EVALUATION OF TRENCHLESS RENEWAL METHODS FOR POTABLE WATER DISTRIBUTION PIPES

by

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ABSTRACT

EVALUATION OF TRENCHLESS RENEWAL METHODS

FOR POTABLE WATER DISTRIBUTION PIPES

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Undoubtedly, potable water pipes, as part of an underground infrastructure system, play a key role in maintaining quality of life, health and well being of human kind. As these potable water pipes reach the end of their useful life, they create high maintenance costs, loss of flow capacity, decreased water quality, and increased dissatisfaction. Trenchless renewal methods (TRMs) are a medium to renew deteriorated potable water pipes, thus decreasing leakage loss, emergency maintenance costs and customer complaints. TRMs also maintain the quality of the water leaving the treatment plant.

America's drinking water systems faces an annual shortfall of at least $11 Billion to replace the aging facilities that are near the end of their useful lives and to comply with existing and future federal water regulations (ASCE, 2009). Due to applicability, capabilities and limitations of specific trenchless renewal methods, it is sometimes difficult to select an appropriate method for a particular pipe conditions and based on the project surface and subsurface characteristics. To assist with solving this problem, this research presents a comparison of trenchless renewal methods as well as a decision support system and a cost module to select a suitable trenchless renewal method based on the particular pipe problems and field characteristics.

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CHAPTER 1

INTRODUCTION AND RATIONALE

1.1 Background

There is no doubt that pipeline systems in general, and potable water pipelines specifically, form an important part of our infrastructure. These pipelines constitute a large and complex system that has been expanded and developed during the last century. The old saying, “out of sight, out of mind!” gives us the impression that our pipelines will last indefinitely. While these pipelines were designed and constructed with adequate safety factors both hydraulically and structurally, they have deteriorated overtime. Usually, signs of wear and failure for underground infrastructure such as water distribution systems are not apparent until a major leak or collapse is found. This commonly leads to emergency repairs, which may cost 10 times more than planned repairs and may result in the loss of millions of gallons of treated water.

There are many technological advances which assist in the mapping, monitoring, analyzing and operating of pipeline systems. It is important to use these technologies to create a cost-effective field for both design and construction of new systems as well as the maintenance and renewal of the old ones. Unfortunately, the new pipeline renewal technologies benefits may never be fully realized due to following reasons:

1. The approval process for new standards, codes, and guidelines are usually slow, and
2. There is reluctance among engineering community to avoid new technologies, until these technologies are used in other projects and incorporated into standards, codes and guidelines.

As part of this research, it will be shown that trenchless renewal methods (TRMs), while relatively new, can be more cost-effective and suitable than traditional open-cut options. These methods can be used to renew the service conditions of the pipe as well as extending its design life (Najafi, 2010). Figure 1.1 presents the classification of trenchless renewal techniques.

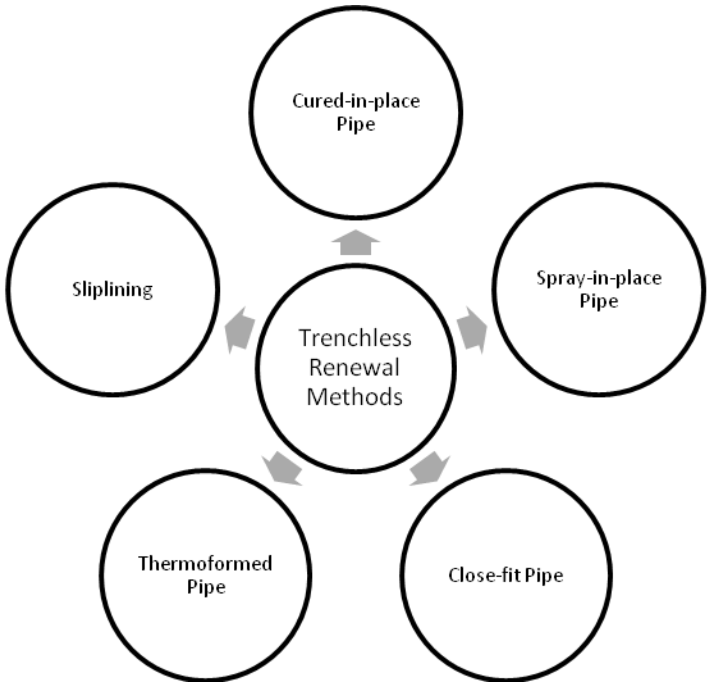

Figure 1.1: Classifications of Trenchless Renewal Methods

1.2 Current Potable Water Distribution Pipe Conditions

The answer to the problem of whether to renew or rehabilitate[1], replace[2] or repair[3] a deteriorated and failing drinking water distribution system is not easy. This is specifically critical if limited budgets and massive volumes of failing pipelines facing our municipalities and cities are considered. The estimated five year funding requirement for drinking water and wastewater is $255 Billion (ASCE, 2009). As shown in Figure 1.2, a short fall of $108.6 Billion is estimated.

[1] Renew and rehabilitate means extending the design life of an old pipeline.
[2] Replace means installing a new pipeline whether in place of the old one or parallel to the old one.
[3] Repair means fixing a failing problem, such as a leaking joint, without consideration to extending the design life of the whole pipeline.

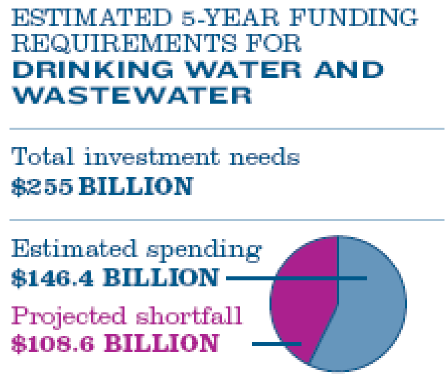

Figure 1.2: Estimated 5-Year Funding Requirements for Drinking Water and Wastewater (ASCE, 2009)

In the U.S., 24% of the waterborne disease outbreaks reported in community water systems during the past decade were caused by contamination entering the water distribution systems, i.e., not due to poorly treated water (Clark et al. 1998). For example, in Cabool, Missouri, during the period of December 15, 1989 to January 20, 1990, residents and visitors (population 2,090) experienced 240 cases of diarrhea and six deaths. An investigation concluded that the illness was caused by waterborne contaminants that entered the distribution system through a series of line breaks and meter replacements (Geldreich et al. 1992).

Based on the studies by the American Water Works Association (Selvakumar et. al., 2002), of the approximately 200,000 public water systems in the United States, about 30% are community water systems that serve primarily residential areas and 90% of the population. There are approximately 863,000 miles of distribution system in the United States with an annual rate of new installations estimated at 11,900 miles and annual replacement rate estimated at 4,100 miles.

1.3 Problem Statement

According to the American Water Works Association (AWWA, 2001) and other sources (Najafi, 2005), internal and external pressures on the pipes, pipe material corrosion, pipe environment, and fluid properties, among other factors, have a major impact on a pipeline's expected useful life. Figure 1.2 illustrates an example of deterioration rate over time for cast iron water pipes.

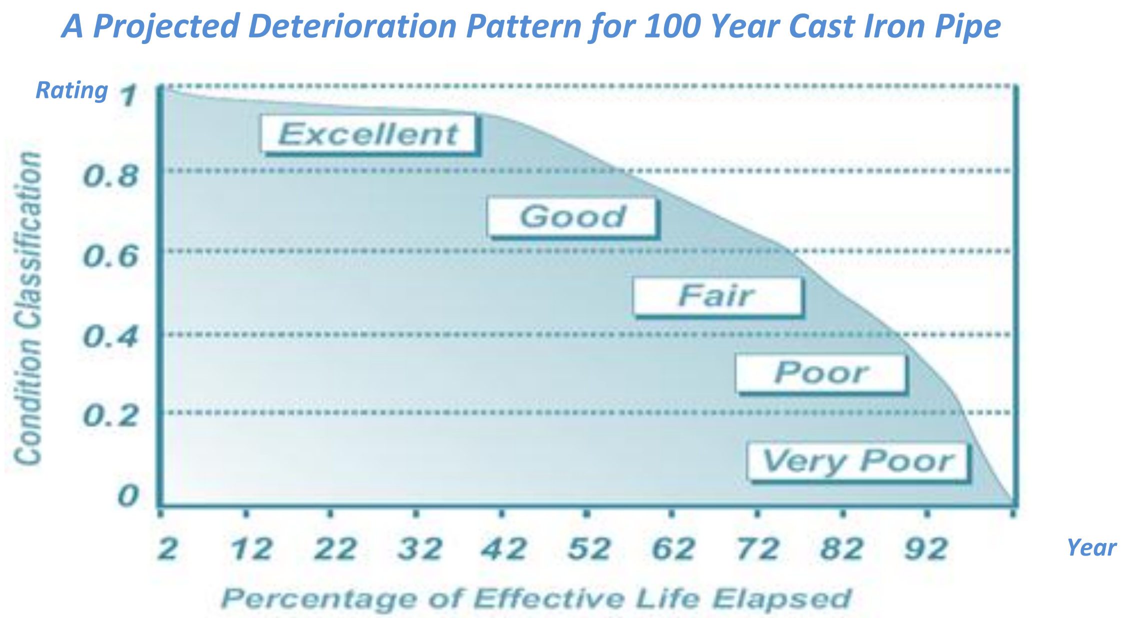

Figure 1.3: Life Cycle Deterioration Curve for Cast Iron Water Pipes (EPA Report, 2002)

As shown in Figure 1.3, water pipes, like any other asset, decrease in performance over time. Conversely, each pipe component is part of an integrated system, and its behavior may affect the overall service of the pipeline system. On the other hand, quality of the service is not constant as new legislations become effective, and customers change their needs and/or expectations. The fact that most water pipes are buried also adds a degree of complexity to the problem due to the difficulty in assessing their conditions. Water pipe asset management is, therefore, a complex and challenging matter and is currently an important agenda item for water supply stakeholders in the industrialized countries (Alegre, et al., 2006b).

The American Society of Civil Engineers (ASCE) Report Card for the year 2009, grades the nation's infrastructure with "D," and drinking water system as "C-" as shown in Figure 1.4 (ASCE, 2009). According to ASCE, pipeline deterioration together with the inflation rates have increased the total cost of repair, renewal and replacement from $1.6 trillion in 2005 to $ 2.2 trillion in 2009 (ASCE, 2009).

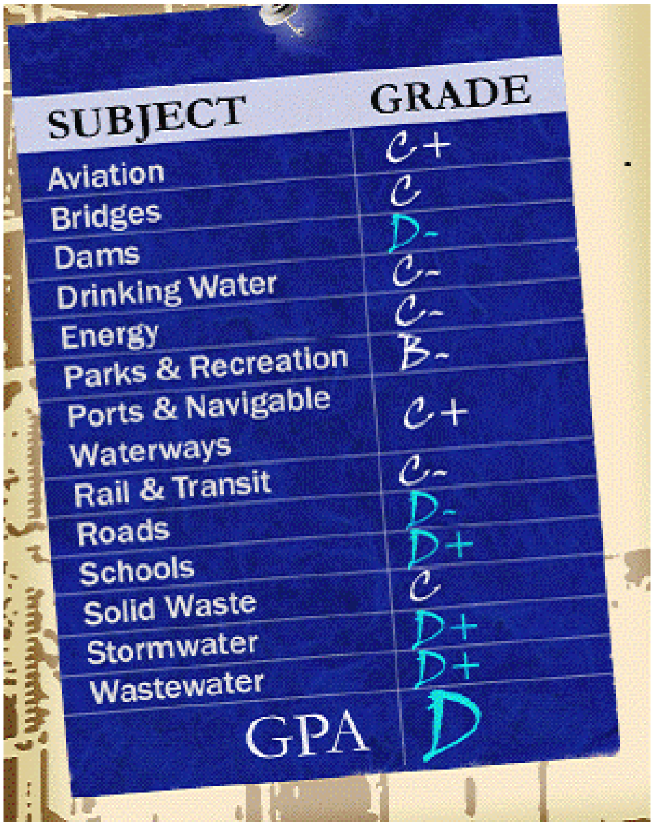

Figure 1.4: ASCE Report Card, GPA “D” (ASCE, 2009)

A majority of the water pipes installed in the United States, beginning in the late 1800s until the late 1960s, were manufactured from cast iron. With time, deteriorating conditions cause reduction in both structural integrity and hydraulic capacity of these pipes. The effects of pipe failure can sometimes be observed on the street when a pipe bursts with consequences of traffic disruptions or pipe blockage with subsequent flooding. Therefore, managing and maintaining the performance of these buried assets is a significant task for utility managers and public works departments.

1.4 Objectives and Scope

1.4.1 Specific Objectives

The specific objectives of this thesis are:

- To describe the current planning/construction procedures for trenchless renewal methods for water pipe distribution systems less than 24 in. in diameter.

- To develop a decision support system useful for selection of a trenchless renewal method for water pipe distribution systems.
- To develop a cost module for cost analysis of a trenchless renewal method selected from the decision support system.

1.4.2 Other Objectives

- To describe the structure of the water supply systems (WSS).
- To explain the water pipe deterioration process and the causes with mechanisms of the water pipe failures.
- To compile the findings of this thesis to establish future studies and recommendations.

1.4.3 Scope

The scope of this thesis is limited to the detailed description of renewal methods for water pipes with use of trenchless technology. These trenchless renewal methods identified by Najafi (2005) include cured-in-place pipe (CIPP), spray-in-place pipe (SIPP), close-fit pipe (CFP), thermoformed pipe (ThP), and sliplining (SL). The decision support system developed in this research does not present evaluation of existing pipes and field characteristics for the point source repairs using in-line replacement and the open-cut method. Likewise, the developed cost module does not present a cost analysis for the point source repairs using in-line replacement and open-cut method. Excellent information about these technologies is available in several publications (Najafi, 2005, Najafi, 2010, Kramer, 1992).

1.5 Methodology

After investigating different trenchless renewal methods (TRMs), this study defines the best approach possible to develop a decision support system and cost module. The information required for this research was obtained through literature search and industry interviews. First, a flow diagram for the logic of the decision support system and cost module was prepared and then a database was developed. This database is divided into two parts: Part 1: TRM Characteristics; and Part 2: Input Data Worksheet. The TRM worksheet provides the different characteristics of the renewal technologies needed in the decision support system to formulate a trenchless renewal method for particular existing pipe and field conditions. The input data worksheet provides the data for the cost module which uses that data to calculate the total cost of the different categories. Microsoft Excel© is used to develop the decision support system and cost module. A series of worksheets were created that are linked to facilitate data entry, analysis and output. These worksheets are discussed in Chapter 4 of this thesis.

1.6 Outline of the Thesis

Chapter 1 introduces the current conditions of water pipelines from EPA, AWWA, and ASCE. The cost associated with renewal and replacement requirements as well as the need for trenchless renewal methods are presented. Additionally, this chapter provides an overview of the objectives and scope of this thesis, the methodology and the expected outcome of this work.

Chapter 2 presents a literature review of the urban water supply systems (WSS). A step-by-step process of water pipe deterioration is discussed in this chapter. Water pipe failure (partially or fully) is part of overall deterioration process. Different failure mechanisms and causes as well as costs associated with these failures are analyzed. An introduction to trenchless renewal methods is discussed along with how these methods can be used to overcome water pipe deterioration problems.

Chapter 3 describes the construction phase of the different trenchless renewal methods. Each trenchless renewal method is subdivided into work plan, work space, jobsite layout, contingency plan, inspection and monitoring, documentations and drawings, project close-out/delivery and safety.

Chapter 4 describes the decision support system and the cost module. Each component of the decision support system and cost module is explained with its features and benefits.

Chapter 5 summarizes the conclusion and recommendations for future research.

1.7 Expected Outcome

The expected outcomes of this thesis are divided into three major areas, as follow:

From the **academic point of view**, this investigation focuses on the feasibility of trenchless renewal methods for water distribution pipelines. This study contributes to topics of design, planning and construction considerations for water distribution pipelines.

From the **general public point of view and quality of life**, this study aims to address attention to catastrophes caused by water pipe failures and sudden water pipe collapsed which can cause higher reconstruction costs. Such failures often lead to increased replacement costs, flooding, roadway damage, interruption of traffic, and even fatal accidents (Wissink, et al. 2005).

From an **industry point of view**, this thesis can serve as guidance to owners, engineers, technicians and operators responsible for water pipe design, evaluation and renewal. The water utility, contractors, owners, designers and engineers may find the decision support system and TRM cost module a high-value tool for selecting the most appropriate TRM based on the existing pipe and field characteristics.

1.8 Chapter Summary

Water is a precious resource essential to human existence. Reliability, availability, safety and efficiency provided by an appropriate TRM can produce the desired performance standards for any water supply service. Reliability assumes the system will operate correctly, availability assumes the system will be operational at all times, safety assumes the absence of hazardous consequences for the users and the environment, and efficiency is related to the level of losses. This chapter provided an overview of the current state of water systems and an introduction to trenchless renewal methods. Objectives, scope, and the expected outcomes of this thesis were highlighted in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Structure of the Water Supply System

The size and complexity of drinking water supply systems may vary dramatically; but they all have the same basic purpose – to deliver water from the source (or treatment facility) to the customer. The objective of an urban water system is to provide safe potable water for domestic use, adequate quantity of water at sufficient pressure for fire protection and water for industrial use. Sources for municipal supplies are wells, rivers, lakes and reservoirs. About two thirds of the water for public supplies around the world comes from the surface-water sources. Often groundwater is of adequate quality to exclude treatment other than chlorination and fluoridation. The structure of a water supply system is illustrated in Figure 2.1. The whole water pipeline system can be divided into two major parts - the transmission system and the distribution system.

2.1.1 Transmission System

A transmission system consists of components that are designed to convey large amounts of water over great distances, typically between major facilities within the system. The common example of a transmission system is a treatment facility and storage reservoirs setup as shown in Figure 2.1. Water transmission pipelines usually have diameters above 12 in. and can be built underground as well as aboveground. The length of pipelines can vary significantly. In some areas the water has to be transported over a distance of several hundred miles. Transmission pipelines may include pump stations in addition to manholes and valves and other appurtenances. To minimize the cost of operation, the pumping may be performed during the time when the energy costs are lower, i.e. off-peak electricity use hours. The flow rate in the transmission pipeline during the pumping is quite high and the water is often stagnant during the rest of the time. Individual customers are usually not served directly from transmission mains. In some cases, distribution systems can be connected along the length of the transmission pipeline (Misiunas, 2005).

