
Robotic Repair*		
Grouting*		
Internal Seal*		
Point CIPP*		
Shotcrete and Guniting*		
Polymer Coating*		
Thermoformed Pipe*		
Polyurea lining systems		
Other (Specify)_____		

*The definitions of all the Trenchless Renewal Methods are explained in the Glossary section in the end of the form

Question 15: Does your company typically perform any **test on the Renewal Methods** after they are being applied to the existing deteriorated culvert?

Methods	Lists the Tests Carried Out
Cured-in-Place Pipe (CIPP)*	
Sliplining*	
Pipe Bursting*	
Pipe Reaming*	
Close-fit Pipe*	
Panel Lining*	
Robotic Repair*	
Grouting*	
Internal Seal*	
Point CIPP*	
Shotcrete and Guniting*	
Polymer Coating*	
Thermoformed Pipe*	
Other (Specify) _____	

*The definitions of all the Trenchless Renewal Methods are explained in the Glossary section in the end of the form

Question 16: Which of the Trenchless Renewal Methods are suitable for the following problems executed in the culvert? Grade the suitability of these methods as

- 4 Not Suitable**
- 3 Moderately Suitable (If there is no other option)**
- 2 Suitable (If the deteriorating factor is not the primary cause of deterioration)**
- 1 Highly Suitable**

Methods	Corrosion & Abrasion	Misalignment & Joint Separation	Seam Defects & Scalling	Delamination & Efflorescence	Spalling & Honey Combing	Other (Specify)
Cured-in-Place Pipe (CIPP)*						
Sliplining*						
Pipe Bursting*						
Pipe Reaming*						
Close-fit Pipe*						
Panel Lining*						
Robotic Repair*						
Grouting*						
Internal Seal*						
Point CIPP*						
Shotcrete and Guniting*						
Polymer Coating*						
Thermoformed Pipe*						
Other (Specify) _____						

*The definitions of all the Trenchless Renewal Methods are explained in the Glossary section in the end of the form

Question 17: Is there any **relation between the existing culvert material and the New Trenchless Renewal Method** to be used? For e.g. suppose Cured In Place Pipe is best solution if the existing culvert is a concrete culvert. If yes specify the relation in terms of :

- 4 **Not Suitable**
- 3 **Moderately Suitable** (If there is no other option)
- 2 **Suitable** (If the Renewal Method is OK to be used for the particular culvert Material but not excellent)
- 1 **Strongly Recommended**

Methods	Concrete	Corrugated Steel Pipe	Corrugated Aluminum Pipe	Plastic Pipe
Cured-in-Place Pipe (CIPP)*				
Sliplining*				
Pipe Bursting*				
Pipe Reaming*				
Close-fit Pipe*				
Panel Lining*				
Robotic Repair*				
Grouting*				
Internal Seal*				
Point CIPP*				
Shotcrete and Guniting*				
Polymer Coating*				
Thermoformed Pipe*				
Other (Specify)_____				

*The definitions of all the Trenchless Renewal Methods are explained in the Glossary section in the end of the form

Question 18: What specification and material does your company use for Trenchless Renewal Methods specifically for culvert applications? Please provide us a copy.

Methods	Specifications	Materials Used
Cured-in-Place Pipe (CIPP)*		
Sliplining*		
Pipe Bursting*		
Pipe Reaming*		
Close-fit Pipe*		
Panel Lining*		
Robotic Repair*		
Grouting*		
Internal Seal*		
Point CIPP*		
Shotcrete and Guniting*		
Polymer Coating*		
Thermoformed Pipe*		
Other (Specify)_____		

*The definitions of all the Trenchless Renewal Methods are explained in the Glossary section in the end of the form

Question 19: Please use this space additional information to be considered in our study. Also please explain if your company uses any other type of Trenchless Technology.

Survey Glossary

Renewal Methods:

Cured in place pipe (CIPP): Lining system in which a thin flexible tube of polymer or glass fiber fabric is impregnated with thermoset resin and expanded by means of fluid pressure into position on the inner wall of a defective pipeline before curing the resin to harden the material. The uncured material may be installed by winch or inverted by water or air pressure.

Pipe bursting: A pipe replacement for breaking the existing pipe by brittle fracture, using force from within, applied mechanically, the remains being forced into the surrounding ground. At the same time a new pipe, of the same or larger diameter, is drawn in behind the bursting tool. The pipe bursting device may be based on an impact molding tool to exert diverted forward thrust to the radial bursting effect required, or by a hydraulic device inserted into the pipe and expanded to erect direct radial force or a static hammer. For a new pipe, generally a HDPE pipe is used, but currently PVC, ductile iron, clay, and GRP is also used. Also know as pipe cracking and pipe splitting.

