AN INVESTIGATION OF WATER PIPELINE RENEWAL PRACTICES

by

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Abstract

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Globally, the use of trenchless technologies is gradually increasing due to the growing need to replace and renew aging utility infrastructure and the need for more flexible solutions for the installation of new pipes. In the United States of America, the American Society of Civil Engineers (ASCE) in 2017 assessed that America's infrastructure is close to failing. It faces an annual shortfall of at least $11 billion to replace the aging facilities that are near the end of their useful lives.

In this research, surveys and interviews of professionals working in trenchless technologies for the North American Society for Trenchless Technology (NASTT) No-Dig Show in California were carried out and the results were analyzed. The surveys focused on the structural lining system classification, the required data to design water pipe rehabilitation method, the most recent growth in trenchless technologies for water main rehabilitation methods, and the safety of renewal methods. Another interview and residential survey was conducted to calculate the social cost of the open cut method. The surveys focused on major hindrances, traffic disruption, property damage, and safety requirements. Survey results indicate that the cured-in-place pipe (CIPP) method will be the method of choice compared with other pipe replacement and renewal methods.

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Chapter 1

1.1 Introduction

In 2017, the American Society of Civil Engineers (ASCE) assessed the condition of drinking water infrastructure in the United States and gave it a grade of D. Wastewater infrastructure got a D+. This means that the pipelines transporting both types of water have severe defects and risk failure within the next five to ten years as shown in Figure 1.1. As the water distribution systems age, they lose capacity due to leaks and tuberculation. Utilities need to be rehabilitated to minimize leaks and breaks. Due to limited funds, utilities must be given the priority for rehabilitation projects in order to get the best return on investment.

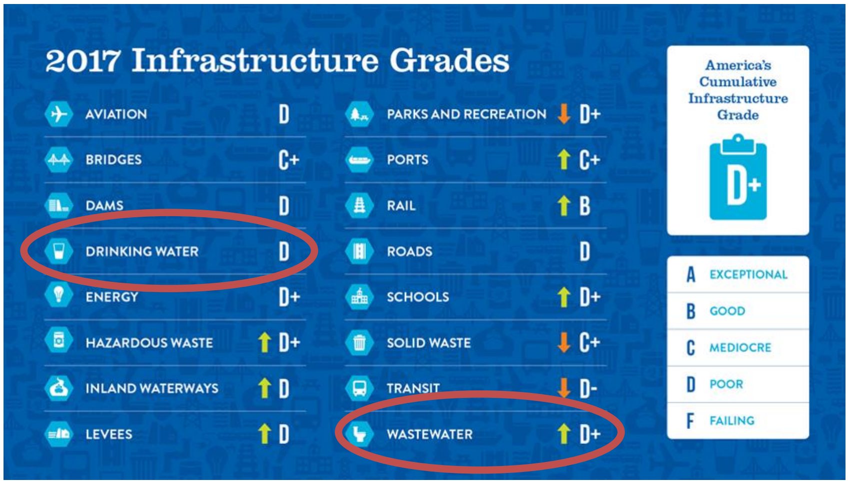

Figure 1.1 Infrastructure Report Card (ASCE, 2017)

Several criteria should be considered to prioritize the pipes that need to be rehabilitated. Pipe improvements can be planned through evaluations, which utilize specialized software. The importance of each factor is significant and varies among utilities. Input to the analysis may involve break history, pipe age, soil pH value, pressure, pipe material and flow velocity.

1.2 Causes of Water Pipe Deterioration

Different factors can influence the rate of water pipe deterioration, which will lead to their failure. In 2003, the Federation of Canadian Municipalities and National Research Council (FCMNRC) grouped these factors into three categories: physical, environmental, and operational factors as shown in Tables 1.1, 1.2, and 1.3

Table 1.1 Physical Factors Causing Pipeline Deterioration (FCMNRC. 2003)

Factor	Description
Pipe material	Pipes made from different materials are failing in different ways.
Pipe wall thickness	Corrosion penetrates the thin-walled pipe quicker than thick-walled pipe.
Pipe age	Pipe degrades over time.
Pipe vintage	Pipes made at a particular time and place may be more vulnerable to failure.
Pipe diameter	Small diameter pipes are more susceptible to beam failure.
Type of joints	Some types of joints such as lead joints experience premature failure.
Thrust restraint	Inadequate restraint can increase longitudinal stresses.
Pipe lining and coating	Lined and coated pipes are less susceptible to corrosion.
Dissimilar metals	Dissimilar metals are susceptible to galvanic corrosion.
Pipe installation	Poor installation practices can damage pipes, making them vulnerable to failure.
Pipe manufacture	Defects in pipe walls produced by manufacturing errors can make pipes vulnerable to failure. This problem is most common in older pit cast pipes.

Table 1.2 Environmental Factors Causing Pipeline Deterioration (FCMNRC. 2003)

Factor	Description
Internal water pressure	Changes to internal water pressure will cause deteriorated pipes to fail.
Leakage	Leakage erodes pipe bedding and increases soil moisture in the pipe zone.
Water quality	Aggressive water causes corrosion to pipes.
Flow velocity	Rate of internal corrosion is greater in unlined dead-ended mains.
Backflow potential	Cross connections with systems that do not contain potable water can contaminate the water distribution system.
O&M practices	Poor practices can compromise structural integrity and water quality.

Table 1.3 Operational Factors Causing Pipeline Deterioration (FCMNRC. 2003)

Factor	Description
Pipe bedding	Improper bedding might cause premature pipe failure.
Trench backfill	Some backfill materials are corrosive or frost susceptible.
Soil type	Due to moisture, some soils are subjected to volume changes, causing changes to pipe loading.
Groundwater	Some groundwater becomes aggressive with pipe materials.
Climate	Climate influences soil moisture.
Pipe location	Corrosion rate increases when road salt migrates into soil.
Disturbances	Underground disturbances lead to actual pipe damage.
Stray electrical	Causes electrolytic corrosion.
Seismic activity	Earthquakes increase stress on pipes.

1.3 Pipe Materials Used for Water Distribution Systems

1.3.1 Asbestos Cement Pipe (ACP)

Asbestos cement pipe (ACP) was used in the mid-1900s in water distribution systems in the United States. AC pipe is a concrete pipe made by mixing Portland cement and asbestos fibers. The estimated lifespan of AC pipe is 70 years according to the International Chrysotile Association (2017); taking into account that the actual service life depends on pipe conditions. The main advantages of ACP pipe are its low cost and smooth interior walls. On the other hand, the limitation is that it easily breaks if not handled and installed properly (USEPA, 2015).

1.3.2 Concrete Pressure Pipe (CPP)

Concrete pressure pipe (CPP) is an engineered product that combines the features of Portland cement concrete and the adaptability of steel to create a robust structure for conveying liquids within a wide range of external loads and internal pressures. CPP is reliable. The estimated lifespan is about 100 years. The main features of CPP are that it is a cost-effective and sustainable solution for conveying liquids like water as well as being able to handle a wide range of external loads and internal pressures (Murphy, 2013).

1.3.3 Cast Iron Pipe (CIP)

Cast iron pipes were widely used during the 19th and 20th centuries as main component of underground infrastructure in most US cities because they are cheaper, had high resistance to corrosion, and are highly durable. As a result, over 50% of the current global water pipe assets are cast iron pipelines (Zhang et al. 2017).

1.3.4 Ductile Iron Pipe (DIP**)**

Ductile iron pipe is a developed form of cast iron pipe. The manufacturing of ductile iron pipe is characterized by the spheroidal nature of the graphite within the iron (Najafi and Gokhale, 2005). According to the Ductile Iron Pipe Research Association (DIPRA) in 2017, ductile iron is twice as strong as cast iron as determined by tensile strength, ring bending, and bursting tests. Table 1.4 shows the advantages and limitations of DIP.

Table 1.4 Advantages and Limitations of Ductile Iron Pipe (Najafi, 2010)

Advantages	Limitations
1. Wide variety of internal and external corrosion protection systems available	1. Highly susceptible to corrosion, both internally and externally, unless protected
2. Internal cement mortar lining prevents tuberculation and enhances hydraulic capability	2. Not all available corrosion protection methods are effective
3. Strong material, with high load bearing strength, impact strength, and beam strength	3. Internal cement mortar lining is easily damaged if truck with a backhoe.
4. Wide variety of joints enable various applications, including trenchless	4. Cathodic protection is cost prohibitive and is rarely used in municipal systems
5. Available for both pressure and gravity applications	5. Polyethylene encasement is easily damaged and subject to improper installation
6. Wide range of diameters and pressure classes available	6. Heavy weight, resulting in high cost of labor
7. Long laying lengths reduce joints in the system	7. Lack of flexibility is an obstacle in trenchless installations
8. Pipe is highly resistant to chemical permeation in contaminated areas	8. Gaskets in the joints are highly vulnerable to chemical attack in contaminated soils

1.3.5 Steel Pipe (SP)

Steel pipes have also been used for water networks in the United States since the early 1850s (Elliot, 1922). They were first made by rolling steel plates into a circular shape and riveting the seams. Steel pipes are a sustainable solution when large diameter pipes are required as well as when the pipes are exposed to high pressure (AWWA, 2004). Table 1.5 presents the advantages and limitations of steel pipes.

Table 1.5 Advantages and Limitations of Steel Pipes (Najafi, 2010)

Advantages	Limitations
1. Various Standards and methods are available for internal and external corrosion protection	1. Prone to internal tuberculation and external corrosion, subject to electrolysis
2. High tensile strength	2. Use of internal and external corrosion protection raises price of the product
3. High compressive strength	3. Low resistance to external pressures in large-diameter sizes
4. Easy to assemble, non-weld joints available	4. Air vacuum valves are necessary in large-diameter lines
5. Adopts well to locations where soil movements occur	5. Welding of joints require skilled labor and is time consuming
6. Good hydraulic properties when internally lined	6. Special care required to ensure proper alignment at joint in welded pipe
	7. Fully dependent on proper installation to limit deflection and collapse.

1.3.6 Polyvinyl Chloride (PVC) Pipes

Polyvinyl Chloride pipe was invented in the late 1900s in Germany. It has an excellent resistance to corrosion and abrasion. In addition, it is lightweight and easy to install (AWWA, 2002). The technology was initiated in the United States in the mid-1950s. By 2000, the use of PVC had reached 5 billion pounds (Najafi and Gokhale, 2005). Table 1.6 presents the advantages and limitations of PVC pipes.

Table 1.6 Advantages and Limitations of PVC Pipes (Najafi, 2010)

Advantages	Limitations
1. Resistant to both internal and external corrosion	1. Sensitive to operating temperature. Must be derated in case of long-term exposure to temperatures above room temperature
2. Gasket-joints and fusible-joints have an excellent track record of leak-free performance.	2. Sensitive to ultraviolet light if exposure is greater than 2 years (unless pipe is formulated with higher ultraviolet [UV]-inhibitor level)
3. All four restrained-joint PVC products have high tensile strengths for HDD and other trenchless processes	3. Less longitudinal flexibility than' alternative thermoplastic piping material
4. Highly abrasion resistant for sewer applications	4. Thinner-walled sewer pipe is sensitive to bedding conditions.
5. Low internal frictional resistance for both pressure and non-pressure application	5. Susceptible to chemical permeation in cases of gross contamination
6. At least 2.5 times stronger than other thermoplastic pipe (higher stiffness, higher HDB)	6. Susceptible to impact damage in cold temperatures
7. Expansion is significantly lower than in alternative thermoplastic piping material	7. Susceptible to rapid crack propagation failure. Tapping of fused PVC pipe must be done with extreme caution.

1.3.7 Concrete Pipe (CP)

There are two types of concrete pipes, reinforced and unreinforced. Small unreinforced pipes are usually used for the drainage of storm water. Larger diameter pipes are used for water transmission networks. According to the Concrete Pipe Association in Australia (2016), the estimated lifespan of a CP is over 100 years. In Australia, CPs are still in service, which were manufactured over 90 years ago. Table 1.7 presents the advantages and limitations of concrete pipes.

Table 1.7 Advantages and Limitations of Concrete Pipe (Najafi, 2010)

Advantages	Limitations
1. Specialized work crew not required for installation	1. In open-cut construction, pipe is sensitive to bedding conditions- shear failure and beam breakage may occur
2. Large selection of available nominal diameters	2. Handling and installation difficulty because of heavy weight except where weight would be advantageous because of flotation concerns
3. Wide variety of pipe lengths available	3. Susceptible to external corrosion in acidic soil environments
4. Relatively low cost of maintenance	4. Highly vulnerable to hydrogen sulfide attacks and internal microbiological-induced corrosion at crown. A concern in sanitary applications only.
5. Capability to withstand very high pressures	5. Generally difficult to repair, particularly in cases of joint leakage or failure in pressure pipes
6. Ideal for pipe jacking applications owing to high compressive strengths.	6. Tendency to leak because of high pipe wall porosity and shrinkage cracking.
7. External sulfate corrosion may be reduced by an additional sacrificial wall thickness determined by the Pomeroy/ Parkhurst 'AZ' design method is more commonly added to the inside of the pipe wall to counter the corrosion from biogenically generated H_2S0_4- Alternatively, it is possible use Type V sulfate-resistant Portland cement.	7. Without internal lining, life span is significantly reduced in the case of sanitary sewer applications and only then if there is a high potential for H_2S generation.
8. Large selection of both structural and pressure strengths	8. Somewhat lower abrasion resistance—internal scouring can occur if solid content and flow velocities are high
9. Internal corrosion can be significantly reduced by using thermoplastic lining	9. Reinforcements in PCCP can corrode or fail without little or no external evidence

1.4 Problem Statement

The basic goal of this research involves Trenchless Renewal Methods (TRM). One of the key premises of TRM is that it allows newer and much more cost effective methods that can compete with open cut options at every level. Deciding whether to renew, reinstate or replace any system is very difficult because of the number of elements involved (Francom et al. 2016). There are some other constraints that might restrict the ability of engineers to come up with more feasible and permanent solutions. The massive volume of work in ever-expanding cities is another area that must be kept in mind (Allouche et al. 2001).