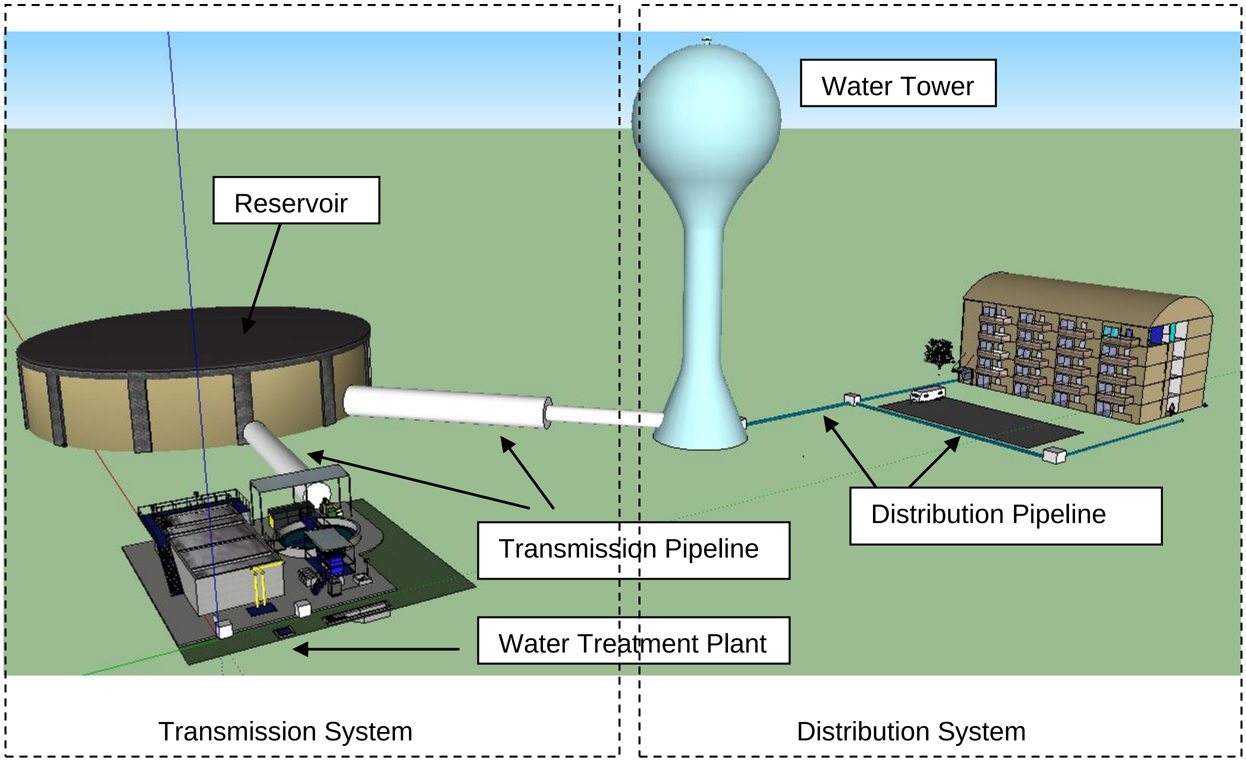

Figure 2.1: Structure of Water Supply System (WSS)

2.1.2 Distribution System

The water transported in transmission pipelines is distributed through the water distribution systems. Generally, a distribution system has a complex topology and contains a large number of elements. Two types of pipes are found in the distribution system: (1) distribution mains, and (2) service connections. Distribution mains are an intermediate step towards delivering water to the end users and are smaller in diameter than transmission mains. Typically, distribution mains follow the general topology and alignment of the city streets. Pipes can be interconnected by junctions and form loops. Typically, the urban distribution system is a combination of looped and branched topologies as shown in Figure 2.1. Figure 2.1 also shows a closer view of the parts of the water distribution system at the street level. Generally, every single branch in the distribution network has a stop valve at each end. Valves are installed for the purpose of isolation in case of a failure event or during maintenance work. They can also be used to reroute flows in the network: In some cases valves are closed permanently to establish pressure zones within the network or to form district metering areas (DMAs). A fire hydrant connector point is another common element in both transmission and distribution parts of the water supply system.

The regulations regarding the density of fire hydrants in a distribution network can vary between counties, but in general, fire hydrants are likely to be installed every 300 ft. Elbows, tees, crosses, and numerous other fittings are used to connect and redirect sections of pipes. Along with isolation valves, various control valves (pressure-reducing, pressure sustaining, etc.) are installed in the system. Finally, the network may contain pumps, air-release devices, water hammer control devices and other operational and maintenance installations. Services, also called service lines, are the smallest pipes in the supply system and transmit the water from the distribution mains to the customers. Usually, service pipes have smaller diameter than distribution mains and run from the street to the property. Households, businesses and industries have their own internal plumbing systems to transport water to sinks, washing machines, and so forth (Misiunas, 2005).

2.2 Pipe Assets

Pipes, valves, pumps, reservoirs and all other components of a water supply system constitute a water supply asset. Pipes are one of the principal assets. As described in the previous section, there are three main types of pipes in the water supply system – transmission mains, distribution mains and services (Misiunas, 2005).

2.2.1 Pipe Materials

Historically, a variety of materials and technologies have been used in the production of water supply pipes. The material of a particular pipe depends mainly on the year of installation and the diameter. For large transmission pipelines (with diameters more than 12 in.) steel, mild steel cement-lined (MSCL) or prestressed concrete cylinder pipes (PCCP) are typically used. Older water distribution mains are typically made of cast iron or asbestos cement, while newer mains mainly use ductile iron and poly-vinyl chloride (PVC). The distribution of pipe materials in existing systems varies between counties and even towns. Pipe material distribution statistics for different countries can be found in the literature. Pipe material data from 500 water companies around Germany was presented in Weimer (2001). Pelletier et al. (2003) reviewed data from three Canadian municipalities. Babovic et al. (2002) showed data from Copenhagen City (Denmark) water supply. In NRC (1995), a pipe material survey from 21 Canadian cities was made. Unwin et al. (2003) showed the pipe material data from a UK water service provider. Finally, Rajani and Kleiner (2004) presented a summary of the pipe material distribution from 13 European countries.

The data from different countries shows that, on an average, cast iron is the dominating pipe material. Depending on the country, 40-60% of pipes were installed using cast iron. The second most widely used material is ductile iron with 25-30% of the whole system. Cast iron and ductile iron are followed by asbestos cement and plastic, each of which, depending on the country, can constitute 10-30% of the network (Misiunas, 2005). However, it has to be noted that the distribution of pipe materials is changing due to extensive use of plastic pipes (PVC and HDPE). The most common materials of service connection pipes are copper, steel, and plastic (Misiunas, 2005). As shown in Weimer (2001), 43% of services in Germany are plastic, 36% are made out of steel and lead constitutes 8% of the service pipes.

2.2.2 Pipe Age

The first urban water supply systems were built more than five hundred years ago. A large portion of originally constructed pipes are still in operation today. Building urban water supply infrastructure required large investments and the existing systems cannot be changed or upgraded over a short period of time. The age of pipes can usually be estimated from their material type. The oldest component of networks is cast iron installations that can go back as far as 1500 (Misiunas, 2005). The average age of cast iron pipes that are present in existing systems is around 50 years (Misiunas, 2005). No cast iron pipes were installed after 1970 (Misiunas, 2005). Steel, ductile iron, asbestos cement and concrete pipes were introduced to urban water supply systems around 50 years ago (Misiunas, 2005). Finally, plastic materials have been used since the 1970s and constitute a large portion of current installations. Overall, considering the distribution of pipe material that was discussed earlier in this thesis, the average age of water supply pipes in developed countries can be estimated to be around 50 years (Misiunas, 2005). It is expected that water pipelines start deteriorating from the initial installation (Misiunas, 2005).

2.3 Pipe Deterioration Process

Pipe failures can be described as a multi-step process as shown in Figure 2.2, and described below (Misiunas, 2005):

1. *Installation*. The new intact pipe is installed.
2. *Initiation of corrosion*. After the pipe has been in operation for some time, the corrosion process start on the interior and/or exterior surface of the pipe.
3. *Crack before leak/Partially Deteriorated:-*. Cracks, corrosion pits and graphitization are typical products of the corrosion process. In some cases cracks can be initiated by mechanical stress. Cement mortar lining, Epoxy lining, Polyurethane lining and Polyurea lining can be used to avoid further corrosion and graphitization. The use of polyurethane and polyurea lining will also provide some structural enhancement to the deteriorated pipe. Cured-in-Place Pipe, Close-fit, Sliplining and Thermoformed lining can be used at this stage to provide full structural strength to the pipe.
4. *Crack/Pipe Section Missing/Fully Deteriorated:-*. Eventually, developing corrosion pits and cracks reduce the residual strength of the pipe wall below the internal or external stresses and the pipe wall breaks. As a consequence, the leak or burst will be initiated depending on the size of the break. In some cases, the size of the failure is not big enough for the leak to be readily detected. Cured-in-place pipe, Sliplining and Thermoformed pipe can be used to avoid complete failure of the pipe.
5. *Complete failure*. The complete failure of the pipe can be caused by a crack, corrosion pit, and already existing leak/burst or a third party interference. Such a failure is usually followed by water appearing on the ground surface or a considerable change in the hydraulic balance of the system.

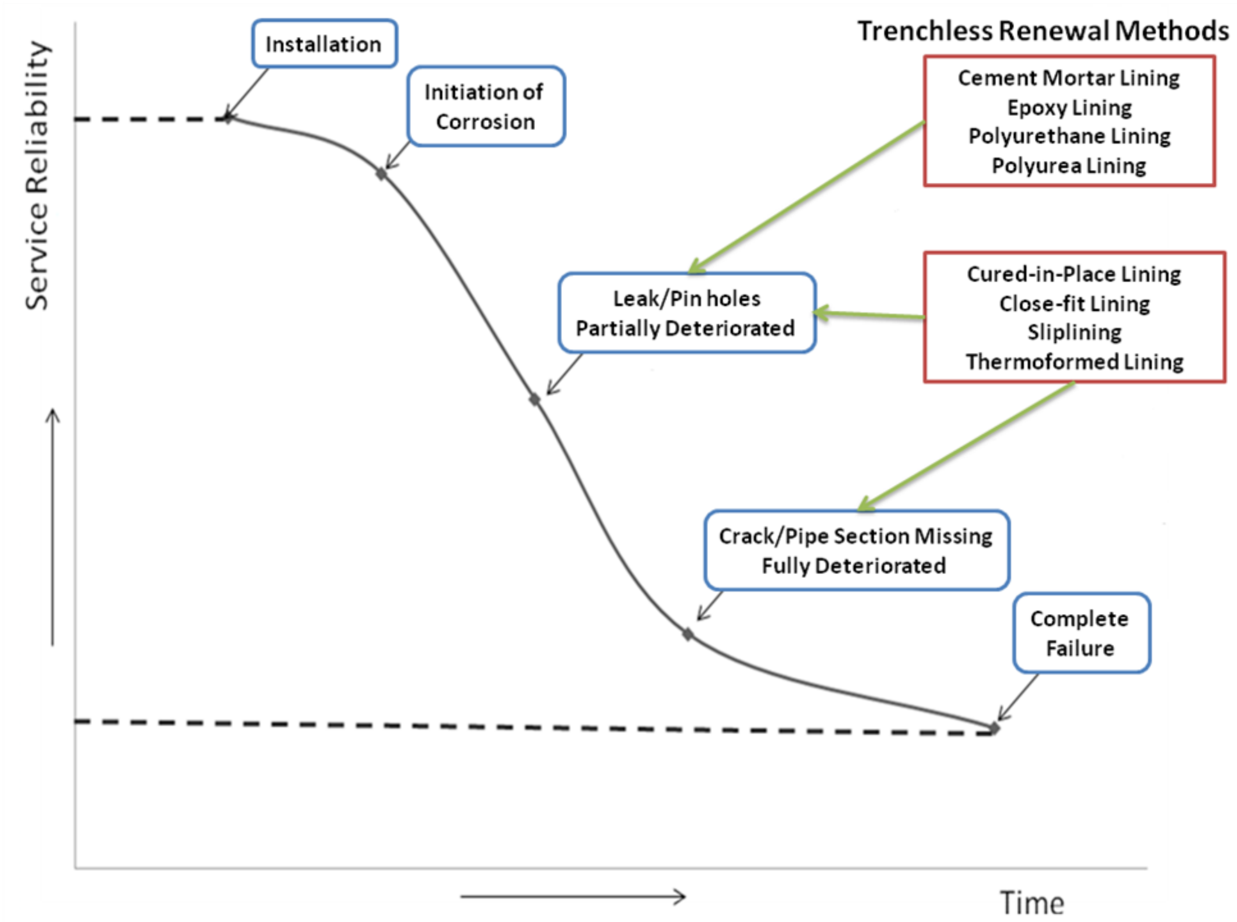

Figure 2.2: Multi-step process of Pipeline Deterioration (Modified from Misiunas, 2005)

Not all pipes will have a failure sequence as shown in Figure 2.2. Wang and Atrens (2004) have shown that stress corrosion cracks (SCC) are likely to be active cracks, i.e. develop with time. In Makar (2000) and Makar et al. (2001), the evidence of a multi-event cracking is presented, indicating that there can be a substantial time interval between the initial and subsequent cracks. According to Saegrov et al. (1999), the sequential development of the failure is influenced by the material of the pipe. Steel and ductile iron pipes are likely to leak before they break. Cast iron and larger diameter prestressed concrete pipes typically break before they leak. Plastic and PVC pipes can do either, depending on the installation and operational conditions.

The deterioration mechanisms in plastic pipes are not well understood, since they are likely to be slower and plastic pipes have been in use only for the last 30–40 years. The time intervals between the different steps in the pipe deterioration process can vary considerably. As an example, in Atkinson et al. (2002), it was shown that, for small cast iron pipes (diameter less than 4 in.), the critical pit depth that corresponds to the situation when service stress exceeds the residual strength of the material is approximately equal to 30% of the pipe wall thickness (Misiunas, 2005). The history of the failure development is likely to be specific for a particular pipe and is extremely difficult to predict. The situation becomes even more complicated when failures caused by the third party interference or other external forces are considered.

2.4 Pipe Failure

Pipe failure occurs when the pipe cannot contain the fluid internally within the pipe due to strength being too low (from wrong material selection, material fatigue, stress concentration due to corrosion, etc.) or the stress is too high (overloads, loss of wall thickness, etc.) resulting in an interference zone between loads and strengths. Generally, pipe failures can be classified by type and by size (Misiunas, 2005).

2.4.1 Causes of Failure

Kleiner et al. (2001) classified the deterioration of pipes in two categories. The first one is structural deterioration, which diminishes the pipe's structural resiliency and its ability to withstand the various types of stress imposed upon it. The second one is deterioration of the inner surface of the pipe resulting in diminished hydraulic capacity, degradation of water quality and reduced structural resiliency in cases of severe internal corrosion. Pipe breakage, with exception of situations when it is caused by a third party interference, is likely to occur when the environmental and operational stresses act upon pipes whose structural integrity has been compromised by corrosion, degradation, inadequate installation or manufacturing defects.

2.4.1.1 Corrosion

It is widely accepted (Makar et al.; 2001; Rajani and Kleiner; 2001) that the predominant deterioration mechanism on the exterior of cast and ductile iron pipes is electro-chemical corrosion with the damage occurring in the form of corrosion pits. The damage to gray cast iron is often identified by the presence of graphitization - a result of iron being leached away by corrosion. Either form of metal loss represents a corrosion pit that will grow with time and eventually lead to a pipe break. The physical environment of the pipe has a significant impact on the deterioration rate. Severe internal corrosion may also impact pipe structure deterioration. Plastic pipe materials also may suffer from chemical degradation. Asbestos cement and concrete pipes are subject to deterioration due to various chemical processes that either leach out the cement material or penetrate the concrete to form products that weaken the cement matrix (Misiunas, 2005).

2.4.1.2 Excessive Forces

Quite often a pipe failure is caused by a combination of some form of forces. External forces can be induced by a number of different sources, such as pipe soil interaction, traffic or climate (Rajani and Tesfamariam; 2004; Hudak et al.; 1998). In some cases, the external load might be applied at a significant distance from the failure location. Rajani and Kleiner (2001) have identified two main types of mechanical stresses that may contribute to the failure of a pipe - longitudinal and transverse. Longitudinal stress can be caused by: (1) thermal contraction due to low temperature of the water in the pipe and the pipe surroundings, (2) bending stress due to soil differential movement or large voids in the bedding near the pipe (as a result of leaks), (3) inadequate trench and bedding practices, (4) third party interference. Transverse stress can be caused by: (1) hoop stress due to pressure in the pipe, (2) ring stress due to soil loading, (3) ring stress due to other external loading, i.e. traffic, and (4) ring loads caused by freezing moisture expansion in the surrounding soil (Misiunas, 2005).

2.4.1.3 Production Flaw

Porosity is one of the most common manufacturing defects in cast iron pipes. Poor manufacture of pipe result in a discontinuity of the pipe material and may act as crack formers. The variation in a pipe wall thickness may lead to a situation where a part of the pipe wall might no longer has a sufficient wall thickness for expected maximum pressures. Yet another manufacturing flaw is the presence of iron phosphate structures throughout the pipe metal. Phosphorus is added to reduce the production costs. However, the iron phosphate compound is brittle and weakens the pipe (Misiunas, 2005).

2.4.1.4 Human Error

Starting with an incorrect design, there are several practices during and after the construction that can contribute to the failure of the pipe. Poor transportation, movement and installation techniques can promote corrosion followed by the failure of the pipe. Accidentally removed coating exposes the pipe to extensive corrosion. Another possible cause of the failure is third party damage. The most frequent example of third-party damage is during an excavation (Misiunas, 2005).

2.4.2 Failure Mechanisms

The failure mechanism varies depending on the material and the diameter of a pipe. Pipe breakage types have been classified by O'Day (1982) into six main categories:

2.4.2.1 Circumferential Cracking

Circumferential cracking (Figure 2.3) is typically caused by bending forces applied to the pipe. Bending stress is often the result of soil movement, thermal contraction or third party interference. Circumferential cracking is the most common failure mode for smaller diameter cast iron pipes. In Hu and Hubble (2005) statistics of asbestos cement water main breaks from the City of Regina in Canada were presented. Circumferential breaks were shown to be the predominant failure mode comprising 90.9% of all pipe failures. It was also demonstrated that the failure rate was decreasing with increasing pipe diameter (Misiunas, 2005).

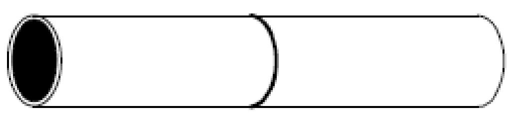

Figure 2.3: Circumferential Cracking (Misiunas, 2005)

2.4.2.2 Longitudinal Cracking

Longitudinal cracking (Figure 2.4) is more common in large diameter pipes. It can be caused by a number of different types of loading, such as internal water pressure and ring stress created by the soil cover load, external load or thermal changes. An initial small crack can expand along the length of the pipeline. In some cases, two cracks on opposite sides of the pipe are initiated, resulting in a complete detachment of the section of the pipe that may be as long as the pipe segments itself (Misiunas, 2005).

Figure 2.4: Longitudinal cracking (Misiunas, 2005)

2.4.2.3 Bell Splitting

Bell splitting (Figure 2.5) is most common in small diameter cast iron pipes. The main reason for bell splitting is the sealing of the joints. Originally, the joints were sealed using lead. In the 1930s and 1940s the lead was substituted by leadite which, as a non-metallic compound, has a different thermal expansion coefficient than lead. This, at low temperatures, can cause bell splitting (Misiunas, 2005).

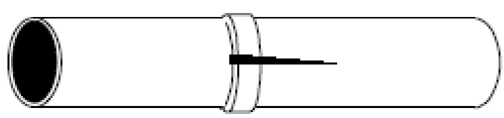

Figure 2.5: Bell splitting (Misiunas, 2005)

2.4.2.4 Corrosion Pitting and Blow-out Holes

In addition to the three breakage types described above, Makar et al. (2001) introduced the following failure modes: Corrosion pitting and blow-out holes. As said previously, corrosion is an important factor that plays a major role in the pipe failure process. A corrosion pit (Figure 2.6a) reduces the thickness and mechanical resistance of the pipe wall. When the wall is thinned to a certain point, the internal pressure blows out a hole (Figure 2.6b). The size of the hole depends on the distribution of corrosion and the pressure in the pipe. In some cases a blow-out hole can be fairly large (Misiunas, 2005).

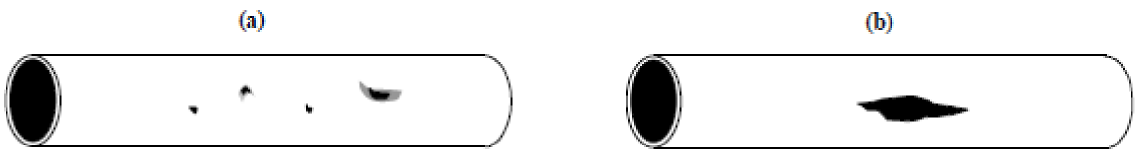

Figure 2.6: (a) Corrosion pitting and (b) Blow-out hole (Misiunas, 2005)

2.4.2.5 Bell Shearing

Large diameter pipes are not likely to suffer from a circumferential failure. Instead, large diameter gray cast iron pipes fail by having a section of a bell shear off as shown in Figure 2.7. The simple compressive loading is likely to cause a longitudinal crack that propagates along the length of the pipeline. Bending, however, often results in the occurrence of bell shearing (Misiunas, 2005).