Pipe Reaming: A variation of directional boring called pipe reaming can be used to replace existing clay, asbestos cement, non-reinforced concrete and PVC pipe. A reamer is pulled through the existing pipe which cuts the pipe into small pieces. The pipe pieces are flushed out the bore hole with the drilling fluid.

Close Fit Pipe: Description of a lining system in which the new pipe makes close contact with the existing defective pipe at normal or minimum diameter.

Panel Lining: Panel Lining is a Modified Sliplining Method. The shape of the culvert is covered by preparing panels and fitting them to the culvert. It can be used to structurally renew large diameter pipes. This method can accommodate different shapes.

Robotic Repairs: One of the new Trenchless Technologies. It comprises of a grinding robot and a filler robot. The former removes intrusions, and also mills out cracks to provide a good surface, the filler robot applies an epoxy.

Grouting: 1. Filling of annular space between the host pipe and the carrier pipe. Grouting is also used to fill the spaces around laterals and between the new pipe and manholes. Other uses of grouting are for localized repairs of defective pipes and ground improvement prior to excavation

during new installations. 2. The process of filling voids, or modifying or improving ground conditions. Grouting materials may be cementitious, chemical, or other mixtures. In trenchless technology, grouting may be used for filling voids around the pipe or shaft, or for improving ground conditions. 3. A method of filling voids with cementitious or polymer grout. **Internal Seal:** A structural repair method in which basically a new pipe is inserted or cured within the old one.

Sliplining: The process of placing a smaller diameter pipe in a larger diameter existing pipe to improve the culvert structure and repair leaks. The annular space between the pipes is usually filled with grout

Shotcrete and Guniting: Sprayed concrete has terms such as shotcreting and guniting. The two last terms are quite similar however it is believed that guniting is more the spraying of concrete with an aggregate size less than 10mm.

Point CIPP: CIPP techniques entail impregnating fabric with a suitable resin, pulling this into place within the sewer around an inflatable packer or mandrel, and then filling the packer with water, steam, or air under pressure to press the patch against the existing sewer wall while the resin cures.

Polymer Coating: It is a thermoset coating made up of inert plastic like Epoxies, Urethanes and Ureas, Polyesters which have a high resistance to corrosion, they are applied by trained professionals using special spraying equipments and as per the manufactures specifications.

Spiral Wound (Grout): In this process a new pipe is installed inside the existing pipe from the continuous strip of polyvinyl chloride (PVC). The strip has tongue and groove casting on its edges. It is fed to a special winding machine placed in a manhole, which creates a continuous helically wound liner that proceeds through the existing pipe. The continuous spiral joint is watertight. Upon completions of the annulus space between the lining and the existing pipe wall is usually required.

Spiral Wound (UngROUT): It is the same process of laying spiral strip as in above Spiral Wound (Grout), but if the lining pipe is closely fitted then there is no need of grouting.

Thermoformed Pipe: A type of renewal method which uses poly vinyl chloride (PVC) or polyethylene (PE) pipe that is expanded by thermoforming to fit tightly to fit inside the host pipe.

Internal Seal: Internal Seals are used for structural repair pipe joints and missing pipe sections. It can be used in both worker entry and non worker entry pipes.

Other Definitions:

Abrasion: Abrasion is the gradual wearing away of the culvert wall due to the impingement of bed load and suspended material.

Corrosion: It is a deterioration or dissolution of a material by a chemical or electrochemical reaction with its environment

Cracking: A fissure in an installed precast concrete culvert . **Corrosion:** It is a deterioration or dissolution of a material by a chemical or electrochemical reaction with its environment.

Debris: Any material including floating woody materials and other trash, suspended sediment, or bed load moved by a flowing stream.

Deflection: Change in the bending radius due to stress, temperature, time and other factors.

Discharge (Q): Flow from a culvert, sewer or channel in CFS.

Efflorescence: Efflorescence is a combination of calcium carbonate leached out of the cement paste and other recrystallized carbonate and chloride compounds. It is a white crystalline or powdery deposit on the surface of the concrete surface and is caused by water seeping through the culvert wall. The water dissolves salts inside the concrete surface, while moving through it, and then evaporates leaving the salts on the surface

Erosion (Culvert): Wearing o grinding away of culvert material by water laden with sand, gravel or stones; generally referred to as abrasion

Joint failure: Failures which occur in the joints due to uneven bedding, poorly compacted backfilling operations, or unexpected settlements.

Hydraulic capacity: Failure occurring due to insufficient capacity or flooding.

pH Value : The log of the reciprocal of the hydrogen ion concentration of a solution. The pH value of 7.0 is neutral; values of less than 7.0 are acid; values of more than 7.0 are acidic.