1.5 Objectives

The specific objectives of this research are:

- To describe trenchless renewal methods for water applications and to decision support for method selection.
- To analyze social costs open-cut vs. trenchless renewal methods for water pipelines.

1.6 Methodology

Figure 1.2 shows the steps to achieve objectives of this thesis.

Figure 1.2 Research Methodology

Chapter 2

Literature Review

2.1 Introduction

Physical and chemical processes such as corrosion, cracking and manufacturing defects lead to gradual deterioration of pipes within a water distribution system. This issue is inevitable and is recognized by all civil engineers. Unfortunately, the estimation of the physical condition of pipes requires monitoring up close and on site. This fact alone limits the effort of keeping proper flow conditions and preventing failures of pipe that might cause costly losses for a city and affect its general population. Figure 2.1 is an example of a severely deteriorated pipe segment compared to a new sample.

Figure 2.1 Deteriorated Pipe vs New Pipe (Bryant, 2011)

It is estimated that approximately $325 billion USD are required for maintenance and replacement of water distribution systems (Stratus Consulting, 1998). Likewise, approximately 80% of all capital funds that were invested in a city's water supply infrastructure were used to maintain and operate water distribution systems alone (Kleiner and Rajani, 2001).

2.2 Pipe Failure Causes

Several physical factors can contribute to pipe failure. In some instances, these factors can be determined easily by doing inspection of the pipe material and its surroundings, while others require a more in-depth analysis. Table 2.1 shows the most typical causes of pipe failure in water distribution systems along with some examples of each one.

Table 2.1 Typical Causes of Pipe Failure in Waterlines (Deb, Arun K. et al. 2002)

Failure Criteria	Examples
Pipe Dimensions	Length, diameter, and shape
Type of Material	Cast iron vs. PVC
Soil Environment	Alkalinity, acidity, and moisture content
Pipe Age	Service life and year of installation
External Forces	Loading from buildings, soil, snow, and traffic
Internal Forces	Pressure and flow within the pipe
Manufacturing	Defects and irregularities
Weather Variations	Expansion and contraction due to temperature changes
Location	Relative to other utility structures or seismically active faults

Besides the causes of failure mentioned above, a few studies have shown other factors that can contribute to pipe failure. A study by Mavin (1996) shows some of these other pipe failure causes:

- Poor storage and handling - Resulting in deformation, cracking, or other physical damage to pipe coatings prior to installation.
- Improper installation - Result of incorrect laying, fitting, tapping, and soil cover.
- Soil Erosion - Causing loss of bed support or soil cover because of flooding from groundwater or rainfall.

- Impact damage - Resulting from installation equipment such as hammers or picks, variable traffic loading or excavation machinery.
- Pipe Corrosion - Creating poor flow conditions and diminishing structural strength because of aggressive water flow or chemical processes.

Additionally, Kane (1996) concluded that:

- The break rate between clean and lined pipes is about 25% of the rate of unlined pipes. As a result, cleaned and lined pipes are recommended for structural soundness.
- In corrosive soil, the break rate of pipe is double compared to noncorrosive soil.
- In wet soil, the break rate of pipes is about 50% higher when compared to dry soil.
- During cold weather, the break rate of pipe is impacted by the severity of cold. Thus, the highest number of pipe breaking happens during the winter season.

2.3 Impact on Municipal Operations

Regardless of the physical causes that may prompt pipe failure, the result remains the same for all possible cases. In case of an unexpected failure within a water distribution system, the city that is dependent upon that distribution system would be subject to economic losses. These types of losses could result in noticeable decreasing of agricultural production, disrupting of commercial manufacturing or even the disruption of food production services. Moreover, public health and safety would instantly be at risk, as critical emergency services would be affected. Fire and police are examples. In addition to this, hospitals would also face a disruption in their normal operations. The possibility of flooding and soil liquefaction near a damaged pipe could threaten the safety of nearby residents and businesses as well.

2.4 Classification of Pipe Failures

Under normal conditions, two types of pipe failure are most common in water mains in a distribution system; these are breaks and leaks along the structure of the pipe. Based on a research publication from Texas A&M University, city engineers use the terms "break" and "leak" to distinguish between the levels of damage in different pipe failures (Yamijala, 2007). Table 2.2 explains the conditional variations between pipe breaks and pipe leaks.

Table 2.2 Differences Between Pipe Leaks and Pipe Breaks (Mays, 2000)

	Breaks	Leaks
Detection	Easily identified by ground level conditions and water pressure	Difficult to detect, specialized equipment is necessary
Service Impact	High likelihood of service interruption	Low likelihood of service interruption
Occurrence	Typical along the length of the pipe	Usually found at pipe fittings and laterals
Repair Urgency	Requires immediate attention	Repairs can be scheduled and are not urgent

Furthermore, Figure 2.2 below shows some of the failure conditions that may result in a pipe break or leak. Since there are several combinations of physical externalities that can cause a pipe to experience any of these failure modes, the following figure is intended to illustrate the most typical causes and types of failure, which a water main may experience.

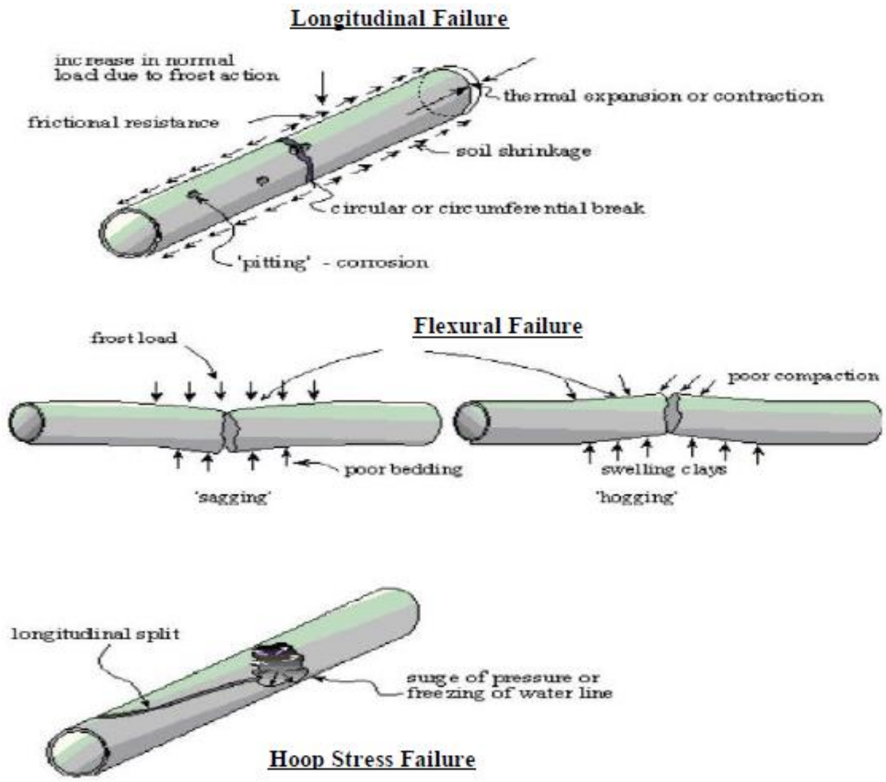

Figure 2.2 Various Water Main Failure Conditions (Kleiner and Rajani, 2001)

As shown in the figure above, breaks and leaks can happen in pipes under varying stress condition such as tension force and compression force. A pipe will break or crack accordingly depending on the strength and direction of these forces. Although determining a breaking pipe is easier than determining a leaking pipe, maintaining both is important to maintain the durability of the water pipe. However, it is necessary to develop and implement an assessment model that can predict the occurrence of such failures before they occur in order to avoid interruption of main utilities.

2.5 Corrosion and Residual Life of Pipes

2.5.1 Corrosion

Corrosion comes from the Latin word ”corrodere” or "rodere" and refers to ground that has been attacked by a chemical or electrochemical reaction. It is a general term for a corroded condition of metal. Metal can be produced by transforming and refining ore. The process requires a huge amount of energy in the form of heat. This indicates that the metal is typically utilized with high-energy content inside. When the metal is subjected to oxygen or humidity, the metal starts to gradually lose energy and the corrosion process starts gradually as well. In general, corrosion is a phenomenon of metal deterioration because of its surrounding environment and chemical reaction.

A model was developed to predict a pit’s corrosion effect outside of the water pipe based on soil properties. The researcher's model is a typical corrosion rate model according to soil corrosion characteristics. On the other hand, empirical models have been developed according to a large collection of data (Rossum, 1969). Rajani et al. (2000) developed two phases of corrosion rate. In the first phase, they showed that corrosion proceeds fast, and in the second phase, they showed a slow linear growth. In other words, corrosion products gradually deter the corrosion.

2.5.2 Corrosion Rate

Based on U.S Environmental Protection Agency (USEPA) information (USEPA, 2013), “The majority of distribution piping installed in the United States, beginning in the late 1800’s up until the late 1960’s, was manufactured from cast iron.” Since the drinking water pipes are made from anti-rust elements such as materials containing chlorine, they are not exposed to corrosion.

One of the most recent studies on corrosion gives an extensive literature review included a focus on external corrosion as well as internal corrosion. De Arriba-Rodriguez et al. (2018) described soil types, water, aeration, redox potential, pH, and resistivity as causes of corrosion.

Lee (2011) stated, “Recognizing that the major cause of external corrosion is soil corrosion, soil properties, including soil resistivity, pH, soil sulphide and moisture and their relationships with the depth of external corrosion have been studied.”

The author also mentioned that a decrease in pipe thickness is due to corrosion. However, the reduction of pipe thickness (i.e. corrosion rate) was determined to be a simple constant and was used as such.

Doyle concluded that the relationship between soil resistivity and depth of external corrosion of pipe is exponentially in inverse proportion. Soil resistivity is inversely proportional with the external pitting rate of CIPs. However, the researcher also concluded that the relationships of pH, pipe's age, and soil sulphide are not related to the external pitting rate.

2.6 Methodologies for Prioritizing Pipe Renewal

After reviewing the literature, several methods four categories for prioritizing renovation of pipes within water distribution systems can be determined as follows (Deb et al. 2002):

1. The Deterioration Point Assignment (DPA) Method
2. Break-Even Analysis
3. Failure Probability and Regression Methods
4. Mechanistic Models

2.6.1 The Deterioration Point Assignment (DPA) Method

The DPA method provides a set of factors of pipe failure depending on properties and the surrounding environment of pipes such as type of soil, location, age of pipe, water volume, and water pressure. The numerical values for these factors are divided into several class intervals to indicate the failure score. The summation of class intervals for any pipe is called the total failure score. Therefore, when the total failure score exceeds a threshold value, the pipe should be renovated or replaced.

2.6.2 Break-Even Analysis

Breakeven analysis is a cost method based on repair and replacement costs. For this method, a predictive technique for pipe cost is necessary to assess the repair cost with the predicted break occurrence time. Over time, the cost of pipe replacement is decreasing whereas the cumulative repair costs are increasing. Thus, the total cost related to pipes is the summation of present values of replacement and cumulative repair. Deb et al. (2002) concluded that the best economic time for replacing pipes is when the total cost is at the minimum. Stacha (1978) compared the annual cost of replacing and repairing. The approach of comparing failure record history and repair record history to the accumulated cost of repair was presented. Then considering the cost difference between accumulated cost and replacement cost should be done to make a repair decision. However, Stacha (1978) stated that utilizing cost difference alone is not sufficient because there are other parameters, which need to be taken into consideration such as water quality and flow capacity.

Male et al. (1990) identified an effective replacement policy used by New York City. They mentioned that the most cost effective system of replacing all pipes is with two or more breaks. During the analysis five alternatives were considered: (1) replacement after one or more breaks (2) replacement after two or more breaks (3) replacement after three or more breaks (4) replacement after four or more breaks and (5) do nothing. They found that alternative 2 is the most proactive policy.

2.6.3 Failure Probability and Regression Methods

This method is similar to the DPA method because both use the same deterioration factors. This method is beneficial to assess the probability of future failure. Clark et al. (1982) suggested several regression equations for a number of years from pipe installation to the first repair of pipe. Another equation was also proposed for the number of repairs over a time measured from the time of the first break. These equations had coefficients of determination (R2) of 0.23 and 0.47, respectively. Thus, while the procedure of Clark et al. (1982) was a significant improvement in predicting pipe breaks, it did raise some concerns because of the low values of the coefficients of determination. Shamir and Howard (1979) utilized a regression analysis on pipe break data in order to create an exponential equation, which predicted the number of breaks in pipes for any given year. The replacement cost was compared with pipe repair cost. The optimal year of pipe replacement was also calculated.

2.6.4 Mechanistic Models

Mechanistic models simulate both the deterioration of the pipe and the total load over time. This method depends on detailed pipe and environmental data. Some mechanistic models have been utilized for corrosion modelling such as change in pit depth with time and soil properties. A set of equations was created by Rossum (1969).

