

**A Comprehensive Decision Support System (CDSS) for Optimal Pipe
Renewal using Trenchless Technologies**

Prashanth Khambhammettu

Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Science
in
Civil Engineering

G.V.Loganathan, Chair
David F.Kibler
Vinod Lohani

April 26, 2002
Blacksburg, Virginia

Keywords: Trenchless technologies, decision support system, optimal replacement,
annualized cost

Copyright 2001, Prashanth Khambhammettu

A Comprehensive Decision Support System (CDSS) for Optimal Pipe Renewal using Trenchless Technologies

By

**Prashanth Khambhammettu
(Abstract)**

Water distribution system pipes span thousands of miles and form a significant part of the total infrastructure of the country. Rehabilitation of this underground infrastructure is one of the biggest challenges currently facing the water industry. Water main deterioration is twofold: the main itself loses strength over time and breaks; also, there is degradation of water quality and hydraulic capacity due to build of material within a main. The increasing repair and damage costs and degrading services demand that a deteriorating water main be replaced at an optimal time instead of continuing to repair it. In addition, expanding business districts, indirect costs, and interruptions including protected areas, waterways and roadways require examination of trenchless technologies for pipe installation.

In this thesis a new threshold break rate criterion for the optimal replacement of pipes is provided. As opposed to the traditional present worth cost (PWC) criterion, the derived method uses the equivalent uniform annualized cost (EUAC). It is shown the EUAC based threshold break rate subsumes the PWC based threshold break rate. In addition, practicing engineers need a user-friendly decision support system to aid in the optimal pipeline replacement process. They also need a task-by-task cost evaluation in a project. As a part of this thesis a comprehensive decision support system that includes both technology selection knowledge base and cost evaluation spreadsheet program within a graphical user interface framework is developed. Numerical examples illustrating the theoretical derivations are also included.

Acknowledgements

I would like to sincerely thank the following people and organizations that have it made it possible to complete the work on this thesis.

- Dr. G. V. Loganathan has provided countless hours of support and assistance on this work. He has been very helpful in teaching me how to perform academic research. He has also provided valuable advice for my personal life. I would like to express my gratitude to him for the amount of time and effort that he has put in to help me succeed in my academic career. Without his continued support, guidance, and motivation I would not have been able to complete this thesis. I am very grateful to Dr. Loganathan.
- Dr. David Kibler has been very willing to serve as a member of my committee. He taught me ‘Urban Hydrology’ which exposed me to many of the problems faced by the practicing engineer. He has also helped me out by recommending my name to prospective employers. He has a sincere interest in the students of the Hydrosystems division and his door has always been open to me. I am very grateful to Dr. Kibler for his help and support.
- Dr. Vinod Lohani has also been willing to serve as one of my committee members. I am very grateful to Dr. Lohani for his willingness to serve on my committee.
- The faculty and students of the Hydrosystems division have encouraged and supported me throughout my time at Virginia Tech. I would like to thank them for their assistance. I would like to specially thank Dr. Newland Agbenowosi for teaching me the intricacies of Visual Basic and for being a great friend and mentor.
- Jerry Snyder, Frank Grablutz, Heidi Schoser, Dr. Yakir and Dr. Deb at Roy F. Weston Inc., and members of the AWWARF 2519 PAC were actively involved in the development of the decision support system. They have provided valuable technical assistance and guidance.
- I am deeply indebted to the web masters of the following sites for permitting me to use the material available on their web-sites. Without their approval, my thesis would have been incomplete.

<http://www.dakotapipelining.com>

<http://www.dbce.csiro.au>

<http://www.catflap.net/digging-deep>

<http://www.corrosionsource.com>

<http://www.aramoon.com>

<http://www.cfi-1.com>

<http://www.insituform.com>

<http://www.pmconst.com>

<http://www.dcca.org>

<http://www.inrock.com>

<http://www.trenchlessdataservice.com>

- Gopalakrishna and Jayasree Khambhammettu, my parents, have always supported me in whatever goals I have set for myself. They have encouraged me to excel in all that I do. I would like to thank them for their love and guidance throughout my life. Their unwavering faith and devotion to their children is worthy of the highest recognition. I express my gratitude to them for their lives of service.

Table of contents

ABSTRACT.....	ii
ACKNOWLEDGEMENTS	iii
TABLE OF CONTENTS	v
LIST OF TABLES.....	viii
LIST OF FIGURES.....	ix
CHAPTER 1 – INTRODUCTION	1
1.1 BACKGROUND	1
1.2 DIFFERENT COST APPROACHES	2
1.3 DECISION SUPPORT SYSTEM.....	2
1.4 OBJECTIVES.....	3
1.5 ORGANIZATION OF THESIS.....	4
CHAPTER 2 - REVIEW OF PIPE RENEWAL TECHNOLOGIES.....	5
2.1 INTRODUCTION	5
2.2 CLEANING	6
2.2.2 <i>Flushing</i>	7
2.2.2 <i>Cable- Attached Devices</i>	8
2.2.3 <i>Mechanically Driven Cleaning</i>	9
2.2.4 <i>Fluid-Propelled Devices</i>	9
2.2.5 <i>Chemical Cleaning</i>	9
2.2.6 <i>Air Cleaning</i>	10
2.2.7 <i>Abrasive Particle Cleaning</i>	10
2.3 PIPE LINING.....	10
2.3.1 <i>Cement Mortar Lining</i>	11
2.3.2 <i>Calcite Lining</i>	12
2.3.3 <i>Epoxy Lining</i>	13
2.3.4 <i>Metallic Phosphate Lining</i>	13
2.4 SPOT REPAIR.....	13
2.5 CATHODIC PROTECTION/ANODE RETROFIT.....	15
2.6 CHEMICAL GROUTING	16
2.7 REINFORCED SHOTCRETE.....	17
2.8 JOINT REHABILITATION	17
2.9 PIPE INSERTION.....	17
2.9.1 <i>Conventional Sliplining</i>	18
2.9.2 <i>Modified sliplining – Using Structural Pipe</i>	20
2.9.3 <i>Modified Sliplining – Non Structural Pipe</i>	23
2.9.4 <i>Inversion Lining/ Cured-in-place Pipe (CIPP)</i>	23
2.10 PIPE REPLACEMENT.....	25
2.10.1 <i>Trenched Replacement</i>	26
2.10.2 <i>Pipe Bursting</i>	28
2.10.3 <i>Pipe Jacking / Microtunneling</i>	33
2.10.4 <i>Horizontal Directional Drilling</i>	37
2.11 SUMMARY	39
CHAPTER 3 - REVIEW OF ELEMENTS OF TRENCHLESS TECHNOLOGIES.....	41
3.1 INTRODUCTION.....	41

3.2 GUIDANCE AND STEERING SYSTEMS	41
3.2.1 The Co-ordinate System	42
3.2.2 Walkover Systems.....	43
3.2.3 Wireline Systems	44
3.2.4 Electromagnetic Systems.....	45
3.2.5 Laser / Optical System	46
3.2.6 Inertial Systems	47
3.2.7 Water Level	48
3.2.8 Inclinometer Method	48
3.2.9 Slanted –Nose Method	51
3.2.10 Hydraulic Jetting Method	51
3.2.11 Differential Excavation Method.....	51
3.2.12 Articulated –Head Method.....	51
3.2.13 Wireline Steering Tool Method	52
3.2.14 Applicability and Compatibility of various methods.....	52
3.3 FORCES INVOLVED	53
3.3.1 Open Trench.....	55
3.3.2 Jacking Technologies (Pipe Jacking, MicroTunneling).....	56
3.3.3 Horizontal Directional Drilling (HDD).....	63
3.3.4 Pipe Bursting	66
3.4 SUMMARY OF CHAPTER	69
CHAPTER 4 – REPLACEMENT ANALYSIS.....	70
4.1 INTRODUCTION	70
4.2 THE EUAC APPROACH	70
4.3 REPLACEMENT METHODOLOGY	76
4.4 EXAMPLE PROBLEMS	81
4.5 SUMMARY	95
CHAPTER 5 - ELEMENTS OF THE COMPREHENSIVE DECISION SUPPORT SYSTEM FOR DISTRIBUTION SYSTEM PIPING	96
5.1 OVERVIEW	96
5.2 RENEWAL OPTION CATEGORY DETERMINATIO	100
5.3 PROBLEM IDENTIFICATION	102
5.3.1 Structural Problems	102
5.3.2 Hydraulic Problems	103
5.3.3 Joint Leaks	104
5.3.4 Water Quality.....	104
5.4 RENEWAL TECHNOLOGIES IN THE DSS	104
5.4.1 Rehabilitation Technologies.....	105
5.4.2 Replacment Technologies.....	105
5.5 PRESENT WORTH COST ANALYSIS	111
5.6 SUMMARY AND FUTURE DEVELOPMENT	112
CHAPTER 6 THESIS SUMMARY	114
6.1 INTRODUCTION	114
6.2 CONTRIBUTIONS OF THIS THESIS	114
6.3 FUTURE RESEARCH	114
CHAPTER 7 BIBLIOGRAPHY.....	116

APPENDIX

**APPENDIX A – ALTERNATIVE METHODS FOR DETERMINATION OF OPTIMAL
REPLACEMENT TIMING**

APPENDIX B –USER INTERFACE WITH THE CDSS

VITA

List of Tables

Table 3.1 - Summary and application of tracking systems (Tanwani and Iseley, 1994).....	50
Table 4.1 - Break Data	82
Table 4.2 - Present Worth Computation – Discrete Compounding	84
Table 4.3 - Present Worth Computation – Continuous Compounding	85
Table 4.4 - Computation of Annualized Costs – Discrete Case	88
Table 4.5 - Computation of Annualized Costs – Continuous Case	89
Table 4.6 - Pipe data	90
Table 4.7 - Break times from the database	92
Table 4.8 - Data required for replacement analysis	94
Table 5.1 - Renewal option categories	99
Table 5.2 - Pipe and Site Characteristics	99
Table 5.3 - Pipe renewal technologies	100
Table 5.4 - Renewal option categories and applicable technologies	106
Table 5.5 - Rehabilitation methods – acceptable values for pipe specific information.....	107
Table 5.6 - Rehabilitation methods – Acceptable values for site specific information.....	108
Table 5.7 - Replacement technologies – Acceptable values for pipe specific information.....	109
Table 5.8 - Replacement technologies – Acceptable values for site specific information	110

Table of Figures

Figure 2.1 - Lining by Rotary Trowel Method	12
Figure 2.2 – Robotic Spot Repair	14
Figure 2.3 - Cathodic protection using buried anodes	16
Figure 2.4 - The Swagelining Process	22
Figure 2.5 – Fold and Form Liner.....	22
Figure 2.6 –ThermoPipe® System.....	24
Figure 2.7 – The Pipe Bursting Process	32
Figure 2.8 – MicroTunneling System	35
Figure 3.1 - Co-ordinate system for Underground Installations	43
Figure 3.2 – Walkover System for HDD	44
Figure 3.3 - Wireline System for HDD.....	45
Figure 3.4 – Laser Guidance System	47
Figure 3.5 – The Herrenknecht – ELS Guidance System	49
Figure 3.6 – Tensor Steering Tool System (InRock Systems).....	52
Figure 3.7 - Force based Technology Classification.....	54
Figure 3.8 - Longitudinal Cross Section of a Pipe (Open Trench Method)	55
Figure 3.9– The Pipe Jacking / Microtunneling Process.....	58
Figure 3.10 - Drilling of the Pilot Bore (Phase 1 of HDD).....	64
Figure 3.11 – Backreaming and Insertion of the new pipe (Phase 2 of HDD).....	64
Figure 3.12 – The Pipe Bursting Head.....	67
Figure 3.13 – A Schematic of the Pipe Bursting Process.....	67
Figure 4.1 – Annualization of Present Worth	76
Figure 4.2 – Cumulative number of breaks for “14449-1952-CI-6”	91
Figure 5.1 - CDSS logic diagram.....	98
Figure 5.2 - Preliminary selection of alternative technologies in the TSM.....	101

Chapter 1 - Introduction

1.1 Background

The unseen water main infrastructure deteriorates under the surface demanding immediate remedial action. Water distribution systems comprise a significant part of the underground infrastructure in the U.S. The AWWA (American Water Works Association) estimates that \$325 billion is needed over the next 20 years to upgrade aging water distribution systems. (*Mainstream*, February 1999). These large expenditures require a time phased prioritization scheme in renewing the mains. Rehabilitation at the optimal time with the appropriate technology will result in significant savings. The twofold question of whether to repair or replace a main and with what technology requires prudent analysis and is the basis of this thesis.

Consider a refrigerator, a television, a computer and a car. Modern technology is so capable that refrigerators and TVs rarely fail. Considering their long life, when they do fail, people tend to buy them new. Computer components do not enjoy the same level of reliability and when they fail, repair is an option. Falling prices and improved capabilities prompt one to consider the trade-off between repair and replacement. Cars do have relatively long life but require maintenance and substantial initial cost; they also deteriorate in value over time. With Cars, the number of visits to a mechanic alerts the owner. As the number and frequency of the visits increase, the owner starts considering enticing low initial cost offers for a new car. In the case of a car, high repair costs and accelerated deterioration require the consideration of the best replacement time. Note, that in all the cases we have assumed a constant need for the service. It is also clear that when the initial cost is substantial, a tradeoff between repair and replacement is warranted. In addition, deterioration of service favors replacement.

The innovations in the manufacturing processes, new materials, and installation technologies have led to alternative better options in laying pipes. However, maintenance (to address the degrading hydraulic capacity and water quality), repair, indirect, and third party liability costs are increasing. These large operational costs dictate that a

deteriorating pipe be replaced at an optimal time instead of continuing to repair it. The issue of optimal replacement has been addressed mainly from the point of view of present worth cost (PWC) minimization. In this thesis, the equivalent uniform annualized cost (EUAC) approach is also considered.

1.2 Different cost approaches

In the PWC method it is assumed that a present sum is available to provide for distributed expenditure in the future. Therefore, the PWC minimization seeks the least PWC value, in general with the assumption that an identical installation-repair-replacement cycle will be repeated. This cycle length is the optimal replacement time.

In the EUAC method, the least annual cost is sought over a cycle. Further continuance of repairing the pipe will lead to an increase in the annual payment. In this thesis it is shown that the minima of the PWC and EUAC methods are not realized at the same time. This difference is attributed to the following. In the PWC method a single sum provides for the future costs and the remaining gets compounded towards interest accumulation; in the EUAC method a continuous stream of payments provide for both costs and interest accumulation. These two different modes of payment and interest accumulation justify that the optimal time need not be the same.

1.3 Decision Support System (DSS)

Until recent times, open trenching is the main method of pipe installation. However the growth in the business districts, the congestion, intervening utilities, waterways, roadways, and protected areas demand less intrusive trenchless technologies as opposed to the open trench method. The trenchless technologies have their own problems. The choice of technology depends on preference, cost, environmental and site conditions, pipe material and technology limitations.

Execution of a trenchless technology project requires intensive site investigation and appropriate planning unlike the traditional method of open trench. Choosing the appropriate guidance system for positioning and installing the pipe, accurate knowledge

of the magnitude of forces that will act on the pipe during installation, disposal of slurry and broken pipe fragments (for Pipe bursting) are some of the elements central to all the technologies. A detailed discussion is provided in Chapter 3. The location (e.g., in a residential / commercial area) has a significant impact on the technology to be used. The pipe material can also influence the selection as some technologies can be used with only specific materials. The type of soil present at the site would also influence the choice of selection. Presence of organic contaminants in the soil is an added constraint, as plastic pipes are known to be permeable to hydrocarbons.

It is very difficult to consider all the aforementioned factors manually and select a viable alternative. A DSS (Decision Support System) on the other hand can make use of an existing knowledge base and decide on the appropriate technology. Practitioners also require a detailed cost estimate for the project embodying costs for each and every task involved in the project. The DSS should include the knowledge base that relates the technology to the pipe and site conditions and the cost-estimating program within a shell that permits interaction.

1.4 Objectives

Based on the foregoing discussion, the following specific objectives are considered:

1. Provide a detailed review characterizing available pipe installation technologies. This synthesis will also form the knowledge base of the DSS.
2. Develop an optimal replacement time model for determining water main replacement priorities
3. Develop a comprehensive decision support system to select an appropriate technology for repair / replacement of a pipe along with a detailed cost analysis
4. Provide numerical examples that will illustrate the methodology and a detailed user's manual of the DSS

1.5 Organization of the thesis

Chapter 1 presents the background, nature of the problem and the objectives of this thesis. Chapters 2 and 3 present an elaborate review of all available technologies, the forces involved, and advantages and disadvantages. Chapter 4 contains the development of an optimal replacement time model. It is shown that the newly developed threshold break rate criterion leads to more economical replacement scheme than the previously suggested optimal replacement time models. Chapter 5 is an introduction to the DSS. Chapter 6 summarizes the key contributions of this thesis. The bibliography chapter contains all the references and other related studies. Several related mathematical results on the optimal replacement time are given in Appendix A. A detailed user's manual with appropriate screen captures is given as Appendix B.

Chapter 2 - Review of Pipe Renewal Technologies

2.1 Introduction

The technologies described in this chapter represent piping renewal technologies that are currently in use in North America, Japan and Europe. The term renewal includes both rehabilitation and replacement technologies. Renewal technologies are grouped into five major categories: cleaning, lining, pipe insertion, pipe replacement, and other rehabilitation methods. The discussion deals with the applicability of each method, their advantages and limitations. The primary focus is on the trenchless methods of rehabilitation and replacement. This chapter is a condensed version of a chapter from the draft report of the AWWARF-2519 project written by *Deb et al.* (2001).

“The term *trenchless technology* is used to describe a wide array of technologies, processes and techniques for creating holes or renovating conduits without disturbing the surface” (*Kramer et al.* (1992)). This chapter concentrates on the applications of trenchless technologies to the water distribution systems. Much of the information presented here is taken from *Cleaning and Lining of Water Mains* (AWWA, M28, (1987)) (*Assessment of Existing and Developing Water Main Rehabilitation Practices* (AWWARF, (1990)), *Demonstration of Innovative Water Main Renewal Techniques* (AWWARF, (1998)), and information obtained from utilities, contractors and vendors of pipeline renewal technologies.

Trenchless pipe replacement methods should be considered when the following factors are present:

- There is a need or desire to minimize surface disruption and site restoration (e.g., mains cross under concrete or recently placed asphalt surfaces).
- Few service connections on main (e.g., transmission main).
- Long straight runs of pipe (e.g., transmission mains).
- Open trench construction would be disruptive due to location or environmental setting of main.
- Access to main, or proposed route of main, is restricted (e.g., private property or under major highways or waterways).

Although trenchless technologies for water pipe rehabilitation and replacement are relatively new in North America, they have been extensively used in Europe for water main replacement. In North America, trenchless technologies have gained prominence in gas pipeline and wastewater collection applications since the 1980's. Trenchless technology includes a large family of methods utilized for installing and rehabilitating underground utility systems with minimal surface disruption and destruction resulting from excavation. Utility systems in the underground infrastructure include water and wastewater distribution systems; gas, petroleum and chemical pipelines; electrical and communications networks; access-ways and other small diameter tunnels utilized in a variety of applications. Trenchless methods have also been used in solving some complex underground transportation and environmental contamination problems. Typical methods of construction include pipe bursting, microtunneling, horizontal directional drilling and pipe jacking. *Ariaratnam et al.* (1999) have conducted a survey of the existing trenchless techniques in various Canadian Municipalities. They conclude that trenchless technology is gaining popularity among municipal engineers in Canada. Pipe lining, Auger boring, Pipe Jacking, Pipe scanning and Evaluation, Pipe bursting, Robotic Spot Repair, Microtunneling are the most popular techniques in that order.

2.2 Cleaning

Cleaning is a fundamental preparatory step in most maintenance and rehabilitation projects and is necessary for the removal of tubercules from unlined cast-iron pipes. In most cases, cleaning is a prelude to pipe lining. The success of any lining procedure is dependent on a thorough cleaning of the main. Methods for determining whether the water main has been sufficiently cleaned include measurements of water quality, such as suspended solids or turbidity, and closed circuit television (CCTV) inspection of the cleaned main. Virtually all-cleaning methods require some means of storing or disposing of the water and solids that result from the process. Cleaning is compatible with all pipe materials. The *AWWA M28* (1987) report lists several methods of cleaning, their advantages and disadvantages.

Advantages and capabilities of cleaning water mains:

- Removal of dirt, debris, and scale from the water main.
- Preservation of water quality delivered to customers.
- Improvement of hydraulic capacity of water main.

The disadvantages and limitations of cleaning water mains :

- The process of cleaning may stir up sediments in the water main and temporarily reduce the quality of water.
- Customers may perceive flushing of water mains as wasting water, especially if there are water conservation measures or use restrictions in effect.
- Service may be temporarily interrupted.
- Requires disposal of water and solids.
- Effects may be temporary.

Effect of service connections, valves, bends, and appurtenances on cleaning efficiency:

- Service connections can act as dead ends where solids stirred up by the cleaning process can accumulate. Precautions, such as temporarily shutting off service connections during cleaning can mitigate this.
- Bends in the main can interfere with some cleaning procedures and must be accommodated in the cleaning process.
- Protruding connections, valves, and reducers can all interfere with the cleaning process.

Expected service life extension:

- Periodic cleaning can help ensure that a water main remains in service for its expected service life.
- A general statement regarding the required frequency of cleaning cannot be made. The required cleaning frequency and extended service life are affected by water chemistry, pipe material, and hydraulic characteristics of the water main.

The various methods of cleaning are described in the subsequent sections.