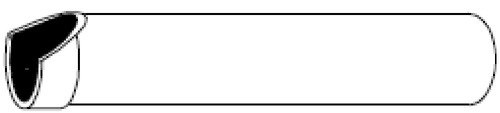

Figure 2.7: Bell Shearing (Misiunas, D. 2005)

2.4.2.6 Spiral Cracking

Spiral cracking (Figure 2.8) is a rather unique failure mode that sometimes occurs in medium diameter pipes. The initially circumferential crack propagates along the length of the pipe in a spiral fashion. Historically, this type of failure is associated with pressure surges, but it can also be related to a combination of bending force and internal pressure (Misiunas, 2005).

Figure 2.8: Spiral Cracking (Misiunas, 2005)

2.5 Frequency of the Failure

Several factors have been indicated in the literature to have an influence on the frequency of pipe breaks. Pipe age, material and diameter are the main factors that influence the frequency of pipe breaks in the supply system. Soil parameters, climate changes, pressure in the system and the type of environment of the pipe have also been shown to affect the rate of pipe failure. One of the common indicators used to quantify the frequency of water distribution pipe failures for a particular system is the annual number of breaks per hundred kilometers of pipe (# of breaks/ 50 miles/year). In Table 2.1, pipe break frequencies presented in three different studies are shown (Misiunas, 2005).

Table 2.1: Pipe Break Frequencies (Misiunas, 2005)

	Breaks/50 Miles/Year				
Source	**Cast Iron**	**Ductile Iron**	**Steel**	**AC**	**PVC**
NRC (1995)	36	9.5	N/A	5.7	0.7
Pelletier et. Al. (2003)	55	20	N/A	N/A	2
Weimer (2001)	27	3	33	N/A	4

Table 2.1 indicates that the majority of breaks occur in cast iron pipes. In most of the water supply systems, cast iron pipes are the oldest pipes, often installed more than 50 years ago. Many studies have also indicated the increase of the pipe failure frequency with time. As a conclusion, pipe age can be referred to as the predominant cause of pipe failure. Thus, the number of incidents in urban water supply systems is likely to be continuously increasing in the future as systems grow older (Misiunas, 2005).

2.6 Consequences of a Failure

Losses associated with a pipe failure can be divided into three main categories in a similar manner as suggested by Makar and Kleiner (2000):

1. Direct costs, such as:

- repair cost that depends on the parameters of the pipe and failure as well as the location of the failure;

- cost of lost water that depends on the severity of the failure, the isolation time, the size of the pipe and the production cost of water;
- cost of damage to the surrounding infrastructure and property (flooding, road collapse, structural damage, etc.) that depends on the severity and location of the failure as well as the time of isolation;
- liabilities (injury, accident, etc.) that depend on the severity and location of the failure.

2. Indirect costs, such as:

- costs of supply interruption (loss of business due to the water outage) that depend on the isolation time of the failure;
- cost of potentially increased deterioration rate of affected surrounding infrastructure and property;
- cost of a decreased fire-fighting capacity, both due to water outage and insufficient hydraulic capacity.

3. Social costs, such as:

- cost of water quality degradation due to contaminant intrusion caused by de-pressurizing;
- cost of decrease in public trust and quality of water supply that depends on the location and isolation time of the failure;
- cost of disruption of the traffic and business that depends on the location and isolation time of the failure;
- cost of disruption of the water supply to special facilities (hospitals, schools, etc.) that depends on the location and isolation time of the failure.

As explained above, failure of the pipe causes financial losses to the utility company as well inconvenience to consumers and social costs to both consumers and the general public. The cost module developed in Chapter 4 of this thesis can be used to compare direct, indirect and social costs due to water distribution pipe failures.

2.7 Trenchless Renewal Methods for Water Pipes

Trenchless technology consists of a set of methods, materials and equipment for inspection, stabilization, renewal (rehabilitation), replacement of existing water pipes, and installation of new pipes or liners with minimum excavation of the ground surface (ODOT, 2005). Renewal is a term often used to encompass rehabilitation and replacement procedures, where a new design life is provided (Najafi, 2005). The most common renewal methods applicable to water pipes are provided below:

2.7.1 Cured-in-place Pipe (CIPP)

In 1971, Eric Wood implemented the first cured-in-place pipe technology in London, England. He called the CIPP process *insitu form*, derived from the Latin meaning "form in place." Wood applied for US patent no. 4009063 on January 29, 1975. The patent was granted February 22, 1977 and was commercialized by Insituform Technologies until it entered the public domain on February 22, 1994 (Cured-in-place pipe, 2010).

Cured-in-place pipe (CIPP) installation is one of the most widely used methods of trenchless pipeline renewal. The cured-in-place pipe (CIPP) process involves the insertion of a resin-impregnated fabric tube into an old pipe by use of water inversion or winching. Usually the fabric is a polyester material, reinforced fiberglass, or similar. Usually hot water or steam is used for inversion process. The pliable nature of the resin-saturated fabric prior to curing allows installation around curves, filling of cracks, bridging of gaps, and maneuvering through pipe defects. CIPP can be applied for structural or nonstructural purposes (Najafi, 2010).

2.7.2 Spray-in-place Pipe (SIPP)

Spray-in-place pipe (SIPP) lining system technology is comprised of advanced polymers, epoxies, cement, and products which have been designed and tested specifically to fit the special requirements of pipelines. Polymers are further classified into polyurea, polyurethane and hybrid polymers that exhibit properties desirable in anti-corrosion systems, at minimum meeting the physical properties common to traditionally specified systems and in most cases far exceeding them. Cement product includes, High Alumina Cement, Reinforced Shotcrete and Fiber Reinforced Cement for renewal of pipelines. The physical properties of these products are readily adjustable and can be tailored to meet the specific requirements of the end-user. Figure 2.9 presents different types of the SIPP lining systems.

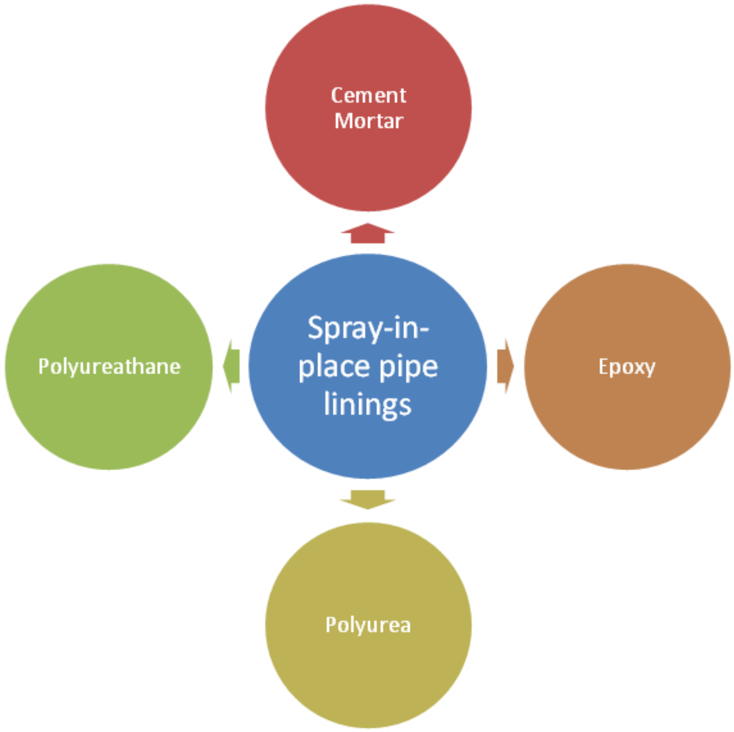

Figure 2.9: Different Types of SIPP Lining Systems

2.7.2.1 Cement Mortar Lining

Cement mortar and epoxy lining are the two pipe lining techniques generally used in water industry. Cement mortar lining of water mains, the most popular lining technique, was developed in Australia in 1905. The original lining process employed hand troweling; that process has been suspended by today's centrifugal spraying machine developed in the United States in the 1930s for large diameter pipe and modified in the Great Britain in the 1950s for use in smaller diameter pipes. It is classified centrifugal lining machines into large, medium and small diameter types. Larger diameter lining machines are used to line pipes that are greater than 24 in. diameter. Before the lining process is started, the pipe must be cleaned, dry and inspected to ensure that any remaining encrustation and water are removed. Commonly, 1:1 sand: mortar mix lining is applied by a lining machine, the construction of which depends on the pipe diameter.

2.7.2.2 Epoxy Lining

The epoxy internal lining of water pipelines was pioneered in the UK and Japan in the 1970s, the UK experience is well documented but the Japanese is not. It is known that products for potable water were approved by the Japanese Government in 1981. The technology was introduced in the UK in 1979 and received Government approval in 1985. In the US, the American Water Works Association Research Foundation (AWWRF) conducted a demonstration study using the epoxy lining technique in 1993 that confirmed its viability for water main rehabilitation, but approval by ANSI/NSF Standard 61 did not happen until several years later, delaying development of the process in the US. The U.S. Navy experimented with the development, testing the installation of epoxy linings inside piping systems on aircraft carriers between 1983 and 1993. The US Army issued a Public Works Technical Bulletin in 2001 for coating metallic piping at Army installations to enhance corrosion protection. In the private sector, companies like the industry leading CuraFlo® (who acquired equipment technology for blow through pipe lining in 1996) have made improvements to the technology over the last 14 years.

The primary reason for using this type of lining technique is to overcome the water quality problems caused by corrosion of iron pipes. Epoxy linings are usually classified as a nonstructural technique. Epoxy lining is applied to the interior surface of host pipes with a smooth surface finish that helps prevent further corrosion and tuberculation. Epoxy can effectively halt the recurrence of these problems if the host pipe is properly cleaned and lining is adequately applied according to specifications and manufacturer's guidelines. Similar to cement-mortar linings, epoxy linings require use of a specialized machine and spray head.

2.7.2.3 Polyurea Lining

The two-component fast set polyurea coating / lining technology was first introduced to the industry in 1988, following the development in 1986.4,5 This technology evolved from the need to develop a more stable, durable and 100% solids polymer system for coating rigid, spray applied polyurethane foam used in roofing and other insulation applications (Primeaux II, 2004).

Polyurea is formed from reaction of two components, isocyanate and amine resin. These components, unlike those created by the crystalline nature of some polyurethane hard segments, form a urea linkage, which is highly flexible. The material is moisture tolerant and has low viscosity, thus it can be easily pumped to remote spray head locations. It provides high build slump resistant linings, and dependent on manufacturer and class of material (structural or non structural) excellent adhesion characteristics. Finished linings are hard, glossy, and free of surface tack or greasiness. Polyurea linings provide long-term corrosion protection and have excellent abrasion resistance (Najafi, 2010).

2.7.2.4 Polyurethane Lining

The earliest polyurethane was developed by Otto Bayer and coworker at I.G. Farbenindustrie, Germany in 1937, formed by the reacting toluene di-isocyanate and poly-hydroxol compounds (Tu et. al., 2008). In April 1996, the AWWA Standards Council authorized the Steel Pipe Committee to develop a new standard for the use of polyurethane coatings on the interior and exterior of steel water pipes and fittings. The first edition of ANSI/AWWA C222 was approved on June 20, 1999. This is the second edition of this standard and was approved on June 8, 2008 (ANSI/AWWA, 2008).

Polyurethane is any polymer consisting of a chain of organic units joined by urethane (carbamate) links. Polyurethane polymers are formed through step-growth polymerization[4] by reacting a monomer containing at least two isocyanate functional groups with another monomer containing at least two hydroxyl (alcohol) groups in the presence of a catalyst (Polyurethane, 2010)..

High strength polyurethane coatings were first used in North America to protect underground steel fuel storage tanks from corrosion in the mid-1970s. The materials were also used to protect oil and gas pipelines in Europe at approximately the same time. Because of further development of the technology during the 1980s, the coating system was used successfully in water and wastewater pipelines and tanks.

2.7.3 Close-fit Pipe (CFP)

This type of trenchless pipeline renewal temporarily reduces the cross-sectional area of the new pipe before it is installed. After placement, the liner expands to its original size and shape at the jobsite in

[4] Step-growth polymerization refers to a type of polymerization mechanism in which bi-functional or multifunctional monomers react to form first dimmers (polymer containing two monomers), then trimers (polymer containing three monomers), longer oligomers (polymer containing four to ten monomers) and eventually long chain polymers (Step-growth polymerization, 2010).

order to provide a closer fit with the existing pipe and for pressure (more common) and gravity applications. This method can be used for both structural and nonstructural purposes. Lining pipe can also be reduced on-site and reformed by heat and/or pressure or may reinforce thin polyethylene pipe. There are two versions of this approach: structural and semi-structural (Najafi, 2010).

2.7.4 Thermoformed Pipe (ThP)

Thermoformed is a terminology used in North America for pipes that are reduced in their cross-section in factory, by folding. After insertion, the liner is heated (thermoform) to conform to the existing pipe dimensions with a close fit. Both PVC and PE can be used for this method, but PVC is more common (Najafi, 2010).

Between 1988 and 2003, more than 21 million ft of thermoformed pipe was installed in the United States (Najafi, 2005). All design properties of the thermoformed pipes are established at the manufacturing facility under ASTM prescribed quality assurance protocols and can negligibly influenced by field construction crews.

2.7.5 Sliplining (SL)

Sliplining (SL) is mainly used for structural applications when the existing pipe does not have joint settlements or misalignments. In this method, a new pipeline of smaller diameter is inserted into the existing pipe and usually the annular space between the existing pipe and new pipe is grouted. This installation method has the merit of simplicity and is relatively inexpensive. However, there can be a loss of hydraulic capacity.

Sliplining can be categorized into two main categories: continuous and segmental. The continuous sliplining method involves accessing the deteriorated pipe at strategic points and inserting high-density polyethylene (HDPE) or polyvinyl chloride (PVC) pipe, joined into a continuous pipe string. The segmental sliplining method involves the use of short sections of pipe that incorporate a flush sleeve joint commonly used in microtunneling and pipe-jacking processes (Najafi, 2010).

2.8 Chapter Summary

This chapter focused on the deterioration and failure of water pipelines in urban water supply systems (WSS). A sequential process of pipe deterioration with a brief overview of existing deterioration modeling and failure prediction techniques with social impacts were presented. Understanding of the deterioration process will be useful in the development of the decision support system for application of a specific renewal method as described in Chapter 4.

CHAPTER 3

CONSTRUCTION OF TRENCLESS WATER PIPELINE RENEWALS

3.1 Introduction

To reduce pipe failure and extend design life of existing pipelines, various trenchless renewal methods were introduced in the Chapter 2. To evaluate the construction phase of the trenchless renewal method, an interview was conducted to obtain general requirements of the different construction elements. Nine questions designed to define industry's approach to the TRM's work plan, work space, jobsite layout, contingency plan, inspection and monitoring, as-built drawings and documentations, project closeout/delivery, clean-up and restoration, and safety were asked. The responses were used to create guidelines which compare the various elements of construction phase. The blank questionnaire is provided in Appendix A. In the following sections the results for each question are presented and explained, emphasizing on the specific elements of the construction phase.

3.2 Cured-in-place Pipe (CIPP)

Cured-in-place pipe provides the reconstruction of water pipelines by the installation of a resin-impregnated flexible tube, which is tightly formed to the original conduit. The resin is cured using either hot water under hydrostatic pressure or steam pressure within the tube. The cured-In-Place Pipe (CIPP) will be continuous and tight fitting.

3.2.1 Work Plan

A Work Plan is a deliverable-oriented hierarchical decomposition of the work to be executed by the project team to accomplish the project objectives and create the required deliverables. It organizes and defines the total scope of the project. Each descending level represents an increasingly detailed definition of the project work. The project owner should provide the contractor with any as-built drawings for the existing pipeline and nearby facilities, geotechnical reports, and the results of any exploratory excavations that were completed to ensure the pipeline is appropriate for renewal method. The owner should note on the contract drawings any area where the contractor is not permitted to locate an excavation.

The following elements should be considered in work plan:

- Setup of traffic control,
- Pipe access (usually through excavation),
- Set up of bypass service lines (if required),
- Opening of the pipe (remove a tee or valve, cut out a portion of the pipe, etc.),
- Pipe cleaning (high pressure water, drag scrapers or pigs),
- Pre inspection (pre-CCTV),
- Locate, shut off and plug service connections,
- Installation of CIPP,
- Reinstate services (internally or through excavation),
- Post inspection (post-CCTV),
- Connection of rehabilitated pipe to adjacent pipe,
- Reset valves, fire hydrant connections or other appurtenances,
- Disinfection,
- Backfill,
- Surface restoration.

The contractor, the owner, and the engineer should meet and jointly review the detailed schedule of activities and ensure that the schedule meets the contractual requirements. The contractor should revise the schedule of activities to address any necessary adjustments regarding the value allocation or level of detail.

3.2.2 Work Space

The workspace should provide enough room for the safe operation of the equipment and for storing the materials. Minimum work space requirements are project specific. The workspace variables depend on the equipment used on site. It varies from project to project.

The most common equipment's typically required on jobsite are:

- Refrigerated truck,
- Boiler truck,
- Equipment truck,
- Television truck,
- Pick-up truck,
- Cleaning equipment(jet truck, winches, scrapers),
- Installation device for inversion of CIPP,
- Forklift and other lifting device,
- Pumps and other miscellaneous items.

In most of the cases, the tube is wet out in a plant setting, so the wet out equipment is not needed on site. Not all of the above equipment is required at the same time; equipment is brought to the job site as needed. Figure 3.1 presents the jobsite layout for the cured-in-place pipe.

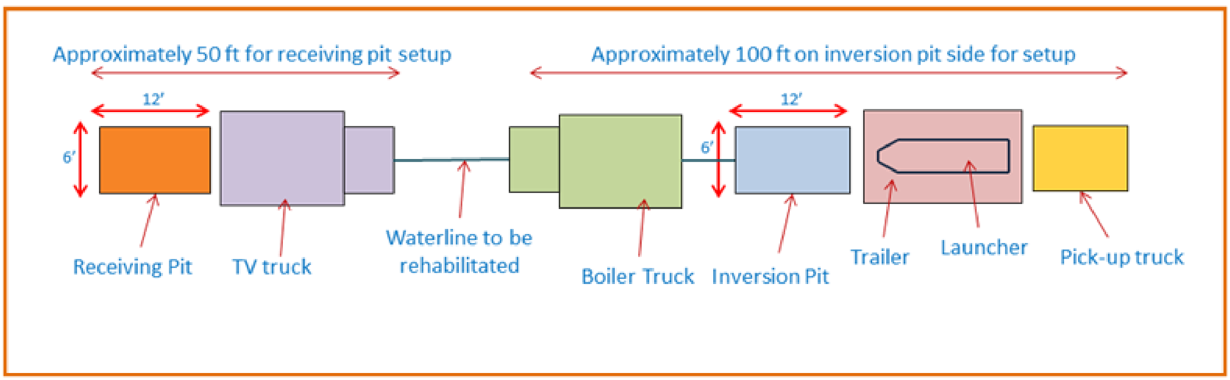

Figure 3.1: General Site Layout for CIPP Renewal of Waterlines (Source: Insituform Technologies)

3.2.3 Installation Process

1. Access the pipe – The space required to access the pipe varies according to the diameter of pipe to be renewed. The minimum space required for access pit is 6 ft x 12 ft as shown in Figure 3.1.
2. Set-up bypass service lines - The bypass should be made by plugging an upstream and pumping the water into a downstream or adjacent system. The pump and bypass lines shall be adequate capacity and size to handle the flow. Leakage during the operation of the bypass should be avoided.