2.7 Trenchless Waterline Rehabilitation Methods

Trenchless technology is a swiftly growing sector of civil engineering and in the construction industry which is based on the idea of subsurface construction with few or no continuous trenches. A plethora of research is available dealing with trenchless technology and renewal methods for water pipes. In this literature review section, we will comprehensively survey these essential trenchless renewal methods for water pipes including cured-in-place pipe, close-fit pipe, spray-in-place pipe, thermoformed pipe, and sliplining. A successful trenchless construction project requires a thorough knowledge of subsurface conditions (Allouche et al. 2001). The suggested interactive approach from a study (Richardson et al. 2003) for trenchless projects is summarized in the Table 2.3.

Table 2.3 Summary of Suggested Interactive Approach for Trenchless Projects (Richardson et al. 2003)

Input	Design Phase	Output
Project requirements/preliminary project information; desk study; case history search; existing geotechnical reports/boring logs search/review	PLANNING	preliminary tunnel profile and alignment; anticipated ground conditions; lessons learned (projects in similar geological environments); generalized soil/rock properties; generalized groundwater elevation data; geotechnical investigation planning document preparation
Preliminary geotechnical investigation/borings; preliminary laboratory testing (soil/rock interface)	PRELIMINARY	preliminary geological section; preliminary material properties (soil/rock); preliminary design parameters; preliminary tunnel profile and alignment adjustment
additional borings (as required); additional laboratory testing; owners review/comment/risk management	FINAL	final tunnel profile and alignment; preliminary material properties (soil/rock); final design parameters; geological/construction risk evaluation; geotechnical baseline report

A study was conducted by USEPA in 2013 and submitted to the American Congress, which claimed that, for the continuation of safe drinking water to the public, pipeline distribution, and transmission structure needs to be invested with $183.6 billion until 2023. This represents 70% of the required total investment ($263.9 billion) for the drinking water infrastructure in the U.S. There were four prime motives to rehabilitate the weakened water structure; 1) to improve the quality of water, 2) to avoid the failure of formation, 3) to avert water loss, and 4) to increase hydraulic capacity (Sever, 2016).

The extended benefits of trenchless water rehabilitation include significantly lower social and economic costs. Lining structures can help effectively renovate any pressure pipe, for instance, steel, clay, concrete, PVC, and iron pipes (Sever, 2016). Afterward, we will survey the literature about trenchless renewal methods for water pipes.

2.7.1. Cured-In-Place Pipe (CIPP)

A cured in place pipe is an important method of trenchless rehabilitation, which is extensively being used to repair existing pipelines. In simple words, the convenient features of this method includes a pipe within a pipe, seamless and jointless with the capability to rehabilitate pipes ranging from five to 114 inches in diameter. Figure 2.3 shows the simplest version of CIPP.

Figure 2.3 CIPP (El-Baroudy, 2013)

For the past 30 years, CIPP has been the most trustworthy way to rehabilitate existing pipelines and has been used broadly in the United States and Europe. In this method, we insert a new polyester pipe into the deteriorated host pipe and cure it in place, which is explicitly shown in the above diagram. There are a wide variety of pipe applications that include, but are not limited to, sanitary sewers, storm drains and pressure pipelines for water, wastewater, and gas. The host pipe needs to have retained a circular shape. Oval and rectangular pipe shapes can be lined with CIPP as well if the forms are known in advance (Matthews et al., 2014).

A polyester felt tube is fabricated to fit the host pipe. It is then inverted (turned inside out) and pulled inside the host (old) pipe. The liner may be designed with sufficient thickness when cured to sustain the loads imposed by exterior groundwater and interior service pressure, and by soil and traffic acting on the pipe, which is shown in the following figure:

Figure 2.4 Polyester Felt Tube (El-Baroudy, 2013)

2.7.2 Spray-In-Place Pipe (SIPP)

Spray-in-place Pipe is another method of trenchless rehabilitation, similar to Cured-in-Place Pipe, which is being used to repair existing pipelines. The principal difference between them is that the Spray-in-place Pipe involves a robotic lining system that improves and manufactures proprietary lining polymeric (Orlov & Averkeev, 2014).

2.7.2.1 Cement Mortar Lining

Cement Mortar Lining is one of the oldest methods, which has been used since the 1850s. A significant advantage of the Cement Mortar is its simplicity of application. Moreover, the application and mixing of Cement Mortar has low risk attached. This is a significant advantage over epoxy linings, which require careful control of ambient conditions, curing, mix ratios, etc. Additionally, Cement Mortar Lining deals with two types of protection, active and passive (Orlov & Averkeev, 2014).

2.7.2.2 Polyurea Lining

Polyurea lining technology provides exceptional resistance from chemical to plenty of liquids, which are high builds thickness in nature, quickly drying finishes and very low perm scores. This method is ideal for the multiple uses of waterproofing, immersion and lining applications, and corrosion control. Based on another study, Polyurea lining technology is very effective for lining large diameter pipes, clear wells, manholes, process tanks, lift stations, etc. Furthermore, environmental awareness is increasing day by day around the world, Polyurea shows to be a very economical and effective choice for business corporations and governments for their structural needs (Orlov and Averkeev, 2014).

2.7.2.3 Polyurethane Lining

Polyurethane pipelining provides us an operational way to control corrosion and abrasion problems attached to transferring material in agriculture and mining industries. Pipe spinning machines allow us to line pipes of greater lengths. There are some key advantages to the use of Polyurethane pipelining. For example, 1) reduce wear which raises the lifespan of industrial plants, 2) the coefficient of friction is lower, and 3) reduction in industrial plant downtime (Jain, 2011).

2.7.3. Close-Fit Pipe (CFP)

This is a globally recognized method, which involves insertion of resin-saturated felt tube made of polyester into an existing pipe. There are two main types of Close fit pipe; 1) mechanically folded liners, and 2) reduced diameter pipes, while the diameter range is 12-24 inches.

During manufacture, the compact pipe is collapsed into a kidney shape. However, it will be restored once the pipe is steam heated to 176 Fahrenheit and then cooled with compressed air. It will then retain its round shape indefinitely.

2.7.4. Thermoformed Pipe (ThP)

The diameter range of Thermoformed Pipe is 300-800 mm. If we talk about the advantages attached to Thermoformed Pipe then the following points must be worthy to mention (Deb et al., 2010):

- Rare or no joints
- Fast installation and higher quality because new pipe is produced in a controlled environment
- Provision of design life of a new pipe
- Cross-sectional reduction is minimal; the reason there is minimum reduction in flow capacity

However, there are some disadvantages with Thermoformed Pipe presented below:

- Limited range of diameter
- Existing flow requires bypass in some cases
- Large working space may be required for some installations
- Limitation of liner lengths by pull-in forces

2.7.5. Sliplining (SL)

Sliplining is a term, which is widely used to explain the ways of lining with discrete pipes as well as continuous pipes. In other words, SL is a process of inserting a new pipe by pushing or pulling into the existing pipe and mortaring the annular space. After the process of placing, the pipe is grouted to hold the lining for extra rigidity. It is extensively used to seal leaks in straight applications.

Some studies postulate that SL is the oldest of trenchless methods. The literature explains it in simple words; it involves the insertion of a new pipe into an existing one, and it is the most straightforward process among all other trenchless techniques. A new pipeline with an exterior measurement smaller than the interior measurement of the host pipe is either pushed or pulled into the host pipe (Sebti et al., 2013). The ideal host pipes for SL are those which have no deformities or very straight in nature. The nature of SL depends on the circumstances; it may be segmental or continuous.

Chapter 3

Trenchless Waterline Rehabilitation Methods

3.1 Introduction

There are factors which should be identified before choosing the renewal method such as pipe history, leakage, cause of failure, and flow capacity.

3.2 Water Pipe Rehabilitation

There are different types of trenchless methods for pipe replacement rehabilitation and repair; each method has advantages and disadvantages. Selecting the appropriate method depends on a project condition. Najafi (2016) has categorized these methods into seven as shown in the Figure 3.1.

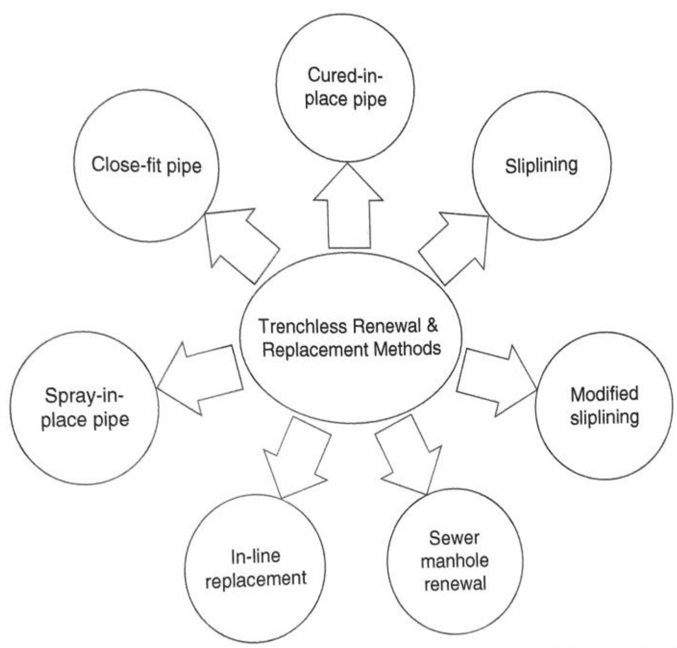

Figure 3.1 Basic Trenchless Renewal Methods (Najafi, 2016)

Water pipes can be renovated by using different trenchless technologies. Najafi (2010) and Rees (2011) state that "the term 'renewal method' refers to all the methods that can extend the service life of a pipeline beyond its original design life." The main difference is whether the methods that will be used for pipe rehabilitation are trenched (also called open-cut) or trenchless. Pipe replacement using the traditional open-cut method requires excavation of the whole existing pipe. On the other hand, trenchless techniques do not require excavating the whole pipe the only need for excavation is making some pits to allow the equipment to access. Beale at el. (2013) mentioned that the application of trenchless technologies is not always feasible. When the trenchless technology is more costly than the traditional open-cut method, trenchless techniques will not be feasible. For example, the presence of surrounding infrastructure such as residential homes, third-party pipes etc., or excessive costs related to moving trenchless equipment may exceed the cost of conventional open-cut. .

The use of trenchless technology in rural areas is less pronounced. According to FCMNR (2003): "Deterioration of water pipes can lead to impaired water quality, reduced hydraulic capacity, leakage, and frequent breaks in water distribution systems."

3.2.1 Cured-In-Place-Pipe (CIPP)

Cured in place pipe is one of the most widely used rehabilitation methods used for structural and nonstructural pipe renewal (Najafi, 2016). The process involves inserting a thermoset resin material into the existing pipe by using hot water. The main feature of the CIPP method is that it can be used to rehabilitate pipes ranging in diameter from 6-in to 60-in. It does not require excavation to rehabilitate a pipeline that is either leaking or structurally unsound, and the estimated lifespan is 50 years (Hashemi and Najafi, 2017). Most of the time, it is comprised of a saturated felt tube that is made of polyester, fiberglass cloth, as well as some other materials is suitable for resign impregnation. The inverted pipe is another area that must be taken care of at an appropriate level. Most of the time, it is done with the help of the upstream access point from where the utility hole and the excavation are carried out. In addition, it might be possible for the inversion of the liner upstream to be carried out from the downstream access point. Despite the fact that it works out well, the potential for risk is on the higher side in such cases. Figure 3.2 shows the installation process of CIPP.

Figure 3.2 Installation Process of CIPP (Insituform Technologies, 2018)

3.2.1.1 Advantages of CIPP

1. Does not cause damage to floors, structures, sidewalks, interior walls, or streets.
2. Increases flow efficiency.
3. Eliminates the intrusion of root.
4. Noncircular shapes can be accommodated.
5. Can be used to repair pipes with multiple angles and bends.
6. Can be used to repair the damaged line instead of entire pipe.
7. A cost-effective method compared with open trench method.
8. Prevents pipe failure and stops pipe leaking, and
9. The flow capacity of the smooth interior surface for the new pipe may be improved, even though there is a slight loss of pipe diameter.

3.2.1.2 Disadvantages of CIPP

CIPP has disadvantages as well (Bugbee al et. 2010)

1. Carrier tube is manufactured according to project requirements.
2. Sealing at the ends might be needed.
3. Higher costs compared to other trenchless renewal methods.
4. Keeping the materials being transported at a temperature no more than 130ºF.
5. Grouting may be required.

3.2.1.3 Considerations of CIPP

- The old pipe needs to be cleaned before insertion of the new pipe.
- Temporary by-pass is required.
- The liner pipe needs to be supported from surrounding material due to the flexibility of the used material.