Point repairs: Repair works on an existing pipe, to an extent less than the run between two access points or manholes.

Repair: Reconstruction of short pipe lengths, but not the reconstruction of the whole pipe line. Therefore a new design life is not provided. In contrast, in pipe line renewal, a new design life is provided to existing pipeline system.

Replacement: All aspects of upgrading with a new design life for the performance of the existing pipeline. Includes rehabilitation and renovation.

Spiral lining: A technique in which a ribbed plastic strip is spirally wound by a winding machine to form liner, which is inserted into a defective pipeline. The annular space may be grouted or the spiral liner expanded to reduce the annulus and form a close fit liner. In larger diameters, the strips are sometimes formed into panel and installed by handful stuff. Grouting the annular space after installation is recommended.

Trenchless Rehabilitation: It is the process of Upgrading to a new design life by forming a new pipe within the existing pipe with minimum or no excavation.

Trenchless methods: Also no-dig techniques for underground pipeline and utility construction and replacement, rehabilitation, renovation (collectively called renewal), repair, inspection, leak detection, and so on, with minimum or no excavation from the ground surface.

Utility tunneling: It is a general approach of constructing underground utility lines by removing the excavated soil from the front of the cutting face and installing liner segments to form continuous ground support structures. The product pipe is then transported and installed inside the tunnel. The annular space between the liner and the pipe is usually filled with grout.

Appendix 3: Form CR-87 and CR-86

STATE OF OHIO DEPARTMENT OF TRANSPORTATION
CULVERT INVENTORY REPORT

CR-87 12-03

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CULVERT FILE NUMBER				1. Entry Class			
LOCATION AND ROUTE INFORMATION							
2. District				3. County			
4. Route				5. Straight Line Mileage			
6. Latitude				7. Longitude			
8. Road ID				9. Maintenance Responsibility			
10. Feature Intersection							
CULVERT							
11. Year built				12. Number of Cells			
13. Shape				14. Material			
15. Span (in.)				16. Rise (in.)			
17. Length (ft.)				18. Gage (no.) / Wall Thickness (in.)			
19. Gage (no.) / Wall Thickness (in.)				20. Type of Protection			
21. Slope of Pipe (%)				22. Skew (degrees)			
23. Inlet End Treatment				24. Outlet End Treatment			
25. Maximum Height of Cover (ft.)				26. Modification Type			
27. Year Modified				28. Modification Material			
29. Modification Size (in.)							
EXTENSION - INLET							
30. Year Extended				31. Shape			
32. Material				33. Span (in.)			
34. Rise (in.)				35. Gage (no.) / Wall Thickness (in.)			
36. Extension Length (ft.)							
EXTENSION - OUTLET							
37. Year Extended				38. Shape			
39. Material				40. Span (in.)			
41. Rise (in.)				42. Gage (no.) / Wall Thickness (in.)			
43. Extension Length (ft.)							
HYDROLOGY / HYDRAULICS							
44. Drainage Area (acres)				45. Design Discharge (c.f.s.)			
46. Abrasive Conditions				47. pH			
48. Channel Protection (Inlet)				49. Channel Protection (Outlet)			

COMMENTS:

INVENTORIED BY: _____ DATE: _____

Culvert Inventory Report CR – 87 (ODOT 2003)

STATE OF OHIO DEPARTMENT OF TRANSPORTATION
CULVERT INSPECTION REPORT

CR-86 12-03

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CULVERT FILE NUMBER _____ CULVERT NUMBER _____ CO _____ ROUTE _____ SLM _____ ID _____ YEAR BUILT _____

DISTRICT _____ SHAPE _____ MATERIAL _____ LENGTH _____

MAX. HEIGHT OF COVER _____ FEATURE INT. _____

LATITUDE _____ LONGITUDE _____

ENTRY CLASS _____ NUMBER OF CELLS _____

CULVERT			
1. General	☐	2. Culvert Alignment	☐
3. Shape	☐	4. Seams or Joints	☐
5. Slab	☐	6. Abutments	☐
7. Headwalls	☐	8. End Structure	☐
CHANNEL			
9. Channel Alignment	☐	10. Protection	☐
11. Culvert Waterway Blockage	☐	12. Scour	☐
APPROACHES			
13. Pavement	☐	14. Guardrail	☐
15. Embankment	☐		☐
	☐		☐
16. Level of Inspection	☐	GENERAL APPRAISAL & OPERATIONAL STATUS	☐

RECOMMENDED REPAIR CODE(S): _____

COMMENTS: _____

INSPECTED BY: _____ DATE: _____ REVIEWED BY: _____ DATE: _____

Culvert Inspection Report CR – 86 (ODOT 2003)