3. Clean the pipe – The pipe should be cleaned with the use of mechanical or hydraulic cleaning equipment. The cleaning operation shall remove any and all existing debris so that each pipe joint can be thoroughly inspected and successfully reconstructed or rehabilitated.
4. Pre-inspection of the existing pipe – Refer to Section 3.7.
5. Locate, shut off and plug service connections – All the service connections should be located, shutoff and plugged with the use of the CCTV camera.
6. Install CIPP – The resin impregnated tube is inverted or winched in to the existing water pipe.
7. Cure CIPP - The resin is cured using either hot water under hydrostatic pressure or steam pressure within the tube.
8. Reinstate services – After the curing, the water pipe should be reopened and restored to the existing service connections and put in service.
9. Post-inspection of the new pipe (CIPP) – Refer to Section 3.7.
10. Disinfect – Refer Section 3.8 for details.

3.2.4 As-built Drawings and Documentations

As-built drawings are sometimes provided for the current system; often these as-built drawings have to be corrected and updated with the current CIPP work. Documentation may include the pre- and post- video files and results of the disinfection testing. Also, the engineer's design drawings showing installed pipe locations and elevations (alignments and profiles) should be verified against the actual installation.

3.3 Spray-in-place Pipe

Spray-in-place pipe (SIPP) provides the renewal of the water pipe with spray of advanced polymers, epoxies and cement to the interior of pipe to enhance the corrosion protection. Polyurea and polyurethane lining give structural enhancement to the pipe.

3.3.1 Work Plan

The work plan of SIPP is similar to the CIPP. For SIPP, It is essential to locate all valves and hydrants along the length of the pipe to be lined. Thorough understanding of the below grade utility infrastructure including adjacent utilities and the structure and composition such as valves, bends, and so on of the pipe to be renewed is necessary. The other elements that should be considered in the work plan include:

1. Determine the condition of deteriorated pipe.
2. Determine location of entry and exit pits not more than 500 ft apart.
3. Locate valves and hydrants of pipe system that are to be replaced.

3.3.2 Work Space

Access pits of 5 ft x 7 ft, are provided every 500 ft depending on the pipe depth. Surface area is made available to accommodate a truck and trailer combination at each pit location, which will allow room for rack feed bore and camera van. Figure 3.2 presents the jobsite layout for the spray-in-place pipe.

The most common equipment's typically required on jobsite are:

1. Lining Rig Truck that accommodates lining devices.
2. Equipment for excavation.
3. Cleaning equipment (Rack Feed Borer).
4. CCTV Truck.

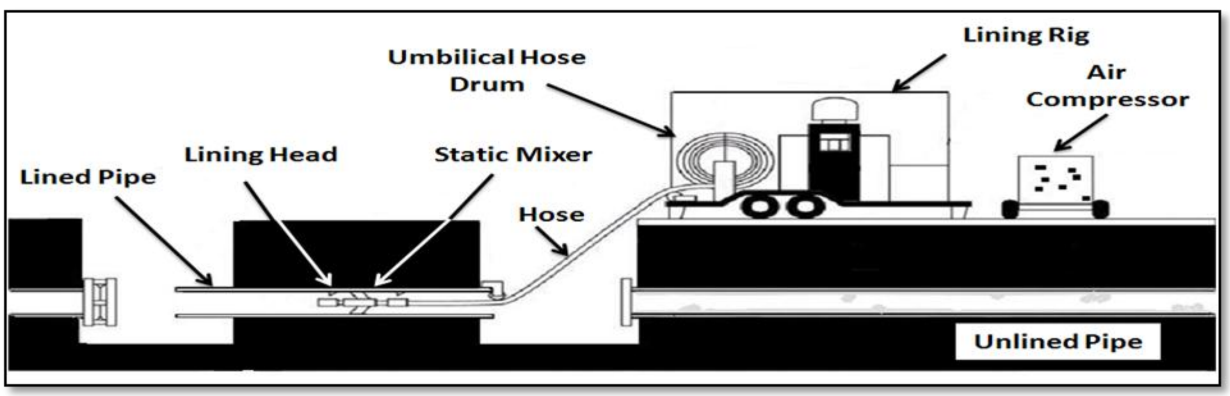

Figure 3.2: General Site Layout for Spray-in-place Pipe (Source: 3M Water Infrastructure)

3.3.3 Installation Process

The installation process for the SIPP is similar CIPP except steps 6 and 7 of the CIPP should be replaced by following steps:

- Lining Preparation - Verify lining mix ratio, material temperature, and pump output as required by liner manufacturer.
- Lining Installation - Monitor the flow rate and the retrieval speed of the spray head. The speed of the spray head must be slow-enough to produce a uniform liner as required per specifications.

3.3.4 As-built Drawings and Documentations

These dimensions are supplied by the client in the form of drawings, videos etc. to be checked by the installer to ensure accuracy. Once this is achieved, the number of setups, and the lengths of the linings to be installed can be determined. The owner or the owner's representative should prepare the contract documents for the projects. These documents should be executed before the work begins.

3.4 Close-fit Pipe

Close-fit pipe (CFP) provides renewal of the water pipe by insertion of the polyethylene (PE) pipe inside the existing pipe by reducing the section of the PE pipe. The PE pipe is than inflated with air or water pressure that causes a close fit to the existing pipe.

3.4.1 Work Plan

The work plan of CFP is similar to the CIPP. The other elements should be considered in work plan. The following elements should be considered in work plan:

- Determine the length of string winch cable required through pipe.
- Determine the force required to pull-in HDPE pipe.
- Determine the equipment to be used to expand pipe.

Parallel operation: Lay and butt fuse entire length of HDPE pipe, position cross-section reduction machine, and pull HDPE pipe through the cross-section reduction machine. Once the cross-section is reduced, the HDPE is either immediately pulled into the existing pipe or set aside for installation into the existing pipe at a later time.

3.4.2 Work Space

The work space required for CFP varies widely from project to project. This is due to the change in the size of the equipments according to the diameter of the existing pipe to be renewed. The following equipment is typically required on the jobsite:

- Equipment truck,
- TV truck,
- Pick-up truck,
- Cleaning equipment (jet truck, winches, scrapers),
- Cross section reduction machine,
- Butt fusion machine,
- Forklift or other lifting device,
- Winch for pulling HDPE,
- Pumps & other miscellaneous items.

Not all of the above equipment is required at the same time; equipment is brought to the job site as needed. Figure 3.3 presents the jobsite layout for the close-fit pipe.

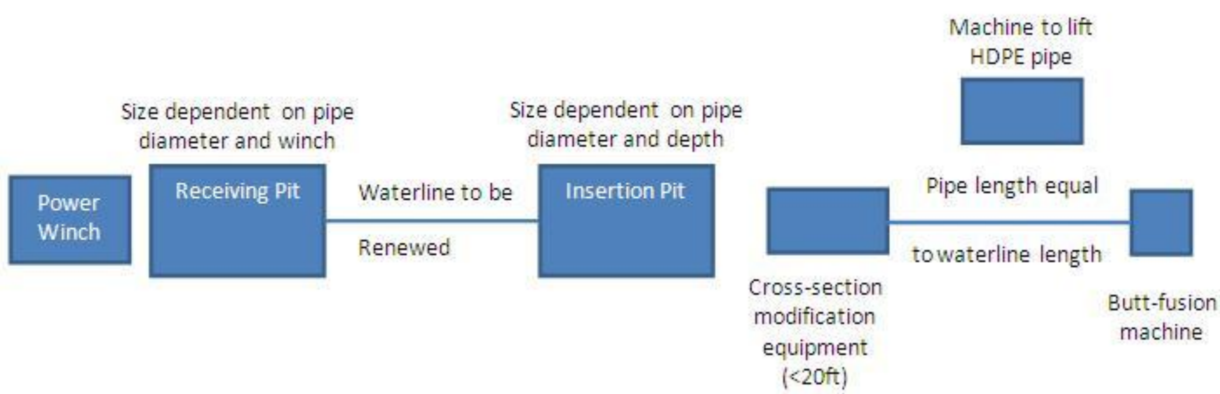

Figure 3.3: General Site Layout for Close-fit Pipe (Source: Insituform Technologies)

3.4.3 Installation Process

The installation process for the CFP is similar CIPP, except Steps 6 and 7 of the installations should be replaced by following steps:

- String the winch cable through the existing pipe.
- Pull-in the PE pipe which is reduced in section through the existing pipe.
- Expand the PE pipe with the use of high air or water pressure.

3.4.4 As-built Drawings and Documentations

The owner or the owner's representative typically prepares contract documents for the projects. These documents are executed before work begins. As-built drawings are sometimes provided for the current system; often these as-built drawings have to be corrected and updated with the current close-fit work. Documentation may include the pre- and post-video files and results of the disinfection testing.

3.5 Sliplining

Sliplining (SL) provides renewal of the water pipe by the insertion of polyethylene or PVC liner pipe into the existing pipe. The liner should be continuous and watertight. Refer to Section 3.4 for Close-fit pipe for Work Plan, Work Space and Installation Process. Figure 3.4 presents the jobsite layout for the sliplining.

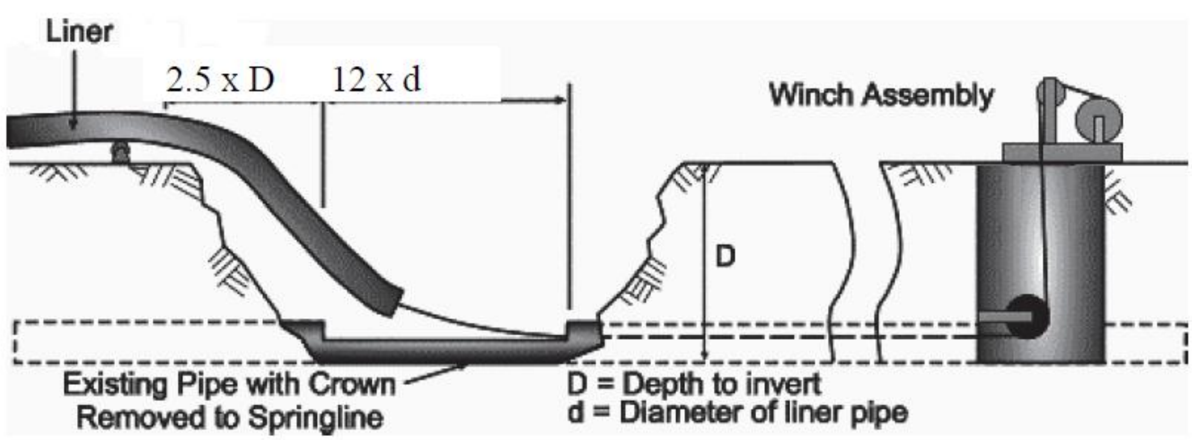

Figure 3.4: General Site Layout for Sliplining (Source: Plastic Pipe Institute)

<u>3.6 Thermoformed Pipe</u>

Thermoformed Pipe (ThP) provides renewal of the water pipe by the insertion of a folded, flexible liner into the host pipe. The liner is re-rounded using steam and air pressure. The finished product is a jointless liner that is formed to the existing pipe. For work plan, work space and installation process of ThP refer to Section 3.2 of CIPP.

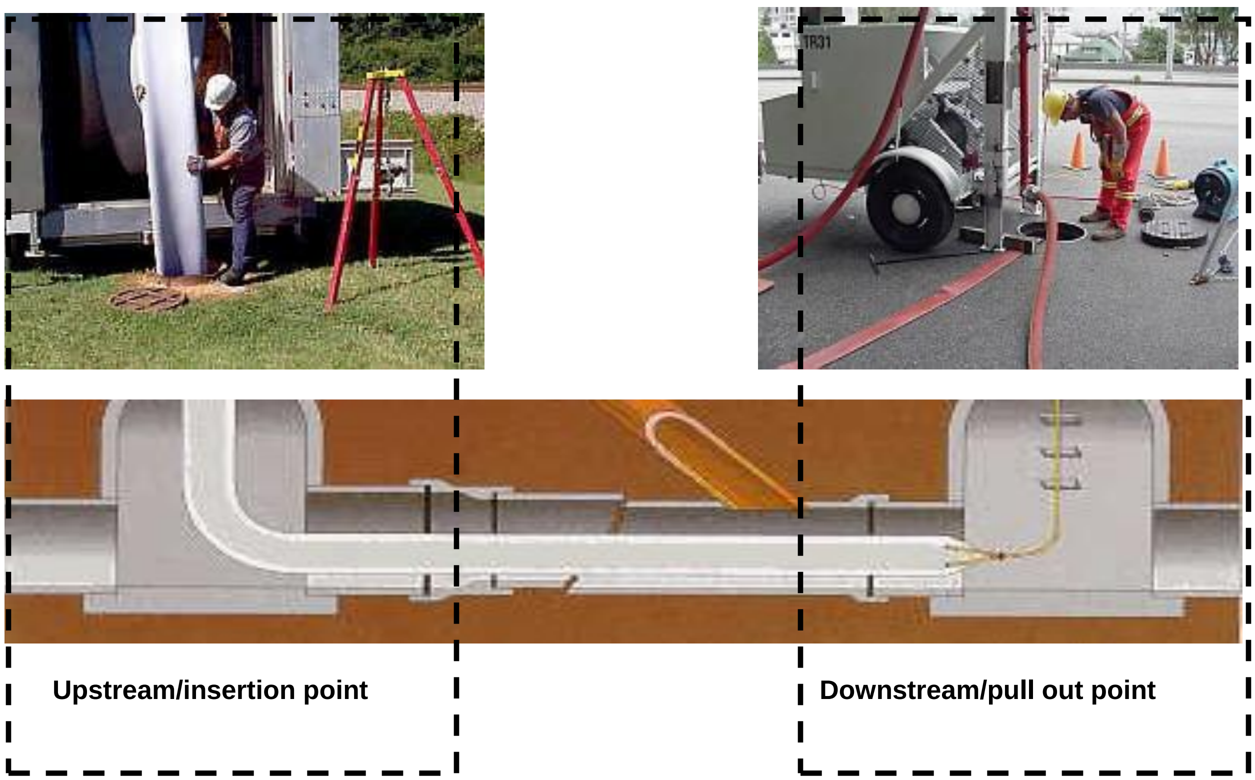

Figure 3.5: General Site Layout for Thermoformed Pipe (Source: Ultraliner Inc.)

3.6.1 As-built Drawings and Documentations

Thermoformed liner reel number is recorded to track all the manufacturing data (such as pipe wall thickness, extruding temperature and pressure, and all required test data in the relevant ASTM standards). Since onsite installation process does not change material properties of thermoformed liner, onsite QA/QC sampling is not necessary. However, if it is required in the specifications, onsite sampling and testing data need to be documented. CCTV videos for pre and post installation are normally required.

3.7 Inspection and Monitoring

The main objective of pipe inspection is to examine the condition of the existing pipe before and after liner installation. Closed-circuit television (CCTV) is usually the method of choice to inspect the interior of water pipes and also to evaluate quality of installed pipe. Valves, water hydrants or other appropriate locations maybe used as inspection insertion points (Najafi, 2010).

3.7.1 Pre-lining Inspection

The purpose of a pre-lining inspection is to ensure a successful liner installation. This inspection provides a good idea of the degree of cleaning required to prepare the host pipe before the start of a lining operation. A pre-lining inspection may also reveal the need for other forms of preparations required before lining, such as removal of protruding lateral service connections. The state or presence of the following issues may be revealed during the pre-lining inspections:

- Leaking valves and ferrules.
- Leaking stop taps.
- Dropped joints.
- Protruding ferrules.
- Structural problems (cracks, holes, and so on).
- Cleaning and possibilities for re-cleaning requirements.
- Pipe bends that can affect cleaning and lining processes.

3.7.2 Post-lining Inspection

The post lining inspection should include the information of the new lining installed in the existing pipe. The contractor should submit final inspection and testing results before requesting final payment.

3.8 Disinfection

Disinfecting of water pipes after renewal is generally required. There are four main types of disinfection methods as described below:

3.8.1 Tablet Method

AWWA C-651 recommends the use of an average chlorine content of $2.08 \times 10^{-4} – 1.25 \times 10^{-3}$ lb/gal (25 – 150 mg/L) for duration of 24 – 72 hours. Preferably, disinfection should be carried out overnight, however, not on a day before the weekend or holidays.

3.8.2 Continuous Feed Method

According to AWWA C-651, the chlorine may be added in the form dissolved calcium hypochlorite, sodium hypochlorite, liquid chlorine or chlorine gas. Among these, dissolved chlorine gas offers the “best” disinfection; however, environmental concerns and regulations have made this option less desirable. The concentrations vary from $2.08 \times 10^{-4} – 5 \times 10^{-4}$ lb/gal (25 – 60 mg/ L) for durations of 24 – 72 hours.

3.8.3 Slug Method

This method is generally used in conjunction with the tablet method. After the tablet method is completed and flushed, a heavy concentrated slug of chlorine is added to the pipe and slowly forced through the system. The concentration of the slug is monitored during disinfection and if the free chlorine residual drops below 4.17×10^{-4} lb/gal (50 mg/L), additional amount of chlorine is added. Several utilities use this method at a concentration of $2.5 \times 10^{-3} – 4.17 \times 10^{-3}$ lb/gal (300 – 500 mg/L). Disposal and treatment of the heavily chlorinated water can become a problem with Slug Method (AWWA, 2005).

3.8.4 Ozonation

Ozone being an unstable molecule of oxygen, readily gives up one atom of oxygen providing a powerful oxidizing agent which is toxic to most waterborne organisms. Ozonation is an effective method to inactivate harmful protozoan’s forming cysts. This method also works well against almost all other pathogens. Ozone gas is prepared by passing oxygen through ultraviolet light or using a “cold” electrical discharge. To use ozone as a disinfectant, it must be created on-site and bubbled through the water.

3.9 Project Closeout/Delivery, Clean-up and Restoration

3.9.1 Reconnecting Water Mains

Fittings, valves, and fire hydrants should be drained, capped, and stored as part of liner installation preparation. After lining installation, it is necessary to support heavy valves (12 in. or 300 mm and larger), with treated timbers, crushed stone, concrete pads, or a thoroughly tamped trench bottom.

All valves should be inspected upon reconnection to ensure proper working order after installation. Valves should be set and jointed to a pipe in the manner as set forth in the AWWA Standards for the type of connection ends furnished. All valves and appurtenances should be installed true to alignment and rigidly supported. Any damage to the above items shall be repaired or replaced before they are installed.

Hydrants should be connected to the pipe as per the original location with proper thrust blocking. Hydrant should be installed in a manner which will provide complete accessibility and minimum possibility of damage from vehicles or injury to pedestrians. The outside of the hydrant above the finished ground line and hydrant concrete pad should be thoroughly cleaned to remove all dirt, dust, and debris.

3.9.2 Surface Restoration & Site Clearing

When the work is completed, additional pieces of pipe, extra fittings, tools, and incidental materials, which include debris and excess spoil material should be removed from the jobsite or right-of-way. All undamaged walkways and pavements should be cleaned. All grass areas must be reseeded and replaced with sod, shrubs, trees, and other plants as per their original conditions or better. Damaged and removed pavement should be replaced according to the municipality, local government, or department of transportation (DOT) specifications and standards.

3.9.3 Waste Disposal

It is the responsibility of the contractor to be familiar with all the regulations for handling and disposing of the lining materials and chemicals. For example, the unused spillage and waste materials must be immediately disposed of, uncured material in an industrial or commercial facility should be incinerated or, as a disposal alternative, uncured waste product should be disposed of in a facility permitted to accept chemical waste.

The contractor is responsible for assuring that all permits and other types of disposal documentation are completed and distributed as required by regulatory agencies. Since regulations vary, consult applicable federal, state, and local regulations before disposal.

3.10 Safety Issues

The contractor is responsible for safety on the jobsite. Safety should be covered according to the relevant Occupational Safety and Health Administration (OSHA) standards. Special attention should be paid for safety of workers, pedestrians, and the traveling public during the entire pipe renewal project. Common safety issues may include trench and pit shoring (if required), vehicular traffic, existing utilities, and overhead power lines (Najafi, 2007). Table 3.1 presents the comparison of work elements for trenchless renewal methods.