2.2.1 Flushing

Flushing involves isolating sections of water main and allowing water to flow until the main flows clear. Sediment, corrosion products, and stagnant water are removed from water mains during flushing. Flushing can be a temporary solution to water quality problems but

should be considered a maintenance procedure rather than a rehabilitation technique. Unidirectional flushing is considered more efficient because sediments and corrosion products are moved in one direction and not dispersed within the main. Because no chemicals are added to the water, flushed water can generally be disposed of in a storm drainage system, depending upon local regulations.

2.2.2 Cable-Attached Devices

In this cleaning method, cable-attached devices are dragged through the sections of pipe to be cleaned. Pipe cleaning using this technique is well suited to heavily tuberculated or encrusted pipes in which fluid-propelled devices might get stuck. The section to be cleaned is drained of water before cable-attached devices are used. However this cleaning method cannot negotiate bends greater than 45 degrees. Three types of cable-attached cleaning devices (drag cleaning, hydraulic-jet devices, and electric scrapers) are discussed below.

Drag Cleaning

During drag cleaning process, mechanical scrapers are pulled through sections of pipe with a winch. They are capable of removing very hard encrustation from the interior of pipes. Once the scraper is set in place, multiple passes can be made in both directions until the pipe is sufficiently clear.

Hydraulic-Jet Devices

High-pressure jets of water are used in hydraulic-jet devices to dislodge and remove encrustation from the interior pipe surface. In addition to cables, a high-pressure hose and an adequate water supply are required. Hydraulic-jet cleaning method generates wastewater as well as solids that must be disposed of in an acceptable manner.

Electric Scrapers

Electric scrapers consist of rotating scrapers and brushes mounted on a cart, which are controlled by an operator. The operator during his visual inspection determines the rate of cleaning progress through the pipe. One major limitation of this technology is the size of the scraper assembly, which mainly limits its application to large diameter pipes. however this cleaning method can not negotiate bends greater than 45 degrees.

2.2.3 Mechanically Driven Cleaning

Generally known as rack feed boring this system utilizes steel rods, which are simultaneously rotated and pushed through the main being, cleaned. The rods are approximately 15 feet long and are controlled from a street located boring rig. The first rod contains a suitably sized and appropriately selected cleaning head to suit the cleaning requirements of each main. However this cleaning method cannot negotiate bends greater than 45 degrees.

2.2.4 Fluid-Propelled Devices

Fluid-Propelled devices use hydraulic pressure to move through the pipe. It requires the availability of water in sufficient volume and pressure to propel the device, thereby limiting the diameter and length of pipe that can be cleaned. Fluid-propelled devices cannot be used in heavily encrusted pipes. Commonly used fluid-propelled devices are listed in the following subsections. Valves, bends greater than 45 degrees can interfere with the fluid-propelled devices' performance

Pigs

Pigs are fluid-propelled devices made of foam of varying densities that are used to scrape and swab sediment and debris from water mains. It requires several passes of the pig through the pipe, starting with smaller-diameter pigs and moving on through larger-diameter pigs. The final pass is made with a pig that has the same diameter as the original interior diameter of the pipe. Pigs have a tendency to get stuck inside the pipe.

Fluid-Propelled Metal Scrapers

Fluid-propelled metal scrapers consist of metal disks with scraper blades around their edges. They are similar to the scraping devices used in drag cleaning but are propelled by hydraulic pressure. They provide a more thorough cleaning than pigs. Since they are less flexible than pigs, fluid-propelled metal scrapers are more prone to getting stuck than pigs.

2.2.5 Chemical Cleaning

Solutions of acid can be used to dissolve mineral deposits within the pipeline. Acid solutions include combinations of sulfuric and hydrochloric acid or in some cases citric acid. The

acid solution is introduced into the pipe and is allowed to stand for a specified period of time. Some techniques recirculate the cleaning solution in a closed loop for several hours to dissolve residues from the pipe. This method requires special handling of the acid solution and extended flushing before the main can be returned to service. Disposal of the waste acid solution requires neutralization and special handling procedures.

2.2.6 Air Cleaning

In air cleaning, air at high pressure is forced through small-diameter sections of main that have been isolated and drained of water. Small amounts of water can be injected into the air stream occasionally, providing added friction to remove scale and deposits from the inside wall of the pipe.

2.2.7 Abrasive Particle Cleaning

During abrasive particle cleaning technique, air is forced through small-diameter pipelines at speed ranging from 130 – 330 fps with controlled amounts of abrasive particulate material added. The particulates range from flint rock to various steel shot and grit specifications. The pipeline to be cleaned with this method must first be isolated, drained, and completely dried. This technique can achieve a high degree of cleaning of the interior pipe surface. However, a particle/dust collection system is required, and the technique can be used only in straight run of pipe with few or no elbows, which reduce air and particulate speeds.

2.3 Pipe Lining

One of the most common and effective rehabilitation methods used in the piping industry is the application of a protective lining on the interior surface of a water main. For effective lining results, a thorough cleaning of the water main is essential. Lining inhibits further corrosion and oxidation of the pipe interior. It also improves the hydraulic conductivity of the pipe. In general, lining methods can be classified as cement mortar lining, calcite lining, epoxy lining, and metallic phosphate lining. These methods, while providing a protective coating to the interior surface of the pipe, do not provide additional structural integrity to water mains. Pipe replacement/insertion techniques (discussed subsequently in this chapter) are the only rehabilitation techniques that provide added structural integrity to water mains.

The advantages and capabilities of pipe lining include:

- Pipe lining provides a protective non-structural coating to the interior surface of the pipe.
- Pipe lining restores hydraulic capacity to the water main by providing a smooth surface.

The disadvantages and limitations of pipe lining include:

- Hydraulic capacity cannot be increased beyond the original pipe's capacity, and is limited by the host pipe's diameter.

Effect of service connections, valves, bends, and appurtenances on pipe lining:

- The number of service connections, valves, bends, and appurtenances will affect the cost of lining projects.

Expected service life extension:

- The service life of the pipe with reasonably good structural condition can be extended 30 to 50 years with lining procedures.

2.3.1 Cement Mortar Lining

Cement mortar lining is the most common rehabilitation technique in use today and is very effective and reliable. It has been in use since the mid-1930s to rehabilitate pipelines. Pipes must be thoroughly cleaned and dried prior to the lining process. Cement mortar lining can be applied to a wide variety of pipe diameters by either a centrifugal or a mandrel process. In the centrifugal process (the most commonly used cement mortar lining method), the lining machine has a rotating head that dispenses mortar and a series of trowels that smooth it to the interior walls of the pipe. For pipes greater than 24 in. in diameter, an operator who rides the machine through the pipe controls the centrifugal unit. In pipes 6 to 24 in. in diameter, a cable winch that is controlled above ground pulls the centrifugal unit. The cement mortar is pumped to the unit through a supply hose. In the mandrel process, the mortar is applied by compressed air and smoothed by a conical mandrel. The lengths of hose and cable used limit the length of water main that can be lined; the allowable lining length also depends on the distance between sharp bends; and tees in the pipe. The general working distance between excavations is 500-1500 ft.

Generally, the longer the length of pipe that can be lined in one operation, the lower the cost will be per unit length.

Cement mortar protects the pipe surface by reducing the oxygen and increasing the pH of the water reaching the pipe surface. The smooth surface created by the mortar increases the hydraulic capacity of the main, which can offset the loss of pipe diameter caused by the 1/8-in. to 3/4-in. layer of cement mortar applied to the interior pipe surface. Figure 2.1 depicts the schematic of the cement mortar lining process.

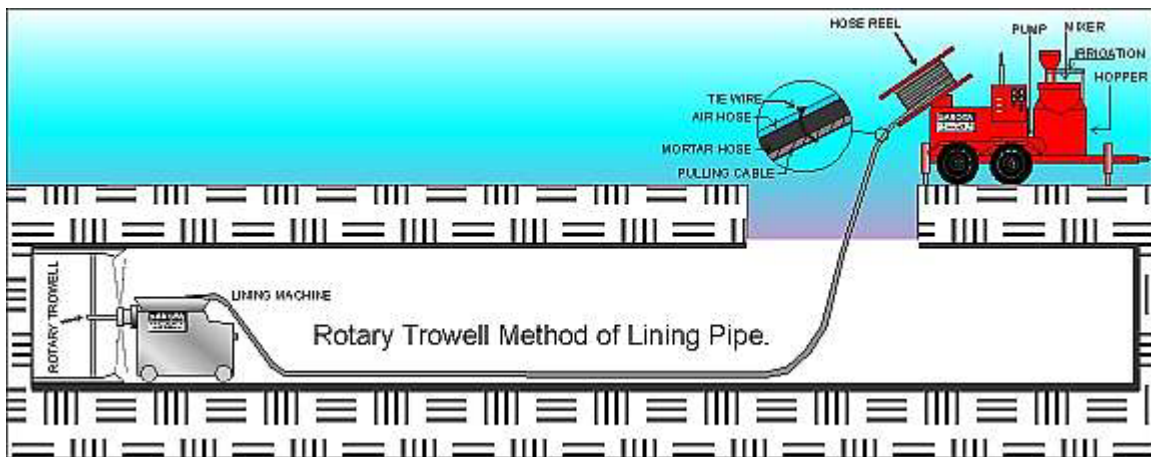


Figure 2.1 – Lining by Rotary Trowel Method

(Source: [http:// www.dakotapipelining.com/description.htm](http://www.dakotapipelining.com/description.htm))

2.3.2 Calcite Lining

The process has been advanced since its development in 1930 and has been used successfully by several major water systems in the U.S. The pipe must be thoroughly cleaned prior to lining. Subsequently, a supersaturated calcite (calcium carbonate, CaCO_3) solution is circulated through the pipe under carefully monitored conditions of temperature, pH, and degree of saturation, producing a hard calcite layer in the interior pipe surfaces. However, a minimum velocity of 10 fps is required for deposition of calcite layer. This condition limits the usage of this method for large diameter pipes because the volume of calcite solution required would not be cost-effective. The thickness of the calcite layer is greatest at the initial point of injection and then decreases along the length of the pipe. The effectiveness of the lining process decreases as

the temperature and calcite concentration of the lining solution decreases. Hence, the greatest length of pipe that can be consistently lined at one time is about 1,000 ft.

(Source: <http://www.dbce.csiro.au/pipes/tech-spray2.cfm>)

2.3.3 Epoxy Lining

The Pipeline must be thoroughly cleaned and dried before applying the epoxy resin to the interior surface. The resin is applied to the bore of the pipeline using a centrifugal method. A spinning head is winched through the pipeline at a constant rate depositing the heated pre-mixed epoxy / hardener material onto the pipe wall. Adequate cure time must be allowed for the epoxy lining to harden before putting the main back into service. This method can provide a smooth lining with a film thickness of 1.0 mm, making it applicable to small-diameter pipes. Epoxy lining is resistant to the effects of corrosive water. The advantage of this method is that unlike cement mortar lining epoxy material does not block the service connection during lining.

2.3.4 Metallic Phosphate Lining

This is a relatively inexpensive method to control corrosion. Zinc orthophosphate is added to the distribution piping to create a protective film on the interior surface of the mains. This process is applicable for both metallic and nonmetallic pipes (such as asbestos-cement pipes). This method inhibits corrosion after lining. For best results, metallic phosphate must be continuously injected into the water system. A thorough cleaning of the affected water mains should precede this form of corrosion control.

(Source: <http://www.dbce.csiro.au/pipes/tech-spray2.cfm>)

2.4 Spot Repair

Haas et al. (1995) presented a cost and performance evaluation of a few sewer spot repair techniques and explained how their approach applies to other maintenance technologies. These techniques can be extended to the water distribution industry as well. In general it was found that the spot repair techniques were less expensive in comparison with open cut methods. They also showed that the material properties and repair performance differed significantly for each of the two methods.

Micro-excavation

A small square is cut on the pavement surface (typically 0.5 x 0.5 m sq. in). An air lance is used to loosen the substratum and a vacuum used to excavate the material, and the defect is rapidly exposed. About 1/3 m³ of concrete is placed at the damaged point and allowed to cure before the restoration of the micro trench. For severe breaks, an inflatable bladder is inserted in the trench prior to placing the concrete. This bladder supports the trench while the concrete starts curing. Sufficient curing time must be allowed before the bladder is deflated and removed. The method is used upto depths of 3 m. The danger is that if the soil is not cohesive enough, the trench will cave in. However, since the operation is quick, three to 4 repairs may be performed in a working day.

Robotic spot repair

A CCTV system is used to locate the position of the crack. A grinding tool (robot- shown in Figure 2.2) prepares the crack by milling it to a depth of 0.375 in. (9.5mm) and a width of 0.5 in. (12.7 mm.). A pneumatic tool replaces the robot to inject the resin with a hardener bead in the crack. After a rapid curing and bonding period, the robot is reintroduced to finish the repair surface.

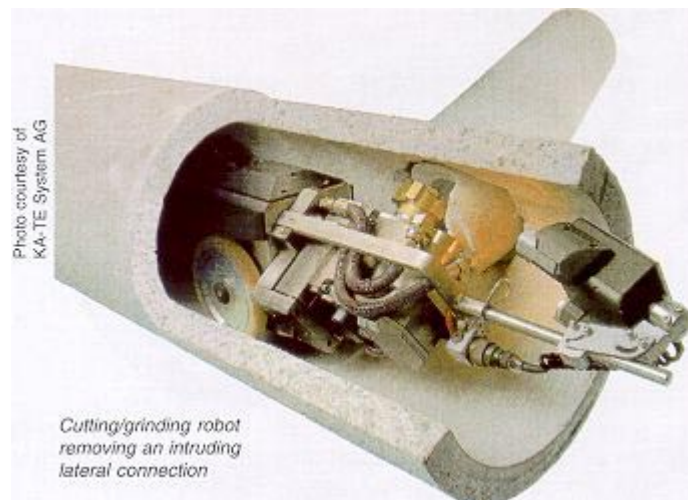


Figure 2.2 – Robotic Spot Repair

(Source: <http://www.catflap.net/digging-deep/isttsectionh.htm>)

2.5 Cathodic Protection/Anode Retrofit

Cathodic protection can be used to combat external corrosion of steel, cast iron, and ductile iron pipes. In general, external corrosion is more serious than internal corrosion. The two principal parts of corrosion protection are pipe coatings and cathodic protection. For pipes already installed in corrosive soils without protective coatings, cathodic protection should be considered. Existing pipes that have protective coatings can benefit from cathodic protection. Small holes or imperfections in protective coatings become the location of pinhole corrosion, which can proceed quite rapidly. Cathodic protection falls into two categories, impressed current and galvanic anodes. Impressed current cathodic protection is not considered practical for water distribution systems because of the complexity of the design requirements for a water distribution system, the requirement to provide continuous regulated electrical power and monitoring locations, to verify that the pipes are being protected, throughout the distribution grid. In addition, experience shows that passive cathodic protection systems (anode retrofit) provide beneficial results. Therefore, anode retrofit of water mains is discussed here.

In corrosion, galvanic cells are formed in which certain areas become anodes and others become cathodes. Electric current flows through the electrolyte, and metal at the anode is dissolved or corrodes. Cathodic protection reverses these currents and thereby makes all the metal to be protected cathodic. The procedure is to insert a new anode into the system, whose potential overcomes the potential of the original anode plus the resistance of the electrical elements. In this way, corrosion is concentrated in the new anode, which can be periodically replaced (*Merritt, (1976)*).

Cathodic protection/anode retrofit has been used by water utilities, including St. Louis County Water, Edmonton, Calgary, Winnipeg, Ottawa-Carleton, and Toronto, to protect metal water mains from corrosion. An anode, generally of zinc or magnesium but occasionally graphite, and aluminum alloys, is electrically connected to the metal water main, which becomes the cathode in the galvanic circuit. Installation of the anode is accomplished by making a small excavation, approximately one square foot, using a hydro-vac to avoid damaging the water main. The wire connected to the anode is bonded to the outside of the main using a Cadweld, Thermoweld, or similar process. The anode is buried in the excavation. The useful life of the anode will depend on the corrosivity of the soil, the anode material used, and the weight of the

anode. The degree of electrical insulation between the pipe sections will also affect the efficiency of the anode retrofit. An evaluation of the possible sources of external pipe corrosion, such as soil corrosivity and DC power lines, is necessary for the design of an anode retrofit program. Figure 2.3 shows the schematic of the process

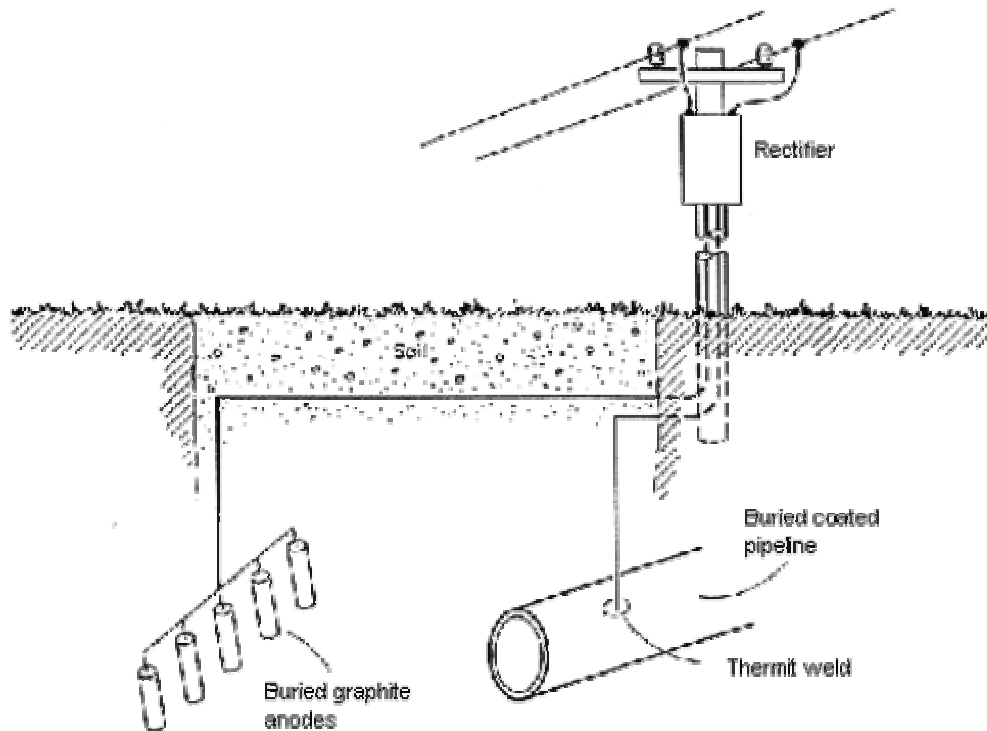


Figure 2.3 - Cathodic protection using buried anodes

(Source: <http://www.corrosionsource.com/learningcenter/cathodic.htm>)

2.6 Chemical Grouting

Chemical grouting has been used most widely in the wastewater industry. In this process, grout is used to seal circumferential cracks and leaking joints in otherwise sound gravity mains. Internal grouting is a commonly used method to seal leaking joints in structurally sound gravity pipes. Chemical grouting may also seal small holes and radial cracks. A wide variety of grout materials including acrylamide, acrylic, acrylate, and polyurethane are available, although not all are compatible with potable water systems. Because someone must enter the main to apply the grout, application is limited to large-diameter mains. More information can be obtained from (<http://www.cfi-1.com/cgkp.html>) and (http://www.aramoon.com/en/chemical_grouting.htm).

2.7 Reinforced Shotcrete

Reinforced shotcrete can also be used to rehabilitate large-diameter pipes. With this method, a reinforcing mesh cage is placed inside the main and then sprayed with a mixture of sand, cement, and water. This method has most commonly been used for the rehabilitation of sanitary and storm sewer tunnels. It may also be applicable to large water transmission pipelines. Some loss of diameter occurs due to the thickness of the shotcrete applied. Pipelines greater than 36 in. in diameter can be rehabilitated with this method. Reinforced shotcrete does not significantly improve the structural integrity of the rehabilitated pipe, and its use in water mains may be limited to specialized applications.

2.8 Joint Rehabilitation

Specialized methods have been developed for pipeline joint rehabilitation. One such method is marketed under the patented process known as WEKO SEAL. Similar processes are marketed under other names. With the WEKO SEAL process, a person enters the pipe and applies a rubber sleeve to the inside of the joint. The sleeve is held in place with reinforcing bands. A built-in valve allows the seal to be pressure and vacuum-tested. More information can be obtained from (<http://www.mpc-tech.com/prod1.html>)

2.9 Pipe Insertion

This is a trenchless pipe rehabilitation technology, which involves the placement of a new pipe (replacement pipe) within an existing pipe (host pipe). In general, pipe insertion is best suited for long transmission mains with few service connections and for situations in which obstacles such as buildings, underground utilities, and railroads do not permit the excavation of the old pipes. The physical condition and size of the host pipe affects whether a trenchless system may be used. Pipe with little or no structural strength is best replaced using open-trench, pipe bursting, sliplining or modified sliplining methods. *Najafi et al.* (1994) described the state-of-the-art review for trenchless pipeline rehabilitation being conducted under the auspices of the Construction Productivity Advancement Research (CPAR) program

Pipe insertion can be considered under three separate categories:

- **Conventional sliplining:** A pipe of standard size is inserted inside an existing host pipe. The inserted replacement pipe is a stand-alone full structural pipe but is smaller in diameter enabling installation inside the replacement pipe, which subsequently leads to capacity reduction.
- **Modified sliplining:** A tight fit lining process, which has been developed to maximize the available space inside the replacement pipe. The replacement pipe is reduced in size, prior to installation, making installation possible. After installation the replacement pipe is reverted back to its original size making a tight fit. Modified sliplining uses non-standard pipe sizes and can use structural or non-structural pipe.
- **Cured-in-place pipe (CIPP) rehabilitation** – uses resin-impregnated fabric to form a new pipe wall conforming to the old pipe wall.