3.2.1.4 Installation Process

One of the more commonly used methods when it comes to installation is the inversion method. The overall installation process is going to be much smoother as compared to the others at the same period. Safety and cost constraints are an issue with this method, but the overall effect on the higher side and maintenance costs are relatively lower. The processes involved are:

1. Pipe access - the space required depends on the diameter of the pipe to be rehabilitated. The minimum space required is 6 ft. * 12 ft. as shown in Figure 3.3.
2. Setting up a temporary bypass adequate for flow capacity.
3. Pipe cleaning - removing all the existing debris before rehabilitation.
4. CIPP installation - inverting the impregnated resin tube into host pipe.
5. CIPP curing - Using hot water or steam pressure to cure the resin within the tube.
6. Post-inspection of the new pipe (CIPP)

7. Reinstate services – The water pipes should be reopened and put in service.

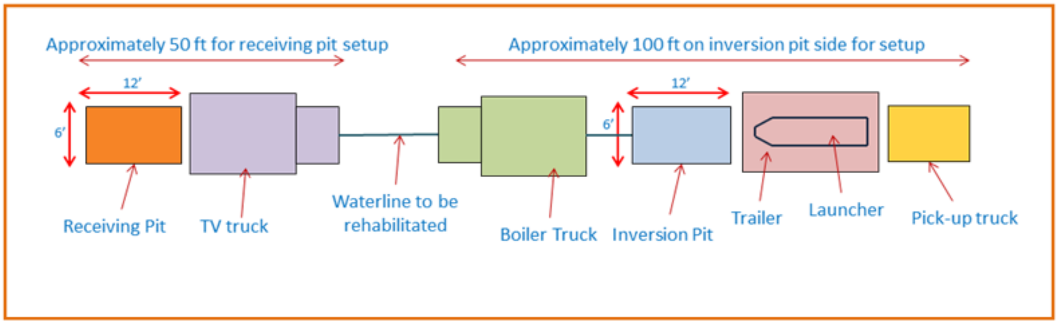

Figure 3.3 Layout for CIPP Waterlines Renewal (Insituform Technologies, 2018)

3.2.2 Sprayed-In-Place Pipe (SIPP)

Sprayed in place pipe is a trenchless pipeline rehabilitation technique. It is an efficient, jointless, seamless, and long-lasting solution for the restoration of aging underground piping systems. SIPP involves a robotic lining system that develops proprietary lining polymeric. It can rehabilitate pipes over 36-in. SIPP material types can be cementitious, polymer or epoxy. This method can be applied in water, sewer, gas, and chemical pipelines (Hashemi and Najafi, 2017).

This method is used these days extensively. It is an efficient and long-lasting solution for the restoration of aging underground piping systems. One of the key elements of this system is how the rehabilitation method is going to be used to make sure that the existing pipelines can be prepared. It involves the placement of the robotic lining system that is developing the manufacturing lining polymeric in an appropriate manner. Most of the time, it is a joint that is seamless and lay out symmetrically. SIPP has four types of lining systems. Figure 3.4 shows the general site layout for SIPP.

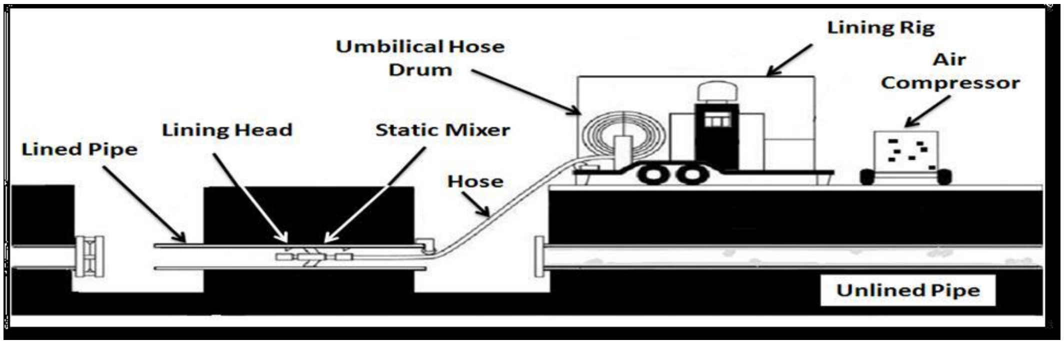

Figure 3.4 Layout for SIPP (3M Water Infrastructure, 2018)

3.2.2.1 Cement Mortar Lining

Cement Mortar Lining is one of the oldest methods used since the 1850s. A significant advantage of the Cement Mortar is its simplicity of application. Moreover, the application and mixing of Cement Mortar have low risk attached. This is a significant advantage over epoxy linings, which require careful control of ambient conditions, curing, mix ratios, etc. Additionally, Cement Mortar Lining deals with two types of protection, active and passive (Orlov & Averkeev, 2014).

3.2.2.2 Epoxy Lining

Epoxy lining is a long-term solution to breaks and leaks, blockages, prevents erosion, water damage, maintains water flow and prevents mold growth. This method acts as a barrier to heavy metals leaching into drinking water lines from metal piping systems. According to some studies, the Epoxy lining is eco-friendly; for instance, zero waste, no carbon emissions, prevents chemical leaching, and conserves water supplies (Wiley, 2017). Figure 3.5 shows the process of epoxy lining.

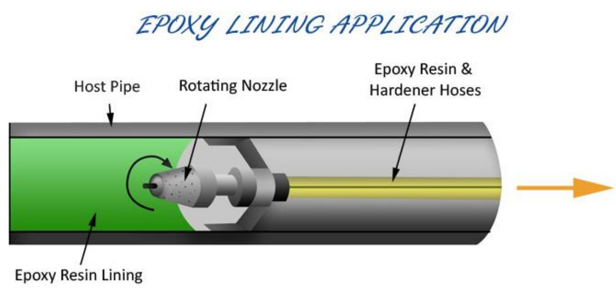

Figure 3.5 Epoxy Lining (ISTT, 2017)

3.2.2.3 Polyurea Lining

Polyurea lining technology provides exceptional resistance from chemical to plenty of liquids, which are high builds thickness in nature, quickly drying finishes and very low perm scores. This method is ideal for the multiple uses of waterproofing, immersion and lining applications, and corrosion control. According to another study, Polyurea lining technology is very effective for the lining big diameter pipes, clear wells, manholes, process tanks, lift stations, etc. Furthermore, the environmental awareness is increasing day by day around the world. Polyurea shows to be very economical and effective choice for the business corporations and governments for their structural needs (Orlov and Averkeev, 2014).

3.2.2.4 Polyurethane Lining

Polyurethane pipelining provides us an operational way out to control corrosion and abrasion problems attached to transferring material in the agriculture industry and mining industry. The pipe spinning machines allow us to line pipe for greater lengths. There are some key advantages of the use of polyurethane pipelining, for example, 1) reduce wear which raises the lifespan of plants, 2) the coefficient of friction lower, and 3) reduction in plant downtime (Jain, 2011).

3.2.2.5 Advantages of Sprayed In Place Pipe

- Increases the service life of the piping system.

- Reduces the frequency of maintenance cost.
- Improve flow capacity and system efficiency.
- Improves water quality,
- Protects the pipe from future corrosion and degradation.

3.2.2.6 Considerations of Sprayed In Place Pipe

- Determination the condition of the degraded pipe.
- The distance between the entry and exit pits should not exceed 500 ft.
- Locating the valves and hydrants of water distribution system to be replaced.

3.2.2.7 Installation Process

The installation process for SIPP is similar to CIPP except steps 4 and 5. These steps should be as follows:

- Lining Preparation - Verifying lining mix ratio, temperature of materials, and the pump.
- Lining Installation - Monitoring the speed and flow rate of the sprayer to get a homogeneous and uniform liner as required.

3.2.3 Close Fit Pipe (CFP)

Close-fit pipe can be used for structural and nonstructural purposes. It is considered an ideal solution to rehabilitate deteriorated pressure pipes that are relatively straight or have only modest bends. CFP reduces the cross-sectional of the new pipe material temporarily before insertion to the host pipe, when internal pressure is applied to the material, it returns to its original size and shape. This technique involves three versions: fold and form for pipes ranging from 4 in. to 30 in. in diameter, drawdown for pipes ranging from 3 in. to 60 in. in diameter, and pulldown for pipes ranging from 3 in. to 24 in. in diameter (Najafi, 2016).

The advantage that this technique tends to offer is that it allows the development of the cross-section of the host pipe across each level. It is contrary to what might happen when loose fit lining techniques are implemented. The method reduces the diameter at the temporary level as well as making sure that the insertion for the existing pipelines is being done appropriately. Once the whole process is completed, the diameter is regained. The old pipeline system is replaced by the new when the whole process happens. Figure 3.6 shows general site layout for close-fit pipe.

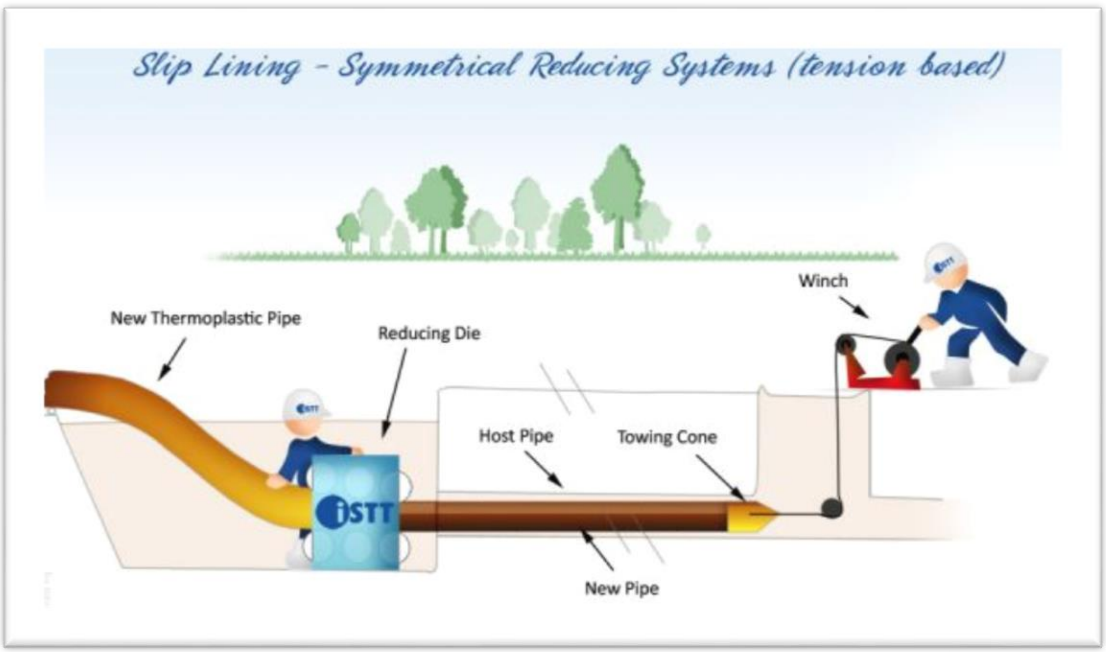

Figure 3.6 Layout for Close Fit Pipe (ISTT, 2017)

3.2.3.1 Advantages of Close-Fit Pipe Method

Some advantages of close fit pipe are mentioned below (Deb et al., 2010);

- Rare or no joint
- There is no need of grouting

- There is flexibility of 45-degree bends for the mechanically folded pipes
- Minimization of the piping area
- New pipe is produced in a controlled environment

3.2.3.2 Disadvantages of Close-Fit Pipe Method

Some disadvantages of close fit pipe are outlined below (Deb et al., 2010).

- Restriction of installation and diameter range.
- Requirements of large working space.
- Requirements of flow bypass.
- Changes in diameters or culverts discontinuation may forbid this technique.
- Special machineries are required, that is why considered as relatively complex.

3.2.4 Sliplining (SL)

Sliplining is a term, which is widely used to explain the ways of lining with discrete pipes as well as continuous pipes. To put in other words, sliplining is a process of inserting a new pipe by pushing or pulling into the existing pipe and mortaring the annular space. After the process of placing, the pipe is grouted to hold the lining for extra rigidity. It is extensively used to seal the leaks in straight applications. When there are no joint settlements or misalignment of the existing pipe, the SL can be used as a solution. The process involves inserting a smaller pipe into the host pipe. The annular space between the existing pipe and the new pipe will be grouted. It can be used to rehabilitate pipes ranging in diameter from 4 in. to 158 in. as a segmental and from 4 in. to 63 in. as a continuous. Continuous sliplining uses a long continuous pipe, such as HDPE, PVC, and GRP. Segmental sliplining is similar to continuous sliplining. The main difference is based on the pipe material used such as PVC, HDPE (Najafi, 2016). In this method, the diameter of the pipe needs to be very precise to make sure that the installation and the rehabilitation process can be carried out appropriately. At the same time, the anchoring of the installed pipe using the grouting can also be done correspondingly. Figure 3.7 shows the process of SL method.

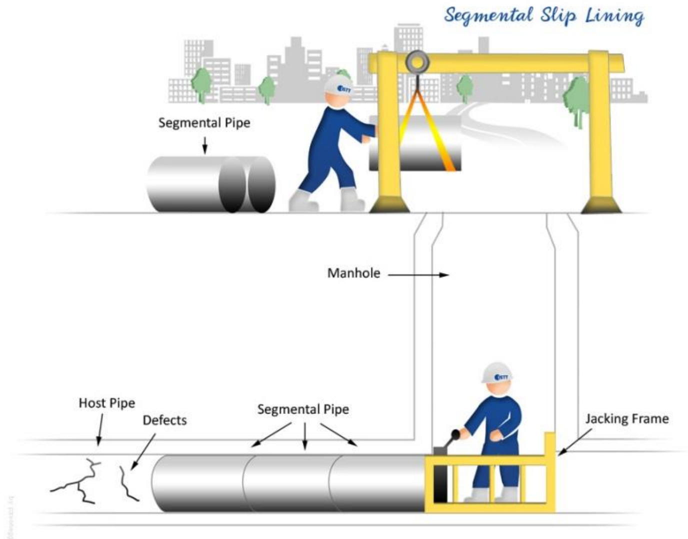

Figure 3.7 Layout of Sliplining Method (ISTT, 2017)

3.2.4.1 Advantages of Sliplining

- Simple method - no need to specialized equipment.
- High experience level by vendor community.
- Relatively low installation costs.