Table 3.1: Comparison of Work Elements for Trenchless Renewal Methods

Methods / Elements	Cured-in-place Pipe (CIPP)	Spray-in-place Pipe (SIPP)	Close-fit Pipe (CFP)	Thermoformed Pipe (ThP)	Sliplining (SL)
Method Description	Renew the existing water pipe by installation of resin impregnated flexible tube	Renew the existing water pipe by spraying the interior of the pipe	Renew the existing water pipe by insertion of reduced cross section of polyethylene pipe	Renew the existing water pipe by installation of polyester reinforced polyethylene (PRP)	Renew the existing water pipe by insertion of polyethylene or PVC pipe
References, Specifications and Publications	ASTM F 1216 ASTM F 1743	ASTM F 1216 ANSI/AWWA C210 ANSI/AWWA C222 ANSI/AWWA C620	PPI Handbook of Polyethylene Pipe AWWA M28	AWWA M28	PPI Handbook of polyethylene pipe
Access and Exit Pit Dimensions	Insertion and Receiving Pit: 6' x 12', possibly at valves and hydrants locations	Insertion and Receiving Pit: 5' x 7', possibly at valves and hydrants locations	Insertion and Receiving Pit: dependent on pipe diameter and depth	Insertion and Receiving Pit: size of the normal manhole	Insertion and Receiving Pit: Width: slightly wider than the liner Length: 2.5xD+12xd where, D = Depth of the invert d = diameter of liner

Table 3.1 - Continued

Methods / Elements	Cured-in-place Pipe (CIPP)	Spray-in-place Pipe (SIPP)	Close-fit Pipe (CFP)	Thermoformed Pipe (ThP)	Sliplining (SL)
Required Equipment	1. Refrigerated truck 2. Boiler truck 3. Equipment truck 4. CCTV truck 5. Pick-up truck 6. Cleaning equipment (jet truck, winches, scrapers) 7. Installation device for inversion of CIPP 8. Forklift or other lifting device Pumps & other miscellaneous items	1. Lining Rig Truck that accommodates lining devices. 2. Equipment for excavation. 3. Cleaning equipment (Rack Feed Borer).CCTV Truck. 4. Pumps & other miscellaneous items.	1. Equipment truck 2. CCTV truck 3. Pick-up truck 4. Cleaning equipment (jet truck, winches, scrapers) 5. Cross section reduction machine 6. Butt fusion machine 7. Forklift or other lifting device 8. Winch for pulling HDPE Pumps & other miscellaneous items	1. Refrigerated truck 2. Boiler truck 3. Equipment truck 4. CCTV truck 5. Pick-up truck 6. Cleaning equipment (jet truck, winches, scrapers) 7. Winch for pulling of lining Pumps & other miscellaneous items	1. Equipment truck 2. CCTV truck 3. Pick-up truck 4. Cleaning equipment (jet truck, winches, scrapers) 5. Butt fusion machine 6. Winch for pulling of HDPE Pumps & other miscellaneous items
Installation Process	1. Set up traffic control 2. Access the pipe 3. Set-up bypass service lines 4. Open the pipe 5. Clean the pipe 6. Inspect the pipe (pre-CCTV) 7. Locate, shut off and plug service connections	1. Set up traffic control 2. Access the pipe (location not more than 500-ft apart) 3. Open the pipe 4. Clean the pipe 5. Inspect the pipe (pre-CCTV) 6. Locate, shut off	1. Set up traffic control 2. Access the pipe 3. Set up bypass service lines 4. Open the pipe 5. Clean the pipe 6. Inspect the pipe (pre-CCTV) 7. Locate and shut off service	1. Set up traffic control 2. Access the pipe 3. Set-up bypass service lines 4. Open the pipe 5. Clean the pipe 6. Inspect the pipe (pre-CCTV) 7. Locate, shut off and plug service	1. Set up traffic control 2. Access the pipe 3. Set-up bypass service lines 4. Open the pipe 5. Clean the pipe 6. Inspect the pipe (pre-CCTV) 7. Locate, shut off and plug service

Table 3.1 - Continued

Methods / Elements	Cured-in-place Pipe (CIPP)	Spray-in-place Pipe (SIPP)	Close-fit Pipe (CFP)	Thermoformed Pipe (ThP)	Sliplining (SL)
	8. Install CIPP 9. Cure CIPP 10. Reinstate services 11. Inspect the CIPP (post-CCTV), 12. Connect renewed pipe to adjacent piping 13. Reset valves, fire hydrant connections or other appurtenances 14. Disinfect 15. Backfill excavations 16. Restore the surface	and plug service connections 7. Install SIPP 8. Inspect the SIPP (post-CCTV) 9. Reset valves, fire hydrant connections or other appurtenances 10. Disinfect 11. Backfill excavations. 12. Restore the surface	connections 8. String winch cable through pipe 9. Pull-in reduced cross-section of HDPE pipe 10. Expand pipe 11. Install end seals 12. Inspect the HDPE (post-CCTV) 13. Connect rehabilitated pipe to adjacent piping 14. Reset valves, fire hydrant connections or other appurtenances 15. Disinfect 16. Backfill excavation	connections 8. Install thermoform lining 9. Inflate the lining with air and then heat with steam 10. Reinstate services 11. Inspect the lining (post-CCTV), 12. Connect renewed pipe to adjacent piping 13. Reset valves, fire hydrant connections or other appurtenances 14. Disinfect 15. Backfill excavations	connections 8. Join the lengths of polyethylene pipe 9. Installation of liner 10. Reinstate services 11. Inspect the lining (post-CCTV), 12. Connect renewed pipe to adjacent piping 13. Reset valves, fire hydrant connections or other appurtenances 14. Fill the annular space with grout 15. Disinfect 16. Backfill excavations
Documentation and Drawings	1. Contract documents 2. Updated as-built drawings after the installation of the lining 3. Pre- and Post- installation video files 4. Results of the disinfection test 5. Test results from laboratory				
Cleanup	1. Complete the balance work 2. Reconnect water mains 3. Surface restoration and site clearing 4. Waste disposal				

Table 3.1 - Continued

<table>
<tr><th>Methods / Elements</th><th>Cured-in-place Pipe (CIPP)</th><th>Spray-in-place Pipe (SIPP)</th><th>Close-fit Pipe (CFP)</th><th>Thermoformed Pipe (ThP)</th><th>Sliplining (SL)</th></tr>
<tr><td>Inspection and Monitoring</td><td colspan="5">Closed Circuit Television or similar methods are used for Pre- and Post-Installation. Monitoring is mostly done by third party inspector.</td></tr>
<tr><td>Safety</td><td colspan="5">It should be covered according to the relevant Occupational Safety and Health Administration (OSHA) and local standards</td></tr>
<tr><td>Measurement and Payment</td><td colspan="5">The payment includes equipment, material, and labor, calculated on a per foot basis per pipe diameter in accordance with the unit prices contained in the contract. Payment should also include considerations for additional work such as bypass pumping, cleaning, pre- and post-CCTV, pit excavation and sheeting, shoring and/or bracing, reconstruction of access pit locations, safety, dust/erosion control, testing, site restoration, service connections and connections of appurtenances and all other work to provide a completed installation.</td></tr>
</table>

3.11 Chapter Summary

To evaluate the construction phase for the trenchless renewal methods, an interview was conducted with several industry experts. Interview results show that:

1. Close-fit pipe and sliplining usually requires more workspace than other methods of trenchless renewal. This is due to the use of HDPE fusion machine, and pipe cross-section reduction machine.
2. Method to clean the existing water pipe for a particular renewal method is necessary to include in the contingency plan.
3. CCTV is most popular method used for both pre- and post- inspection of the water pipes for all the trenchless renewal methods.
4. As-built drawings provided to the contractor should be corrected and updated with the current trenchless renewal method work.
5. Pre- and Post-inspection videos and any test conducted on the field or in the lab should be included in the documentations of the project.

CHAPTER 4

DECISION SUPPORT SYSTEM (DSS) AND COST MODULE (CM)

4.1 Introduction

A computerized tool is developed that helps the user to select the appropriate trenchless renewal method for the water distribution pipelines. This tool also gives the cost details for the selected TRM. Utility engineers and contractors alike must determine the best approach for carrying out best TRM for a particular project. This tool formulates and evaluates a proper TRM for a particular project based on a series of questions along with the database developed with the help of the interview conducted in Chapter 3. The database is presented in Appendix B of this thesis.

4.2 Logic for DSS and CM

The selection of the trenchless technology renewal method depends on the existing pipe characteristics, project conditions, surface and subsurface conditions, and capabilities and limitations of the method itself. Important factors concerning the techniques are cost and time requirements, as well as applicability. Figure 4.1 presents the logic behind the DSS and CM. The pipe problems that presented in this tool are grouped into structural, hydraulic, joint leaks and water quality (Deb, A.K. 2002). Table 4.1 also presents the renewal options presented by the tool on the basis of the input received from the types of problems. Further evaluation is done considering existing pipe and field characteristics (see Table 4.2), and appropriate trenchless renewal method(s) are then selected. Table 4.3 lists the trenchless renewal method available in the decision support system. The user can then proceed to cost module to perform a detailed cost estimation of the selected trenchless renewal method(s). The cost module provides a method to calculate present worth and equivalent uniform annual cost analysis of each technology. The model helps the user to select the most suitable and economical trenchless renewal method for a project.

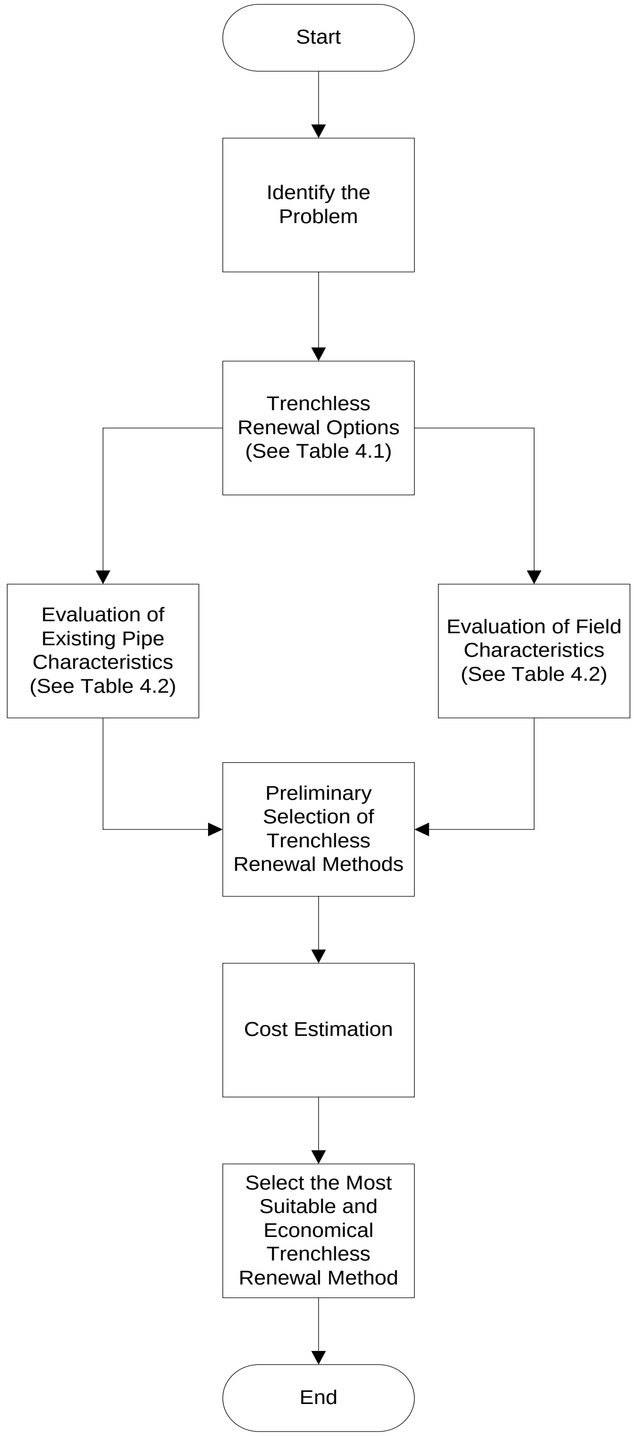

Figure 4.1: Logic Diagram for Decision Support System (DSS) and Cost Module (CM)

Table 4.1: Trenchless Renewal Option Categories

No.	Categories
1	Replace the pipe with Larger Diameter
2	Point Source Repairs
3	Non-structural Liner (Class I Lining)[5]
4	Semi-structural Liner (Class II and III Lining)[6]
5	Structural Liner (Class IV Lining)[7]

Table 4.2: Existing Pipe and Field Characteristics

No.	Categories
1	Existing Pipe Material
2	Existing Pipe Diameter
3	Renewal Length
4	Soil Conditions
5	Hydrocarbons
6	Water Table
7	Water alkalinity
8	Water pH
9	Work Space
10	Existing Pipe Misalignment
11	Angle of Bend

[5] Non-structural Liner (Class I Lining) - The liner protects the inner surface of the existing pipe from corrosion. The liner has minimal capability to bridge any existing discontinuities. It does not provide any structural enhancement.
[6] Semi-structural Liner (Class II & III Lining) – The long-term burst strength of the liner is less than the maximum operating allowable pressure (MAOP) of the existing pipeline. However, it is designed to bridge holes and gaps.
[7] Structural Liner (Class IV Lining) – The long term burst strength of this liner is more than or equal to the maximum operating allowable pressure (MAOP) of the existing pipeline. It is basically a new pipe within the existing pipe.

Table 4.3: Trenchless Renewal Methods

Replace the Pipe with the larger diameter	**Non-structural Liner (Class I & II Lining)**	**Semi-structural Liner (Class III Lining)**	**Structural Liner (Class IV Lining)**	**Point Source Repairs**
• Pipe bursting[8] • Open-cut Method	• Cement Mortar Lining • Epoxy Lining	• Cured-in-Place Pipe • Polyurea Lining • Polyurethane Lining	• Cured-in-place Pipe • Close-fit Pipe • Sliplining • Thermoformed Pipe	• Chemical Gel Grouts, Cement Based Grouts • Epoxy Resins, Cement Mortar • Internal Seal • Point CIPP

4.3 Decision Support System (DSS)

As said earlier, the decision support system presented in the Figure 4.2 provides the appropriate trenchless renewal method(s) for a particular project on the basis of the existing pipe and field characteristics. In decision support system the technology knowledge of the particular trenchless renewal method is also used. The DSS formulates the most appropriate trenchless renewal method with the help of the following five steps:

1. Identify problems in existing water distribution pipe.
2. Evaluate flow of existing water distribution pipe.
3. Generate trenchless renewal option categories.
4. Evaluate existing pipe and field characteristics.
5. Generate the option (s) for trenchless renewal method(s).

[8] Pipe bursting is a trenchless replacement method. This method is used when a new pipe of same or larger diameter is installed in the place of the existing pipe with breaking the existing pipe and pulling and/or pushing a new pipe. This method is more applicable when the existing pipe is fully deteriorated and/or has insufficient hydraulic capacity. For more information refer to Najafi (2010).

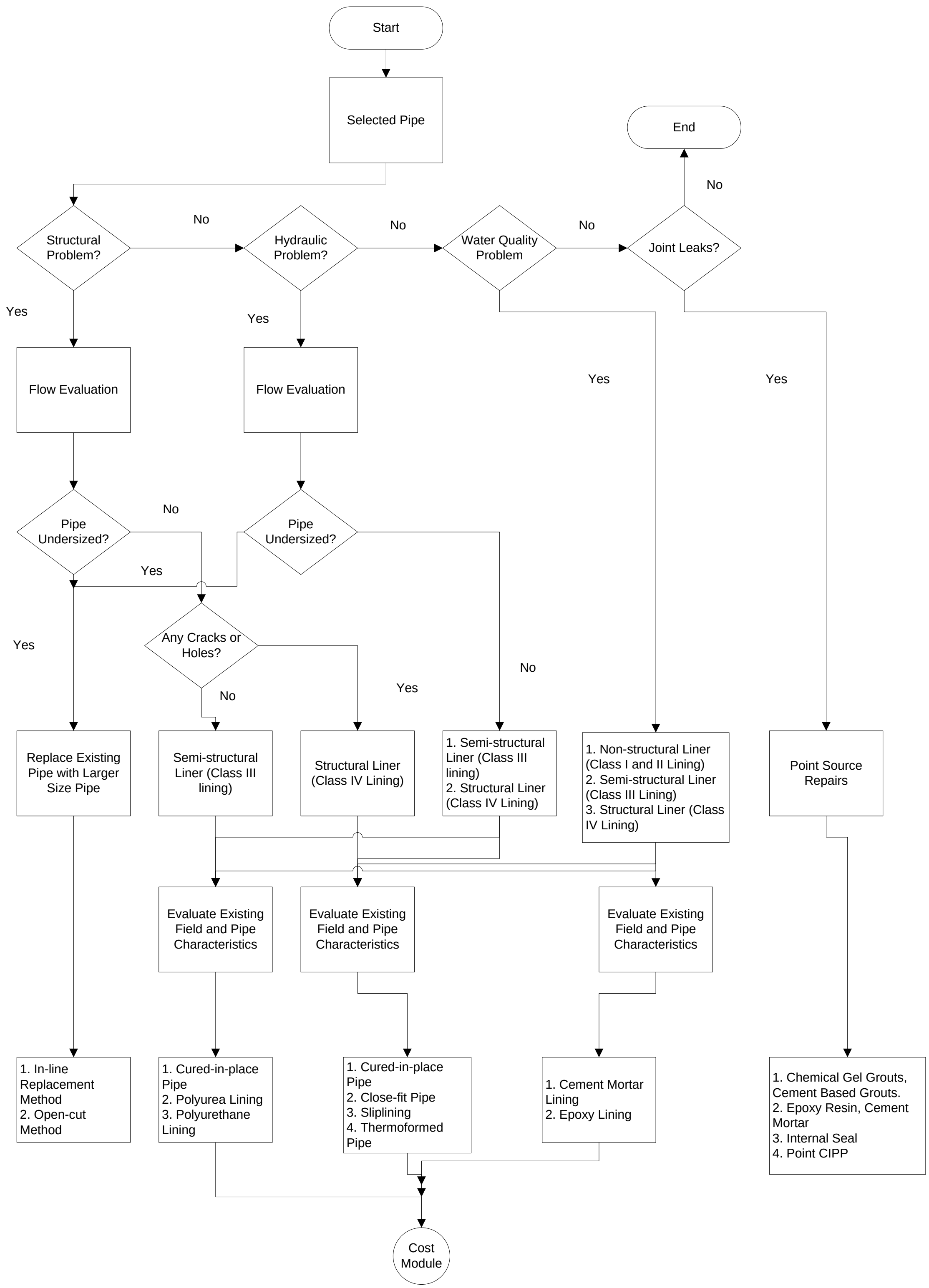

Figure 4.2: Flow Diagram to Formulate Trenchless Renewal Method for Water Pipes (Adapted: Najafi, 2010)

4.3.1 Identify Problems in Existing Pipe

Once the pipe is selected for the renewal, the problems associated with pipe are evaluated in order to determine the type of trenchless renewal options that are available for the pipe. In the DSS, the problems for a pipe are broadly classified into four categories as follows:

1. Structural problems.
2. Hydraulic problems.
3. Water quality problems.
4. Joint leaks.

The DSS follows the hierarchical structure with the most serious pipe problems being addressed first and any remaining problems associated with the pipe will be covered by default (Deb, 2002). For example, addressing the structural problems will automatically address the problems related to hydraulic problems, water quality and joint leaks. Figure 4.3 illustrates the problem description screen.