The advantages and capabilities of pipe insertion include:

- Pipe insertion techniques require less excavation than traditional pipe replacement methods.

The disadvantages and limitations of pipe insertion include:

- Pipe insertion techniques can reduce the diameter of the host pipe. Pipe insertion techniques are not appropriate for cases where it is necessary to increase the hydraulic capacity beyond that of the host pipe. However, the reduced diameter of the inserted pipe is offset by an increase in the smoothness (C value) of the replacement pipe.
- Work cannot be performed in the winter, when there is a danger of freezing the bypass systems.

2.9.1 Conventional Sliplining

Conventional sliplining can be performed using differing pipe materials, including polyvinylchloride (PVC), high density and medium density polyethylene (HDPE and MDPE), polypropylene, polybutylene, fiberglass, ductile iron, and steel. The liner is either pushed or pulled into place. Sliplining can be used to correct a variety of structural problems. The annular space between the existing host pipe and the new replacement pipe is generally grouted to provide support. *Stephens* (1996) provides a brief insight into the complexity of annular space grouting of sliplined pipe. The grout viscosity, initial set time, density, compressive strength,

injection pressure, grouting procedure, and other parameters are some of the most important functions of an annular grout design. The article says that “To grout a pressure-sensitive reliner pipe with a small annular space, the grout should be fluid enough, as tested per ASTM C939, to exit the flow cone in under 25 seconds, preferably under 18 seconds. The grout mix should remain fluid and not thicken for a minimum of 2 hours.”

Since sliplining reduces the inside diameter of a pipe segment, the hydraulic capacity of the lined pipe should be estimated before sliplining is undertaken. This will ensure that flow will be adequate to meet water supply needs. Sliplining is well suited for rehabilitation of sections of main with few service connections or sharp bends.

The advantages and capabilities of sliplining include:

- Sliplining has been used for many years.
- Sliplining uses factory-produced and quality assured pipe materials that have had prior approval for water supply system use.
- Reduced excavation and site restoration requirements.
- Sliplining is a practical way to rehabilitate pipe that is structurally unsound.
- Sliplining is a practical way to rehabilitate pipes that suffer from water quality, leakage, poor pressure, flow or structural problems.
- Sliplining can be an efficient alternative to replacement with generally higher production rates and lower costs.
- The use of the existing pipe as the host pipe for the liner prevents possible disruption of other utilities.
- Using polyethylene as the replacement pipe results in a “joint-free” pipe, as heat-fusion jointing is generally used.
- Sliplining results in improved C values.

Among the disadvantages and limitations sliplining are the following:

- Sliplining results in reduced cross-sectional area. However, the low friction coefficient of the replacement pipe may compensate for the reduced cross-sectional area.

- The annular space between the host and replacement pipes may require the use of grouting or spacers.
- Service connections and insertion pits must be excavated.
- Construction inspection is more difficult than with conventional open trench replacement because some of the work of sliplining may not be visible. This may require CCTV inspection after installation.
- Sliplining needs a surface entry pit for entry of the replacement into the host pipe.

2.9.2 Modified Sliplining - Using Structural Pipe

In this technique, a thermoplastic pipe, which has been deformed to reduce its diameter, is inserted into the host pipe. HDPE or MDPE pipe usually used, is selected and sized according to the required “stand alone” pressure and the host pipe interior bore size. The host pipe is used as the available 'hole in the ground', for installation purposes, but has no function over the performance of the new replacement pipe. The Rolldown® and Swagelining processes are examples of this process where PE is cold deformed in the field, prior to installation. After size reduction and installation into the host pipe the new pipe is allowed to revert back to its original size resulting in a tight fit between the replacement pipe and the host pipe thus maximizing the available diameter of new pipe.

Advantages of modified sliplining using structural pipe

- All of the benefits highlighted for conventional sliplining apply except that a larger diameter pipe bore is available with modified sliplining as the new pipe is sized in such a way to become a tight fit after installation.

Disadvantages of modified sliplining using structural pipe

- Non standard pipe sizes are used.

Rolldown® Method

The Rolldown® method is a tight fit lining or modified sliplining process, which was developed in 1980 for use with PE pipe. The objective of this method was to overcome the traditional problem of sliplining where reduced external diameters, cause a significant reduction in pipe bore and leave an annular space between the old pipe and the new pipe insertion. In the

Rolldown® process, a new PE pipe is rolled down using a series of specially designed and sized hemispherical rollers. The PE pipe is cold-rolled to reduce its diameter by hydraulically pushing the pipe through this series of rollers, rather than pulling the pipe with high tensile forces. The following two features associated with Rolldown® are achieved by maintaining high axial compression loading on the PE pipe as it passes between the specially designed roller sets. These are:

- During the Rolldown® process, the PE pipe experiences pipe wall thickening with the pipe elongation kept to a minimum.
- The PE pipe is able to stay in its cold rolled, reduced-diameter state for a considerable period of time.

With the PE pipe in its rolled down condition, it becomes a conventional sliplining operation to install the new pipe into the host pipe. After sliplining, the PE pipe is reverted to near its original size using hydrostatic pressure. It should be noted, however, that under high ambient temperatures, the rolled down PE pipe will expand in diameter faster, but will not completely revert back to the original diameter without hydrostatic pressure.

Swagelining Method

The Swagelining method (Figure 2.4) was developed by British Gas for tight fit lining of gas mains in order to overcome the flow losses associated with pipe bore reduction when conventional sliplining is used. By maximizing bore size and using the available 'hole in the ground' it has been possible to rehabilitate pressure pipe with minimum excavations. The major difference between Swagelining and Rolldown® is the methodology used to reduce the pipe in size prior to installation. Like Rolldown®, Swagelining is a field, cold formed, process but in this case the pipe is pushed and pulled through a 'die'. The reduced size is maintained by winch tension with reversion taking place as the winch tension is reduced after full pipe installation has been completed. Swagelining also uses PE as the replacement pipe material. Swagelining can also offer structural or non-structural rehabilitation of pipelines.

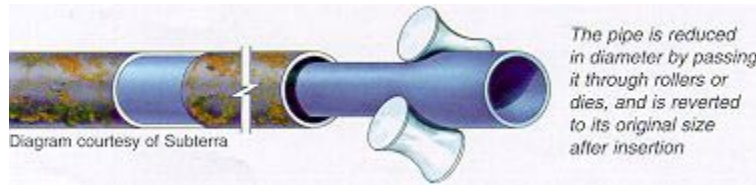


Figure 2.4 - The Swagelining Process

(Source: <http://www.catflap.net/digging-deep/isttsectione.htm>)

Fold-and-Form Pipe

In this method, replacement pipe is deformed into a “U-shape” during the factory extrusion process and coiled onto reels ready for insertion into existing pipelines (Figure 2.5). The U-shape makes insertion into a pre-cleaned host pipe easy, and once in place, the new U-shaped pipe is reverted back to shape and size using a combination of heat and pressure. The heat activates the material’s memory (manufactured round and then deformed into a U-shape) and the pipe reforms to create a snug fit within the host pipe. Pipes of this type can be manufactured from various materials, including PE and PVC. Polyethylene pipe can be joined using a butt fusion process, which creates a reliable leak-free joint. The Fold and Form process was developed primarily for sewer renovation projects but can be used for rehabilitation of pressure pipe provided that the U-form pipe material specifications comply with the rehabilitation design requirements. Because the liner expands against the old pipe, the process results in minimal annular space between the liner and the pipe and a minimal loss of cross-sectional area and hydraulic capacity.



Figure 2.5 – Fold and Form Liner

(Source: <http://www.catflap.net/digging-deep/isttsectione.htm>)

2.9.3 Modified Sliplining - Non Structural Pipe

Modified sliplining can also be used where a non-structural pipe liner is installed inside the host pipe. The liner is installed in the same way as described above in the swagelining, fold and form processes but uses a thinner wall pipe which on final installation and reversion relies upon the host pipe for its structural strength. Subline is a cold, field formed, polyethylene pipe lining process for non-structural pipe rehabilitation and uses cold water at the mains pressure for the reversion process.

The utilization of this technique is ideal for situations where the existing potable water pipe is in good structural condition but suffers from joint leakage, internal corrosion, water quality or tuberculation type problems. The hydraulic capacity can be improved as the lining material provides a smooth bore with lower friction coefficients over the rougher host pipe bore. Even with the reduced diameter of the host pipe, now containing the thin wall liner, hydraulic capacity improvements are still possible.

2.9.4 Inversion Lining/Cured-in-Place Pipe (CIPP)

Inversion lining, also known as cured-in-place pipe (CIPP), uses resin-impregnated fabric to form a new pipe wall conforming to the old pipe wall. Variations on this technology have been used for sectional or spot pipe repairs. This technology has found its greatest application in the wastewater industry, although the technology has been used to rehabilitate water mains where access to the pipe made traditional excavation and replacement prohibitive.

The CIPP installation uses an inversion process similar to that used for sewer pipe rehabilitation. The conventional CIPP process requires construction of scaffolding to raise the static head of the column of water used for the inversion process. The height of the scaffolding varies based on diameter, length, and type of liner being installed but could be as high as 25 feet in some instances. In some cases, a Constant Head Inversion Pressure (CHIP) unit is used instead of scaffolding. The CHIP unit is a patented device that provides the required water pressure and feeding device for the liner into the host pipe. The CHIP unit derives its energy from compressed air and uses an air over water arrangement to provide the pressure for inversion. This pressure turns the resin-impregnated jacket “inside out” while propelling it through the host pipe and pressing the resin coated face against the host pipe wall. The resin is then cured using either

steam or hot water. Three patented CIPP processes approved by NSF for use in water pipes are described below as examples of the CIPP technology.

Thermopipe®

Thermopipe®, a proprietary product of Insituform Technologies, Inc., (Figure 2.6) was developed to function as a structural pipe insert with a long-term independent pressure rating of 150 psi. The system is applicable to distribution mains up to 8 inches in diameter. Although thermopipe® is a fold-and-form pipe liner, it is rated by the manufacturer as forming a structural liner capable of functioning without support from the host pipe. Thermopipe® can navigate bends up to 45 degrees.

Thermopipe® CIPP liners are considered Class IV liners which are considered fully-structural, self supporting liners with a 100 psi pressure rating and can survive failure of the host pipe. The advantages/capabilities and disadvantages/limitations associated with thermopipe are the same as those associated with the general CIPP category and the fold-and form technology.



Figure 2.6 –ThermoPipe® System

(Source: http://www.insituform.com/watermains/water_index.html)

Insituform®

This patented process, used to reline deteriorated pipelines, was developed in Great Britain in 1971. The process, known as Insituform®, was introduced in the U.S. in 1977. This process uses a liner made of polyester felt material impregnated with thermosetting resin and bonded to a plastic membrane. Liners are formed into tubes of various diameters. The liner tube is attached to the top of a vertical inversion tube, which enters into the pipe to be rehabilitated. When water is added to the inversion tube, its hydraulic pressure pushes the liner through the pipe. Once the liner is in place, the water is heated and circulated to set the resin. After the liner

is cured, its ends are cut flush with the old pipes. Service connections and branches are then cut out of the new liner; however, this technology is generally used where few service connections or branches exist. These are considered Class III liners, which are considered semi-structural, self-supporting liners that can support external loading and vacuum conditions.

Paltem®

The Paltem® CIPP technology has been widely used in Japan over the past 10 years for the rehabilitation of both gas and water pipes. In February 1996 the process received approval NSF International under ANSI/NSF Standard 61 for use with potable water.

The Paltem® system which is available in the diameter range of 4 to 39 in., consists of two main components:

- A circular woven seamless polyester fiber “jacket” coated on the outer face with an extruded layer of PE.
- An epoxy resin thermoset adhesive which is applied to the uncoated face of the jacket prior to installation and which adheres the jacket to the inner surface of the host pipe.

Prior to installation of the liner, the host pipe wall must be cleaned to provide a suitable surface for resin adherence. If the pipe has an existing protective internal coating, which is not easily removable, by cleaning, then tests on a pipe sample are necessary to determine the suitability of the coating as a substrate of the liner. For example, the degree of adhesion between Paltem® and the inner cement lining of AC pipes depend on the condition of the cement surface at the time of lining. Due to this, CIPP contractors recommend the use of alternative liners with AC pipes. Paltem® CIPP liners are considered Class II liners which are considered semi-structural, non-self supporting liners that cannot support external loading and vacuum conditions.

2.10 Pipe Replacement

Replacement of the pipes is necessary when a pipe fails to provide adequate service to customers or when a pipe does not have enough structural strength and becomes prone to failure. The two broad categories of water main replacement methods are trenched construction and trenchless construction.

The advantages and capabilities of pipe replacement include:

- The new pipe can be increased in size to accommodate increased water demands.
- Repair costs will be lower after the pipe is replaced since new pipe can be expected to have lower break rates than older pipe.
- Increased flow capacity due to higher C values.
- Less loss of water due to decreased leakage.

The disadvantages and limitations of pipe replacement include:

- Total pipe replacement is more disruptive than the alternative of repairing breaks as they occur.
- Temporary water service must be provided to the customers while the main is being replaced.
- Pipe replacement is usually more expensive than repair or rehabilitation.

Effect of service connections, valves, bends, and appurtenances on pipe replacement:

- All service connections must be re-established.
- All valves, bends, and appurtenances must be re-connected to the new host pipe.

Expected service life extension:

- The service life will be extended to the full design life of the replacement pipe.

2.10.1 Trenched Replacement

Open Trench

Conventional “open trench” construction is the most frequently used method for replacement of water mains in the U.S. For many water utilities, the practice is to install the new main in a trench parallel to the old main. In some cases, removal of the old main is not worthwhile or necessary, and old, damaged water main are simply abandoned or given to electric or cable utilities. Because the old main is kept in service until the new main is in place and ready for connection to the customers' service lines, service interruptions are minimized. In those cases where the old main has to be shut down before the new main is in place, bypass pipes can be laid to provide uninterrupted service to customers.

The advantages and capabilities of open trenching construction include:

- It is the most widely used method of water main replacement than with any other pipe replacement or rehabilitation method.
- Water mains can be replaced with minimal disruption of water service.
- Water mains of any diameter can be used, allowing for an increase in the water capacity to any required level.
- Contractors are usually easy to find and locally available.

The disadvantages and limitations of open trenching construction include:

- Trenched construction can cause disruptions in traffic and commercial business.
- Traffic congestion and disturbed road surfaces can increase traffic accidents.
- Trenched construction can cause disruption and inconvenience to pedestrian traffic.
- Production of dust, fumes, and noise can affect the health and well being of pedestrians and nearby residents.
- As with new construction, trenched construction may cause the disruption other utility services.
- Other utilities may need to be relocated.
- Temporary water service may be required.
- Weather conditions can restrict implementation schedules.

Effect of service connections, valves, bends, and appurtenances on conventional open trench replacement:

- All service connections must be re-established.
- All valves, bends, and appurtenances must be re-connected to the new host pipe.

Expected service life extension:

- The service life will be extended to the full design life of the replacement pipe.

Narrow Trench

Narrow trenching is a variation on the conventional “open trench” construction for pipeline installation/replacement. Narrow trenching techniques can reduce the impacts of open

cut trenching methods. By reducing the trench width, the amount of surface restoration, bedding material, and overall time to complete the project can be reduced. Other modifications of conventional open trench construction techniques include alternative shoring techniques, and alternative backfill materials can increase the efficiency of more traditional construction methods.

The advantages and capabilities of narrow trenching include:

- There is less excavation and disturbance of pavement with narrow trenching than with conventional open trench construction.
- Reduced noise and dust impact.
- Reduced project duration.

The disadvantages and limitations of narrow trenching include:

- Installing pipe in a non-manned-entry trench may be more difficult than manned-entry trench.

Effect of service connections, valves, bends, and appurtenances on narrow trenching:

- All service connections must be re-established.
- All valves, bends, and appurtenances must be re-connected to the new host pipe.

Expected service life extension:

- The service life will be extended to the full design life of the replacement pipe.

Trenchless Replacement

2.10.2 Pipe Bursting

Pipe bursting is a patented process that utilizes specialized equipment that breaks apart an old pipe while placing a new pipe in the space formerly occupied by the old pipe. The pipe bursting technology is a total pipe replacement method. The next chapter, which is a review on the elements of trenchless technologies, provides a discussion on the forces produced during the pipe bursting process.

The advantages and capabilities of pipe bursting include:

- Pipe bursting can be used on pipes in any condition, including highly deteriorated pipes.
- Pipe bursting can be used to replace clay, concrete, cast iron, and PVC pipe.
- Replacement pipe can be made of almost any material, including HDPE, PVC, steel, ductile iron and fiberglass pipes.
- The replacement pipe can be of equal or 25% to 50% larger diameter than the original pipe, as compared with lining methods where the outside diameter of the new pipe is limited to the inside diameter of the host pipe.
- Reduced excavation quantities compared with traditional open cut replacement methods. Vendors claim 80% less excavation compared to conventional open trench methods.
- Pipe bursting works well in areas with compressible soils and where the vibration and compaction will not disturb surrounding utilities or roadbeds.
- Pipe replacement in locations with constrained spaces, such as alleys, private property, or hilly areas, can be accommodated.

The disadvantages and limitations of pipe bursting include:

- Mechanical vibration and soil compaction during pipe bursting can disturb nearby utilities and roadbeds.
- Construction noise levels can be significant; but are similar to those generated by traditional open cut methods.
- Pipe bursting/pipe splitting is possible on cast iron (starting at 2 inch diameter) and steel (2 inch to 8 inch diameter) and trials with ductile iron have proved successful.
- Pipe bursting may not be appropriate for all subsurface conditions.
- Shards from the old pipe may damage the replacement pipe. A new, oversized, thin wall protective sleeve can be installed which is then sliplined with the new pipe to overcome this problem.
- May damage adjacent structures/utilities from resulting shock waves.
- Work cannot be performed in the winter, when there is a danger of freezing the bypass systems.

Effect of service connections, valves, bends, and appurtenances on pipe bursting:

- All service connections must be re-established.
- All valves, bends, and appurtenances must be re-connected to the new host pipe.

Expected service life extension:

- The service life will be extended to the full design life of the replacement pipe.

Three specific pipe bursting methods are described below. These are hydraulic pipe bursting, pneumatic pipe bursting, and static pull pipe bursting. They vary in the method they break the old pipe and insert the new pipe.

Hydraulic pipe bursting method

The hydraulic pipe bursting process uses a bullet shaped head with hydraulic power supplied to the head. The hydraulic power is used to open and close the bursting head, thus breaking the existing pipe. The bursting head is attached at the front to a cable that passes through the existing pipe. Once the head opens and breaks the pipe, the cable, which is attached to a constant-tension winch, pulls the bursting head (and the replacement pipe that is attached to the rear of the head) forward. The constant tension winch prevents overloading of the replacement pipe. The winch cable's primary function is holding the bursting head from moving as the head is cycled opened and closed. It is not for pulling the cone shaped head forward to break the pipe. This process repeats itself as the head cycles opens and closes, then pull forward slightly to seat against the next unbroken section of pipe.

The advantages and capabilities of hydraulic pipe bursting include:

- The hydraulic fins can generate a great deal of bursting force. Pipe clamps can be burst with hydraulic bursting clamps.

The disadvantages and limitations of hydraulic pipe bursting include:

- Hydraulic bursting heads are powerful devices but are not sealed units allowing entry of water and contaminants into the working mechanism. Ongoing maintenance vital for successful field operations.

Pneumatic Pipe Bursting Method

The pneumatic pipe bursting method uses air pressure to drive a bullet shaped hammer through the existing pipeline. The front of the bullet hammer has knife blades that cut or fracture the existing pipe with each blow from the pneumatic pressure. The pneumatic pipe bursting head is considerably longer than the hydraulic pipe bursting method, thus requiring longer launching and receiving pits. The pneumatic pipe bursting method attaches the replacement pipe to the back of the bursting head, pulling the replacement pipe as the head progresses. If the pipe material and soil conditions are suitable, the pneumatic method is capable of faster rates of installation than the hydraulic method, because the hydraulic method must cycle open and close the head of the machine regardless of the pipe type or soil condition.

The advantages and capabilities of pneumatic pipe bursting include:

- Suitable for bursting cast iron and asbestos cement pipe

The disadvantages and limitations of pneumatic pipe bursting include:

- Pneumatic bursting heads are less powerful than hydraulic bursting heads and may not be suitable for bursting pipe with heavy joints or repair clamps.
- There is a potential for contamination from pneumatic bursting head exhausting contaminants into the replacement pipe.
- Cannot easily burst steel or ductile iron pipe.

Static Pull Pipe Bursting Method

The static pull pipe bursting method uses a hydraulically powered pulling and pushing machine to pull rigid cone bullet through the existing pipe material to break up the pipe. Attached to the pulling rods and at the back of the pulling head is the replacement pipe. Depending on the structural features of the final replacement pipe, the new pipe is either attached to the head (as in the case of a flexible pipe such as HDPE), or pushed along with the head (as in the case of a rigid pipe such as ductile iron) through the use of rigid tow rods that physically push the replacement pipe behind the bursting head.

In addition to the installation procedures mentioned earlier in the chapter, a typical static pull pipe bursting operation would also include threading the rigid pulling rods through the

existing pipe until the pipe insertion pit is reached. The rigid bursting head is sized based on the amount of upsizing required. The rigid replacement pipe is attached to the bursting head through the use of smaller, dry threaded tow rods and a pushing assembly that bears on the end of the last pipe joint. As each new joint of pipe is attached, the pipe bursting machine is operated to pull the rods back to the machine pit. Periodically, the operation will halt so that a section of the rod can be removed into the machine pit. This process continues until the bursting head has been pulled completely back into the machine pit, ending the replacement.