3.2.4.2 Disadvantages of Sliplining

- Reduces the cross sectional area to 10% or more.
- Requires excavation for entry and exit pit, reconnection of laterals and valves as well as for every bend.
- Requires grouting.
- In case of existing bends, steel pipe is not recommended.

3.2.5 Modified Sliplining (MSL)

In this method, the new pipe that will be inserted is close-fit to host pipe and the annular space should be grouted. There are two variations of MSL method: panel-lining method (PLM) and spiral wound method (SWM). PLM is used to rehabilitate large gravity pipeline (more than 48 in.). The main feature of this method is that it can be used to renew non-circular pipeline. Fiberglass composites are the main material type of this method. On the other hand, SWM also can be used to rehabilitate large gravity pipeline ranging from 4 in. to 100 in. at a maximum of 1000 ft. (Najafi, 2016).

Most of the time when MSL is installed, the method being used is to make sure that the installation process for the existing pipeline system is carried out correctly. The complication with this method is to make sure that the correct variations are carried out as well as ensuring that in the long-run, the habitual context of the MSL is being taken care of. The other aspect is to make at overall modifications that look after the infrastructure.

3.2.6 Inline Replacement (ILR)

This method is only used on occasions when the condition of the pipe is far from ideal and cannot be repaired. The reason that this method is not used extensively is that it is not cost effective and eats up a lot of time. For instance, when there are instances of pipe bursting, removal of the pipe or even the scenario when the pipe eating or pipe insertion scenarios are witnessed, this is the most commonly used solution. In general, there are two categories of ILR: pipe bursting and pipe removal.

3.2.6.1a Pipe Bursting (PB)

The pipe bursting method can be used to replace pipes ranging in diameter from 4 in. to 140 in. at a maximum of 750 ft. On the other hand, pipe removal uses Horizontal Directional Drilling (HHD), Horizontal Auger Boring (HOA) or Microtunneling (MT) to perform the work. In this method, the deteriorated pipe will be broken into small pieces and will be taken out of the borehole. Pipe bursting uses a vibrating hammer or pulling head to break the deteriorated pipe, a new pipe will be pulled or pushed in to replace the damaged host pipe. Figure 3.8 shows the layout for the pipe bursting method.

3.2.6.1b Pipe Removal

The pipe removal method can be used to replace pipes up to 36 in. at a maximum of 300 ft. (Najafi, 2016). Pipe bursting also can be used to upsize a pipeline; this feature can be considered a unique advantage among the other trenchless technologies (Hashemi and Najafi, 2017).

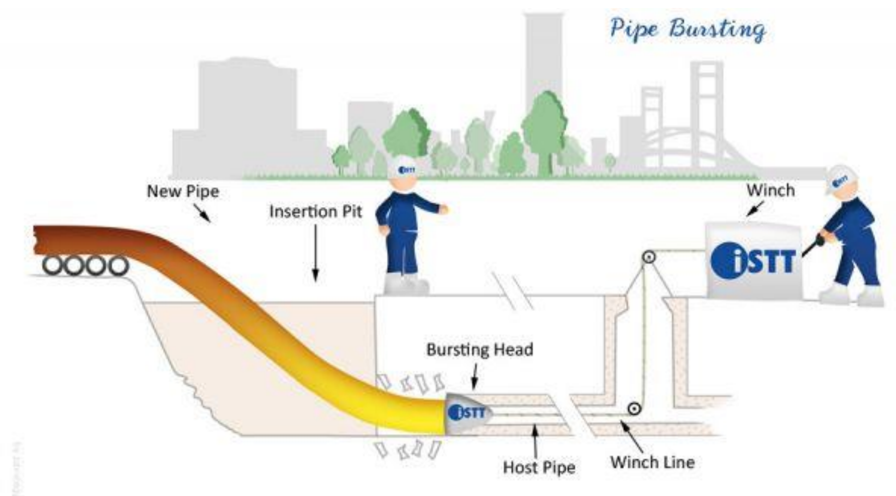

Figure 3.8 Layout for pipe bursting method (ISTT, 2017)

3.2.6.2 Advantages of Pipe Bursting Method

- The new pipe will follow alignment of the old pipe.
- Since the old pipe will be left underground, there is no need for its disposal.
- Upsizing the old pipes is possible

3.2.6.3 Disadvantages of Pipe Bursting Method

- Requires excavation for entry and exit pits as well as for reconnection of laterals and valves.
- Requires a large working area above the ground to layout the pipes before insertion.
- Not recommended for existing pipes made of ductile materials such as steel.
- Steel piping not recommended for installation by this method.

3.2.7 Thermoformed Pipe (ThP**)**

The diameter range of Thermoformed Pipe is 4 to 30 in. If we talk about the advantages attached to Thermoformed Pipe, then the following points must be worthy to mention (Deb et al., 2010):

- Rare or no joints
- Fast installation and higher quality because new pipe is produced in a controlled environment
- Provision of design life of a new pipe
- The cross-sectional reduction is minimal: that is why there is minimum reduction in flow capacity. Similarly, there are some disadvantages attached with Thermoformed Pipe presented below:
- Limited range of diameter
- Existing flow bypass is required in some cases
- Large working space may be required for some installations
- Limitation of liner lengths by pull-in forces.

3.3 The Work Crew

The work crew should be qualified and well trained in the field and in safety. They should be fully familiar with the equipment, the mechanisms. As the supervisor of the work represents the contractor, he should have at least two years of experience, should be present at all stages of the work, and be responsible for controlling work at all times.

3.4 Chapter Summary

- CIPP, SIPP, CFB, and PB leave a smooth surface and increase flow capacity.
- Water bypass is required for CIPP, SIPP, CFB, ThP, and PB. Some methods take longer such as PB. In contrast, SIPP takes a shorter time and may skip bypass.
- SIPP needs more surface preparation than the other methods.
- All methods require access pit excavation. However, the pipe bursting method requires a larger excavation pit because of the continuous nature of the new pipe.
- PB is the only technique that is able to increase the diameter of the existing pipe.
- SIPP can be used for any pipe diameter.
- SIPP has the thinnest layer compared with other trenchless methods.
- All methods require grouting except PB and SIPP.

Chapter 4

Discussion of Results

4.1 Water Line Trenchless Technologies Survey And Interviews Results

Twenty-two (22) participants were asked during NASTT's No-Dig Show, Palm Springs, California, held on March 25 – 28, 2018, from industry professionals. The participants were as follows: nine manufacturers, seven contractors, four engineers, and two distributors. As shown in Figure 4.1. The respondents have on average of 5 years of experience.

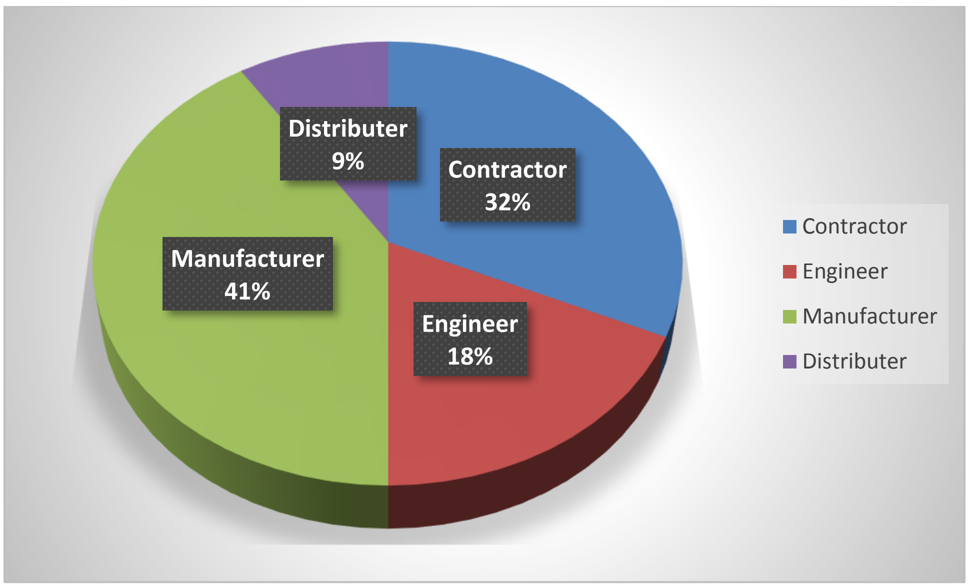

Figure 4.1 Survey Participants

4.2 Discussion of the Results

Following the completion of the questionnaire, the results were analyzed with Microsoft Excel. The questionnaire is included in Appendix A.

4.2.1 Structural vs. Non-Structural Lining Rehabilitation Method.

American Water Works Association (AWWA, 2014) M28 has published structural classifications for pressure pipe liners. The description of each lining is described in Table 4.1.

Table 4.1 Structural Classification of Linings (AWWA, 2014)

Liner characteristics	Non-Structural	Semi-Structural		Fully-Structural
	CLASS I	CLASS II	CLASS III	CLASS IV
Internal corrosion barrier	Yes	Yes	Yes	Yes
Bridges holes/gaps at pipe operating pressure	No	Yes	Yes	Yes
Inherent ring stiffness	No (depends on adhesion)	No (depends on adhesion)	Yes	Yes
Long-term independent pressure rating ≥ pipe operating pressure	No	No	No	Yes
Survives “burst” failure of host pipe	No	No	No	Yes

Table 4.2 presents the results of the structural vs. non-structural lining rehabilitation method. Categories are structural / non-structural / semi-structural / both. The results show that SL, CIPP, CFL, and PB are mostly structural methods, whereas the SIPP method may be either structural or non-structural.

Table 4.2 Structural vs. Non-structural Lining System

Method	Structural	Non-Structural	Semi-Structural	Both
Pipe Bursting (PB)	12	0	0	1
Close-Fit Lining (CFL)	6	1	4	3
Sliplining (SL)	9	2	1	3
Cured In Place Pipe (CIPP)	8	2	3	5
Spray-In-Place Pipe (SIPP)	4	4	4	2

Figure 4.2 shows the results graphically.

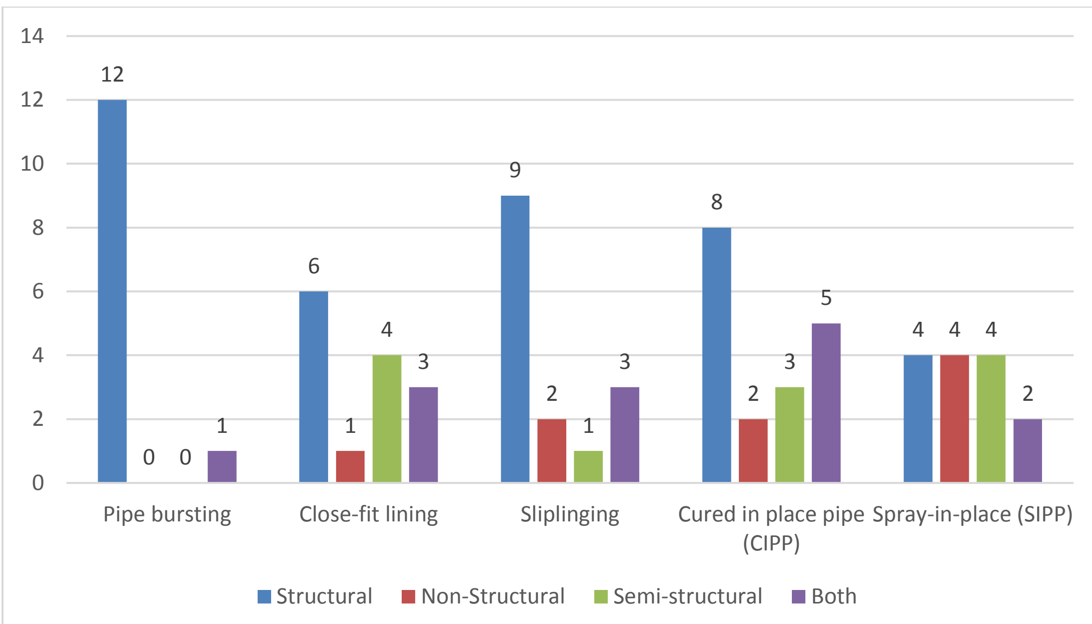

Figure 4.2 Structural vs. Non-Structural Lining System

4.2.2 Is the Market Direction For the Structural or Non-structural Method?

Based on participants' answers, 68% think that the market direction tends to be structural rather than non-structural. On the other hand, 27% of participants think that the market is both structural and non-structural. Figure 4.3 shows the results graphically.