Project Name:		
Problem Description		
1	Structural Problems	Yes
2	Hydraulic Problems	No
3	Joint Leaks	No
4	Water Quality Problem	Yes
	Go to Sheet	**Flow Evaluation**

Figure 4.3: Problem Description Screen

4.3.2 Evaluate Flow of Existing Pipe

If the problem associated with the pipe is structural or hydraulic, user is prompted to do a flow evaluation. Figure 4.4 shows the flow evaluation screen. The flow evaluations of the existing pipe in its original and renewed condition are estimated from the Hazen-Williams formula as follows (Deb, 2002):

$$Qe = 1.318\left(\frac{\pi D_e^2}{4}\right)Ce\left(\frac{D_e}{4}\right)^{0.63}S^{0.54} \quad (4.1)$$

and

$$Qd = 1.318\left(\frac{\pi D_d^2}{4}\right)C_d\left(\frac{D_d}{4}\right)^{0.63}S^{0.54} \quad (4.2)$$

and

$$Qr = 1.318\left(\frac{\pi D_r^2}{4}\right)C_r\left(\frac{D_r}{4}\right)^{0.63}S^{0.54} \quad (4.3)$$

Where

Q_{e},= Flow in Existing Pipe (cfs)

$Q_{d\,=}$ Flow in Deteriorated Pipe (cfs) and

Q_r = Flow in Renewed Pipe (cfs)

D = diameter (ft)

C = Hazen-Williams C-Value

S = hydraulic grade slope

e = existing pipe condition

d = deteriorated pipe condition

r = renewed condition

The following equations are obtained from the Eqs. (4.1), (4.2) and (4.3):

$$\frac{Q_d}{Q_e} = \left[\frac{D_d}{D_e}\right]^{2.63}\left[\frac{C_d}{C_e}\right] \quad (4.4)$$

and

$$\frac{Q_r}{Q_e} = \left[\frac{D_r}{D_e}\right]^{2.63} \left[\frac{C_r}{C_e}\right] \quad (4.5)$$

Eq. (4.4) will display the reduction of the flow capacity of the pipe from its original (new) stage. Eq (4.5) will display the increase in the flow capacity if pipe when it is renewed. It helps the user to decide which trenchless renewal option is most suitable based on hydraulic capacity.

Existing Pipe			
1	Existing pipe material at the time of installation	Cast Iron	
2	C- value of the existing pipe when it was installed (Ce)	130.00	
3	Diameter of the existing pipe (De)	4.00	in.
4	C-value of the pipe in its current (deteriorated) condition (Cd) (measured by the flow test in field)	90.00	
Renewed Pipe			
5	Expected C-Value of the renewed pipe (less than 150)	140.00	
6	Diameter of renewed pipe	4.00	in.
Flow Evaluation			
7	% of original flow capacity for the existing pipe	69.23	
8	% of original flow capacity for the renewed pipe	107.69	
9	Is the Pipe Undersized?	No	
10	If Q 9 is No, Does the Pipe have Holes and Cracks?	No	
	Go to Sheet	Trenchless Renewal Options	

Figure 4.4: Flow Capacity Evaluation Screen

4.3.3 Generate Trenchless Renewal Options

On the basis of flow evaluation the DSS will suggest one or multiple trenchless renewal options. The trenchless renewal options include: Replace the pipe with larger diameter, point source repairs, non-structural liner (Class I and/or Class II linings), semi-structural liner (Class III lining), and structural liner

(Class IV lining). Select one of the trenchless renewal methods if multiple trenchless renewal methods are displayed. Figure 4.5 shows trenchless renewal options categories screen.

Trenchless Renewal Options:	**Semi-Structural Liner**
Select One Trenchless Renewal Option:	**Semi-Structural Liner (Class III Lining)**
Go to Sheet	**Additional Project Information**

Figure 4.5: Trenchless Renewal Options Categories Screen

4.3.4 Evaluate Existing Pipe and Field Characteristics

Once the trenchless renewal option is selected, the DSS will ask additional 11 questions related to more detailed aspects of existing pipe and project characteristics. This feature will provide a tool to formulate one or multiple trenchless renewal methods for parameters selected. Figure 4.6 presents the screen for pipe and field characteristics.

Existing Pipe and Field Characteristics		
Renewal Length?	1,000.00	ft
Angle of Bend?	45.00	degree
Are Hydrocarbon present?	No	
Is the Pipe Misaligned?	No	
Loss of diameter by 10 %?	OK	
Cover depth to top of pipe?	5.00	ft
Site Conditions?	Hard Ground	
Water Table?	Low	
Work space?	Unrestricted	
Water pH?	>6	
Alkalinity ?	More than 55 mg/l as CaCO3	

Figure 4.6: Existing Pipe and Field Characteristics Screen

4.3.5 Generate Trenchless Renewal Methods

On the basis of parameters described above, such as flow evaluation and existing pipe and project characteristics, appropriate trenchless renewal method(s) is/are selected. Figure 4.7 shows the preferred renewal methods for the project.

Trenchless Renewal Method Applicable for this Project	**Cured-in-place Pipe**	**Polyurea Lining**	**Polyurethane Lining**	**N/A**
For Cost Summary of Above Mentioned TRMs Go to Sheet	**Project Information for CM**			

Figure 4.7: Preferred Renewal Methods Screen

4.4 Cost Module (CM)

The cost module plays an important role in the selection of the trenchless renewal method. It provides conceptual cost estimation for the selected trenchless renewal method. Figure 4.8 presents the flow diagram for the cost module. Once the renewal method is selected, the CM asks a series of questions related to the project, technology and maintenance information. This information along with the field and existing pipe characteristics and the series of cost spreadsheets for each category calculates the rough cost estimation of the project. It also calculates the present worth and the equivalent uniform annual costs for each selected technology. The CM consists of the flowing steps:

1. Compile project, technology and maintenance information.
2. Use cost module interface.
3. Generate cost summary.

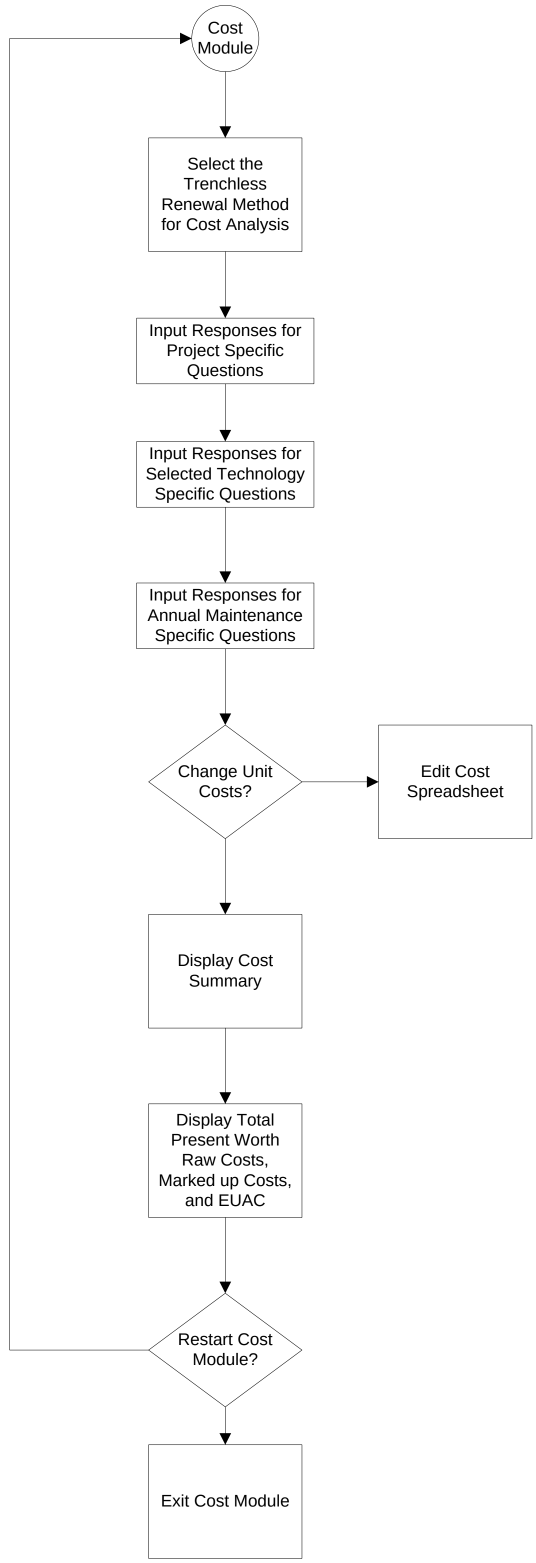

Figure 4.8: Flow Diagram for Cost Module

4.4.1 Project, Technology and Maintenance Information

Once the technology for renewal is selected for cost analysis, the user has to provide responses for a series of 35 questions. Figure 4.9 presents the screenshot for cost module – project preliminaries. These questions are divided into three categories:

1. Technology Specific: This considers thickness of liner, material of renewal pipe, flushing, cleaning, bypass, and traffic management requirements.
2. Project Specific: This includes estimated project duration, entrance and exit pit details, number of service connections to be excavated, excavation details of service pit, sheeting and shoring requirements, number of bends, number of isolation valves to be replaced and number of service connection valves to be replaced.
3. Maintenance Specific: These include number of years no maintenance is expected, annual maintenance cost, construction cost factors, and cost indexes.

Cost of Pipe Renewal			
	Select Trenchless Renewal Method	**Cured-in-place Pipe**	
Project Information for Cost Module (CM)			
1	Thickness of Cement Mortar Lining	-	in.
2	Renewal/Replacement Material for CFP and SL		
3	Is bypass required?	No	
4	Is traffic management required?	No	
5	Will native soil be used as backfill?	No	
6	Is flushing required?	No	
7	Estimated No. of Service Connections to be Excavated	-	
8	Length of Service Pit	3.00	ft

Figure 4.9: Cost Module – Project Preliminaries Screen

4.4.2 Cost Module Interface

Once the model receives all the responses to the questions, it calculates the cost estimation of the particular trenchless renewal method. This is done by a series of worksheets provided in the model for each category of the cost. The worksheets are provided in the Appendix B. The different categories of the costs are shown in Table 4.4

Table 4.4: Work sheet Names and Description (Adapted from Deb, A.K. 2002)

No.	Worksheet Name	Description
1	Unit Cost	Displays the unit cost for all the equipments, materials and labor.
2	Pre-construction Survey	Includes cost for surface survey, groundwater measurement, and flow testing
3	Mobilization and Demobilization	Includes cost associated with mobilization and demobilization for a trenchless renewal project
4	Site Preparation	Includes costs for clearing and grubbing of project site
5	Permit Fees	Includes all permitting cost associated with the project
6	Flushing	Includes the cost of labor and water used in the flushing process
7	Cleaning	Includes cleaning costs associated with mechanical, scraper, hydraulic scraper or pigs
8	Bypass	Includes costs for bypassing of water services including temporary bypass lines and ramping materials for driveways
9	Traffic Management	Includes costs for cones, barriers, direction signs and flagmen
10	Excavation – Entrance & Exit Pits; and Service Pits	Includes costs for trenching, sheeting and shoring, dewatering, disposal and pavement removal where necessary for applicable excavation sites
11	Reconnection – Water Mains and Service	Includes costs of reconnection for tapping service, fittings and valves
12	Restoration – Entrance & Ext Pits; and Service Pits	Includes costs for backfill, and pavement replacement for associated excavation
13	Pressure Test	Includes costs for equipment and personnel necessary to perform pressure test
14	Disinfection	Includes costs for equipment and chemicals necessary for disinfection
15	Renewal/Installation	Includes the costs associated with the actual installation/renewal technology selected.

4.4.3 Generate Cost Summary

Once the cost module interface is completed, a cost summary is generated. This gives the total cost calculations for the selected trenchless renewal method. Table 4.5 displays a sample cost summary worksheet for cured-in-place pipe. It displays the total cost of each cost category taken from worksheet mentioned in Table 4.4. The cost summary first displays the direct cost of the of trenchless renewal method calculated from the unit costs extracted from R.S. Means of 2009. This direct cost is adjusted by the user by entering the present year cost index and location index in cost specific question. Following equations are used for year and location adjustment:

$$Cost_A = \frac{Index_A}{Index_{1999}} \times Cost_{1999} \qquad (4.5)$$

where,

A = Year for which costs are being calculated

$Index_A$ = Cost index for year which costs are being calculated

$Index_{1999}$ = Cost index for 2009 = 182.8.

Similarly, the costs can be adjusted for different locations by multiplying the cost by ratio of the cost index for the desired location by national average cost index.

$$Cost_X = \frac{Index_X}{Index_N} \times Cost_N \qquad (4.6)$$

where,

X = Location for which cost are being calculated

$Index_X$ = Cost index for desired location

$Index_N$ = National average cost index

Once the direct cost is adjusted using the cost indexes, construction cost factor (contractor profit margin (%), project oversight (%), engineering design/support (%), legal and administrative fees (%) and contingency (%) entered. During this step, CM calculates the marked up costs for the project.

Once the total direct cost for selected trenchless renewal method is calculated, the associated O&M cost is calculated with the help of the inputs received in the first step of CM. The present worth (PW) cost of the O&M costs are calculated by the following equation:

$$P = A\left\{\frac{(1+i)^n - 1}{i(1+i)^n} \times \frac{1}{(1+i)^m}\right\} \qquad (4.7)$$

where

P = Present worth cost

A = Periodic (i.e., annual) uniform O&M cost

i = Interest rate

n = Number of periods (i.e., years) O & M cost are incurred

m = Number of initial periods (i.e., years) O&M costs are incurred

The present worth as calculated by equation 4.7 is added to the direct cost and marked up cost to get the total present worth of the project for direct cost and marked up cost. The equivalent uniform annual cost (EUAC) is calculated using the equation 4.8.

$$EUAC = P\left\{\frac{i\,(1+i)^{n+m}}{(1+i)^{n+m}-1}\right\} \qquad (4.8)$$

EUAC helps to compare the different trenchless renewal methods with different design lives. Tables 4.5, 4.6 and 4.7 present the detailed cost summary for cured-in-place pipe method. The prices shown in the tables *depend on the specific project and site conditions and may vary dependent on project specifics*. *The dark grey shaded cells are output variables while the light grey shaded cells are the input variables.* Figure 4.10 and 4.11 presents the cost breakdown for this renewal method on the basis of the percentage and cost.

Table 4.5: Cured-in-place Pipe Detailed Cost Summary[9]

No.	Description	Total Costs ($)	Equipment Costs ($)	Labor Costs ($)	Operating Costs ($)	Material Costs ($)	Disposal Costs ($)
1	Pre-Construction Survey	2,040	900	1,085	-	55	-
2	Mobilization/Demobilization	1,156	358	797	-	-	-
3	Site Preparation	1,092	511	570	-	-	10
4	Permit Fees	500	-	-	500	-	-
5	Flushing	576	208	343	-	25	-
6	Cleaning	3,197	743	778	-	25	1,650
7	Bypass Water Service	888	145	343	-	400	-
8	Traffic Management	404	164	240	-	-	-
11	Excavation - Entrance and Exit Pits	2,293	685	855	-	753	-
12	Excavation - Service Connections	187	56	74	-	-	55
13	Installation/Renewal	4,237	1,545	689	-	2,003	-
14	Reconnection Water Main	766	-	224	-	542	-
15	Reconnection Service	306	75	224	-	7	306
16	Restoration - Entry and Exit Pits	3,645	869	1,038	-	1,737	-
17	Restoration - Service Connections	178	72	86	-	19	-
18	Pressure Test	206	35	171	-	-	-
19	Disinfection	257	75	171	-	11	-
	Direct Costs	25,542	6,447	7,694	500	9,185	2,021
Direct Costs Adjusted for Year & Location		47,889	14,142	16,877	1,096	20,149	4,435
Direct Costs per foot – 48 $/foot							

9 Cost information in this table is for information only and may not apply in actual project conditions.

Table 4.6: Mark Up Cost for Cured-in-place Pipe

No.	Description	Value	Total
1	Contractor Profit & Overhead	10 %	$ 4,788
2	Legal and Administrative Fees	5 %	$ 2,394
3	Engineering Design/Support	15 %	$ 7,183
4	Contingency	10 %	$ 4,788
5	Markup[10] Subtotal	$ 19,153	-
6	Total Markup	$ 67,042	-
Markup Cost per foot - 82 $/foot			

Table 4.7: Annual Maintenance Costs for Cured-in-place Pipe

No.	Description	Value
1	Initial No. of Years Where No Maintenance Costs are Expected (m)	20
2	No. of Years Maintenance Costs will be Incurred (n)	50
3	Expected Annual Uniform Maintenance Costs (A)	1,000
4	Interest Rate (i) - From Input Sheet	7
5	Present Worth of O&M Costs (P)	$ 3,566
6	Total Project Present Worth Costs (Direct Costs)	$ 51,455
7	Total Project Present Worth Costs with Markup	$ 84,977
8	Equivalent Uniform Annual Costs (EUAC) (Direct Costs)	$ 3,633
9	Equivalent Uniform Annual Costs (EUAC) – with Markup	$ 6,001

[10] Markup includes contractor's profit, contingency and overhead.

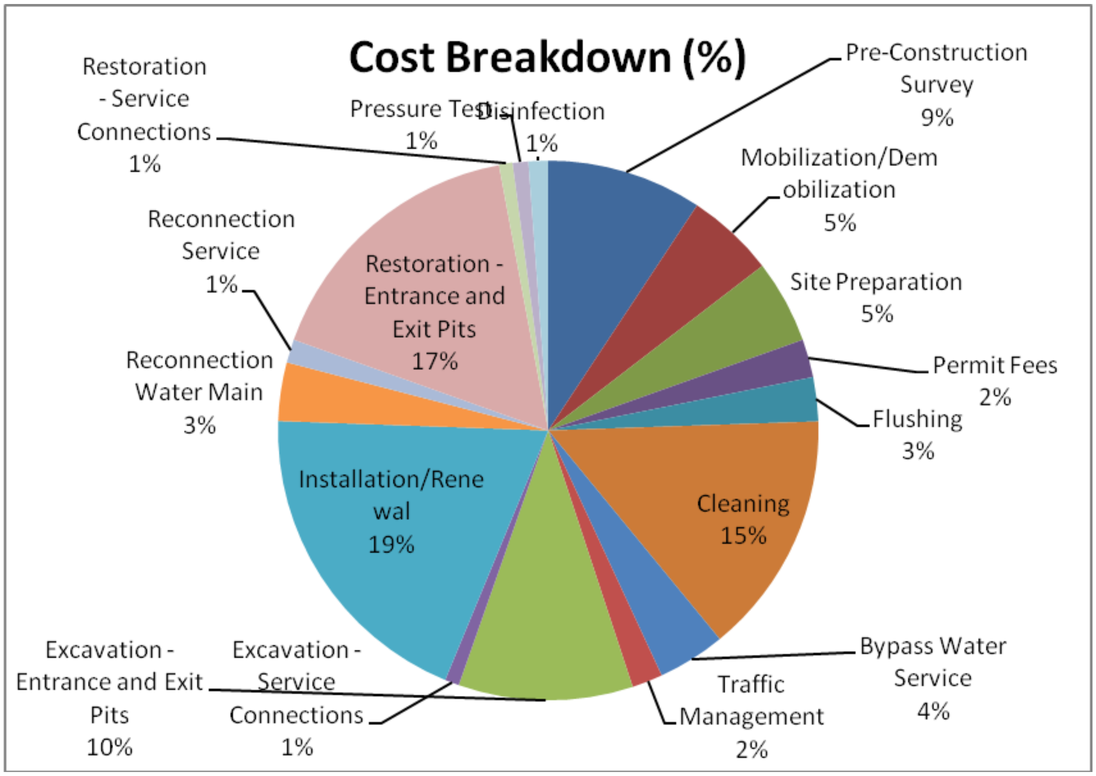

Figure 4.10: Cost Breakdown for Cured-in-place Pipe

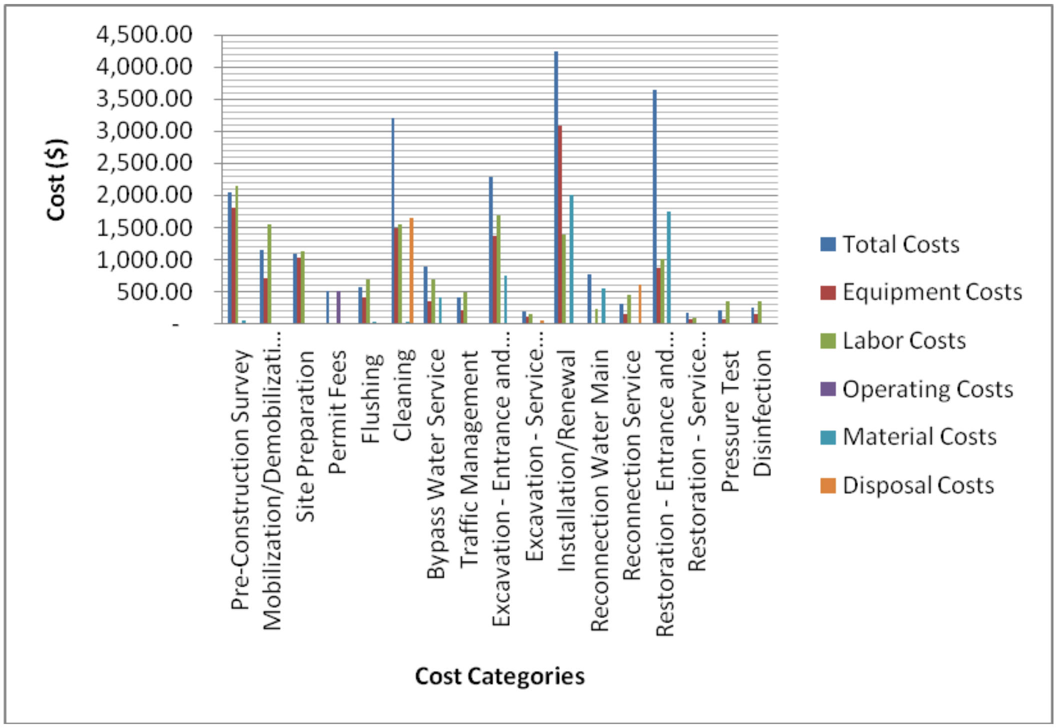

Figure 4.11: Cost Breakdown for Cured-in-place Pipe

4.5 Benefits of the Decision Support System (DSS) and the Cost Module (CM)

The main benefits of the DSS and CM are as follows:

1. It facilitates the selection of the most appropriate renewal technology for water pipes based on the existing pipe and field characteristics.
2. It provides the cost breakdown for each trenchless renewal method and also provides life cycle costs of the project by considering operation and maintenance costs. This information can be used to compare multiple trenchless renewal methods for same project.