The advantages and capabilities of static pull pipe bursting include:

- The static bursting head has no moving parts.
- Static pull pipe bursting using rod pullers and purpose designed bursting/splitting heads are suitable for bursting cast iron, asbestos cement and PVC pipe and splitting steel pipe.

The disadvantages and limitations of static pull pipe bursting include:

- Static bursting heads are not as powerful as the pneumatic bursting heads.

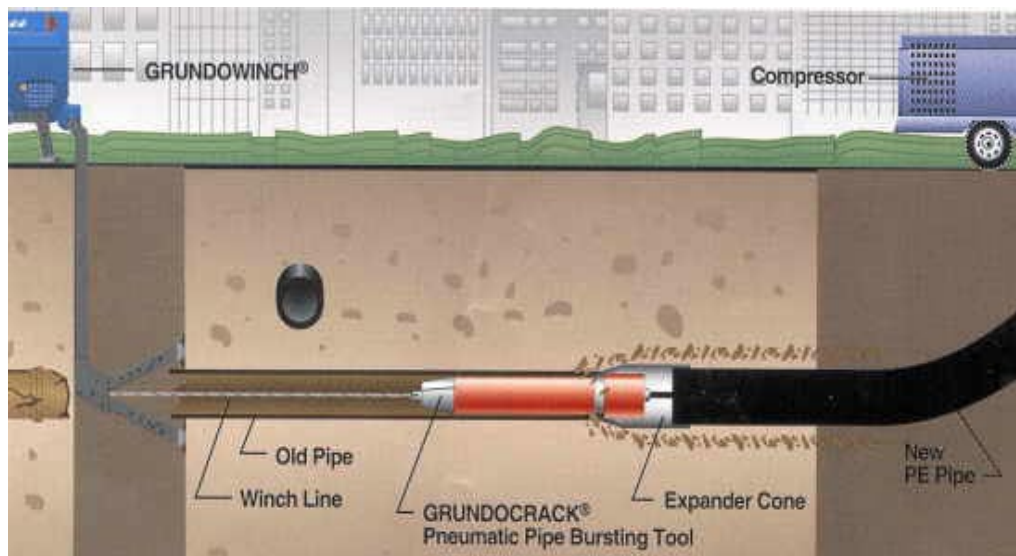


Figure 2.7 – The Pipe Bursting Process

(Source: <http://www.pmconst.com/pipeburst.html>)

Variations on the Pipe Bursting Method

A similar process called pipe crushing also utilizes a pulling rod assembly to crush the host pipe while pulling a replacement pipe behind the crushing head. A variation of the process called pipe reaming uses a reaming head to break the host pipe into small pieces, which are removed from the bore using drilling fluid (mud).

The advantages and capabilities of pipe reaming include:

- The host pipe is essentially removed.
- Drilling fluid creates a larger bore, which can be used to accommodate a larger replacement pipe.

The disadvantages of pipe reaming include:

- Drilling fluid can create voids around the new pipe, which can collapse after installation.
- Proper disposal of broken pipe pieces may be a problem.

2.10.3 Pipe Jacking / Microtunneling.

Microtunneling is a trenchless pipe replacement technology that involves forcing a new pipe horizontally through the ground with a remotely controlled hydraulic jack (Figure 2.8). Historically the term microtunneling has referred to the construction of tunnels of non-man-size inside diameter. The technique can, however, be used to install pipelines of a wide range of diameters. Microtunneling systems have been used to install pipelines in a single pass operation in lengths up to 1,500 feet, and in diameters from 6 inches to 10 feet. However, in general practice, microtunneling cannot be used to install pipes smaller than 14 inches in diameter or larger than 78 inches in diameter. The pipe must be large enough to contain slurry pipes, hydraulic hoses, and electrical cables and leave sufficient space for a laser guidance beam. The microtunneling procedure consists of five independent processes (*Stice et al. (1995)*).

- Mechanized Excavation
- Propulsion
- Soil Removal (Slurry or Auger)

- Guidance Control
- Pipe Lubrication

The excavation system includes a cutting head selected for its effectiveness in the site's particular soil conditions, boring and steering mechanisms, a laser-control target and a series of pressure-control flow meters and valves. A significant feature of the system (technology) is its ability to independently counterbalance earth and hydrostatic pressures by carefully controlling the propulsion and spoil removal systems. Groundwater is maintained at its original level without the addition of a de-watering system.

The propulsion system consists of pipe jacking units that are specifically designed for compactness and high capacity. Jacking forces can range from 100 to more than 1,000 tons. The resistance from face pressure and resistance from friction along the length of the steering head and pipe string determine the force requirements. The next chapter provides a discussion on this aspect. The propulsion system provides the operator with information about penetration rate and total jacking pressure, both factors in controlling the counterbalance of forces and maintaining safe operating limits.

Of the two types of soil removal systems, the slurry system is a closed loop system whereby, after the slurry is discharged and separated, it becomes the charging slurry for the system. It has been very effective in situations involving extremely high hydrostatic pressures (including underwater retrieval). The auger removal system uses flighted augers to transport the cuttings back to the drive shaft to be periodically removed.

All microtunneling systems rely on remote control capability. The operator is situated in a safe and comfortable environment outside of the pit and tunnel. Information is relayed back to the control panel where the operator monitors the line and grade of the machine, slurry flow rates and pressures, advancement rate and the forces generated by the propulsion system. The operator also monitors activity in the shaft using closed-circuit television capability. The heart of the guidance control system is a laser that provides the alignment and grade information for the machine to follow. The target that receives the laser information is the mechanism for

transmitting information back to the operator's control panel so that any necessary corrections can be made.

The pipe lubrication system, consisting of a mixing tank and the pumping equipment necessary to transmit the lubricant from an external reservoir to the applications points inside the machine and pipe barrel, is optional, but its use typically reduces total thrust requirements by 30%.

The miniaturized technologies for microtunneling are, by definition, "remotely controlled, laser-guided pipe jacking processes that do not require man entry." The techniques involve the use of a laser target device in the tunneling machine as a way to navigate pipe for extensive horizontal distances underground. The processes require construction of the vertical drive and reception shafts, which are sized relative to the dimensions of the pipe and the machinery selected for a particular job. The shafts typically range between 10 and 20 feet in diameter but can be as small as 6 feet. The next chapter, a review of the elements of trenchless technologies provides a discussion on the forces produced during jacking projects.

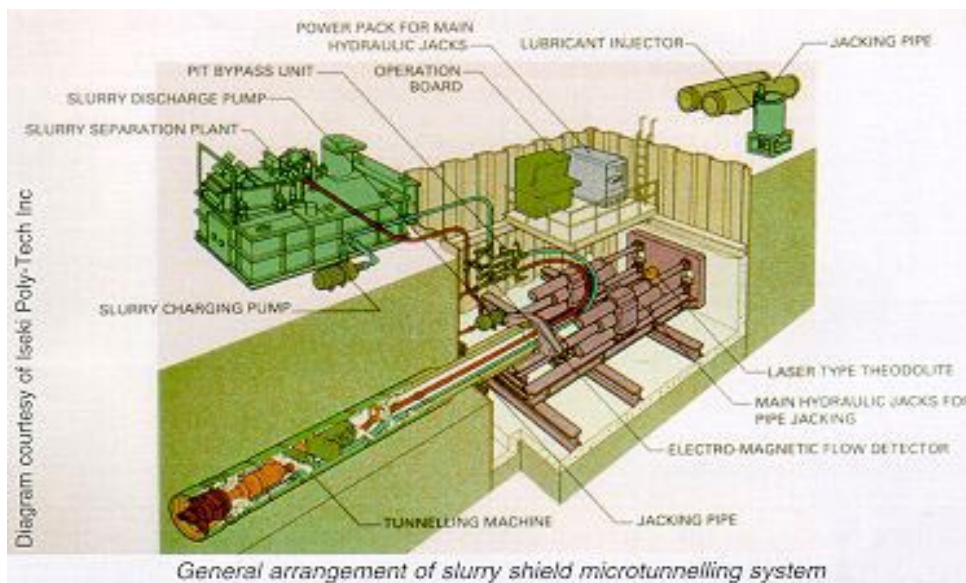


Figure 2.8 – MicroTunneling System

(Source: <http://www.catflap.net/digging-deep/isttsectione.htm>)

The advantages and capabilities of microtunneling include:

- The ability to control the amount of excavation and the resulting impact on surface facilities and activities.

- Deep installations can be accomplished.
- The ability to install pipes in areas of high groundwater without de-watering.
- Accurate line and grade tolerance can be maintained.
- Pipe diameters from 12 inches to 12 feet can be installed.
- Pipes of concrete, steel, fiberglass-reinforced polyester, vitrified clay pipe, and PVC can be installed with microtunneling.

The disadvantages and limitations of microtunneling include:

- Microtunneling cannot be used to install pipes smaller than 12 inches in diameter or larger than 12 feet.
- The drilling fluid requires fluid-handling equipment and must be disposed of after the installation is completed.

Effect of service connections, valves, bends, and appurtenances on microtunneling:

- Since microtunneling involves the installation of a new pipe along a new line and grade, any service connections to the new pipe would require excavation and connection to the new pipe.

Expected service life extension:

- The service life will be extended to the full design life of the replacement pipe.

Technologies related to pipe jacking include auger boring, wet/guided boring, pipe ramming, and impact moling, which are briefly described below.

Auger Boring. Auger boring consists of using a dry rotating auger normally driven through jacked steel casing, which is jacked as the auger advances. Some steerage is possible using a two casing system. Pipes up to 60 inches in diameter can be installed with this method. High water table can increase the cost of this method by requiring sheet piling of entry and exit pits. The cost also increases when entry or exit pits must be excavated in rock.

Wet/Guided Boring. A boring machine with a hollow-stem rod excavates a bore using pressurized water or drilling fluid. A cutting head and dry percussive drill head can also be used.

Steerage is possible by rotating the bore rod and a locating transmitter can be placed behind the bore head for guidance. The borehole can be reamed larger by pulling a reamer back through the bore. This method is generally applicable to smaller diameter, short length installations.

Pipe Ramming. Pipe ramming utilizes an impact mole (see impact moling below) to drive an open-ended pipe through the ground. This is a non-steerable method of pipe installation, which is normally used for short installations, less than 150 feet, under roads or railway embankments where settlement is not permissible. It is also used for river crossings because there is less water penetration into the bore than with drilling methods. Bores up to 6 feet in diameter are possible in the right soil conditions.

Impact Moling. Impact moles are also known as earth piercing tools, soil displacement hammers, impact hammers, percussive moles, and pneumatic moles. Impact moling involves the use of a pneumatic hammer to drive a casing through the compressible soil. The friction of the ground on the mole prevents the mole from being driven backwards. Different heads are available for different soil types. Moles are typically launched from a pit using a launching cradle. Monitoring equipment can determine the path of the mole although the mole cannot be steered.

2.10.4 Horizontal Directional Drilling (HDD)

Horizontal directional drilling (HDD) has been used to install pipeline crossing roadways, rivers, and other obstacles. The HDD industry has experienced significant growth in the last decade and has become commonplace as a method of installation. HDD is compatible with several replacement pipe materials, such as HDPE and restrained-joint PVC. HDD is generally performed in a four-step process, 1) pilot hole drilling, 2) pilot hole reaming, 3) Drilling mud injection, and 4) pipe pull-back.

The pilot hole established the path of the installed pipe. Typically, the path of the drill head is tracked electronically. Design considerations include radius of curvature of the path and its effect on the pipe to be installed, particularly pullback force. In softer soils, the jetted drilling fluid cuts through the soil. In harder soils, the drill head is turned by rotating the drill string, or the hydraulic pressure of the drilling fluid is converted into mechanical energy by a mud motor

to rotate the drill bit. As the drill rods are pushed into the borehole, additional drill pipe stems are attached. In cases where the ground is unstable, a washover pipe (casing) can be pushed down the borehole path to prevent the collapse of the borehole.

After the drill head emerges from the pilot hole, a reamer is attached to the drill head. The diameter of the reamer is larger than the pipe diameter, typically 120% to 150% of the replacement pipe diameter. Drilling mud and cuttings will fill the annular space around the new pipe. The mud and drill cuttings will provide no soil support for the replacement pipe. Earth loads and possible pipe buckling must be calculated before installing the pipe.

Drilling mud, generally a mixture of sodium montmorillonite (bentonite) and water, is then injected into the reamed hole to reduce drill torque, lubricate the pipe, and provide annular flushing of the freshly cut borehole soil debris, and gives stability and support to the borehole.

The replacement pipe is pulled back through the drilling mud through the reamed hole pathway. The pipe is usually pulled through from the side of the crossing opposite the drill rig. During pullback axial tension, constant insertion velocity, mud circulation rate, and footage length installed are recorded.

Mini-HDD rigs can handle pipes up to 12 inches in diameter and are used primarily for utility construction in urban areas. HDD rigs are capable of handling pipes as large as 48 inches in diameter. The length of the bore, diameter of the replacement pipe, and geotechnical properties of the soil determine the size of the drill rig required.

The advantages and capabilities of HDD include:

- Minimizes traffic disruption.
- Can install pipe through crossings not accessible to other equipment.

The disadvantages and limitations of HDD include:

- A comprehensive geotechnical investigation and design study is required before implementing HDD.

- Pipe material and the required pull-back force and collapse resistance may limit feasibility of HDD.
- Space is required for fusing and joining of PE replacement pipe on the exit side of the bore.
- Directional drilling leaves voids around the new pipe. For this reason, road crossings may not be permitted using HDD in some areas. In those cases an alternative technique, such as auger boring which does not leave voids around the new pipe, should be considered.

Effect of service connections, valves, bends, and appurtenances on HDD:

- Service connections, valves, and appurtenances are not possible with HDD.
- Moderate bends with large radii of curvature are possible with HDD although compound curves are not recommended.

Expected service life extension:

- The service life will be extended to the full design life of the replacement pipe.

2.11 Summary

This chapter has a review of pipeline renewal technologies focusing on trenchless technologies.

The advantages and capabilities of trenchless replacement include:

- The new pipes can be of equal or greater diameter and capacity than the mains they are replacing.
- Pipe bursting minimizes disruption to traffic and reduces the possibility of interference with other utilities.
- Some technologies, such as microtunneling, can be used to place pipes through high groundwater areas without de-watering.
- Shorter preparation time than conventional replacement.
- Faster production rates than for conventional replacement.
- Shafts can be enclosed and winterized allowing the potential for year-round construction.

- Improved personnel safety due to fewer personnel and remote operation.
- Lower liability insurance premiums for contractors due to less disruptive technology (*O'Brien & Gere, (1998)*).
- Minimize pedestrian and vehicular disruption.
- Minimize disturbance to landscaping.
- Reduced interference with other utilities.
- Reduced noise and dust generation.

The disadvantages and limitations of trenchless replacement include:

- Service connections must be excavated.
- Temporary water service must be provided.
- Trenchless replacement is generally more costly than open trench construction for standard applications within the U.S. and Canada.
- Although trenchless replacement has been used since 1980 in Europe, it is a relatively new technology in the U.S. and Canada.
- Currently in the U.S. and Canada, trenchless technology is only used in situations where no other solutions will work.
- There are only limited jobs out for bid in the U.S. and Canada, which tend to drive up costs for this technology.

There are substantial improvements in the number and types of trenchless applications over the past several years, better modifications to machinery and pipe, and there is a growing number of qualified contractors/operators. The trenchless technology industry is fast growing. It is believed that the reviews presented in chapters 2 and 3 will be helpful in understanding the technology and form the basis in the development of the knowledge base of the decision support system (DSS) presented in chapter 5.

Chapter 3 - Review of Elements of Trenchless Technologies

3.1 Introduction

Chapter 2 contains a summary of the various trenchless technologies, the equipment required, compatible pipe materials, and site constraints. The reader should note that there are common components, in general for all the technologies. This chapter provides a discussion on these elements from a general perspective. Together, Chapters 2 and 3 provide a comprehensive review on trenchless technologies. To ensure successful implementation of a project, one needs to have a good idea about the following factors.

- Guidance and Steering systems
- Forces involved in underground installations
- Site Characteristics
- Pipe Materials

3.2 Guidance and Steering Systems

Unlike the traditional open trench method, trenchless technologies involve situations where the boring tool / pipe is out of the operator's sight. Hence there is need for systems which can track the tool / pipe under the surface. Steering systems which can change the direction of boring, the alignment of the bore path are also required. The need for accurate tracking and steering systems is best emphasized in urban areas, with congested sub-surface infrastructure. For a given trenchless renewal project, the following criteria should be borne in mind in selecting the appropriate instrumentation system.

- *Measurement consideration*
The system should be able to meet the accuracy standards required for the project. For example: an accurate system is required for trenchless installation in an area, which is congested with other utilities.
- *Range*
Installations spanning a long distance require instrumentation systems with a longer range, which are costlier than short-range systems
- *Data rate*
The mode of information transfer between the operator and the transmitter is very important. Some processes require real time data transfer while in some methods; there is a flexibility to suspend the operation and send the probe back to the surface and act upon that information.
- *Cost*
Increased accuracy entails an increase in the cost of the guidance system. There should be a trade-off between accuracy and cost.
- *Ease of use*
Importance has to be given to the time one requires to gain mastery over the guidance system.

3.2.1 The Co-Ordinate System

A standard co-ordinate system is required to accurately pinpoint the location of the tool /pipe in the borehole. For this purpose a system that specifies the tool's position in 6 degrees of freedom, is used. The X, Y, Z co-ordinates, azimuth, inclination and roll angle are used. The azimuth or lead is the angular sweep in the XY plane and the inclination or the pitch refers to the angular motion in the YZ plane. The roll angle or tool face is the angular motion in the ZX plane., that is, the direction the tool will steer if the steering member (e.g., slanted face, deflection shoe) is maintained in a particular orientation. Figure 3.1 gives a visual representation of this co-ordinate system. The subsequent sections present a summary of the most common types of guidance and steering systems used in the trenchless industry.

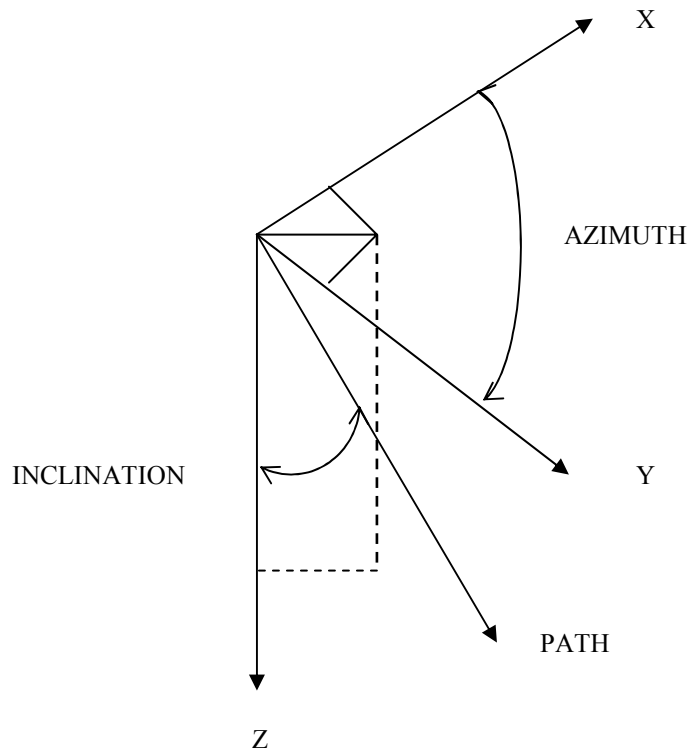


Figure 3.1 - Co-ordinate system for Underground Installations
(From Kramer et al. (1992))

Tracking Systems

3.2.2 Walkover Systems

The most common method utilized is the "walkover" guidance system. This is used primarily where there are very few surface obstructions and in depths of less than 20 meters. These systems are comprised of a transmitter that is in the bottom hole assembly (BHA). A beacon / Sonde is locked into a fixed position that depicts the face of the bit. A signal is sent out from the beacon showing the drilling tool's progress through the ground. A technician, who is above the bore path on the ground holding a portable receiver, receives this signal. He/she can track the bore path in this manner and stop periodically to instruct the drilling unit's operator to make the necessary adjustments to keep the bore path on target. The name comes from the mode of operation as the technician "walks over" the borehole on the ground tracking the drill bit under the ground. Current improvements to this system now make it possible for the technician to be up to 30 meters away from the BHA and receive the same information accurately. Figure 3.2 shows a walkover system in action.

This system is very cost effective and gives the crew excellent control in all three dimensions of their bore. It should be noted that obstacles such as busy freeway intersections or river crossings cannot be physically "walked over". Often magnetic interference from overhead power lines or underground traffic signals, buried trash, or rebar in foundations will interfere with accurate signal readings. The very nature of the operation shows that this method cannot be used for installations where accuracy is very important. Horizontal directional drilling projects generally use the walkover method to track the drill bit.