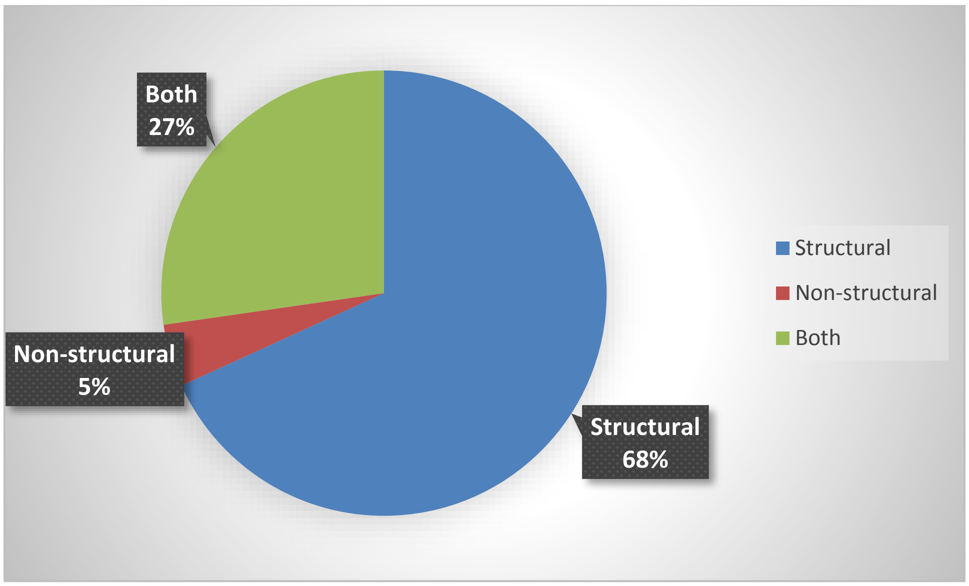

Figure 4.3 Market Direction

4.2.3 The Required Data of Designing Water Pipe Rehabilitation Method**.**

Collecting information is important before designing a water pipe rehabilitation method. Inspection data and internal pressure is considered necessary by 16 of 17 participants prior to design. Thirteen participants saw that cleaning the pipe and checking external pressure is necessary. In addition, two experts saw that knowing of negative pressure and material properties are important as well, as shown in Table 4.3.

Table 4.3 Results of Required Data of Designing Rehab Method

Inspection data	16	Negative pressure (vacuum)	2
Cleaning pipe	13	Pipe diameter	1
Internal pressure	16	Materials properties	2
External pressure	13	Temperature	1
Performance testing	1		

This data is reflected in Figure 4.4.

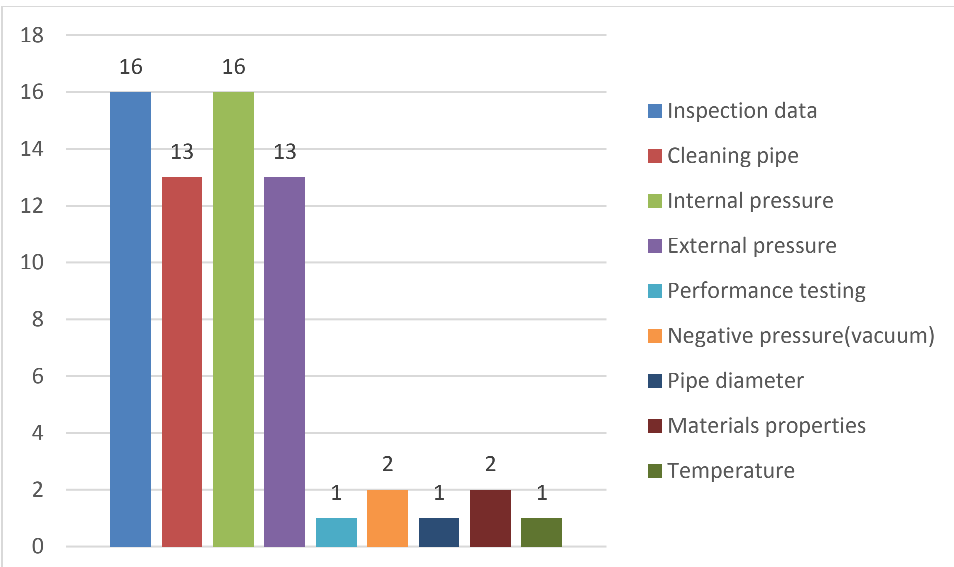

Figure 4.4 The Required Data of Design Rehabilitation Method

4.2.4 The Expected Growth in Trenchless Technologies for Water Mains Rehabilitation Methods.

Participants expected an increase in use of trenchless methods in the future, especially for potable water rehabilitation and replacement. Participants were asked to rate the method with the most potential on a scale of one (most promising) to five (least promising). Fifty percent of participants expected that CIPP would be the most popular method in the future followed by SL and SIPP, then PB and CFL respectively. Table 4.4 shows the findings.

Table 4.4 Result of Most Promising Pipeline Rehabilitation Method

	Pipe Bursting	Close-Fit Lining	Sliplining	Cured In Place Pipe (CIPP)	Spray In Place Pipe (SIPP)
1 (most promising)	3	2	5	11	5
2	3	7	3	5	7
3	4	5	5	2	3
4	8	3	1	2	4
5 (least promising)	4	5	8	2	3

Figure 4.5 shows the results graphically. CIPP, SIPP, and SL are dominant followed by PB and CFL respectively.

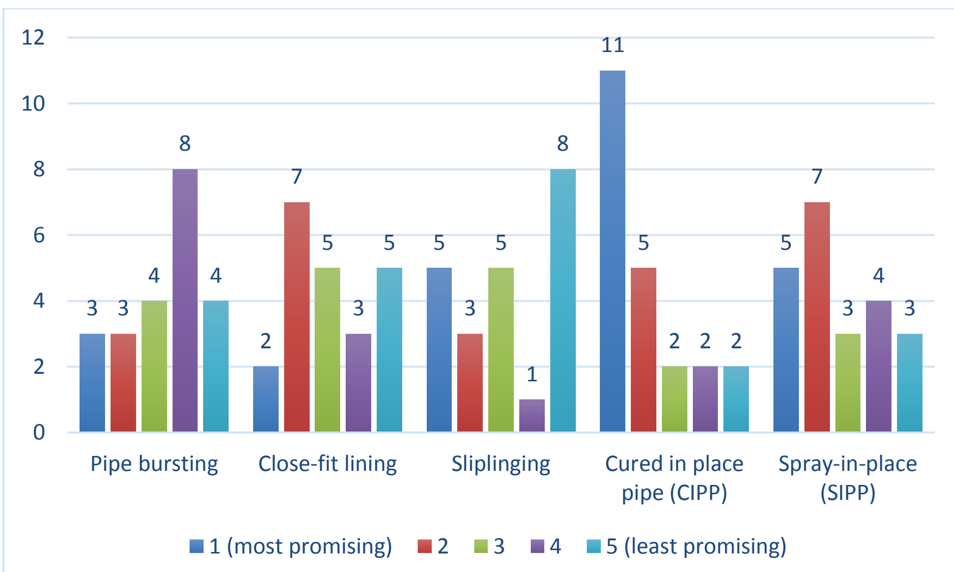

Figure 4.5 Chart of Most Promising Pipeline Rehabilitation Method

4.2.5 Trenchless Rehabilitation Methods vs. Open-trench

Figure 4.6 shows the results. Eighty two percent of the participants stated that trenchless technology would be a stronger role player than the traditional open trenching method.

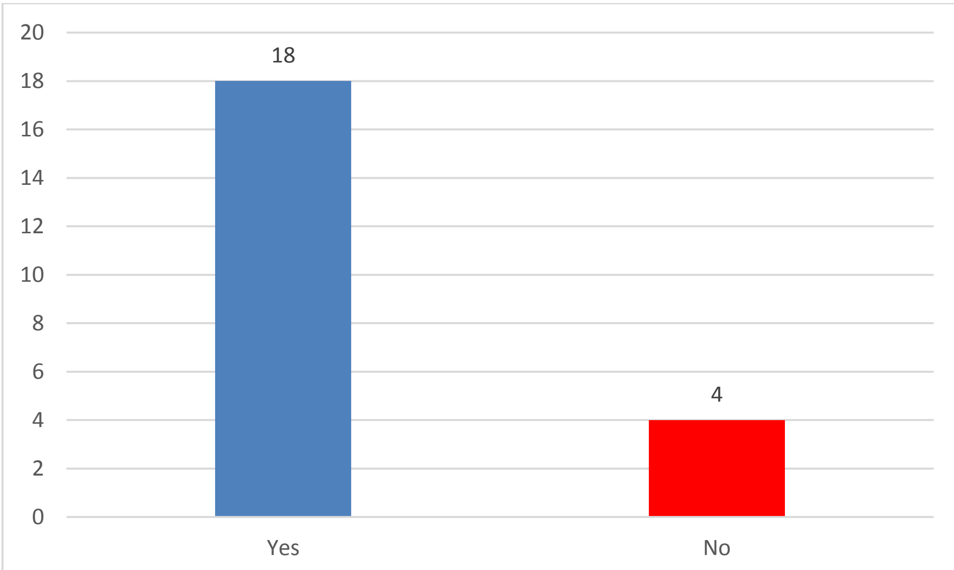

Figure 4.6 Utilization of TT in Future vs. Open-trench

4.2.6 The Main Factors of Choosing Waterline Rehabilitation Method.

Participants were requested to rate the most important factors of choosing the rehabilitation method on a scale of one (more important) to three (less important). Table 4.5 presents the findings. The results show that the environmental factor is the most important followed by cost and speed of delivery.

Table 4.5 The Main Factors of Choosing Waterline Trenchless Method

Category	Speed of service delivery	Cost	Environmentally Friendly
1 (very important)	4	8	9
2	9	6	6
3 (less important)	9	6	4

Figure 4.7 shows the results graphically.

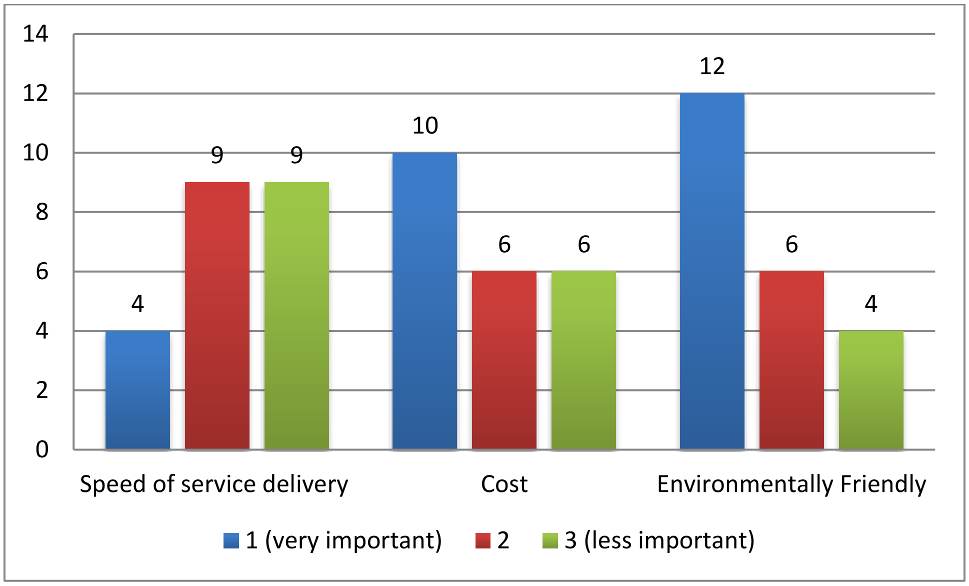

Figure 4.7 Important Factors of Waterline Trenchless Method

4.2.7 Safety

As with any pipe replacement or renewal project, there are risks. These risks can be minimized by using trenchless technology compared with open trenching. Participants were asked to rate the method on a scale of one (less risk) to five (more risk) on workers during the work. Table 4.6 presents the result. CIPP showed less risk to workers followed by SL and PB. Figure 4.8 shows the results graphically.

Table 4.6 Safety Degree of Waterline Trenchless Method

Category	Pipe bursting	Close-fit lining	Sliplining	Cured in place pipe (CIPP)	Spray-in-place pipe (SIPP)
1 (less risk)	6	3	6	8	5
2	3	8	2	5	5
3	4	7	9	5	3
4	6	2	1	1	3
5 (more risk)	3	0	4	2	3

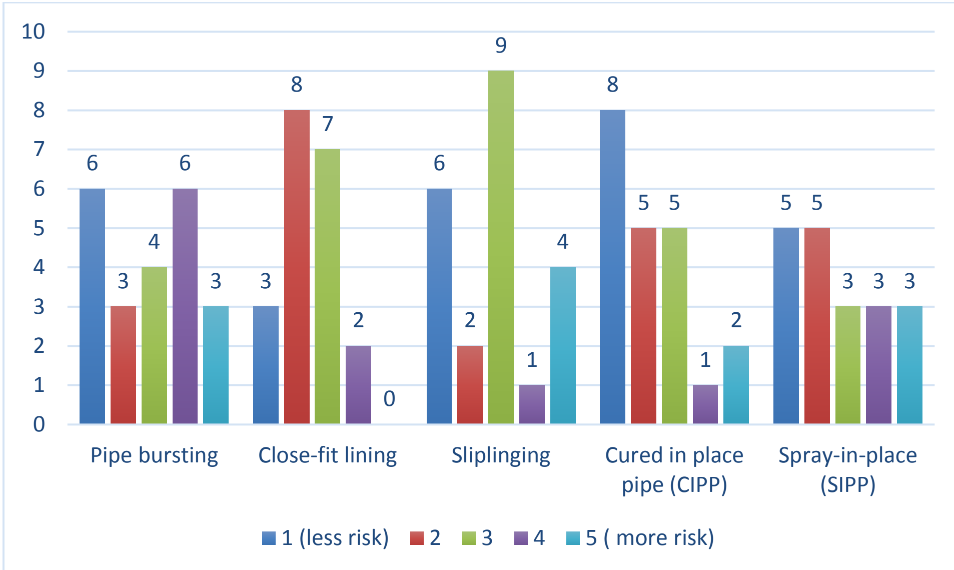

Figure 4.8 Safety Degree of Waterline Trenchless Method

<u>4.3 Davis Drive Water Pressure Plane Expansion Project</u>

The project includes replacement and expansion of 2 miles of new water and sanitary sewer mains along South Davis Drive, Arlington Texas. The contract was given to SYB Construction Co., Inc. The project will be constructed in two phases. Phase one includes the installation of an 8 to 16 inch water main and 8 inch sanitary sewer mains under South Davis Drive between West Park Row Drive and UTA Boulevard using the traditional open trench method. The estimated duration to complete this project is 375 calaender days and the estimated cost is $5,425,236. The project began on February 5, 2018. After completion of the work, approximately 23,150 square yards of asphalt pavement will be reconstructed by street reclamation, along with sidewalk improvements.