4.6 Chapter Summary

This chapter described various components of the decision support system and the cost module. The decision support system helps the user to select an appropriate trenchless renewal method, while the cost module gives the detailed cost estimation of selected trenchless renewal method.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

5.1 Conclusions

This research described the current planning/construction procedures for trenchless renewal methods for water pipe distribution systems. Causes of water pipe deterioration with mechanisms of the failures were also described. These deterioration models were used to develop different criteria for the decision support system and cost module. A decision support system was developed that is useful for selection of a trenchless renewal method for water pipe systems. A cost module was developed to perform cost analysis for the selected trenchless renewal method from the decision support system.

Other conclusions of this thesis are summarized as follows:

1. Close-fit pipe usually requires more workspace than other methods of trenchless renewal. This is due to the use of the HDPE fusion and space need by the pipe cross-section reduction machine.
2. The contingency plan should include cleaning the existing water pipe as may be necessary for a particular renewal method.
3. CCTV is the most popular method used for both pre- and post- inspection of the water pipes for all trenchless renewal methods.
4. As-built drawings provided by the owner should be corrected and updated by the contractor with the current trenchless renewal method work.
5. Pre- and Post-inspection videos/DVDs and any tests conducted on the field or in the lab should be included in the documentations of the project.

Decision support system and cost module developed in this thesis are viable tools for the selection of the trenchless renewal method for a specific existing pipe and field characteristics. The cost module gives detailed analysis of the cost for a trenchless renewal method. These tools may be used by the utility owners, contractors, owners, designers and engineers to select the most suitable trenchless renewal method for their specific renewal project.

5.2 Recommendations for Future Research

Based on this study, the following recommendations for future research are proposed:

1. Develop the decision support system and the cost module for the trenchless construction methods (TCMs).
2. Expand the present decision support system and the cost module for point source repair, inline replacement methods, and open-cut methods.
3. Expand the decision support system to include social costs of a specific method based on advantages and limitations of different construction methods.

APPENDIX A

INTERVIEW QUESTIONNAIRE

CUIRE

The University of Texas ARLINGTON™

Evaluation of Trenchless Renewal Method for Potable Water Pipes
Construction Phase – Method Name

Personal Details:		
Respondent's Agency:		
Respondent's Name:		
Title:		
Address:		
City:	**State:**	**Zip code:**
Phone Number:	**Fax Number:**	
E – mail Address:		

1. What are the different elements that may be included in the **WORK PLAN** prior to installing the Cured-in-place pipe for the renewal of distribution and transmission water pipes?

2. What are the minimum requirements for the **WORK SPACE** while installing Cured-in-place pipe for distribution and transmission water pipes?

3. Please provide us with the sample **JOBSITE LAYOUT** of a typical Cured-in-place pipe installation for distribution and transmission water pipes. (Drawings, Data etc.)

4. What are the different elements that may be included in the **CONTINGENCY PLAN** prior to installing the Cured-in-place pipe for the renewal of distribution and transmission water pipes?

5. What is the different **INSPECTION AND MONITORING** methods used prior, during and post installation of the Cured-in-place pipe for distribution and transmission water pipes?

6. List the sample **DOCUMENTATIONS and DRAWINGS** required during the installation of the Cured-in-place pipe for the renewal of distribution and transmission water pipes.

7. What are the different requirements for **PROJECT-CLOSEOUT/DELIVERY** for renewal of distribution and transmission water pipes in Cured-in-place-pipe?

8. What are the **SAFETY** requirements during the installation of the Cured-in-place pipe for renewal of distribution and transmission water pipes?

9. Please feel free to include any more information about the construction phase not included in the above questions.

End

CUIRE

The University of Texas ARLINGTON™

Glossary:

Work Plan: A work plan outlines in specific detail how a project will be conducted. For example, elements included in the work plan for a pipe bursting project are traffic control, excavation and shoring, protection of adjacent structures and utilities, dewatering design, bypassing, supervision and inspection, public safety, spoil removal and scheduling, including work days and work hours.

Work space: the area required for safe operation of the equipment used in the renewal process of a water pipe.

Contingency plan: The contingency plan may include symptoms of problems, such as collapse of existing pipe while renewal, obstructions and unexpected interferences and so on.

Inspection and Monitoring: the various inspection and monitoring methods that may require for quality assurance and quality control of the installation of lining prior, during and post installation.

Documentations and Drawings: for example post lining test results, CCTV video recordings, as-built drawings, any documents used prior, during and after installation and so on.

Project Close-out and Delivery: list of the steps and actions necessary for a Project Closeout, once renewal operation is complete. The steps needed before the final payment is given to the contractor.

Safety: a partial checklist for safety that may be required for renewal of the water pipes. For example: material safety data sheet (MSDS), personal protection equipment (PPE) and so on.

APPENDIX B

SAMPLE COST WORKSHEETS

Table B.1: Pre-construction Survey Worksheet

Description	Quantity	Units	Unit Cost	Units	Total ($)
Equipment Costs					
Pickup truck 4x4	1	day	145.5	$/day	145.50
Video Camera	1	day	120	$/day	120.00
Misc. 1					
Labor Costs					
Field Technician	2	Person-day	171.6	$/Person-day	343.20
Misc. 1					-
Operating Costs					
Misc. 1					-
Misc. 2					-
Material Costs					
Misc. 1					-
Disposal Costs					
Misc. 1					-
Equipment Costs					
Geoprobe	1	day	500	$/day	500.00
Depth to water meter	1	day	50	$/day	50.00
Labor Costs					
Field Technician	1	Person-day	227.2	$/Person-day	227.20
Equipment Operator	1	Person-day	171.6	$/Person-day	171.60
Operating Costs					
Misc. 1					-
Material Costs					
Misc. 1					-
Disposal Costs					
Misc. 1					-
Locate Other Services					
Equipment Costs					
Metal Detector	1	day	30	$/day	30.00

Table B.1 - Continued

Description	Quantity	Units	Unit Cost	Units	Total ($)
Pipe/Utility Locator	1	day	30	$/day	30.00
Labor Costs					
Field Technician	1	Person-day	171.6	$/Person-day	171.60
Equipment Operator					-
Operating Costs					
Misc. 1					-
Material Costs					
Marking Paint and supplies	1	Lot	50	$/Lot	50.00
Misc. 1					-
Disposal Costs					
Misc. 1					-
C-Value Testing					
Equipment Costs					
Pilot tube/Pressure gauge assembly	0.5	day	50		25.00
Misc. 1					-
Labor Costs					
Laborer	1	Person-day	171.6	$/Person-day	171.60
Misc. 1					-
Operating Costs					
Misc. 1					-
Material Costs					
Water	1000	gallons	0.005	$/gallon	5.00
Misc. 1					-
Disposal Costs					
Misc. 1					-
User entered other cost					
Total Equipment Costs					900.50
Total Labor Costs					1,085.20
Total Operating Costs					-
Total Material Costs					55.00
Total Disposal Costs					-
Total Cost					2,040.70

Table B.2: Mobilization & Demobilization Worksheet

Description	Quantity	Units	Unit Cost	Units	Total ($)
Equipment Costs					
Flatbed Truck, 3 ton	2	day(s)	179.45	$/day	358.90
Misc. 1					-
Labor Costs					
Equipment Operator	2	Person-day	227.2	$/Person-day	454.40
Laborer	2	Person-day	171.6	$/Person-day	343.20
Misc. 1					-
Operating Costs					
Misc. 1					-
Material Costs					
Misc. 1					-
Disposal Costs					
Misc. 1					-
User entered other cost					
Total Equipment Costs					358.90
Total Labor Costs					797.60
Total Operating Costs					-
Total Material Costs					-
Total Disposal Costs					-
Total Cost					1,156.50

Table B.3: Site Preparation Worksheet

Description	Quantity	Units	Unit Cost	Units	Total ($)
Equipment Costs					
Brush Chipper, 6" cutter head, 35 hp	1	day	114.95	$/day	114.95
Chain Saw, 18" long, gas engine	1	day	27.3	$/day	27.30
Pickup Truck 4x4	1	day	145.5	$/day	145.50
Wheel Barrow	1	day	5	$/day	5.00
Rake with tractor	1	day	218.9	$/day	218.90
Misc 1					-
Labor Costs					
Equipment Operator	1	Person-day	227.2	$/Person-day	227.20
Laborer	2	Person-day	171.6	$/Person-day	343.20
Misc 1					-
Operating Costs					
Misc 1					-
Material Costs					
Misc 1					-
Disposal Costs					
Solids, nonhazardous	2	c.y.	5	$/c.y.	10.00
Misc 1					-
User entered other cost					
Total Equipment Costs					511.65
Total Labor Costs					570.40
Total Operating Costs					-
Total Material Costs					-
Total Disposal Costs					10.00
Total Cost					1,092.05

Table B.4: Permit Cost Worksheet

Description	Quantity	Units	Unit Cost	Units	Total ($)
Equipment Costs					
Misc. 1					-
labor Costs					
Misc. 1					-
Misc. 2					-
Operating Costs					
Permit fee	1	Permit	500	each	500.00
Material Costs					
Misc. 1					-
Disposal Costs					
Misc. 1					-
User entered other cost					-
Total Equipment Costs					-
Total Labor Costs					-
Total Operating Costs					500.00
Total Material Costs					-
Total Disposal Costs					-
Total Cost					500.00

Table B.5: Flushing Cost Worksheet

Description	Quantity	Units	Unit Cost	Units	Total ($)
Equipment Costs					
Pickup Truck 4x4	1	day	145.5	$/day	145.50
Pigs	1	day	10	$/day	10.00
3" Diaphragm pump	1	day	33.15	$/day	33.15
3" Suction pump	1	day	10	$/day	10.00
3" Discharge pump	1	day	10	$/day	10.00
Misc 1					-
Labor Costs					
Laborer foreman/supervisor	0	Person-day	187.6	$/Person-day	-
Laborer	2	Person-day	171.6	$/Person-day	343.20
Misc 1					-
Operating Costs					
Other					-
Material Costs					
Water	5000	gallons	0.005	$/gallon	25.00
Misc 1					-
Disposal Costs					
Water, non-hazardous	0	gallons	0.005	$/gallon	-
Solids, non-hazardous	0	c.y.	5	$/c.y.	-
Misc 1					-
User entered other cost					
Total Equipment Costs					208.65
Total Labor Costs					343.20
Total Operating Costs					-
Total Material Costs					25.00
Total Disposal Costs					-
Total Cost					576.85

Table B.6: Cleaning Cost Worksheet

Description	Quantity	Units	Unit Cost	Units	Total ($)
Equipment Costs					
Cleaning tool	1	day	35	$/day	35.00
Winch Truck	2	day	250	$/day	500.00
Jet Truck	0	day	300	$/day	-
Pickup Truck 4x4	1	day	145.5	$/day	145.50
Pigs	1	day	10	$/day	10.00
3" Diaphragm pump	1	day	33.15	$/day	33.15
3" Suction pump	1	day	10	$/day	10.00
3" Discharge pump	1	day	10	$/day	10.00
Misc. 1					-
Labor Costs					
Equipment Operator	2	Person-day	217.6	$/Person-day	435.20
Laborer	2	Person-day	171.6	$/Person-day	343.20
Misc. 1					-
Operating Costs					
Misc. 1					-
Material Costs					
Water	5000	gallons	0.005	$/gallon	25.00
Misc. 1					-
Disposal Costs					
Water, non-hazardous	5000	gallons	0.33	$/gallon	1,650.00
Solids, nonhazardous	0	c.y.	5	$/c.y.	-
Misc. 1					
User entered other cost					
Total Equipment Costs					743.65
Total Labor Costs					778.40
Total Operating Costs					-
Total Material Costs					25.00
Total Disposal Costs					1,650.00
Total Cost					3,197.05

Table B.7: Bypass Cost Worksheet

Description	Quantity	Units	Unit Cost	Units	Total ($)
Equipment Costs					
Pickup Truck 4x4	1.00	day	145.50	$/day	145.50
2" Centrifugal booster pump	-	day	25.15	$/day	-
Misc. 1					
Labor Costs					
Laborer	2.00	Person-day	171.60	$/Person-day	343.20
Operating Costs					
Misc. 1					-
Misc. 2					-
Material Costs					
Ramping Material	-	s.y.	0.56	$/s.y.	-
Temporary Fire Hydrant	-	Each	1,085.00	$ each	-
6" Bypass Line	-	ft	6.00	$/ft	-
4" Bypass Line	-	ft	4.00	$/ft	-
2" Bypass Line	100.00	ft	3.00	$/ft	300.00
1" Bypass Line	100.00	ft	1.00	$/ft	100.00
Misc. 1					-
Disposal Costs					
Misc. 1					-
Misc. 2					-
User entered other cost					
Total Equipment Costs					145.50
Total Labor Costs					343.20
Total Operating Costs					-
Total Material Costs					400.00
Total Disposal Costs					-
Total Cost					888.70

Table B.8: Traffic Management Cost Worksheet

	Quantity	Units	Unit Cost	Units	Total ($)
Equipment Costs					
Safety Equipment	2.00	lot	2.00	$/lot-day	4.00
Barriers with flashers	4.00	day	10.00	$/day	40.00
Cones	50.00	day	1.00	$/day	50.00
Direction signs with posts	4.00	day	10.00	$/day	40.00
Arrow Boards	2.00	day	15.00	$/day	30.00
Misc 1					-
Labor Costs					
Flagman	2.00	Person-day	120.00	$/Person-day	240.00
Police	-	Person-day	185.00	$/Person-day	-
Misc 1					-
Operating Costs					
Misc 1					-
Material Costs					
Misc 1					-
Disposal Costs					
Misc 1					-
Misc 2					-
User entered other cost					
Total Equipment Costs					164.00
Total Labor Costs					240.00
Total Operating Costs					-
Total Material Costs					-
Total Disposal Costs					-
Total Cost					404.00

Table B.9: Excavation Cost Worksheet

	Entrance/Exit Pit Excavation Cost Worksheet							Service Pit Excavation Cost Worksheet				
	Description	**Quantity**	**Units**	**Unit Cost**	**Units**	**Total**		**Quantity**	**Units**	**Unit Cost**	**Units**	**Total**
	Equipment Costs											
	Pavement Saw	0.25	day/pit	110.65	$/lot-day	27.66		0.0625	day/pit	110.65	$/lot-day	6.92
	Dump truck (12 ton)	0.25	day/pit	364.30	$/day	91.08		0.0625	day/pit	364.3	$/day	22.77
	Backhoe loader (80 hp)	0.25	day/pit	290.10	$/day	72.53		0.0625	day/pit	290.1	$/day	18.13
	2" Diaphragm suction pump	-	day/pit	29.15	$/day	-		0	day/pit	29.15	$/day	-
	2" suction line	-	day/pit	6.50	$/day	-		0	day/pit	6.5	$/day	-
	2" Discharge line	-	day/pit	8.80	$/day	-		0	day/pit	8.8	$/day	-
	Pickup Truck 4x4	0.25	day/pit	145.50	$/day	36.38		0.0625	day/pit	145.5	$/day	9.09
	Misc. 1											
	Labor Costs											
	Equipment operator	0.50	Person-day/pit	227.20	$/Person-day	113.60		0.1875	Person-day/pit	227.2	$/Person-day	42.60
	Laborer	0.75	Person-day/Pit	171.60	$/Person-day	128.70		0.1875	Person-day/Pit	171.6	$/Person-day	32.18
	Misc. 1					-						-
	Operating Costs											
	Misc. 1					-						-
	Material Costs											
	Steel Plate - 1" thick	2.00	each	35.50	$/each	71.00		-	each	-	$/each	-
	Misc. 1					--						-
	Disposal Costs											

Table B.9 - Continued

	Entrance/Exit Pit Excavation Cost Worksheet							Service Pit Excavation Cost Worksheet				
	Description	**Quantity**	**Units**	**Unit Cost**	**Units**	**Total**		**Quantity**	**Units**	**Unit Cost**	**Units**	**Total**
	Trench Material - entrance	-	c.y./pit	20.00	$/c.y.	-		2.7777	c.y./pit	20	$/c.y.	55.56
	Trench Material - exit	-	c.y./pit	20.00	$/c.y.	-			c.y./pit		$/c.y.	-
Sheeting and Shoring Cost Worksheet												
		Quantity	Units	Unit Cost	Units	Total						
	Equipment Costs											
	Ladder - 6 foot	0.25	day/pit	3.25	$/day	0.81						
	Misc. 1					-						
	Labor Costs											
	laborer	0.25	Person-day/Pit	171.60	$/Person-day	42.90						
	Operating Costs											
	Misc. 1					-						
	Material Costs											
	Trench bracing - entrance	9.00	feet/pit	10.00	$/foot	90.00						
	Trench bracing - exit	9.00	feet/pit	10.00	$/foot	90.00						
	Misc. 1					-						
	Disposal Costs											
	Misc. 1					-						

Table B.9 - Continued

Entrance/Exit Pit Excavation Cost Worksheet							Service Pit Excavation Cost Worksheet				
Description	**Quantity**	**Units**	**Unit Cost**	**Units**	**Total**		**Quantity**	**Units**	**Unit Cost**	**Units**	**Total**
User entered other cost											
			No. of pits								
Total Equipment Costs			3.00	228.45	685.35						
Total Labor Costs			3.00	285.20	855.60						
Total Operating Costs			3.00	-	-						
Total Material Costs			3.00	251.00	753.00						
Total Disposal Costs			3.00	-	-						
Total Cost				764.65	2,293.95						
Total Equipment Costs			1.00	56.91	56.91						
Total Labor Costs			1.00	74.78	74.78						
Total Operating Costs			1.00	-	-						
Total Material Costs			1.00	-	-						
Total Disposal Costs			1.00	55.56	55.56						
Total Cost					187.24						