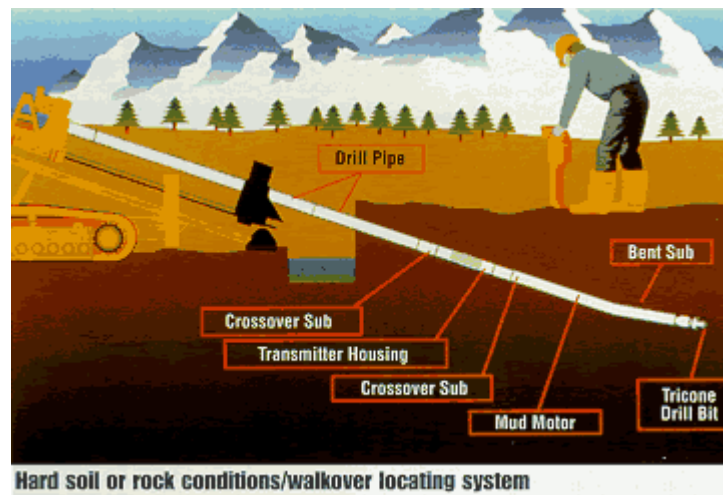


Figure 3.2 – Walkover System for HDD

(Source: <http://www.dcca.org/guidelines/dccaguidemidsize.htm>)

3.2.3 Wireline Systems

When there is need to go deeper or under obstructions such as buildings or storage tanks, a "wireline" guidance system may be used. This system consists of a probe device or measuring instrument that is mounted in the bottom hole assembly (Figure 3.3). The device tracks the bore path and sends information through a wire inside the drill pipe. This information is collected and calibrated, usually by a computer-based system. This

method of guidance, although very accurate, is a time consuming operation. It comes at a much higher cost.

One of the major drawbacks is the need to make a connection in the wire for each new rod put into the ground. Since the wire conducts power and signals, there is virtually no limit to the depth or length that a bore may be guided. A wireline system may be used with an auxiliary system that utilizes a surface grid. This grid forms a magnetic field and results in increased accuracy. The information produced is transmitted to the surface computer and is printed out for evaluation. However, this method is known to produce erroneous results in areas where there are magnetic materials present. These magnetic materials generate their own field, which interferes with the field produced by the wireline.

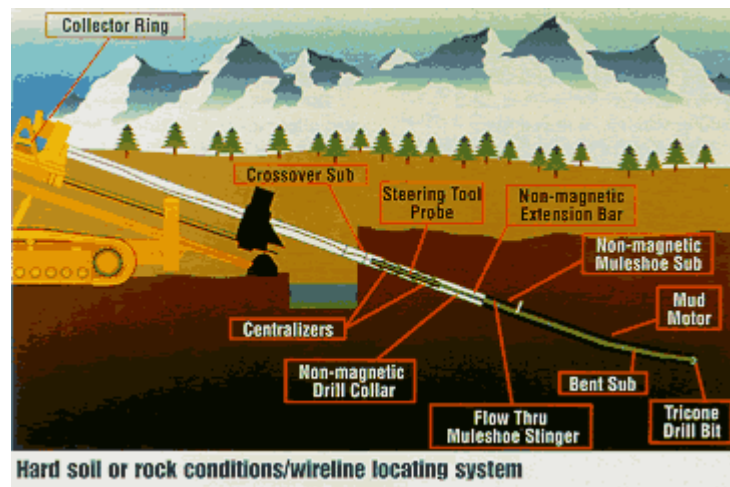


Figure 3.3 - Wireline System for HDD

(Source: <http://www.dcca.org/guidelines/dccaguidemidsize.htm>)

3.2.4 Electromagnetic systems

These systems are based on the principle of generation and detection of electromagnetic fields. A series of cables are positioned above the drilling path on the ground and secured in place. They can be weighted down to the bottom of a stream (for stream crossings) or placed above the pavement surface (for installations below roads).

These cables transmit electromagnetic signals into the bore path. A detector/receiver located inside the drilling head receives them and locates its position with respect to the center of the cable to the precision of 1 inch (25mm). This information is continuously relayed back to the computer at the controls.

An alternative technique uses the earth's magnetic field for locating the drill tool. This is not an accurate method because magnetic field varies from place to place. Hence, its applications are limited to operations which do not require a high degree of accuracy (eg:- installation of pressure lines). Sometimes, the transmitter is located inside the drill head and the receiver is located inside a receiving pit. The distance over which this signal is transmitted is limited to 30m (100 ft). The presence of magnetic materials in the earth is known to cause erroneous results in the location of the tool. In such cases, proprietary systems, which generate a magnetic field to counter the earth's magnetic field, can be used. The TruTracker ® System manufactured by InRock Technologies is one such example (Look at <http://www.inrock.com/igs/p-trutraker.htm> for further reference). Many other systems with similar capabilities have been developed by other firms.

3.2.5 Laser /Optical systems

A Laser beam is set up in the starting line at grade and is made to strike a target board in the borehole. This method is very accurate but requires a clear optical passage. The target board can be either active or passive. For passive boards, the information is transmitted from a TV Camera located inside the pipe. Active boards on the other hand are equipped with photo diodes. When the laser beam impacts on the board, the photo diodes are activated generating an electrical impulse. The impulse is transmitted to a monitor where the position and the number of activated photo-diodes are reproduced. Digital signal processing enables the photo-diodes to generate automatic steering commands. Sometimes, a theodolite is used instead of a laser beam. In this case the target, an LED (Light Emitting Diode) is sighted with the theodolite. This process utilizes a passive target.

These methods are commonly used for straight pipe but can be modified to monitor pipe jacking along curves. If there is a temperature gradient in the optical passage, the light beam is subject to diffraction at the transition from a dense to a thin medium. They are also subject to drift due to oscillations of the optical resonator depending on the temperature. The use of a theodolite has the advantage over a laser in that the optical ray is not subject to drifting. Additionally, laser beams also have a tendency to spread with distance. Hence, for long distance pipe jacking operations, a slight temperature gradient can result in an oversized laser beam, which in turn would lead to errors in the installation. To summarize, the laser systems are most effective in microtunneling and pipe jacking projects spanning short distances.

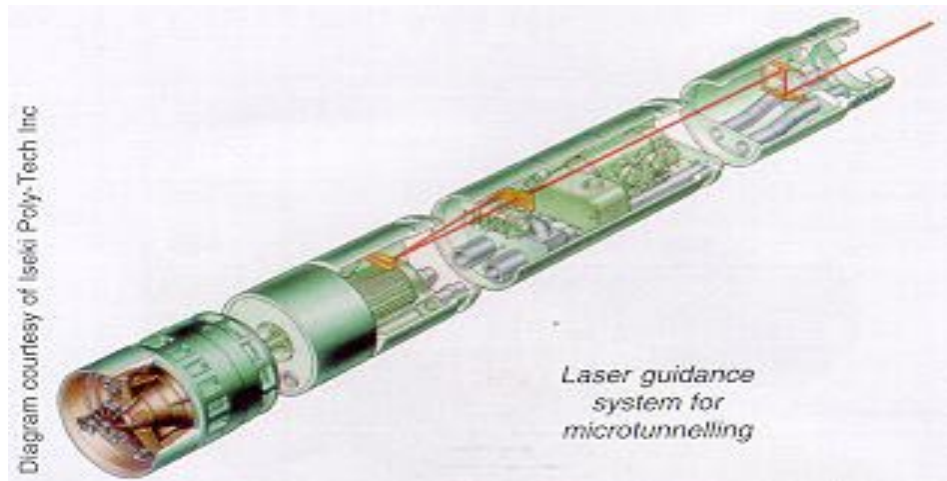


Figure 3.4 – Laser Guidance System
(Source: <http://www.catflap.net/digging-deep/isttsectionm.htm>)

3.2.6 Inertial systems

Tanwani and Iseley (1994) talked about inertial guidance systems for trenchless technologies. The reading of a gyroscope is transmitted electrically to the surface using a wire line. Since the gyroscopes are very sensitive, they are not used for pipe jacking jobs known for high vibrations and impact loads. Like lasers, inertial systems are also subject to drift. The drift characteristics of a particular system must be carefully studied before it is used on the site. The advantage here is that they are very accurate regardless of the route or distance and they are not affected by magnetic interference. The size of the

systems limits their usage to large-sized projects. Research is underway to extend the capabilities of these systems to small diameter pipes.

3.2.7 Water Level

The water level is used to measure the grade of the pipe as it is being installed. A water level sensing head is attached to the leading edge of the pipe. A pit mounted control and indicator board is located at a convenient point near the operator. A hose connects the bottom of the indicator tube to a water pipe running along the top or the inside of the pipe. The system is filled with water and both ends of the system are vented to ambient pressure. The level of water in the indicator will then show the level of the vent at the other side. Modern electronic levels are capable of measuring more accurately and display the data electronically. (*Tanwani and Iseley, (1994)*)

3.2.8 Inclinometer Method

This method is used in Pipe Jacking projects. Electronic inclinometers / mechanical pendulums are used to measure the inclination of the pipe / boring tool in the direction of jacking. To measure the roll of the tool two inclinometers can be set up in perpendicular directions. In addition, the distance jacked is measured and all the information is integrated to accurately pinpoint the tool. (*Tanwani and Iseley, (1994)*)

Research is underway to improve the capabilities of the existing guidance systems. Some firms have incorporated the principles of fuzzy logic in their systems to accurately pinpoint the position of the drilling tool. Figure 3.5 depicts one such system. We are at a stage of technological advance that there are guidance systems available for every conceivable kind of trenchless installation. Table 3.1 gives a summary of the capabilities of most of the guidance systems. However, it is not sufficient to have an appropriate guidance system alone. There is still need for a system, which can steer the drilling tool or the pipe along the planned borehole. The next section presents a summary of the common steering systems in the trenchless industry



Figure 3.5 – The Herrenknecht – ELS Guidance System

(Source : <http://www.trenchlessdataservice.com/sponsors/herrenk/micro.htm>)

Table 3.1 – Summary and application of tracking systems (Tanwani and Iseley, (1994))

Tracking System	Applications	Measurements	Cost	Comments
Laser / Optical System	Pipe Jacking, utility tunneling, microtunneling	Horizontal and vertical deviation	Medium	High degree of precision
Walkover Systems	Compaction Method, slurry boring mine directional drilling, auger boring	Horizontal and vertical deviation, roll, orientation of tool	Low	Surface access required, limited in depth, not very precise
Electromagnetic Systems	Directional drilling, minidirectional drilling	Horizontal and vertical deviation, Horizontal and vertical orientation, roll	Medium to High	Performance of systems may be affected by magnetic fields
Inertial Systems	Pipe Jacking, Microtunneling	Horizontal and vertical deviation, Horizontal and vertical orientation, roll, length installed	High	Limited applicability due to size constraints and inability to withstand excessive vibration and impact loads
Water Level	Auger Boring	Vertical deviation	Low	Limited to Auger Boring
Inclinometer	Pipe Jacking	Vertical inclination, roll	Low	Not very precise

Steering Methods

3.2.9 Slanted-Nose Method

The nose of the drill head consists of a slant-shaped anvil, which can be withdrawn or extended from a sleeve. The anvil generates a bias that can be used to steer the drill bit. When the drilling path is straight, the anvil is retracted inside the sleeve. For curved paths, the anvil is extended in the direction of the curve. Once the pilot hole is made, a reamer is attached to the tool and pulled back to enlarge the hole. The horizontal directional drilling (HDD) industry stands to benefit from this technique. The accuracy expected from the anvil is limited.

3.2.10 Hydraulic Jetting Method

Fluid jets (a mixture of water and bentonite slurry) are used to cut the earth ahead of the boring tool. The bentonite clay provides a stable lining to the hole and is especially useful in fine sand. The clay lining also lubricates the borehole wall reducing the frictional drag on the tool. Steering is done by changing the direction of the cutting jets. This method is applicable for the installation of small diameter lines or pilot holes for larger pipes.

3.2.11 Differential Excavation Method

This method is based on the principle that the pipe follows the hole cut by the cutting head. In this method, the position of the cutting head can be changed with respect to the position of the pipe. Excavation is carried out in the desired direction prompting the pipe to follow the tool. This method is generally used for large-diameter pipes and produces good results in stiff clay. The steering capabilities of this tool are limited and hence it cannot be used for bends with a small radius of curvature.

3.2.12 Articulated- Head Method

The drilling head is made of two articulated units, the steering head and the follower. These two units can be deflected in relation to each other and in all directions by hydraulic steering cylinders or by steering screws. The steering screws can be remotely controlled for nonman-entry size pipes. For larger pipes, the controls can be

either inside the pipe or remotely controlled. If a change in the direction of the jacking pipe is required, the screw is rotated such that the steering head is deflected in that particular direction. This results in the pipe moving in that direction.

3.2.13 Wireline Steering Tool Method

The steering tool consists of a downhole probe, wire line, interface module/computer and driller's console. The downhole probe contains an orientation module (magnetometers and accelerometers) for magnetic measurements of azimuth, inclination and roll. The wire line performs three functions:

- It acts as a tensile member for tripping the steering tool in and out of the borehole
- Supplies electric power to the down hole probe
- Carries data signals from the probe to the surface.



Figure 3.6 – Tensor Steering Tool System (InRock Systems)

(Source: http://www.inrock.com/igs/p-steering_tool.htm)

3.2.14 Applicability and Compatibility of various methods

The combination of tracking-steering systems must be chosen based on the type of installation. Typically, the laser/optical system can be used in conjunction with the slanted-nose method, differential excavation method or the articulated-head method. The jet cutting method creates obstructions in the optical passage and cannot be used. The

pipe locator/walkover system can be used with most types of trenchless applications. Accuracy limitations limit its usage.

Electromagnetic systems like the walkover system cannot be used in areas with steel obstructions and strong magnetic influence. The movement of construction traffic above the bore path has also been observed to induce an error in the readings. Apart from these disadvantages, it has been found that they are very accurate and can be used in a wide range of operations.

Inertial systems have been used successfully on a number of microtunneling projects around the world. They are very accurate and can be used even in areas with high magnetic influence. The size of the gyro has however limited their application to smaller diameter installations.

The water level has been used in conjunction with the articulated head method. It cannot be used for the installation of small-diameter pipelines. Its advantage lies in the fact that it is a time-tested method and is not affected by magnetic interference. Wireline steering systems are common in the HDD industry.

3.3 Forces Involved

Pipe renewal is associated with various forces based on the mode of installation. Figure 3.7 presents a classification of the various technologies on the basis of the forces involved. The various elements of the classification tree are described in this section.

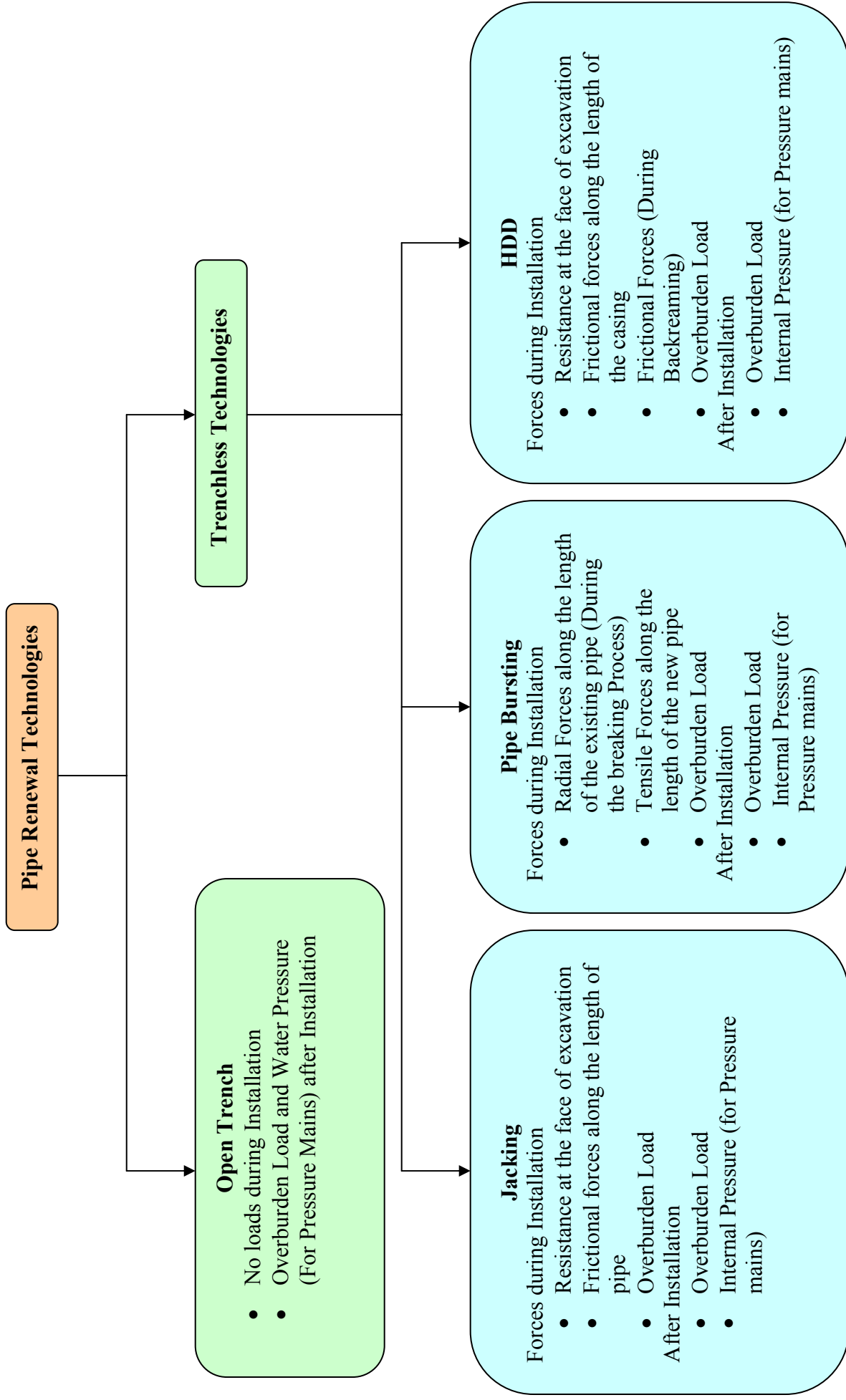


Figure 3.7 - Force based Technology Classification

3.3.1 Open Trench

Description of Method

Conventional “open trench” construction is the most frequently used method for replacement of water mains in the U.S. For many water utilities, the practice is to install the new main in a trench parallel to the old main. In some cases, removal of the old main is not worthwhile or necessary, and old, damaged water mains are simply abandoned or given to electric or cable utilities. Because the old main is kept in service until the new main is in place and ready for connection to the customers' service lines, service interruptions are minimized. In those cases where the old main has to be shut down before the new main is in place, bypass pipes are laid to provide uninterrupted service to customers. Water mains of any diameter can be used, allowing for an increase in the water capacity to any required level.

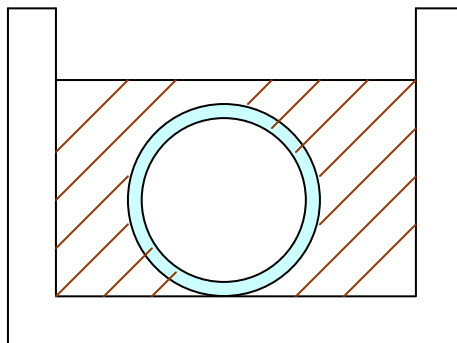


Figure 3.8 – Longitudinal Cross Section of a Pipe (Open Trench Method)

Forces

The above figure represents a pipe installed with the open trench technique. The hatched lines represent the ‘backfill’ in the trench. Pipe behavior can be broadly classified as flexible or rigid, depending on how it performs when installed. Flexible pipe can move, or deflect, under loads without structural damage. PVC, polyethylene pipe (HDPE) are examples. Rigid pipe is sometimes classified as pipe that cannot deflect significantly without structural distress, such as cracking. Reinforced and non-reinforced concrete pipe are examples.

Both flexible and rigid pipe depend on proper backfill. Backfill characteristics, and also trench configuration in the case of rigid pipe, enter into the design procedures. For flexible pipe, deflection allows loads to be transferred to and carried by the backfill. Rigid pipe transmits most of the load through the pipe wall into the bedding. Proper backfill is very important in determining how the load is transferred.

3.3.2 Jacking Technologies (Pipe Jacking, Microtunneling)

Description of Method

Pipe jacking can be described as the principle of using hydraulic rams to push pre-formed sections to line the hole formed by a cutting head or shield. Generally, this technique is used for the installation of man-entry size pipe. *Kramer et al.* (1992) provide a very informative discussion about the pipe jacking technique. Pipe jacking method can be conveniently divided into 3 areas: (1) the face, (2) the line, and (3) the jacking equipment, setup

The Face

A shield or cutting edge is fitted to the leading end of a pipe jack. Shields range from a rudimentary steel can on the end of the first section to highly sophisticated tunnel machines with earth-pressure stabilization chambers. The shield provides the following functions.

- Temporary support to the soil
- Hard-faced cutting edge
- Mounting for cutting and face-stabilization equipment

The Line

The pipes and casings can be installed in different ways. In the *Single Pass* method, the pipe driven becomes the permanent liner. In the *Double Pass method* a temporary casing is first installed to stabilize the hole. Later, the permanent pipes will be jacked in pushing the casing out. In the *Casing System* method the permanent pipe is laid inside a casing and the annular space is grouted. Pipe Jacking and microtunneling are

examples of the *Single Pass* method. Horizontal Directional Drilling (HDD) is an example for the *Double Pass* method. However, the method of installation is distinctly different for the HDD method. The most distinct difference is that the pipes are not installed in sections and jacked forward. Rather a single flexible pipe is pulled through the hole by the drilling tool.

The Jacking Pit

A pit is excavated at the entry point of the pipe and houses the jacking equipment. The jacking rig consists of a set of rams (usually hydraulic); a means of transferring the load uniformly onto the end of the pipe; and a reaction element, usually a block, anchor or tie. Equipment for spoil removal is usually required at most sites. The shield /cutting edge is set on the launch cradle and driven through the wall of the pit. Sealing and Stabilizing techniques are available to ensure that no ground failure or inundation occurs as the pipe is pushed through the pit wall.