Water service will be replaced from the new main to the water meter and sanitary sewer services will be replaced from the new main to the property line. All streets within the project limits will be repaved.

- Grass area affected by construction will be restored by the contractor.
- Streets may be closed to through traffic during construction, but residents will be provided access to their properties.
- Some parking within the project area may be restricted at times during the installation of pipes and subsequent street reclamation.
- The project will extend the life of public facilities, reduce maintenance costs, and improve service to these areas.

4.3.1 Municipality Interveiw

An interview was conducted with one of the designer team engineers in the City of Arlington, Texas; the engineer was asked 5 questions regarding project background and related social cost:

4.3.1.1 Reason Why the Trenchless Technology Was Not Considered?

- There are a lot of pipe connections along Davis Drive from Park Row Drive to UTA Boulevard
- The street needs to be repaired, so the traditional open cut method is a good choice to restore the street after completion of the project. City of Arlington will pay for street restoration cost.

Trenchless technology will be used in another project where the street does not require maintenance. Horizontal Directional Drilling (HDD) is the method that will be used for that project.

4.3.1.2 What Is the Reason for Selecting PVC Pipe? Why Were Other Types of Pipe Not Considered?

PE pipe requires a long trench; PVC pipe requires a shorter trench. The City of Arlington does not want to block the street for the length of time required in order to minimize traffic disruption.

4.3.1.3 Did You Consider Property Damage**?**

Yes, property damage was considered.

4.3.1.4 Did You Consider Interruption of Service for Water, Electricity, Sewer etc..)

Yes, only interruption of water happened for no more than two hours.

4.3.1.5 Did You Consider Any Safety Requirements?

Yes, all safety requirements are according to OSHA standards.

4.3.2 Residental Survey

A residential survey was conducted by interviewing residents face to face. A total of 18 residents were reached;13 of the 18 agreed to the interview and answered five questions. The participants were selected randomly from West Park Row Drive to UTA Blvd. on Davis Drive. The questions were as follows:

1- The residents were asked about major hindrances which impacted their daily activities. The hindrances were noise, dust, traffic disruptions and access to their properties. Table 4.7 shows the results.

Table 4.7 Experience of Major Hindrances

1- What are the major hindrances which impacted on their daily activities?		
Category	Number	%
Dust	2	16
Noise	3	23
Traffic Disruption	6	46
Access to your Property	1	7
Interruption of service (water, electricity, sewer)	1	7
Total	13	100

Disruption of traffic was mentioned by 46% of the participants as a major hindrance that impacted their daily activities during the project works. The second hindrance was noise followed by dust, access to property and interruption of service respectively. This is shown in Figure 4.9.

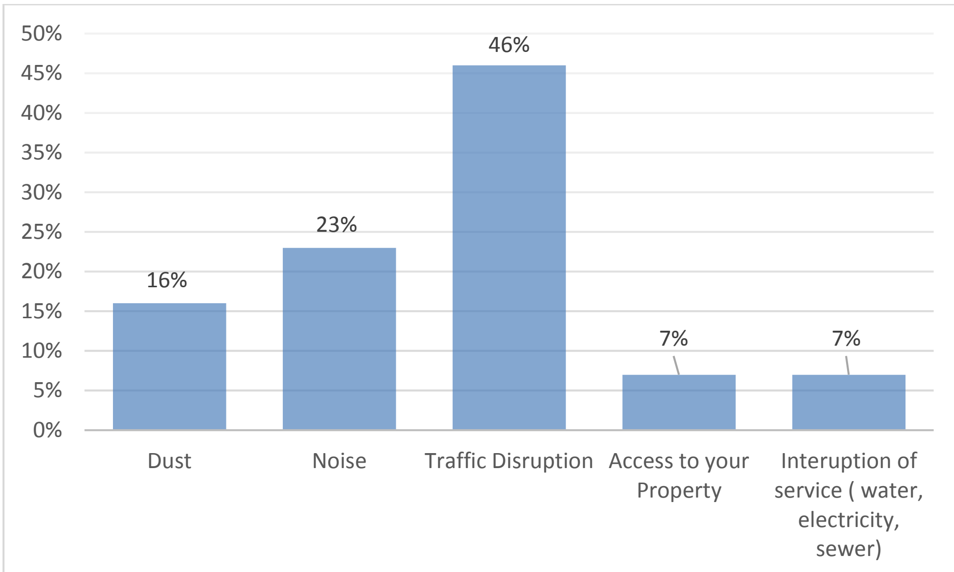

Figure 4.9 Results of Question 1

2- The second question was if they received notice from the contractor or City of Arlington telling them about the project.In other words were they notified about potential interruption of traffic and other hindrances that might impact daily activities. The result was that 76% of them received notice regarding the project. Figure 4.10 shows the result of question 2.

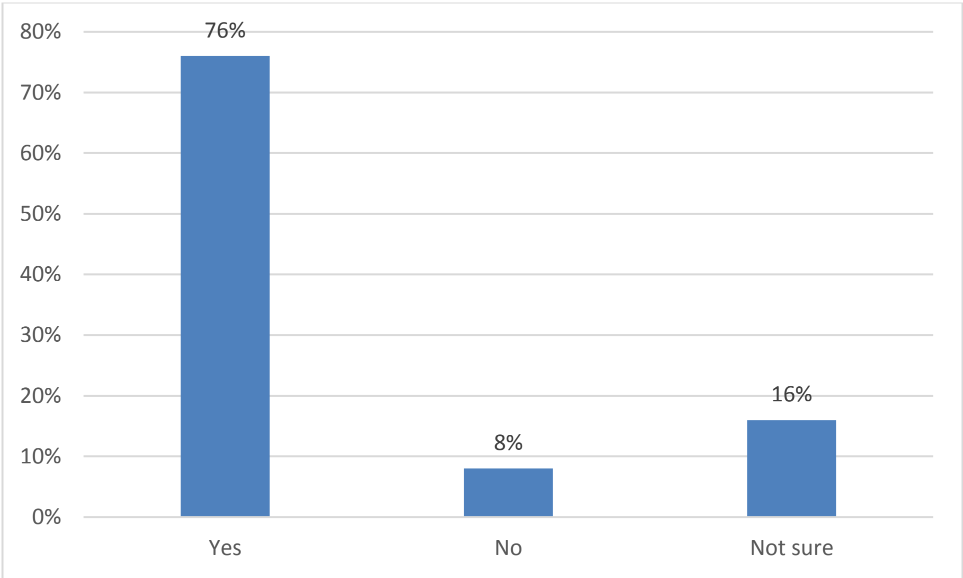

Figure 4.10 Results of Question 2

3- The third question was if the time it took to go to work increased or not. For 92% of respondents, the time did increase after the project began. Figure 4.11 presents the results of question 3.

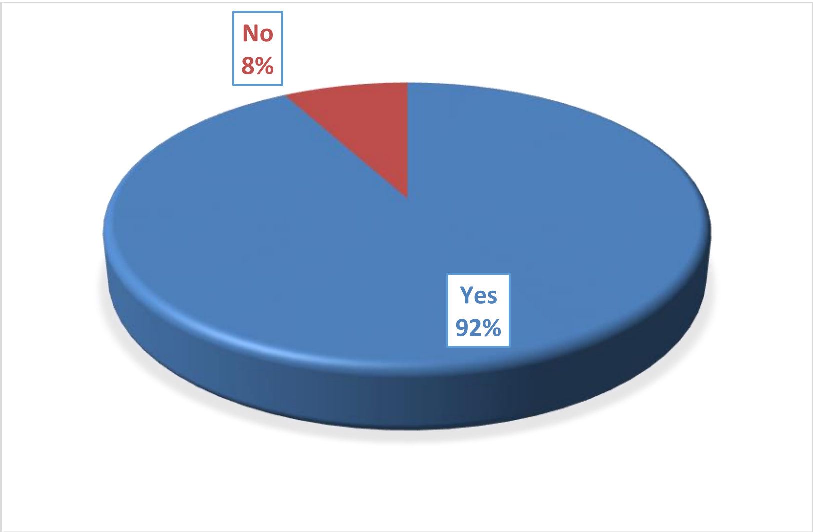

Figure 4.11 Results of Question 3

4- The forth question regarded the extra minutes when going to work or shopping.

The result of question four is shown in Table 4.8.

Table 4.8 Result of Question 4

4- How many extra minutes do you spend in the car when you go to work or shopping?		
Minutes	Percentage %	number
0 to 2	23%	3
2 to 4	23%	3
4 to 6	46%	6
6 to 8	8%	1

The result shows that 46% of the residents needed an average of 5 extra minutes to get to the work site. As shown in Figure 4.12.

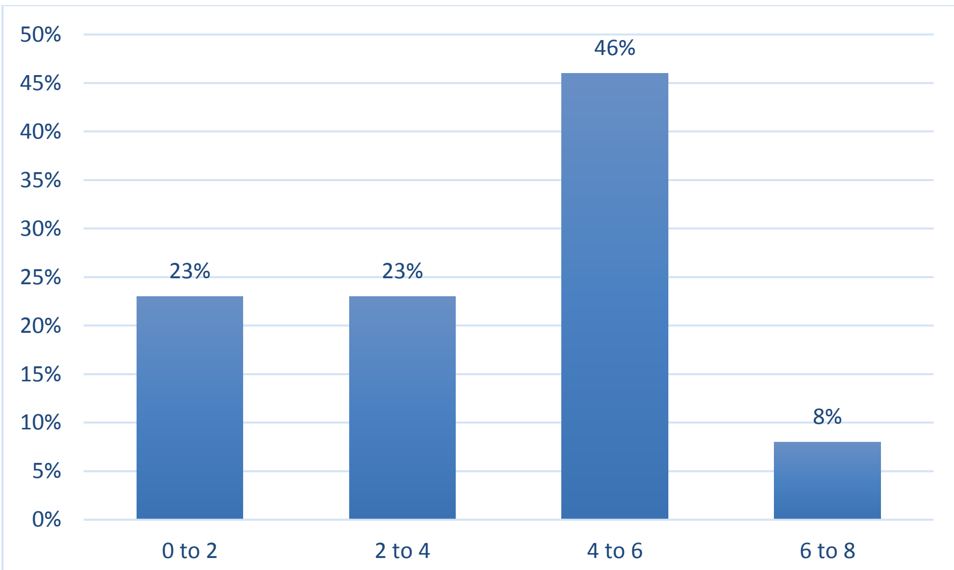

Figure 4.12 Results of Question 4.

5- The fifth question is regarding the extra miles when going to work or shopping.

The results for question five are shown in Table 4.9.

Table 4.9 Result of Question 5

5- How many extra miles do you spend in the car when you go to work or shopping?		
Miles	Percentage %	number
0 to 1	38%	5
1 to 2	54%	7
2 to 3	8%	1
3 to 4	0%	0

Figure 4.13 presents the results of question 5 graphically.

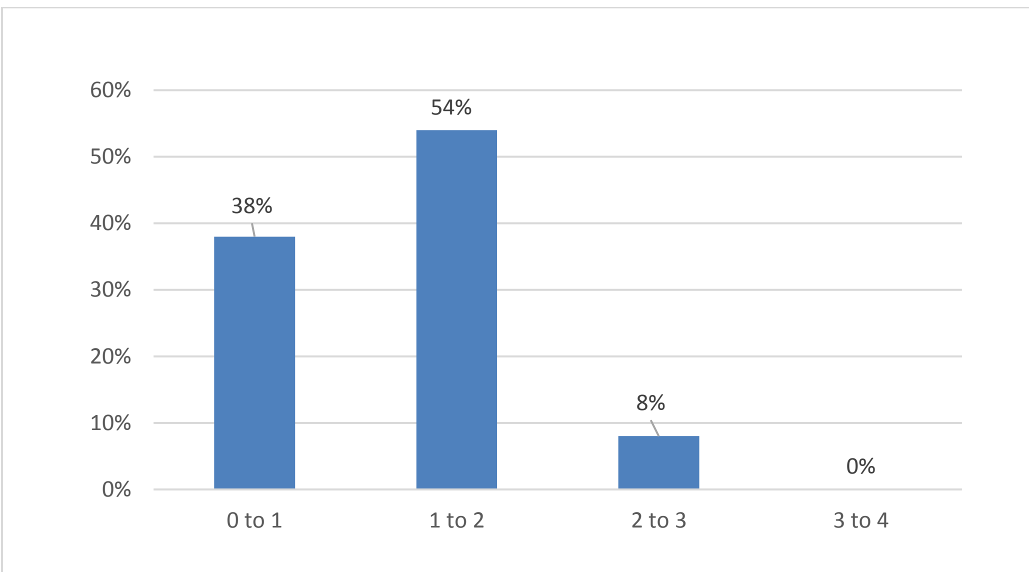

Figure 4.13: Results of Question 5

Chapter 5

Conclusions and Recommendation for Future Research

5.1 Conclusions

The outcomes of the questionnaire showed the following:

- The SL, CIPP, CFP, and PB methods are mostly structural methods, whereas the SIPP method may be either structural or non-structural.
- The market direction tends toward structural rather than non-structural.
- Cleaning pipe, inspection data, internal pressure and external pressure are required data for the design phase of the rehabilitation method.
- CIPP will show the most growth in the future followed by SL, SIPP, PB and CFP respectively.
- Trenchless technology will play a larger role in future than the traditional open trenching method.
- "Friendly to the environment" factor is more important when selecting the rehabilitation method, besides the cost and speed of delivery.
- Trenchless technologies offer a low price advantage compared to traditional open-cut options of underground installations.