Table B.10: Reconnection of Water Main Cost Worksheet

Description	Quantity	Units	Unit Cost	Units	Total ($)
Equipment Costs					
Misc. 1					
Labor Costs					
Skilled Worker	1.00	Person-day/pit	224.40	$/Person-day	224.40
Misc. 1	-	Person-day	171.60	$/Person-day	-
Operating Costs					
Misc. 1					
Material Costs					
Clamps	2.00	Each	110.00	$/each	220.00
Bends	-	Each	183.00	$/each	-
Isolation valves	1.00	Each	222.00	$/each	222.00
Spool piece	2.00	Each	50.00	$/each	100.00
Misc. 1					-
Disposal Costs					
Misc. 1					-
Misc. 2					-
User entered other cost					
Total Equipment Costs					-
Total Labor Costs					224.40
Total Operating Costs					-
Total Material Costs					542.00
Total Disposal Costs					-
Total Cost					766.40

Table B.11: Reconnection of Service Main Cost Worksheet

Description	Quantity	Units	Unit Cost	Units	Total ($)
Equipment Costs					
Welding machine (300 amp)	-	day	82.35	$/day	-
Tapping Machine (plastic)	-	day	75.00	$/day	-
Pipe tapping Tool (metal)	1.00	day	75.00	$/day	75.00
Misc.1					-
Labor Costs					
Skilled Worker	1.00	Person-day/pit	224.40	$/Person-day Pit	224.40
Other					
Operating Costs					
Misc.1					-
Material Costs					
Replacement valves	1.00	Each	5.00	$/each	5.00
Compression fittings - 1 in.	2.00	Each	1.00	$/each	2.00
Saddle Tap	1.00	Each	30.20	$/each	30.20
Misc.1					-
Misc.2					-
Disposal Costs					
Misc. 1					-
Misc. 2					-
User entered other cost					
Total Equipment Costs					75.00
Total Labor Costs					224.40
Total Operating Costs					-
Total Material Costs					37.20
Total Disposal Costs					-
Total Cost					336.60

Table B.12: Restoration Cost Worksheet

Restoration Entrance and Exit Pit Cost Worksheet						Restoration Service Pit Cost Worksheet				
Description	**Quantity**	**Units**	**Unit Cost**	**Units**	**Total ($)**	**Quantity**	**Units**	**Unit Cost**	**Units**	**Total ($)**
Equipment Costs										
Backhoe Loader (80 hp)	0.25	day/pit	290.10	$/day	72.53	0.06	day/pit	290.10	$/day	18.13
Water truck (5000 gal)	-	day/pit	205.10	$/day	-	-	day/pit	205.10	$/day	-
Dump Truck (12 ton)	0.25	day/pit	364.30	$/day	91.08	0.06	day/pit	364.30	$/day	22.77
Tamper, Single, 25 lb	0.25	day/pit	14.80	$/day	3.70	0.06	day/pit	14.80	$/day	0.93
Steel wheel roller	0.25	day/pit	490.20	$/day	122.55	0.06	day/pit	490.20	$/day	30.64
Misc. 1										
Labor Costs										
Equipment Operator	0.75	Person-day/pit	227.20	$/Person-day	170.40	0.19	Person-day/pit	227.20	$/Person-day	42.60
Labor foreman/supervisor	0.25	Person-day/pit	187.60	$/Person-day	46.90	0.06	Person-day/pit	187.60	$/Person-day	11.73
Laborer	0.75	Person-day/pit	171.60	$/Person-day	128.70	0.19	Person-day/pit	171.60	$/Person-day	32.18
Misc. 1										
Operating Costs										
Misc. 1										
Material Costs - Entrance										
Binder -2" thick	3.00	s.y/pit	2.71	$/s.y.	8.13	1.00	s.y/pit	2.71	$/s.y.	2.71
Wearing - 2"thick	3.00	s.y/pit	3.20	$/s.y.	9.60	1.00	s.y/pit	3.20	$/s.y.	3.20
Aggregate - 8"thick	3.00	s.y/pit	13.40	$/s.y.	40.20	1.00	s.y/pit	13.40	$/s.y.	13.40
Cement - 6" thick	-	s.y/pit	55.50	$/s.y.	-	-	s.y/pit	55.50	$/s.y.	-
Top soil	-	s.y/pit	5.00	$/s.y.	-	-	s.y/pit	5.00	$/s.y.	-
Grass seed	-	s.y/pit	1.00	$/s.y.	-	-	s.y/pit	1.00	$/s.y.	-
Backfill Material - New	-	c.y/pit	20.00	$/c.y.	-	-	c.y/pit	20.00	$/c.y.	-

Table B.12 - Continued

Restoration Entrance and Exit Pit Cost Worksheet						Restoration Service Pit Cost Worksheet				
Description	**Quantity**	**Units**	**Unit Cost**	**Units**	**Total ($)**	**Quantity**	**Units**	**Unit Cost**	**Units**	**Total ($)**
Misc. 1					-					-
Material Costs - Exit										
Binder -2" thick	27.00	s.y/pit	2.71	$/s.y.	73.17					
Wearing - 2"thick	27.00	s.y/pit	3.20	$/s.y.	86.40					
Aggregate - 8"thick	27.00	s.y/pit	13.40	$/s.y.	361.80					
Cement - 6" thick	-	s.y/pit	55.50	$/s.y.	-					
Top soil	-	s.y/pit	5.00	$/s.y.	-					
Grass seed	-	s.y/pit	1.00	$/s.y.	-					
Backfill Material - New	-	c.y/pit	20.00	$/c.y.	-					
Misc. 1					-					
Misc. 2					-					
Disposal Costs										
Misc. 1					-					-
Misc. 2					-					-
User entered other cost										
			No. of Pits							
Total Equipment Costs			3.00	289.85	869.55					
Total Labor Costs			3.00	346.00	1,038.00					
Total Operating Costs			3.00	-	-					
Total Material Costs			3.00	579.30	1,737.90					
Total Disposal Costs			3.00	-	-					
Total Cost				1,215.15	3,645.45					
Total Equipment Costs			1.00	72.46	72.46					
Total Labor Costs			1.00	86.50	86.50					

Table B.12 - Continued

Restoration Entrance and Exit Pit Cost Worksheet						Restoration Service Pit Cost Worksheet				
Description	**Quantity**	**Units**	**Unit Cost**	**Units**	**Total ($)**	**Quantity**	**Units**	**Unit Cost**	**Units**	**Total ($)**
Total Operating Costs			1.00	-	-					
Total Material Costs			1.00	19.31	19.31					
Total Disposal Costs			1.00	-	-					
Total Cost				178.27	178.27					

Table B.13: Pressure Test Cost Worksheet

Description	Quantity	Units	Unit Cost	Units	Total ($)
Equipment Costs					
2" Centrifugal booster pump	1.00	day	25.15	$/day	25.15
Pressure Gauge	1.00	day	10.00	$/day	10.00
Other					
Labor Costs					
Laborer	1.00	Person-day/pit	171.60	$/Person-day	171.60
Misc. 1					-
Operating Costs					
Misc. 1					
Material Costs					
Misc. 1					-
Misc. 2					-
Disposal Costs					
Misc. 1					-
Misc. 2					-
User entered other cost					
Total Equipment Costs					35.15
Total Labor Costs					171.60
Total Operating Costs					-
Total Material Costs					-
Total Disposal Costs					-
Total Cost					206.75

Table B.14: Disinfection Cost Worksheet

Description	Quantity	Units	Unit Cost	Units	Total ($)
Equipment Costs					
Chlorine Metering Pump	1.00	day	75.00	$/day	75.00
Misc. 1					
Labor Costs					
Laborer	1.00	Person-day	171.60	$/Person-day	171.60
Misc. 1					-
Operating Costs					
Other					
Material Costs					
Disinfection Chemicals (Cl2)	1.00	gallon	1.00	$/gallon	1.00
Chlorine Test Kit	1.00	each	10.00	$/each	10.00
Misc. 1					-
Disposal Costs					
Misc. 1					-
Misc. 2					-
User entered other cost					
Total Equipment Costs					75.00
Total Labor Costs					171.60
Total Operating Costs					-
Total Material Costs					11.00
Total Disposal Costs					-
Total Cost					257.60

Table B.15: Cured-in-place Pipe Installation Cost Worksheet

Description	Quantity	Units	Unit Cost	Units	Total ($)
Equipment Costs					
CIPP Truck	1.00	day(s)	1,500.00	$/day	1,500.00
CCTV	1.00	day(s)	45.00	$/day	45.00
Other 1					
Other 2					
Labor Costs					
Skilled Worker Foreman	1.00	Person-day (s)	240.40	$/Person-day	240.40
Skilled Worker	2.00	Person-day (s)	224.40	$/Person-day	448.80
Other 1					
Other 2					
Operating Costs					
Other 1					
Other 2					
Material Costs					
Product Piping	1,000.00	feet	2.00	$/ft	2,000.00
Sand	1.00	c.y.	3.75	$/c.y.	3.75
Other 1					
Other 2					
Disposal Cost					
Other 1					
Other 2					
User Entered Total Cost					
Lining Equipment Cost					1,545.00
Lining Labor Cost					689.20
Lining Operating Cost					-
Lining Material Cost					2,003.75
Lining Disposal Cost					-
Total Lining Cost					4,237.95

Table B.16: Cement Mortar Lining Installation Cost Worksheet

Description	Quantity	Units	Unit Cost	Units	Total ($)
Equipment Costs					
Cement Mortar Lining machine	1.00	day(s)	100.00	$/day	100.00
Cement Mortar Winch and Cable	1.00	day(s)	50.00	$/day	50.00
Cement Mortar Mixer - 6 cf, 7 hp	1.00	day(s)	38.55	$/day	38.55
Cement Mortar Pump	1.00	day(s)	80.00	$/day	80.00
Air Compressor (250 cfm)	1.00	day(s)	124.90	$/day	124.90
50 ft air hose (1.5 in. diameter)	1.00	day(s)	16.40	$/day	16.40
CCTV	1.00	day(s)	45.00	$/day	45.00
Other 1					
Other 2					
Labor Costs					
Skilled Worker Foreman	1.00	Person-day (s)	240.40	$/Person-day	240.40
Skilled Worker	2.00	Person-day (s)	224.40	$/Person-day	448.80
Other 1					
Other 2					
Operating Costs					
Other 1					
Other 2					
Material Costs					
Cement Mortar	-	c.y.	94.50	$/c.y.	-
Sand	1.00	c.y.	3.75	$/c.y.	3.75
Other 1					
Other 2					
Disposal Cost					
Other 1					
Other 2					
User Entered Total Cost					
Lining Equipment Cost					454.85
Lining Labor Cost					689.20
Lining Operating Cost					-
Lining Material Cost					3.75
Lining Disposal Cost					-
Total Lining Cost					1,147.80

Table B.17: Epoxy Lining Installation Cost Worksheet

Description	Quantity	Units	Unit Cost	Units	Total ($)
Equipment Costs					
Epoxy Lining machine	1.00	day(s)	100.00	$/day	100.00
Epoxy Lining Winch and Cable	1.00	day(s)	50.00	$/day	50.00
Epoxy Mixer - 6 cf, 7 hp	1.00	day(s)	50.00	$/day	50.00
Epoxy Drum Pump	1.00	day(s)	30.00	$/day	30.00
Air Compressor (250 cfm)	1.00	day(s)	124.90	$/day	124.90
50 ft air hose (1.5 in. diameter)	1.00	day(s)	16.40	$/day	16.40
CCTV	1.00	day(s)	45.00	$/day	45.00
Other 1					
Other 2					
Labor Costs					
Skilled Worker Foreman	1.00	Person-day (s)	240.40	$/Person-day	240.40
Skilled Worker	2.00	Person-day (s)	224.40	$/Person-day	448.80
Other 1					
Other 2					
Operating Costs					
Other 1					
Other 2					
Material Costs					
Epoxy Lining	55.00	gallons	15.00	$/gallon	825.00
Sand	1.00	c.y.	3.75	$/c.y.	3.75
Other 1					
Other 2					
Disposal Cost					
Other 1					
Other 2					
User Entered Total Cost					
Lining Equipment Cost					416.30
Lining Labor Cost					689.20
Lining Operating Cost					-
Lining Material Cost					828.75
Lining Disposal Cost					-
Total Lining Cost					1,934.25

Table B.18: Polyurea Lining Installation Cost Worksheet

Description	Quantity	Units	Unit Cost	Units	Total ($)
Equipment Costs					
Polyurea Lining machine	1.00	day(s)	150.00	$/day	150.00
Polyurea Lining Winch and Cable	1.00	day(s)	75.00	$/day	75.00
Polyurea Mixer - 6 cf, 7 hp	1.00	day(s)	75.00	$/day	75.00
Polyurea Drum Pump	1.00	day(s)	30.00	$/day	30.00
Air Compressor (250 cfm)	1.00	day(s)	124.90	$/day	124.90
50 ft air hose (1.5 in. diameter)	1.00	day(s)	16.40	$/day	16.40
CCTV	1.00	day(s)	45.00	$/day	45.00
Other 1					
Other 2					
Labor Costs					
Skilled Worker Foreman	1.00	Person-day (s)	240.40	$/Person-day	240.40
Skilled Worker	2.00	Person-day (s)	224.40	$/Person-day	448.80
Other 1					
Other 2					
Operating Costs					
Other 1					
Other 2					
Material Costs					
Polyurea	55.00	gallons	45.00	$/gallon	2,475.00
Sand	1.00	c.y.	3.75	$/c.y.	3.75
Other 1					
Other 2					
Disposal Cost					
Other 1					
Other 2					
User Entered Total Cost					
Lining Equipment Cost					516.30
Lining Labor Cost					689.20
Lining Operating Cost					-
Lining Material Cost					2,478.75
Lining Disposal Cost					-
Total Lining Cost					3,684.25

Table B.19: Polyurethane Lining Installation Cost Worksheet

Description	Quantity	Units	Unit Cost	Units	Total ($)
Equipment Costs					
Polyurethane Lining machine	1.00	day(s)	150.00	$/day	150.00
Polyurethane Lining Winch and Cable	1.00	day(s)	75.00	$/day	75.00
Polyurethane Mixer - 6 cf, 7 hp	1.00	day(s)	75.00	$/day	75.00
Polyurethane Drum Pump	1.00	day(s)	30.00	$/day	30.00
Air Compressor (250 cfm)	1.00	day(s)	124.90	$/day	124.90
50 ft air hose (1.5 in. diameter)	1.00	day(s)	16.40	$/day	16.40
CCTV	1.00	day(s)	45.00	$/day	45.00
Other 1					
Other 2					
Labor Costs					
Skilled Worker Foreman	1.00	Person-day (s)	240.40	$/Person-day	240.40
Skilled Worker	2.00	Person-day (s)	224.40	$/Person-day	448.80
Other 1					
Other 2					
Operating Costs					
Other 1					
Other 2					
Material Costs					
Polyurethane	55.00	gallons	35.00	$/gallon	1,925.00
Sand	1.00	c.y.	3.75	$/c.y.	3.75
Other 1					
Other 2					
Disposal Cost					
Other 1					
Other 2					
User Entered Total Cost					
Lining Equipment Cost					516.30
Lining Labor Cost					689.20
Lining Operating Cost					-
Lining Material Cost					1,928.75
Lining Disposal Cost					-
Total Lining Cost					3,134.25

Table B.20: Sliplining Installation Cost Worksheet

Description	Quantity	Units	Unit Cost	Units	Total ($)
Equipment Costs					
Winch Truck	2.00	day(s)	250.00	$/day	500.00
Butt fusion machine	1.00	day(s)	187.00	$/day	187.00
Grout pump hoses & hopper	1.00	day(s)	31.50	$/day	31.50
CCTV	1.00	day(s)	45.00	$/day	45.00
Other 1					
Labor Costs					
Skilled Worker Foreman	1.00	Person-day (s)	240.40	$/Person-day	240.40
Skilled Worker	2.00	Person-day (s)	224.40	$/Person-day	448.80
Other 1					
Other 2					
Operating Costs					
Other 1					
Material Costs					
Piping Material	1,000.00	feet	1.91	$/foot	1,910.00
Grout	-	c.y.	3.30	$/c.y.	
Sand	1.00	c.y.	3.75	$/c.y.	3.75
Other 1					
Other 2					
Disposal Cost					
Other 1					
Other 2					
User Entered Total Cost					
Lining Equipment Cost					763.50
Lining Labor Cost					689.20
Lining Operating Cost					-
Lining Material Cost					1,913.75
Lining Disposal Cost					-
Total Lining Cost					3,366.45

Table B.21: Close-fit Pipe Installation Cost Worksheet

Description	Quantity	Units	Unit Cost	Units	Total ($)
Equipment Costs					
Winch Truck	2.00	day(s)	250.00	$/day	500.00
Butt fusion machine	1.00	day(s)	187.00	$/day	187.00
Pipe deformation equipment	1.00	day(s)	100.00	$/day	100.00
Boiler	-	day(s)	25.00	$/day	-
2" Centrifugal booster pump	-	day(s)	25.15	$/day	-
Air Compressor (250 cfm)	1.00	day(s)	124.90	$/day	124.90
50 ft air hose (1.5 in. diameter)	1.00	day(s)	16.40	$/day	16.40
CCTV	1.00	day(s)	45.00	$/day	45.00
Labor Costs					
Skilled Worker Foreman	1.00	Person-day (s)	240.40	$/Person-day	240.40
Skilled Worker	2.00	Person-day (s)	224.40	$/Person-day	448.80
Other 1					
Operating Costs					
Other 1					
Material Costs					
HDPE Piping Material	1,000.00	feet	1.91	$/foot	1,910.00
Sand	1.00	c.y.	3.75	$/c.y.	3.75
Disposal Cost					
Other 1					
User Entered Total Cost					
Lining Equipment Cost					973.30
Lining Labor Cost					689.20
Lining Operating Cost					-
Lining Material Cost					1,913.75
Lining Disposal Cost					-
Total Lining Cost					3,576.25

Table B.22: Thermoformed Pipe Installation Cost Worksheet

Description	Quantity	Units	Unit Cost	Units	Total ($)
Equipment Costs					
Thermoformed Truck	1.00	day(s)	100.00	$/day	100.00
Thermoformed Winch and Cable	1.00	day(s)	50.00	$/day	50.00
Boiler	1.00	day(s)	25.00	$/day	25.00
Air Compressor (250 cfm)	1.00	day(s)	124.90	$/day	124.90
50 ft air hose (1.5 in. diameter)	1.00	day(s)	16.40	$/day	16.40
CCTV	1.00	day(s)	45.00	$/day	45.00
Other 1					
Other 2					
Labor Costs					
Skilled Worker Foreman	1.00	Person-day (s)	240.40	$/Person-day	240.40
Skilled Worker	2.00	Person-day (s)	224.40	$/Person-day	448.80
Other 1					
Other 2					
Operating Costs					
Other 1					
Other 2					
Material Costs					
Product Piping	1,000.00	feet	10.00	$/feet	10,000.00
Sand	1.00	c.y.	3.75	$/c.y.	3.75
Other 1					
Other 2					
Disposal Cost					
Other 1					
Other 2					
User Entered Total Cost					
Lining Equipment Cost					361.30
Lining Labor Cost					689.20
Lining Operating Cost					-
Lining Material Cost					10,003.75
Lining Disposal Cost					-
Total Lining Cost					11,054.25

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Abhay Jain completed his Bachelor's Degree in Civil Engineering from M.H. Saboo Siddik College of Engineering affiliated to Mumbai University, India. While pursuing his Master of Science Degree from The University of Texas at Arlington (UT Arlington) since fall 2008, he has been involved in various research projects related to trenchless technology topics. Mr. Jain has achieved high degrees of academic development in UT Arlington including the scholarship award for Master's and Ph.D. students received in fall of 2008. He has also given technical presentation at American Society of Civil Engineers (ASCE) Pipelines Conference of 2010 in Keystone, Colorado. For the near future Mr. Jain plans to continue his participation in trenchless technology industry in the U.S. by working for the Center for Underground Infrastructure Research and Education (CUIRE).