Once the shield has entered the ground, the lead pipe is set in the rear of the shield. The jacks push the pipe forward, which in turn pushes the shield forward, excavating the soil. Once the pipe is pushed forward through its length, the jacks are retracted to their original position. A new section is placed in the jacking pit and jacked forward. Once the sections are joined, they behave as a single unit. Successive sections of pipe are set, jointed, and jacked through until the pipe comes out at the reception pit.

For long drives intermediate jacking stations (IJS) are stationed at regular intervals along the drive. The main station jacks the pipes to the first IJS, which in turn jacks them to the next, and so on. If a single station were to jack all the pipe sections, the jacking force would have to be very high. Proceeding from the main jacking station, the jacking force decreases, section by section, by the amount of the given frictional resistance. Theoretically, the highest jacking force occurs in the first pipe in front of the main jacking station. High forces cause the joints nearer the first station to buckle. Usage of IJS remedies this problem. A thrust transfer ring serves to transfer the jacking force from one pipe to another. The ring also compensates for manufacturing irregularities on

the pipe end surface in order to avoid the occurrence of the stress peaks. The jacking process is illustrated in Figure 3.9

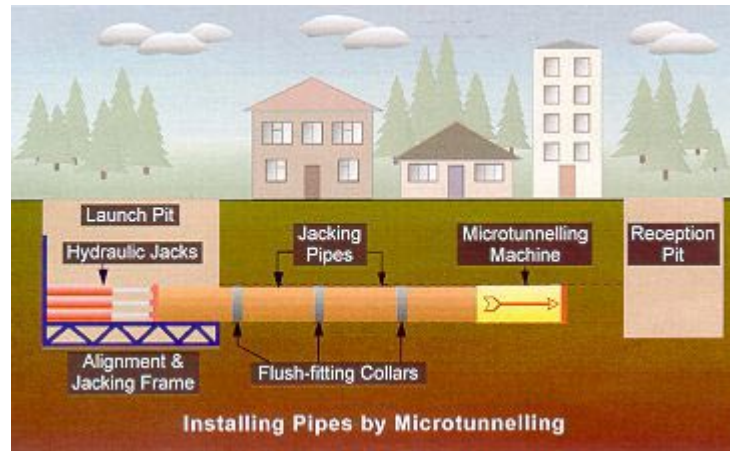


Figure 3.9– The Pipe Jacking / Microtunneling Process

(Source: <http://www.catflap.net/digging-deep/isttsectionm.htm>)

Jacking System Capacity

The estimated jacking load determines this parameter. The thrust used to propel the tool is typically provided by the main jacking system. If the pipeline diameter is large enough, (30 inches or more), intermediate jacking systems can be used to provide additional thrust.

Intermediate Jacking System (IJS)

Intermediate jacking stations are utilized when

- Jacking force exceeds the axial capacity of the pipe
- Jacking force exceeds the thrust capacity of the jacking frame
- Jacking forces exceed the thrust wall capacity

Thrust Wall Design

It is used to distribute the load from the main jacks through the shaft/bore wall to the soil. The thrust wall should be designed with a factor of safety, usually around 2.0 to keep deformation within acceptable bounds.

Pipe Design and Strength

Pipe manufacturers use estimated jacking loads to specify the anticipated forces that will be applied to the pipe. These loads are multiplied with a safety factor and the pipe will be designed for that load.

Economic Impact of Jacking Load Predictions

The Shaft cost is dictated by: size of the shaft, number of shafts, type of shafts and the method of construction, the depth. To minimize the overall project cost, the engineer should minimize the number of shafts. Estimated jacking loads allow the engineer to space the shafts according to the maximum drive length. If the shafts are spaced without regard to the estimated jacking force, it is possible to either overestimate or underestimate the drive length. Underestimation leads to additional expense due to unnecessary shaft construction. Overestimation can result in unsuccessful drives due to depletion of the jacking force. IJS add economic benefit to a project by reducing the number of shafts

Jacking Force

The Jacking force that must be applied by the hydraulic jacks to install the pipe sections in the sub-surface is a very important design parameter. The contractor needs to know the magnitude of the required force in order to select appropriate equipment for the operation. Underestimation of the force results in unsuccessful installation. Overestimation can result in excessive stresses at the pipe joints making them fail and buckle. Traditionally, an estimate of the force required is arrived at by combining the jacking force required to overcome face pressure (Penetration Resistance) with that due to the interface friction between the pipe sections and the soil. An appropriate equation is given by *Najafi and Iseley, (1991)*.

$$F \geq S + \sum R \quad (3.1)$$

F - Jacking Force Required

S - Penetration Resistance

$\sum R$ - Net Frictional Resistance along the length of the pipe

The inherent variability in the jacking operation poses problems to methods predicting forces. Empirical and statistical methods are used to predict the various parameters in the above equation. *Coller et al* (Part I, 1996) present a “rule-of-thumb” method to compute the penetration resistance. In this method, various parameters like face pressure component (penetration resistance), frictional resistance, effect of depth, groundwater levels, overcut, lubrication, soil properties etc., are all lumped into a single jacking stress value and the jacking force (F) is expressed as

$$F = \pi d_p L f_r \quad (3.2)$$

F – Jacking Force Required

d_p - Outer diameter of the pipe

L – Length of the pipe

f_r - Jacking Stress

A statistical analysis of various case histories can also be used to quantify the effect of various factors. The International Working Group No.3 (*ISTT*, (1994)) was the first to use it. *Lys and Garrett* (1995) have suggested a statistical method to compute the maximum axial force required for Microtunneling operations. Data from various jacking jobs concerning pipe diameter, drive length, jacking force for the maximum force was recorded. The form of the frictional resistance (R) is given by

$$R = \pi MDL \quad (3.3)$$

M – Statistical parameter

D – Outer diameter of the pipe

L – Length of drive

A histogram for the Force/surface area of the pipe-soil interface was used to generate a normal distribution for ‘M’. The mean for the normal distribution was found to be 0.05 tons/ft² and the standard deviation was 0.02 tons/ft². From the normal distribution, the parameter ‘M’ for any job could be predicted with a specific probability.

Coller et al. (Part I, 1996) developed correlations to determine the effects of the major factors influencing microtunneling forces. The correlations were based on an in-depth analysis of microtunneling projects throughout North America. The trends in the plots of *Jacking Force vs. Time* were identified and attempts were made to learn the causes of the trends and to quantify the effects. They made the following conclusions after a careful study.

- *Lubrication*

Bentonite slurry is pumped into the annular space in the jacking shaft to reduce friction at soil-boring head interface and to stabilize the shaft. Traditionally, the unit volume of the slurry being pumped is equal to the volume of the annular space. But in areas with high ground water flow, the lubricant is washed away making it necessary to pump a larger quantity for the same performance.

- *Dewatering*

Dewatering wells are used to reduce the groundwater flows into the shafts. It was observed that activating the dewatering wells builds up the normal stresses (Penetration Resistance). Turning off the wells reduced the effective stresses on the pipe lowering the jacking forces.

- *Overcut on the pipeline and shield*

Overcut is defined as the difference between the excavated diameter of the bore and the outer diameter of the shield or pipe. Typical overcuts range from 0.25 to 1.5 in. on the radius depending on the diameter of the machine, the depth below the surface, and the ground conditions encountered during drilling/tunneling. Low overcuts increase the frictional resistance, thereby the jacking force, ultimately causing the joints to fail.

Coller et al. (Part II, 1996) computed the jacking stresses by dividing the jacking force with pipe surface area and plotted them against distance from the drive shaft. It was observed that the jacking stresses (F/A where $A = \pi DL$ with D being the pipe diameter and L the length of drive) rapidly decrease from initially high values toward asymptotic minimum values. Twelve drives with 7 in clay and five in sand were analyzed. The

analysis included the determination of minimum F/A values and the distances where they occurred. The authors made the following conclusions from the recorded data

- The shape of the F/A vs. distance curve is a parabola decreasing with distance toward an asymptotic minimum value
- The distance over which F/A decreases in clays to its asymptotic minimum value is approximately half of that for sands. This means that the resistance offered by clayey soils is higher compared with sandy soils
- The asymptotic decrease in the stresses is a direct result of the Jacking Force along the length of the drive.

Najafi and Iseley (1991) state that the jacking pipes must be designed taking the soil and traffic loads into account. Consideration must also be given to the longitudinal jacking force applied during installation, other service stresses. The pipe should also be capable of withstanding wall stresses, deformation, buckling and fatigue. In areas with possibility of land subsidence, allowance should be made for possible ground movements. Unexpected obstructions and steering errors can bring about a sudden increase of the jacking force. It is necessary to install pressure relief valves at the main jacking station and/or indicators on the control panel to insure that the allowed jacking force is not exceeded. *Chapman and Ichioka* (1999) affirm the same points in their article. They also say that Stoppages during installation, for example overnight, at weekends and holidays, allow consolidation of clay-based slurry and the disturbed clay at the pipe-soil interface. This consolidation manifests itself in the form of a sharp increase in the jacking force.

Summary

The prediction of jacking forces is a very important part of the jacking operation. Accurate estimation can reduce the cost of the project, the time for installation. However, the inherent variability of the operation makes it difficult for people to come with an accurate predictive model. The large number of parameters, which influence the jacking force, is also a big deterrent. Empirical and statistical methods are used.

3.3.2 Horizontal Directional Drilling (HDD)

Description of Method

The most important advantage of HDD is that it can be used to bore with great accuracy. Installations can be made under paved surfaces, buildings, streams and lakes. Because starting pits are not required, the operation is launched from the surface. Horizontal drilling causes minimal surface damage, produces little secondary contamination, eliminates cross contamination of vertically stacked aquifers (*Griffin, (1995)*).

Directional drilling involves the use of a drilling rig, typically situated on the surface of the ground, which bores into the ground at an angle using an angled bore head. The drill rig is set up at the borehole entrance and used to make a pilot hole through a curved section. Boring can be accomplished using a high-pressure jet of drilling fluid and/or a rotating drill head powered by a mud motor. Soil displaced by the boring operation is suspended in the drilling fluid and flows back out to the entry pit. The bore head is pushed along the bore path by the drilling rig with the drilling fluid pumped under high pressure through the hollow drill pipe. A curved/wedge shaped drill bit is used to push its way through the soil. The curve on the bit forces the assembly in a curved path. In softer soils, the jetted drilling fluid cuts through the soil. If the soil is too hard to be cut only with the jetted drilling fluid, the drill head is turned by rotating the drill string or the hydraulic pressure of the drilling fluid is converted into mechanical energy by a mud motor to rotate the drill bit. As the pipe is pushed into the borehole, additional drill pipe stems are attached. In cases where the ground is unstable, a washover pipe (casing) can be pushed down the borehole path to prevent the collapse of the borehole. The curve will be straightened back to horizontal as the hole approaches the target depth and desired location.

The location of the drill head is determined by a guidance system. With the feedback from the guidance system, the driller guides the drill head by rotating the drill string and by increasing or decreasing thrust. Upon exiting the surface of the ground, the drill bit is detached and normally a reamer is attached and pulled back through to enlarge

the borehole. If required, consecutively larger reamers are used until the borehole is approximately 25% larger than the outside diameter of the pipe to be installed. Once the borehole is sufficiently enlarged the reamer is attached to a swivel and the swivel is attached to the pipe to be installed. The pipe is then pulled back through the borehole.

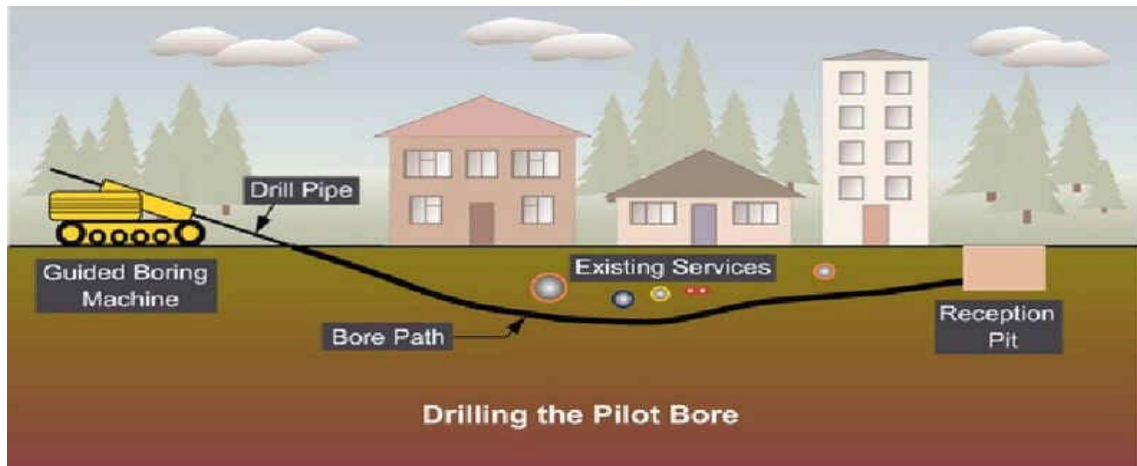


Figure 3.10 - Drilling of the Pilot Bore (Phase 1 of HDD)

(Source: <http://www.catflap.net/digging-deep/isttsectionj.htm>)

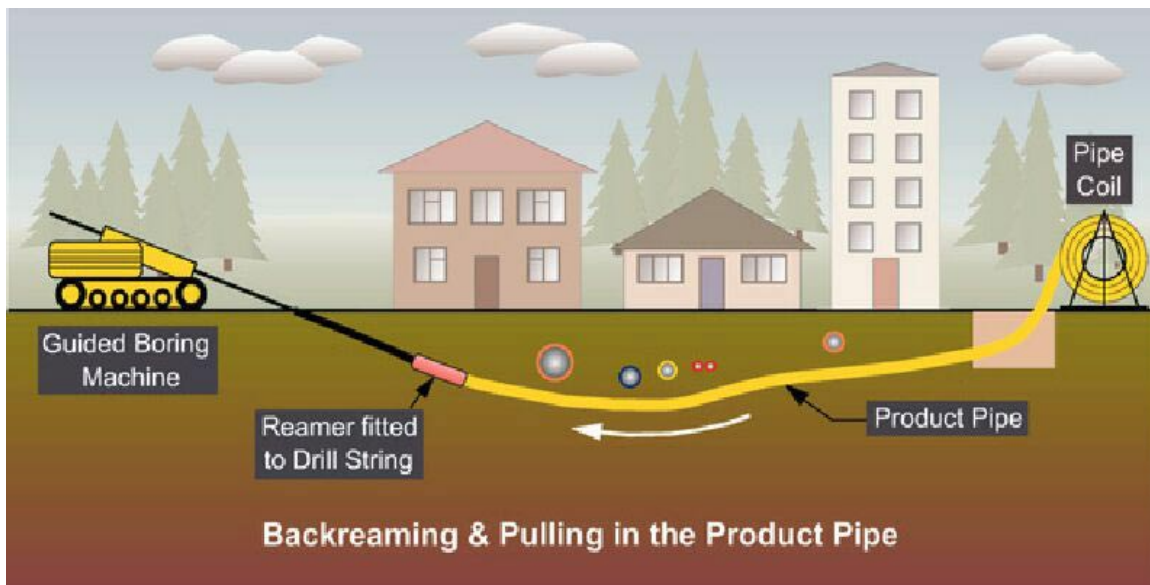


Figure 3.11 – Backreaming and Insertion of the new pipe (Phase 2 of HDD)

(Source: <http://www.catflap.net/digging-deep/isttsectionj.htm>)

Down hole Mud Motors

Drilling fluid is pumped under pressure through a drilling string to a motor causing the motor to rotate and drill its way through the soil. Mud motors allow drilling into some formations and depths not accessible by compaction bits. They are especially applicable to sandy soils and where geological conditions require bentonite slurry or other stabilizing additives to maintain an open borehole.

Forces

Mast et al. (1996) describe the environmental impacts of the HDD technology, the design factors, materials, procedure and equipment in their article. As the casing moves in a curved section, the soil closes on it resulting in *drag forces (friction)* and *bending forces*. The drilling mud may also result in a large *suction force* increasing the stress as the casing is pulled through the borehole. Drilling fluids are used to provide lubricating effect. The stresses often necessitate the use of tensile pipe material (e.g., HDPE, fiberglass, PVC). Additionally, pressures from drilling fluids may cause damages to underground utilities, change soil texture, or flow along trench lines beyond the control area. *Kaback* (1995) has suggested that care must be taken so that the borehole does not infringe upon underground structures, beach utilities, or compromise soil stability.

In the borehole, an excess mud pressure is maintained in order to enable sufficient outflow of mud and cuttings. At high pressures the borehole will fail through uncontrolled expansion or hydraulic fracturing. Hence, there has to be a limit to the allowable mud pressure. *Luger and Hegarden* (1988) applied the cavity expansion theory to predict this maximum allowable mud pressure for directional drilling operations. In the same article, it was also mentioned that the pressure reading down-hole differs significantly from those taken at the mud pump. The mud pressure losses can be attributed to: resistance during mud supply in the drill pipe, annular space between wash pipe and drill pipe, wash pipe, entry and exit losses at the nozzles, motor losses. They conclude that their prediction technique in conjunction with accurate down hole measurements provides optimum guarantees for borehole stability and prevention of damage in the surroundings of the drilling.

Summary

From an environmental standpoint, it is important that the soil be disturbed as little as possible. The Horizontal directional drilling projects cause very little damage to the soil because of minimal excavation. Also, introduction of unnecessary foreign material to the subsurface should be avoided. Additives like grease and lubricants are inadvertently introduced during the operation. The drag forces caused by the soil closing on the casing and the bending forces render most materials unsuitable for the operation. Additionally, pressures from drilling fluids may cause damages to underground utilities,

3.3.3 Pipe Bursting

Description of Method

Pipe bursting also known as Pipe Splitting, is a technique that uses radial forces to break out and enlarge the existing pipe and thereby permit a new pipe to be simultaneously installed. The fragments are forced outward into the soil, and a new pipe is pulled into the bore formed by the bursting device. A large pulling force is applied to a cone shaped bursting head through rods, cable and chain. The bursting head is pulled through the pipe, causing the pipe to fail in tension by the radial force applied to the pipe wall from the cone within the pipe. As the host pipe is burst, the bursting head pushes the broken pipe pieces into the soil as it displaces the surrounding soil, thus creating a cavity for the new pipe. To facilitate the installation of a new pipe of larger diameter, the degree of expansion is slightly greater than the external diameter of the replacement pipe. The technique has since developed to allow upsizing of the existing service, essentially by increasing the degree of expansion used.

The typical project is divided into sections/lengths based on the capability of the pipe-bursting machine. The length that can be burst is also dependent on pipe material, soil conditions, and geometry of the original installation. Access pits must be excavated at both ends of the pipeline. On one end, there is the machine pit, which contains the pipe-bursting machine that pulls the busting head. On the other end, we have the insertion pit through which the new pipe and bursting head are inserted into the host pipe. There

are three pipe bursting systems in use in the North American Trenchless Industry ; the static, pneumatic, and hydraulic expansion systems. The main difference between the methods is in the manner the force is generated and is transferred to the host pipe. *Lueke et al.* (1999) have developed a simulation model for pipe bursting projects. Results obtained from this model can assist owners, engineers, contractors, and equipment manufacturers in designing, planning and managing pipe bursting projects.

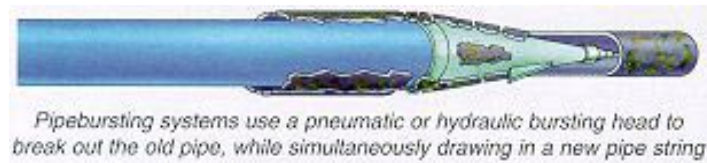


Figure 3.12 – The Pipe Bursting Head
 (Source: <http://www.astt.com.au/instal.htm>)

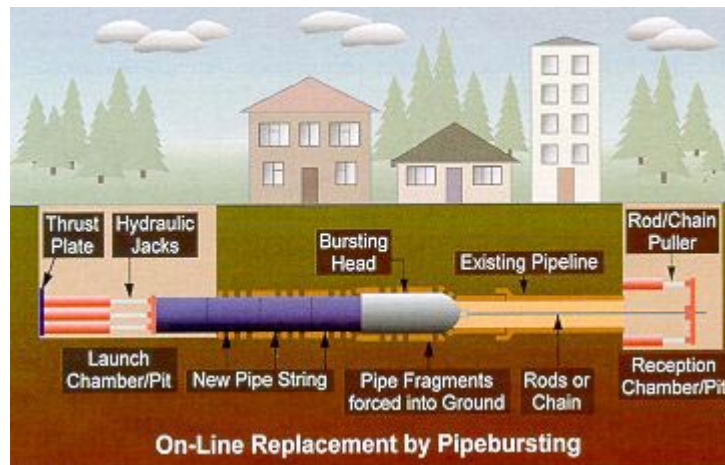


Figure 3.13 - A Schematic of the Pipe Bursting Process
 (Source: <http://www.astt.com.au/instal.htm>)

Forces

The powerful forces generated during the operation are of major concern to the contractors administering the project. These forces can damage nearby utilities, weaken foundations of residences if proper care is not taken. *Rogers* (1996) provides a discussion on ground displacement from trenchless construction by pipe bursting. The study aims to predict subsurface displacements thereby providing a tool for managers to understand the

impacts of bursting operations. The author focuses the analysis on clayey and sandy soils. Displacements away from the operation have been seen to diminish at distances greater than 300 mm (1 ft) from the pipe in dense sand, and over a smaller distance in loose sand. Ground displacement occurs because of the following reasons

- Outward movement of the displaced pipe fragments (immediate)
- Inward movement due to the relaxation and subsequent settlement of the ground following the burst (delayed)

The response of the soil depends on the ground type and conditions. A clay soil would be expected to undergo constant volume (undrained) shearing. In normally consolidated clay deposits, the undrained shear strength, C_u increases with the effective overburden pressure. (Das, (1990)). Negative pore water pressure would be generated (suction) in the case of heavily over-consolidated clay and positive pressures in the case of normally or lightly over-consolidated clay. These pore water pressures will change in time, as water is expelled or added to the soil. The resulting effects would result in expansion (causes heave at the surface) and consolidation (causes settlement at the surface).