For the construction-related social costs of open trench method:

- The traffic disruption issue was the most significant problem impacted residents' daily activities. Followed by noise, dust, access to property, and interruption of service respectively.
- Fuel consumption was increased due to extra mileages and detours.

From the literature, it is concluded that:

- CIPP, SIPP, CFB, and PB leave a smooth surface that lead to increased flow capacity.
- Water bypass is required for the CIPP, SIPP, CFB, ThP, and PB. Some methods take longer such as PB. In contrast, SIPP takes less time and may skip bypass.
- All methods require access pit excavation. However, the pipe bursting method requires a larger excavation pit because of the continuous nature of the new pipe.
- PB is the only technique that is able to increase the diameter of the existing pipe.
- SIPP can be used for any pipe diameter.
- SIPP has the thinnest layer compared with other trenchless methods.
- All methods require grouting except PB and SIPP.
- The trenchless operations can be performed beneath existing services such as buildings and roadways unlike the open-cut method, which is impossible use in this way.
- Local business, roadways, trains, and walkways can remain in operation as disturbance is minimized by trenchless methods.
- Less use of equipment minimizes disturbance to the environment.

5.2 Recommendation for Future Research

Due to limited time, this research does not include all renewal trenchless methods. Therefore, the recommendations for future research can be summarized as follow:

- Develop a cost module for trenchless construction methods (TCMs) and compare the cost of each method.
- Develop a cost model to calculate the social costs of a specific method based on advantages and limitations and compare with social costs of open cut method.

Appendix A

Abbreviations

Abbreviation	Meaning
ASCE	American Society of Civil Engineers
NASTT	North American Society for Trenchless Technology
AWWA	American Water Works Association
TRM	Trenchless Renewal Methods
USEPA	U.S Environmental Protection Agency
DPA	Deterioration Point Assignment
WRF	Water Research Foundation
ISTT	International Society of Trenchless Technology
UTA	University of Texas at Arlington
CP	Concrete Pipe
CIP	Cast Iron Pipe
DIP	Ductile Iron Pipe
PVC	Polyvinyl Chloride
HDPE	High Density Polyethylene
GRP	Glass Fiber Reinforced Plastics
PLM	Panel Lining Method
SWM	Spiral Wound Method
SIPP	Spray-In-Place Pipe
ILR	In-Line Replacement
ThP	Thermoformed Pipe
CFP	Close Fit Pipe
CIPP	Cured In Place Pipe
PB	Pipe Bursting

Appendix B

Questionnaire Survey Form

Your organization:

Municipality	
Contractor	
Engineer	
Other: specify	

1- Which method is structural / non-structural / semi-structural / both?

Pipe bursting	
Close-fit lining	
Sliplining	
Cured in place pipe (CIPP)	
Spray-in-place (SIPP)	

2- Is the market going for structural and non-structural?

3- What type of equipment do you need of designing a water pipe rehabilitation method?

Inspection data	
Cleaning pipe	
Internal pressure	
External pressure	
Other, Please specify	

4- Where do you foresee the most growth in trenchless technologies for Water Mains Rehabilitation Methods?
(Please rank each category in a scale from 1 – least promising to 5 – most promising)

	Pipe bursting		Cured in place pipe (CIPP)
	Close-fit lining		Spray-in-place (SIPP)
	Sliplining		
	Other (please specify) :		

5- Do you expect trenchless rehabilitation methods for water mains to become a bigger role player than open-cut?

	Yes		No

6- What is more important?
(Please rank each category in a scale from one – very important to three – less important)

	Speed of service delivery
	Cost
	Environmentally Friendly

7- Which method has fewer risks for workers from the following?
(Please rank each category in a scale from one – less risk to 5 – high risk)

	Pipe bursting
	Close-fit lining
	Sliplining
	Cured in place pipe (CIPP)
	Spray-in-place (SIPP)

Appendix C

Residential Interview Form

Evaluation of Construction Related Social Costs and
Their Impact on the Community
Residential Survey

1- What are the major hindrances which impacted on their daily activities?

Category	
Dust	
Noise	
Traffic Disruption	
Access to your Property	
Interruption of service (water, electricity, sewer)	

2- Were you notified before the project's activities began in order to plan ahead?

Yes	No	Not sure

3- Has your travel time to work increased?

Yes	No

4- How many extra minutes do you spend in the car when you go to work?

Minutes	
0 to 2	
2 to 4	
4 to 6	
6 to 8	

5- How many extra miles do you spend in the car when you go to work?

Mile	
0 to 1	
1 to 2	
2 to 3	
3 to 4	

Appendix D

Davis Drive Project Documents

Staff Report

ARLINGTON
THE AMERICAN DREAM CITY

Construction Contract for Davis Pressure Plane Expansion, Phase 1, Project No. WUOP16011	
City Council Meeting Date: 09/26/17	Action Being Considered: Minute Order

RECOMMENDATION
Authorize the City Manager or his designee to execute a construction contract for Davis Pressure Plane, Phase I with SYB Construction Co., Inc., of Irving, Texas, in an amount not to exceed $5,425,236.

PRIOR BOARD OR COUNCIL ACTION
On June 28, 2016, City Council approved Minute Order MO06282016-014 authorizing the execution of an Engineering Services Contract with Halff Associates, Inc., of Dallas, Texas, for the design of the Davis Upper Pressure Plane Expansion Phase 1, in an amount not to exceed $333,000.

ANALYSIS
The current Water Master Plan has identified water main improvements which will expand the Upper Pressure Plane into the area generally bounded by Cooper Street, Fielder Road, Arkansas Lane and Sanford Street. These improvements will increase the water pressure in this area which is currently experiencing lower than average daily operating pressures. However, since the proposed improvements have been divided in two phases, the pressure increase will not occur until both phases are complete which is anticipated for CIP year 2019.

Phase 1 improvements consists of constructing approximately 8,500 linear feet of 8-inch, 12-inch, and 16-inch water main. It also includes replacement of approximately 3,300 linear feet of 8-inch sanitary sewer main. Once the water and sanitary sewer improvements are complete, approximately 21,600 square yards of asphalt pavement will be reconstructed by street reclamation along Davis Street from Park Row Drive to UTA Boulevard along with sidewalk improvements. This project will extend the life of the public facilities, reduce maintenance costs, and improve service to these areas.

Date of Bid:	September 7, 2017
Number of Bids Received:	Two
Number of Bids from Arlington Firms:	None
Bidder Prequalification:	Yes
Engineer's Estimate:	$5,885,000
Range of Bids:	$5,425,236 To $5,425,236
Low Bid:	$5,425,236
Recommended Low Bidder:	SYB Construction Co., Inc., of Irving, Texas
Contract Scope:	Construct 3,530 LF of 6 to 8-inch water main, 4,725 LF of 12-inch water main, 275 LF of 16-inch water main, and 3,350 LF of 8-inch sanitary sewer main, and 21,550 SY asphalt street reclamation.
Contract Time:	375 calendar days

VENDOR	MWBE	TOTAL
SYB Construction Co., Inc.	**WO**	**$5,425,236.00**
Jackson Construction, Ltd.	No	Non-responsive

*WO=Woman Owned Business

This project included an alternative for use of "Green Cement" to promote improved air quality in North Texas. Staff recommends awarding the green cement alternate in the amount of $1.00.

FINANCIAL IMPACT

Funding Sources:

Water Bond Fund	658502-18140205-68252	$1,761,707.77
Sanitary Sewer Bond Fund	648502-17973204-68250	$669,624.67
Street Bond Fund	358504-65900698-68153	$503,890.66
Street Maintenance Fund	728501-61550695-63132	$2,490,012.90

FY 2017	FY 2018	FY 2019
$0	$5,425,236	$0

ADDITIONAL INFORMATION

Attached: Bid Tab
Location Map

Under separate cover: None

Available in the City Secretary's Office: None

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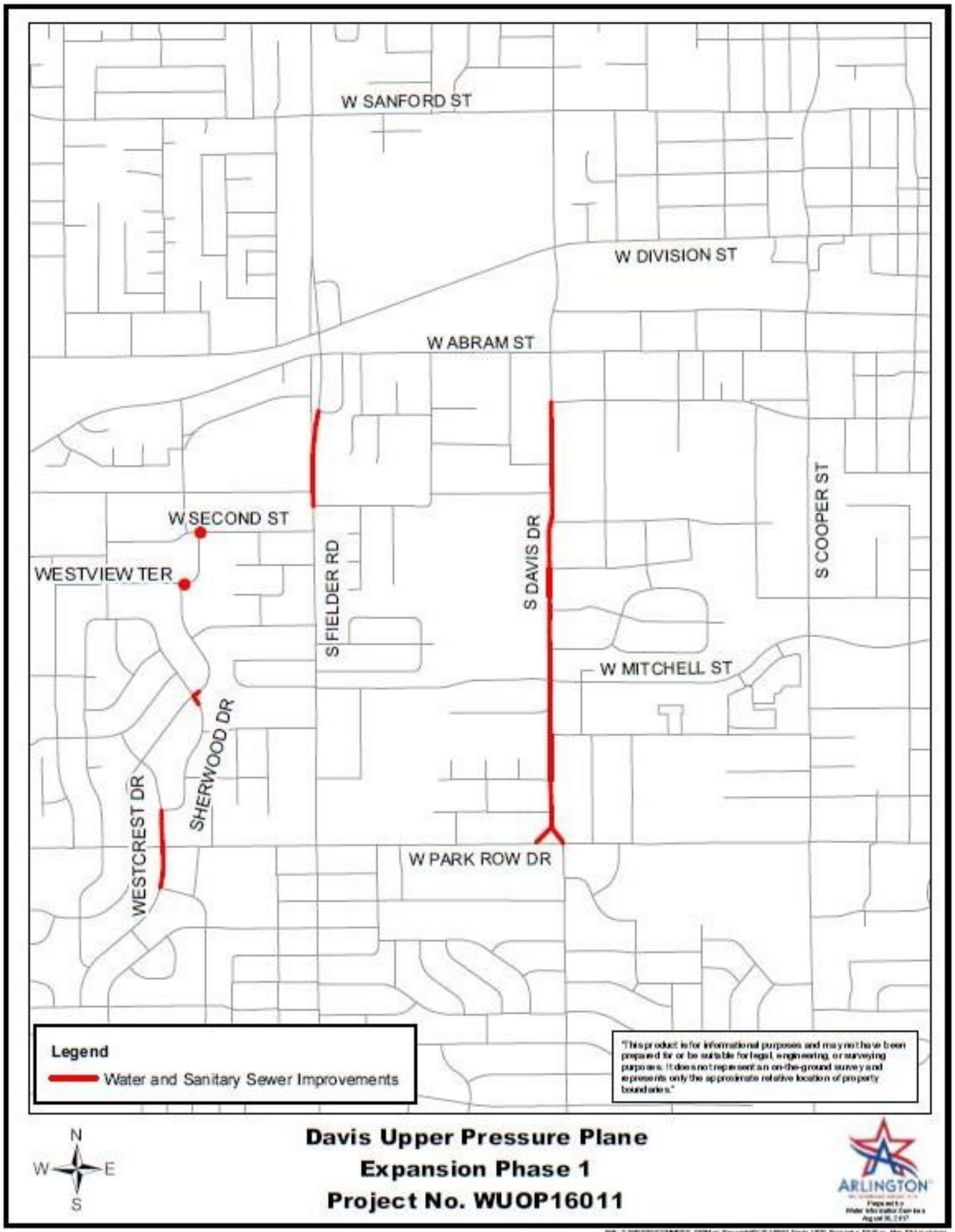
W SANFORD ST
W DIVISION ST
W ABRAM ST
S COOPER ST
W SECOND ST
WESTVIEW TER
S FIELDER RD
S DAVIS DR
W MITCHELL ST
SHERWOOD DR
WESTCREST DR
W PARK ROW DR
Legend
Water and Sanitary Sewer Improvements
"This product is for informational purposes and may not have been prepared for or be suitable for legal, engineering, or surveying purposes. It does not represent an on-the-ground survey and represents only the approximate relative location of property boundaries."
N
W
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Davis Upper Pressure Plane
Expansion Phase 1
Project No. WUOP16011
ARLINGTON

Appendix E

Davis Project Photos

Fig. E1. Pipes delivered and stored in the right of way

Fig. E2. Blocking one lane of the street before start digging

Fig. E3. Trenches dug to the curb after pavement is cut to trench width using a pavement saw

Fig. E4. Shoring system that used to support the laterals A

Fig. E5. Installation of pipe after trenching and supporting the lateral soil

Fig. E6. Trench backfilled with sand or gravel

Fig. E7. Loader used for backfilling

Fig. E8. Compaction machine used after backfilling

Fig. E9. Temporary pavement installed as work progresses forward

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