“In dense sand, the soil movements are predominantly upwards and outwards, with residual surface heave. The outwards movements dominate the area around the burst zone, where only small vertical displacements occur due to the facility for dilation in dense sand. Superimposing the movements in the perpendicular plane results in a tempering of outward and upward movements. In loose sand, compression occurs readily and outward movements diminish rapidly. Here, settlement at the burst-zone region dominates the pattern, and a residual surface settlement occurs. Since these two cases represent extremes, interpolation is necessary for practical cases. In dense sand, the forward and upward movement in the longitudinal cross-section modifies to upward movement as the burster passes underneath and to backward movement caused by the settlement trough, but no downward movement since the dilation of the sand beneath has fully compensated for the bursting force. In loose sand, a similar forward and upward pattern of displacements occurs as the burster approaches and passes, although with a

much reduced magnitude since compression of the underlying sand is possible. The dominance of the settlement trough is thereafter apparent with downward backward and subsequently forward displacements as the trough wave passes".(Rogers, (1996))

Summary

Pipe bursting operations differ in the manner the bursting force is generated and transferred to the host pipe. The forces generated during the operation can damage nearby utilities and weaken foundations of buildings. The soil conditions dictate how the forces are propagated in the soil.

3.4 Summary of chapter

This chapter presented an overview of the elements common to various trenchless technologies. The focus of this chapter was on the required guidance systems and the forces generated for the project. Combined with chapter 2, this chapter works as a useful guidebook on trenchless technologies. Chapter 5 presents a discussion on the influence of the pipe material, site characteristics on trenchless technology selection.

Chapter 4 - Replacement Analysis

4.1 Introduction

When a pipe breaks, the utility dispatches a crew to repair the pipe. This activity involves labor, material, and compensation to the affected party costs. Also, a decision on whether to repair or replace the pipe has to be made. After a while, it is more economical to replace the pipe instead of continuing to repair it. Timely replacement can result in significant savings. The traditional optimal replacement analysis involves minimizing the present worth cost of a pipe. In this chapter this traditional approach is brought into question by proving that the equivalent uniform annual cost yields a minimum that lags the minimum of the present worth analysis in time indicating that an optimal delayed replacement is possible. As a consequence it follows that the time between replacements for the annual cost approach is greater than the replacement time for the present worth cost analysis. A new threshold break rate criterion is also suggested as a result of this analysis. A comprehensive numerical example illustrating the theory developed in this chapter is presented.

4.2 The EUAC Approach

The Present Worth is an equivalent total amount at the present when compounded will provide for a cost stream incurred over a period of time. *Shamir and Howard (1979), Kleiner (1998), Park (2000), and Agbenowosi (2001)* have adopted this approach to obtain analytical solutions for the pipe replacement problem. The main focus of this chapter is not on the present worth cost approach but on the equivalent annual cost approach. In this method, a constant amount known as the Equivalent Uniform Annualized Cost (EUAC) is invested at the end of every year. The EUAC is minimized to obtain the optimal replacement time. This estimate is not the same as the one obtained from the present worth approach. It is shown that the minimum obtained by the EUAC approach never occurs before the present worth minimum. The following statement lends credibility to the usage of the EUAC approach over the present worth approach. “For most economy alternatives comparing mutually exclusive design alternatives, the authors of this book prefer comparisons of equivalent uniform annual costs to comparisons of present worths.” (p.105, Principles of Engineering Economy by *Grant et al.* 1982). In addition, *Kurtz*

(1984), *Fabrycky and Blanchard* (1991), *Lang and Merino* (1993) have all used the EUAC approach to estimate the optimal replacement time.

EUAC Theorem

Theorem: If the present worth cost distribution and the annualized cost distribution are unimodal, the minimum of the equivalent uniform annualized cost (A) always lags the minimum of the present worth cost (P).

Proof

The relationship between A and P (see eq. (4.1)) is exploited in this proof.

Case 1: Continuous (rapid) compounding

As given in *Fabrycky and Blanchard* (1991) the EUAC (A) is related to the present worth cost (P) by

$$A = \frac{P(e^r - 1)}{(1 - e^{-rt})} \quad (4.1)$$

in which:

- A - Equivalent Uniform Annualized Cost
- P - Present Worth Cost
- r - rate of interest (compounded continuously)
- t - time(from the start)

Taking the derivate with respect to t on both sides, we have

$$\frac{dA}{dt} = \frac{(e^r - 1)(1 - e^{-rt}) \frac{dP}{dt} - Pr(e^r - 1)e^{-rt}}{(1 - e^{-rt})^2} \quad (4.2)$$

When A is a minimum, $dA/dt = 0$. Let t^* be the corresponding value of t. Incorporating this stationarity condition in eq.(4.2) we obtain

$$(1 - e^{-rt^*}) \frac{dP}{dt} - Pr e^{-rt^*} = 0 \text{ at } t = t^* \quad (4.3)$$

Therefore,

$$\left(\frac{dP}{dt}\right)_{t=t^*} = \frac{\text{Pr} e^{-rt^*}}{(1 - e^{-rt^*})} \quad (4.4)$$

and

$$\left(\frac{dP}{dt}\right)_{t=t^*} = \frac{\text{Pr}}{(e^{rt^*} - 1)} \quad (4.5)$$

For all $t > 0$, $(e^{rt} - 1)$ is always greater than zero. The numerator (Pr) is always positive. Hence we can conclude,

$$\left(\frac{dP}{dt}\right)_{t=t^*} > 0 \quad (4.6)$$

From eq.(4.6) we find that at time t^* , $\left(\frac{dA}{dt}\right)_{t=t^*} = 0$ but $\left(\frac{dP}{dt}\right)_{t=t^*} > 0$. The positive derivative of P at t^* shows that P is increasing at t^* . For a unimodal “U” shaped (convex) function it further indicates that the optimal P is already reached at a time $t^{**} < t^*$. Let t^{**} be the value of t corresponding to the minimum of the present worth cost. This means that

$$\frac{dP}{dt} = 0 \quad (\text{For } t = t^{**}) \quad (4.7)$$

From eqs.(4.2) and (4.7) we have

$$\left(\frac{dA}{dt}\right)_{t=t^{**}} = \frac{-\text{Pr}(e^r - 1)e^{-rt^{**}}}{(1 - e^{-rt^{**}})^2} \quad (4.8)$$

For

$$\text{Pr}(e^r - 1)e^{-rt^{**}} > 0 \quad (\text{for all } r \text{ and } t > 0) \quad (4.9)$$

and

$$(1 - e^{-rt})^2 > 0 \quad (\text{for all } r \text{ and } t > 0) \quad (4.10)$$

$$\left(\frac{dA}{dt} \right)_{t=t^{**}} < 0 \quad (4.11)$$

From eq.(4.11) it follows that A is decreasing at t^{**} when P attains its minimum.

For the unimodality condition, the annualized cost curve should decrease monotonically until it reaches the minimum. Since the function is still decreasing at t^{**} , we conclude that the minimum will occur at $t^* > t^{**}$ or it lies to the right of the present worth minimum on the time axis.

Case 2: Discrete compounding

For the case of compounding interest at discrete points in time we can write

$$A = \frac{Pr(1+r)^t}{(1+r)^t - 1} \quad (4.12)$$

Let A' and P' be two differentiable functions passing through all values of A and P respectively. Then, we have

$$A' = \frac{P'r(1+r)^t}{(1+r)^t - 1} \quad (4.13)$$

Differentiating with respect to t on both sides,

$$\frac{dA'}{dt} = \frac{r[(1+r)^t - 1] \frac{d}{dt} [P'(1+r)^t] - P'r(1+r)^t \frac{d}{dt} (1+r)^t}{[(1+r)^t - 1]^2} \quad (4.14)$$

and hence

$$\frac{d}{dt} [P'(1+r)^t] = \frac{dP'}{dt} (1+r)^t + P' \frac{d}{dt} (1+r)^t \quad (4.15)$$

from which

$$\frac{d}{dt} [P'(1+r)^t] = \frac{dP'}{dt} (1+r)^t + P'(1+r)^t \log(1+r) \quad (4.16)$$

From eq.(4.16), eq.(4.14) becomes

$$\frac{dA'}{dt} = \frac{r[(1+r)^t - 1] \left[\frac{dP'}{dt} (1+r)^t + P'(1+r)^t \log(1+r) \right] - P' r (1+r)^{2t} \log(1+r)}{[(1+r)^t - 1]^2} \quad (4.17)$$

When A is at its minimum, $dA'/dt = 0$. Let t^* be the corresponding value of t . Incorporating t^* in eq.(4.17) we see that the numerator is zero. Hence,

$$r[(1+r)^t - 1] \left[\frac{dP'}{dt} (1+r)^t + P'(1+r)^t \log(1+r) \right] = P' r (1+r)^{2t} \log(1+r) \quad (4.18)$$

Simplifying eq.(4.18) we have

$$[(1+r)^t - 1] \left[\frac{dP'}{dt} + P' \log(1+r) \right] = P' (1+r)^t \log(1+r) \quad (4.19)$$

and

$$\frac{dP'}{dt} = \frac{P'(1+r)^t \log(1+r)}{[(1+r)^t - 1]} - P' \log(1+r) \quad (4.20)$$

By simplifying,

$$\frac{dP'}{dt} = \frac{P' \log(1+r)}{[(1+r)^t - 1]} \quad (4.21)$$

For all values of $r, t > 0$,

$$P^t \log(1+r) > 0 \quad (4.22)$$

and

$$(1+r)^t - 1 > 0 \quad (4.23)$$

From eqs.(4.22) and eqs.(4.23) we find

$$\left(\frac{dP^t}{dt} \right)_{t=t^*} > 0 \quad (4.24)$$

Equation (4.24) shows that the minimum of A occurs later than the minimum of P.

When P' is minimum, $dP'/dt = 0$. Let t^{**} be the corresponding value of t. Incorporating t^{**} in eq.(4.17) and equating dP'/dt to 0, we get

$$\frac{dA'}{dt} = \frac{P^t r [(1+r)^t - 1] (1+r)^t \log(1+r) - P^t r (1+r)^{2t} \log(1+r)}{[(1+r)^t - 1]^2} \quad (4.25)$$

Simplifying,

$$\frac{dA'}{dt} = \frac{-P^t r (1+r)^t \log(1+r)}{[(1+r)^t - 1]^2} \quad (4.26)$$

From $P^t r (1+r)^t \log(1+r) > 0$ and $[(1+r)^t - 1]^2 > 0$ we conclude,

$$\left(\frac{dA'}{dt} \right)_{t=t^{**}} < 0 \quad (4.27)$$

From the arguments presented in the previous case it follows that the minimum of the annualized cost always lies to the right of the minimum of the present worth cost.

In this section we have seen that the minimum of the annualized cost lags the minimum of the present worth cost in time. If we assume continual payment for a service, it makes more sense to use the minimum EUAC method.

4.3 Replacement Methodology

This section describes a methodology to obtain the replacement time by minimizing the equivalent uniform annualized cost (EUAC). Consider the cost stream shown in Figure 4.1

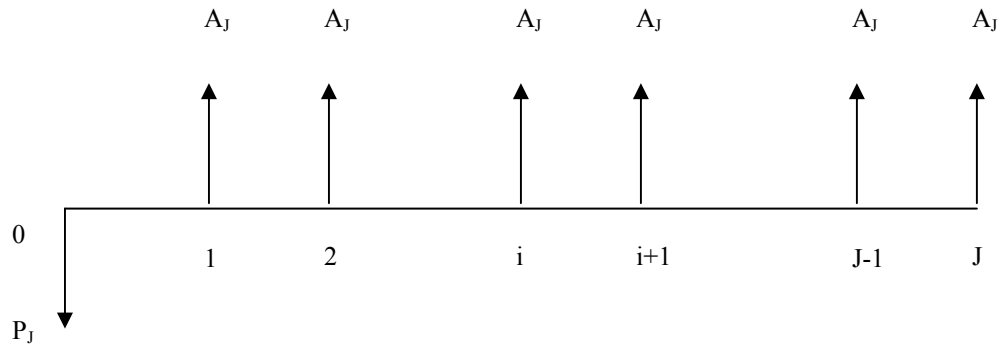


Figure 4.1 – Annualization of Present Worth

The Present Worth at time 0 is denoted by P_J . The scenario depicted in Figure 4.1 represents a scheme where an equal payment of A_J is made at the end of each year to cover the renewal costs. The present worth equivalent of this payment scheme at time 0 is calculated by summing the individual contributions of present worth p_i for each year. If the optimal time of replacement is J years, we have a payment scheme where a constant payment is made J times. Thus, we have J contributions to the present worth. This is represented in eq.(4.28) as

$$P_J = p_1 + p_2 + \dots + p_J \quad (4.28)$$

in which:

$$p_i = \frac{A_J}{(1+r)^i} \text{ for } i=1,2,\dots,J \quad (4.29)$$

From eqs. (4.28) and (4.29), P_J is written as

$$P_J = \frac{A_J}{(1+r)} + \frac{A_J}{(1+r)^2} + \dots + \frac{A_J}{(1+r)^J} \quad (4.30)$$

The same form can be extended to a payment scheme of (J+1) years as

$$P_{J+1} = \frac{A_{J+1}}{(1+r)} + \frac{A_{J+1}}{(1+r)^2} + \dots + \frac{A_{J+1}}{(1+r)^J} + \frac{A_{J+1}}{(1+r)^{J+1}} \quad (4.31)$$

Subtracting eq.(4.30) from eq.(4.31) we get,

$$P_{J+1} - P_J = \left[\frac{1}{(1+r)} + \frac{1}{(1+r)^2} + \dots + \frac{1}{(1+r)^J} \right] [A_{J+1} - A_J] + \frac{A_{J+1}}{(1+r)^{J+1}} \quad (4.32)$$

The multiplier of the term $[A_{J+1} - A_J]$ on the right hand side of eq.(4.32) is the sum of a geometric series. For a geometric series of the form

$$S = a + am + am^2 + \dots + am^q \quad (4.33)$$

it is obtained

$$S = a \left(\frac{1 - m^{q+1}}{1 - m} \right) \quad (4.34)$$

eq.(4.32) can be rewritten as:

$$P_{J+1} - P_J = x \left[1 + x + x^2 + \dots + x^{J-1} \right] [A_{J+1} - A_J] + \frac{A_{J+1}}{(1+r)^{J+1}} \quad (4.35)$$

Where, $x = \frac{1}{(1+r)}$

Applying the result in eq.(4.34) to eq.(4.35) we obtain

$$P_{J+1} - P_J = \frac{1}{r} \left[1 - \frac{1}{(1+r)^J} \right] [A_{J+1} - A_J] + \frac{A_{J+1}}{(1+r)^{J+1}} \quad (4.36)$$

which is simplified as

$$P_{J+1} - P_J = \frac{A_{J+1} - A_J}{r} - \frac{A_{J+1}(1+r)}{r(1+r)^{J+1}} + \frac{A_J}{(1+r)^J} + \frac{A_{J+1}}{(1+r)^{J+1}} \quad (4.37)$$

Simplifying,

$$P_{J+1} - P_J = \frac{1}{r} (A_{J+1} - A_J) - \frac{1}{r} \left[\frac{A_{J+1}}{(1+r)^{J+1}} - \frac{A_J}{(1+r)^J} \right] \quad (4.38)$$

Rewriting eq.(4.38) as

$$r\Delta P_{J,J+1} = A_{J+1} \left(1 - \frac{1}{(1+r)^{J+1}} \right) - A_J \left(1 - \frac{1}{(1+r)^J} \right) \quad (4.39)$$

$$\text{where: } \Delta P_{J,J+1} = P_{J+1} - P_J \quad (4.40)$$

and simplifying we have

$$r(1+r)^{J+1} \Delta P_{J,J+1} = [(1+r)^{J+1} - 1](A_{J+1} - A_J) + rA_J \quad (4.41)$$

From eq.(4.41) we have

$$\Delta P_{J,J+1} = \left[\frac{(1+r)^{J+1} - 1}{r(1+r)^{J+1}} \right] (A_{J+1} - A_J) + \frac{A_J}{(1+r)^{J+1}} \quad (4.42)$$

and

$$\left[\Delta P_{J,J+1} - \frac{A_J}{(1+r)^{J+1}} \right] \left[\frac{r(1+r)^{J+1}}{(1+r)^{J+1} - 1} \right] = A_{J+1} - A_J \quad (4.43)$$

Imposing the optimality condition at J, for unimodal A_J we must have

$$A_{J+1} - A_J \geq 0 \quad (4.44)$$

The condition expressed in eq.(4.44) is not unique to the optimum alone. It holds true for any two consecutive years, which fall after the optimum. However, eq.(4.44) will be satisfied for the least J with the additional condition $A_{J-1} - A_J \geq 0$. Therefore, the first encounter of the condition

in eq.(4.44) will signal the optimal point. In eq.(4.43) the term $\left[\frac{r(1+r)^{J+1}}{(1+r)^{J+1} - 1} \right]$ is positive for all

positive values of r and J. Therefore, we must have

$$\Delta P_{J,J+1} - \frac{A_J}{(1+r)^{J+1}} \geq 0 \quad (4.45)$$

$$\text{and } (1+r)^{J+1}(P_{J+1} - P_J) \geq A_J \quad (4.46)$$

Consider the actual cost stream for P_J given by

$$P_J = \frac{a_1}{(1+r)} + \frac{a_2}{(1+r)^2} + \dots + \frac{a_J}{(1+r)^J} + \frac{F_J}{(1+r)^J} \quad (4.47)$$

in which: a_i = year i break costs

F_J = year J pipe replacement cost

For replacement occurring in year (J+1) we have

$$P_{J+1} = \frac{a_1}{(1+r)} + \frac{a_2}{(1+r)^2} + \dots + \frac{a_J}{(1+r)^J} + \frac{a_{J+1}}{(1+r)^{J+1}} + \frac{F_{J+1}}{(1+r)^{J+1}} \quad (4.48)$$

From eqs.(4.47) and (4.48) we have

$$P_{J+1} - P_J = \frac{a_{J+1}}{(1+r)^{J+1}} + \frac{F_{J+1}}{(1+r)^{J+1}} - \frac{F_J}{(1+r)^J} \quad (4.49)$$

Substituting eq.(4.49) in eq.(4.46) we obtain

$$a_{J+1} + F_{J+1} - F_J(1+r) \geq A_J \quad (4.50)$$

$$\text{using } a_{J+1} = Brk_{cur} C_{J+1} \quad (4.51)$$

with Brk_{cur} = number of breaks per year at year (J+1) = Brk_{cur} = current break rate

and C_{J+1} = cost per break in year (J+1) we have

$$Brk_{cur} \geq \frac{A_J + F_J(1+r) - F_{J+1}}{C_{J+1}} = Brk_{th} \quad (4.52)$$

we may interpret the right hand side of eq.(4.52) as a threshold break rate given by

$$Brk_{th} = \frac{A_J + F_J(1+r) - F_{J+1}}{C_{J+1}} \quad (4.53)$$

By taking $F_{J+1} \approx F_J$, $C_{J+1} = C$ and taking average break rate $Brk_{ave} = \frac{A_J}{C_{J+1}}$ we have

$$Brk_{th} = Brk_{ave} + r \left(\frac{F}{C} \right) \quad (4.54)$$

Park (2000) using a present worth minimization analysis has shown that an estimate of the threshold break rate may be written as

$$Brk_{th,1} = \frac{\ln(1+r)}{\ln\left(1 + \frac{C}{F}\right)} \quad (4.55)$$

Using the approximation $\ln(1+x) \approx x$ for small x, eq.(4.55) yields

$$Brk_{th,1} = r \left(\frac{F}{C} \right) \quad (4.56)$$

Equation (4.56) differs from eq.(4.54) in the additive term Brk_{ave} . This term shows the consequence of using the equivalent uniform annualized cost (EUAC) approach as opposed to the present worth (PW) approach as done in *Park* (2000).

Further insight can be gained by considering eq.(4.46) as

$$(1+r)(P_{J+1} - P_J) \geq \frac{P_J r}{(1+r)^J - 1} \quad (4.57)$$

and therefore

$$\frac{P_{J+1}}{P_J} \geq \left[\frac{(1+r)^{J+1} - 1}{(1+r)[(1+r)^J - 1]} \right] \geq 1 + \varepsilon \quad (4.58)$$

Note that for a present worth minimum we will have

$$\frac{P_{J+1}}{P_J} \geq 1 \quad (4.59)$$

However, the EUAC condition $A_{J+1} - A_J \geq 0$ yields

$$\frac{P_{J+1}}{P_J} \geq 1 + \varepsilon \quad (4.60)$$

The offset ε shows the shift in optimal time for the EUAC minimum. We also have from eq.(4.58)

$$\varepsilon = \frac{1}{(1+r)^J - 1} \quad (4.61)$$

The numerical example (4.1) shows the effect of ε , in shifting the optimal time for the EUAC from the PW optimal time. Other related conditions of EUAC optimal time are presented in Appendix A.

4.4 Example Problems

Example 4.1: Given the break cost of \$1000 per break, replacement cost of \$150,000 and discount rate of 7.5% and break data in Table 4.1

Table 4.1 – Break Data

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Breaks	3	5	7	9	11	13	15	17	19	21	25	29	33	37	41	45	49	53	57	61	65

Year	21	22	23	24	25	26	27	28	29	30
Breaks	69	73	77	81	85	89	93	97	101	105

Compute the following:

- What are the cumulative costs if the pipe were to be replaced in the year, J?
- What is the amount that should be deposited in year 0 to cover the cumulative costs up to and including year J? (Present worth)
- What is the optimal year of replacement J* for which the Present Worth cost is the minimum?
- What is the equal annual cost for the year J?
- What is the optimal year of replacement J** for which the equal annual cost is the minimum?

Solution

- The cumulative cost is the sum of the repair costs (up to and including the Jth year) and the replacement cost in the Jth year

Let us suppose that the pipe is replaced in the 5th year

$$\text{Total repair cost} = \$1000 \cdot (3+5+7+9+11) = \$34000$$

$$\text{Replacement cost} = \$150000$$

$$\text{Cumulative cost} = \$34000 + \$150000 = \$184000$$

- The present worth is obtained by discounting the yearly repair costs and the replacement cost to the origin and forming the sum.

Discrete Compounding of Interest

Let us suppose that the pipe is replaced in the 3rd year

The Present worth would be obtained by summing up the repair and replacement components.

$$\text{Repair component} = \frac{\$3000}{1 + 0.075} + \frac{\$5000}{(1 + 0.075)^2} + \frac{\$7000}{(1 + 0.075)^3} = \$12,752$$

$$\text{Replacement component} = \frac{\$150,000}{(1 + 0.075)^3} = \$120,744$$

$$\text{Present Worth} = \$12,752 + \$120,744 = \$133,496$$

Continuous compounding of Interest

Let us again suppose that the pipe is replaced in the 3rd year

The Present worth would be obtained by summing up the repair and replacement components.

$$\text{Repair component} = \$3000e^{-0.075} + \$5000e^{-0.075 * 2} + \$7000e^{-0.075 * 3} = \$12,676$$

$$\text{Replacement component} = \$150000e^{-0.075 * 3} = \$119,778$$

$$\text{Present Worth} = \$12,676 + \$119,778 = \$132,454$$

Table 4.2 gives the present worth computations for all the years for the discrete case and Table 4.3 contains the results for the continuous case

Table 4.2 - Present Worth Computation – Discrete Compounding

Time in Years (i)	Breaks	Yearly Repair Cost (Bi) Discounted to Origin	Cumulative Repair Cost (Ri)	Discounted Replacement Cost (\$) $(\frac{F_i}{(1+r)^i})$	Present Worth (Pi)
0	3	\$2,791	\$2,791	\$139,535	\$142,326
1	5	\$4,327	\$7,117	\$129,800	\$136,917
2	7	\$5,635	\$12,752	\$120,744	\$133,496
3	9	\$6,739	\$19,491	\$112,320	\$131,811
4	11	\$7,662	\$27,153	\$104,484	\$131,637
5	13	\$8,423	\$35,577	\$97,194	\$132,771
6	15	\$9,041	\$44,618	\$90,413	\$135,031
7	17	\$9,532	\$54,150	\$84,105	\$138,256
8	19	\$9,910	\$64,060	\$78,238	\$142,298
9	21	\$10,189	\$74,249	\$72,779	\$147,028
10	25	\$11,284	\$85,533	\$67,701	\$153,234
11	29	\$12,176	\$97,709	\$62,978	\$160,687
12	33	\$12,889	\$110,597	\$58,584	\$169,182
13	37	\$13,443	\$124,040	\$54,497	\$178,537
14	41	\$13,857	\$137,896	\$50,695	\$188,591
15	45	\$14,147	\$152,044	\$47,158	\$199,202
16	49	\$14,330	\$166,374	\$43,868	\$210,242
17	53	\$14,419	\$180,793	\$40,807	\$221,600
18	57	\$14,425	\$195,218	\$37,960	\$233,178
19	61	\$14,360	\$209,578	\$35,312	\$244,890
20	65	\$14,234	\$223,812	\$32,848	\$256,660

Table 4.3 - Present Worth Computation – Continuous Compounding

Time in Years (i)	Breaks	Yearly Repair Cost (Bi) Discounted to Origin	Cumulative Repair Cost (Ri)	Discounted Replacement Cost (\$) ($F_i e^{-ri}$)	Present Worth (Pi)
0	3	\$2,783	\$2,783	\$139,162	\$141,945
1	5	\$4,304	\$7,087	\$129,106	\$136,193
2	7	\$5,590	\$12,676	\$119,778	\$132,454
3	9	\$6,667	\$19,344	\$111,123	\$130,466
4	11	\$7,560	\$26,904	\$103,093	\$129,997
5	13	\$8,289	\$35,193	\$95,644	\$130,837
6	15	\$8,873	\$44,066	\$88,733	\$132,800
7	17	\$9,330	\$53,396	\$82,322	\$135,718
8	19	\$9,674	\$63,070	\$76,373	\$139,444
9	21	\$9,920	\$72,990	\$70,855	\$143,845
10	25	\$10,956	\$83,946	\$65,735	\$149,681
11	29	\$11,791	\$95,736	\$60,985	\$156,722
12	33	\$12,447	\$108,184	\$56,579	\$164,762
13	37	\$12,948	\$121,131	\$52,491	\$173,622
14	41	\$13,311	\$134,442	\$48,698	\$183,140
15	45	\$13,554	\$147,996	\$45,179	\$193,175
16	49	\$13,692	\$161,688	\$41,915	\$203,603
17	53	\$13,740	\$175,428	\$38,886	\$214,314
18	57	\$13,709	\$189,137	\$36,076	\$225,213
19	61	\$13,611	\$202,748	\$33,470	\$236,217
20	65	\$13,455	\$216,203	\$31,051	\$247,254

- c) J^* can be determined from Tables 4.2 and 4.3. For the discrete case, the 5th year has the lowest Present Worth of \$131,637. For the continuous case, the 5th year has the lowest Present Worth of \$129,997. Note that the costs for the continuous compounding case are lower than the corresponding costs for the discrete case.

Using the expression developed by *Park et al.* (2000), threshold break rate is calculated

$$\text{Threshold} = \frac{\ln(1+r)}{\ln\left(1 + \frac{a(i,k)}{F}\right)}$$

$$\text{Threshold} = \frac{\ln(1+0.075)}{\ln\left(1 + \frac{1000}{150,000}\right)} = 10.88 \text{ Breaks}$$

From tables 4.2 and 4.3 observe that the optimum indeed occurs for a break rate of 11 breaks/ year. Therefore, $J^* = 5$.

- d) The annualized costs are obtained by multiplying the present worth costs with the annualizing factors $\frac{r(1+r)^J}{(1+r)^J - 1}$ for the discrete case and $\frac{e^r - 1}{1 - e^{-rJ}}$ for the continuous case

Discrete Case

Let the pipe be replaced after 3 years.

The Present Worth cost = \$133,496 (from Table 4.2)

$$\text{Annual Cost} = \frac{\$133,496 * 0.075 * (1 + 0.075)^3}{(1 + 0.075)^3 - 1} = \$51,334$$

Continuous Case

Let the pipe be replaced after 3 years.

The Present Worth cost = \$132,454 (from Table 4.3)

$$\text{Annual Cost} = \frac{\$132,454(e^{0.075} - 1)}{(1 - e^{-0.075*3})} = \$51,200$$

e) Tables 4.4 and 4.5 show the annualized costs of the various years for both the discrete and continuous compounding cases respectively.

Table 4.4 – Computation of Annualized Costs – Discrete Case

Time (Years) (i)	Breaks	Present Worth P (i)	Annualized Cost A (i)	$\frac{R_j r(1+r)^{j-1}}{(1+r)^j - 1}$ From Appendix A (1)	$\frac{F_j [(1+r)^{j+1} - 1]}{(1+r)^j - 1}$ From Appendix A (2)	(1)+(2)-F	B(i) (\$)
0	3	\$142,326	\$153,000	\$2,791	\$311,250	\$164,041	\$3,000
1	5	\$136,917	\$76,253	\$3,687	\$233,539	\$87,226	\$5,000
2	7	\$133,496	\$51,334	\$4,562	\$207,681	\$62,242	\$7,000
3	9	\$131,811	\$39,355	\$5,413	\$194,785	\$50,199	\$9,000
4	11	\$131,637	\$32,536	\$6,243	\$187,075	\$43,318	\$11,000
5	13	\$132,771	\$28,286	\$7,051	\$181,957	\$39,007	\$13,000
6	15	\$135,031	\$25,494	\$7,836	\$178,320	\$36,156	\$15,000
7	17	\$138,256	\$23,604	\$8,600	\$175,609	\$34,209	\$17,000
8	19	\$142,298	\$22,308	\$9,342	\$173,515	\$32,857	\$19,000
9	21	\$147,028	\$21,420	\$10,062	\$171,853	\$31,915	\$21,000
10	25	\$153,234	\$20,947	\$10,876	\$170,505	\$31,381	\$25,000
11	29	\$160,687	\$20,773	\$11,750	\$169,392	\$31,142	\$29,000
12	33	\$169,182	\$20,820	\$12,661	\$168,460	\$31,121	\$33,000
13	37	\$178,537	\$21,031	\$13,592	\$167,670	\$31,262	\$37,000
14	41	\$188,591	\$21,365	\$14,532	\$166,993	\$31,525	\$41,000
15	45	\$199,202	\$21,791	\$15,472	\$166,409	\$31,881	\$45,000
16	49	\$210,242	\$22,286	\$16,405	\$165,900	\$32,305	\$49,000
17	53	\$221,600	\$22,831	\$17,327	\$165,454	\$32,782	\$53,000
18	57	\$233,178	\$23,414	\$18,234	\$165,062	\$33,296	\$57,000
19	61	\$244,890	\$24,022	\$19,124	\$164,714	\$33,838	\$61,000
20	65	\$256,660	\$24,647	\$19,993	\$164,404	\$34,397	\$65,000

Table 4.5 – Computation of Annualized Costs – Continuous Case

Time (Years) (i)	Breaks	Present Worth P (i)	Annualized Cost A (i)	$\frac{R_J(1-e^{-r})}{1-e^{-rJ}}$ From Appendix A (1)	$\frac{F_J(e^r - e^{-rJ})}{1-e^{-rJ}}$ From Appendix A (2)	Total (1)+(2)-F	B(i) (\$)
0	3	\$141,945	\$153,000	\$2,783	\$311,683	\$164,466	\$3,000
1	5	\$136,193	\$76,151	\$3,676	\$233,871	\$87,548	\$5,000
2	7	\$132,454	\$51,200	\$4,546	\$207,983	\$62,529	\$7,000
3	9	\$130,466	\$39,205	\$5,393	\$195,075	\$50,468	\$9,000
4	11	\$129,997	\$32,377	\$6,217	\$187,359	\$43,576	\$11,000
5	13	\$130,837	\$28,121	\$7,017	\$182,239	\$39,257	\$13,000
6	15	\$132,800	\$25,323	\$7,796	\$178,603	\$36,398	\$15,000
7	17	\$135,718	\$23,428	\$8,551	\$175,893	\$34,444	\$17,000
8	19	\$139,444	\$22,126	\$9,284	\$173,801	\$33,086	\$19,000
9	21	\$143,845	\$21,233	\$9,996	\$172,142	\$32,137	\$21,000
10	25	\$149,681	\$20,752	\$10,797	\$170,796	\$31,594	\$25,000
11	29	\$156,722	\$20,569	\$11,657	\$169,687	\$31,344	\$29,000
12	33	\$164,762	\$20,604	\$12,551	\$168,758	\$31,309	\$33,000
13	37	\$173,622	\$20,802	\$13,464	\$167,972	\$31,436	\$37,000
14	41	\$183,140	\$21,121	\$14,384	\$167,299	\$31,683	\$41,000
15	45	\$193,175	\$21,530	\$15,303	\$166,718	\$32,021	\$45,000
16	49	\$203,603	\$22,007	\$16,214	\$166,213	\$32,427	\$49,000
17	53	\$214,314	\$22,533	\$17,112	\$165,771	\$32,883	\$53,000
18	57	\$225,213	\$23,095	\$17,994	\$165,382	\$33,376	\$57,000
19	61	\$236,217	\$23,682	\$18,858	\$165,038	\$33,896	\$61,000
20	65	\$247,254	\$24,284	\$19,700	\$164,732	\$34,432	\$65,000

Observation

From the A(i) column of Table 4.4, we observe that the minimum of the Annualized Cost

occurs in the 12th year. ($J^{**} = 12$). From eq.(4.52) we have $Brk_{th} = Brk_{ave} + r \left(\frac{F}{C} \right)$

$= Brk_{ave} + 11.25$. Using $Brk_{ave} = \frac{A_J}{C_{J+1}} = (20,773/1000) = 20.8$, we have $Brk_{th} = 32.05$. This

yields an optimal replacement time between 11 and 12 years. The same observation applies to the continuous case.

Example 2: *Park* (2000) has provided the following pipe break data as a function of pipe age for a 6-inch cast iron pipe that was installed in 1932.

Table 4.6 - Pipe data

PIPE ID	Installation (year)	Length (ft)	Discount Rate (%)	Installation cost per ft. (\$/ft)	Repair-cost per break (\$)
14449-1952-CI-6	1952	1363.5	7%	92.77	2814

The recorded historic break times in *months* of the pipe, 14449-1952-CI-6, obtained from the break database are as follows: (In Table 4.7, MTB(i) stands for “months to the ith break from the installation”).

Table 4.7 - Break times from the database

MTB(1)	MTB(2)	MTB(3)	MTB(4)	MTB(5)	MTB(6)	MTB(7)	MTB(8)
277	361	373	426	437	469	480	546

Compute the optimal replacement time using the present worth and annualized cost approaches.

Solution: *Park* (2000) plotted the data as shown in Figure 4.2 and fitted the equation for the cumulative number of breaks by the ith year given by

$$y_i = (1 - wf) (B_{lin} + A_{lin} x_i) + wf \cdot B_{exp} e^{A_{exp} x_i} \tag{4.62}$$

$$= (1 - wf) (-8.648649 - 0.38378 \cdot x_i) + wf \cdot 0.06578 \cdot e^{0.11736 \cdot x_i} \text{ (From Table 4.8)} \tag{4.63}$$

in which:

x_i = age in *years* for the number of cumulative breaks

i , A_{lin} , B_{lin} , A_{exp} , B_{exp} , and wf are parameters.

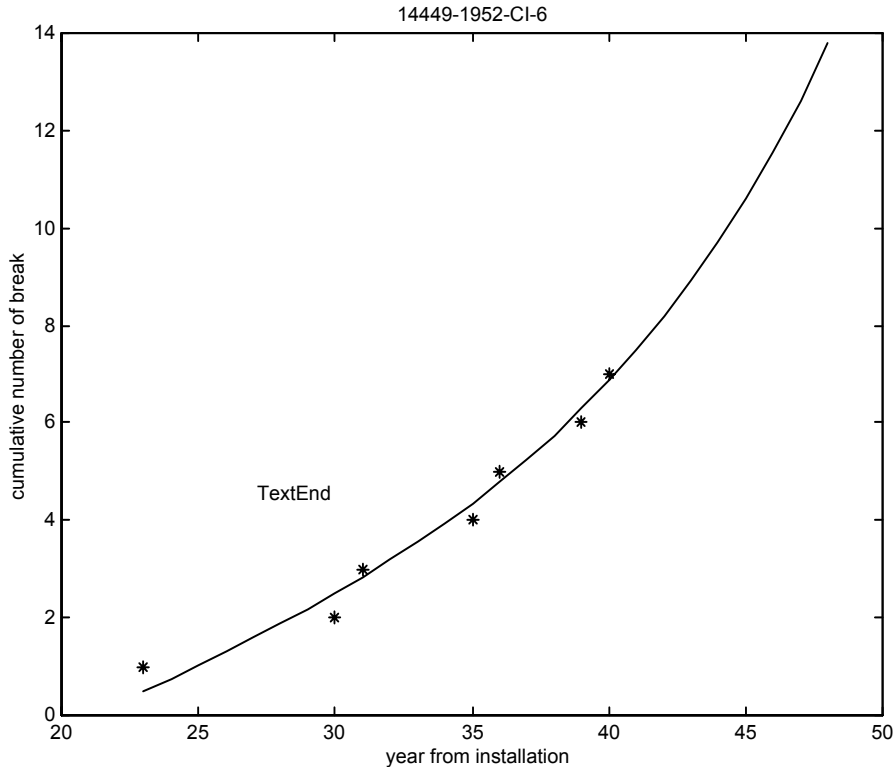


Figure 4.2 – Cumulative number of breaks for “14449-1952-CI-6”(Park (2000))

The equation fits the data well past the age of 25 years. Table 4.8 shows the relevant data. The ‘ $prsnBrk_{th}$ ’ is the threshold break rate based on the present worth method and is given by

$$prsnBrk_{th} = \frac{\ln(1+r)}{\ln\left(1 + \frac{C}{F}\right)} \quad (4.64)$$

in which: r = discount rate, C = repair cost per break, F = replacement cost.

The fitted equation parameters A_{lin} , B_{lin} , A_{exp} , B_{exp} , and wf are given next. The GBRM parameter refers to the optimal replacement time, t_1^* obtained from the derivative of the fitted equation above (eq.(4.62)) and the present worth threshold rate and is given as

$$t_1^* = \frac{1}{A_{\text{exp}}} \ln \left(\frac{\text{prsntBrk}_{\text{th}} - (1 - WF)A_{\text{lin}}}{wf * A_{\text{exp}} * B_{\text{exp}} * e^{-A_{\text{exp}} * t_0}} \right) = \frac{1}{0.117} \ln \left(\frac{3.08 - (1 - 0.47)0.38378}{0.47 \times 0.117 \times 0.0676 \times e^{-0.117 * 0}} \right) \cong 57 \quad (4.65)$$

Table 4.8 - Data required for replacement analysis

Pipe#	14449-1952-CI-6
prsntBrk _{th} (Threshold rate for present breaks)	3.075023911
A _{lin} (Parameter)	0.38378
B _{lin} (Parameter)	-8.648649
A _{exp} (Parameter)	0.11736
B _{exp} (Parameter)	0.06578
Wf (Weighting factor)	0.47
GBRM	56.86645941
t ₀	0
Replacement Cost	126491.895
Year of Installation	1952
Replacement Year (from present worth method)	2009
Replacement Year (from annualized cost)	2011

The offset constant $t_0 = 0$. Using the given costs, the calculations are performed as shown in Table 4.9. The rows corresponding to the years 57, 58, and 59 are particularly significant. The

prsntBrk_{th} value of 3.075 is contained between the #Brks/year values of 2.956 and 3.298 corresponding to the years of 57 and 58. Also, note that the minimum present worth value lies between the present worth cost values of \$13856 and \$13865 for the same rows representing the ages 57 and 58. Based on the least present worth cost of \$13,856 we can select the age of 57 as the replacement year, i.e. $1952 + 57 = 2009$. The newly derived EUAC based threshold break rate depends on the annualized cost as well and is given by AnnBRK_{th}. The current break rate represented by #Brks/yr of 3.684 corresponding to the age of 59 years exceeds the threshold

value 3.4987 under the column AnnBrkth. Therefore, the EUAC based optimal year of replacement is $1952 + 59 = 2011$. Also, note that as we have shown the least EUAC must occur between the ages of 58 and 59 years with the current break rate expected to exceed the AnnBRKth between the same ages; the corresponding actual pipe (current) break rates are 3.298 and 3.684 and the AnnBRKth values are 3.4987 and 3.4987.

Table 4.9 – Replacement Analysis

Year	Cumulative Breaks	#Brks/yr	Break Cost	Reduced Break Cost	Cumulative Break Cost	Replacement Cost	Present Worth	Annual Cost[EUAC]	Annual Brkth
24	0.81	0.261	733	145	7021	24937	31959	2786	4.1368
25	1.08	0.268	754	139	7160	23306	30466	2614	4.0756
26	1.36	0.276	776	134	7294	21781	29075	2459	4.0203
27	1.64	0.285	801	129	7423	20356	27779	2317	3.9701
28	1.94	0.295	830	125	7547	19025	26572	2189	3.9246
29	2.24	0.306	862	121	7669	17780	25449	2073	3.8832
30	2.56	0.319	898	118	7786	16617	24403	1967	3.8454
31	2.90	0.334	939	115	7902	15530	23432	1870	3.8110
32	3.25	0.350	984	113	8015	14514	22528	1781	3.7796
33	3.62	0.368	1036	111	8126	13564	21690	1701	3.7509
34	4.00	0.389	1093	110	8235	12677	20912	1627	3.7247
35	4.42	0.412	1158	108	8344	11848	20191	1559	3.7007
36	4.85	0.437	1231	108	8452	11073	19524	1498	3.6788
37	5.32	0.467	1313	107	8559	10348	18907	1441	3.6588
38	5.82	0.499	1405	107	8666	9671	18338	1390	3.6405
39	6.35	0.536	1509	108	8774	9038	17813	1343	3.6238
40	6.93	0.578	1626	109	8883	8447	17330	1300	3.6085
41	7.56	0.624	1757	110	8992	7895	16887	1261	3.5946
42	8.23	0.677	1904	111	9104	7378	16482	1225	3.5820
43	8.97	0.736	2070	113	9216	6895	16112	1193	3.5705
44	9.77	0.802	2257	115	9331	6444	15776	1164	3.5601
45	10.65	0.876	2466	117	9449	6023	15471	1137	3.5507
46	11.61	0.960	2702	120	9569	5629	15198	1113	3.5422
47	12.66	1.055	2968	123	9692	5260	14953	1092	3.5347
48	13.82	1.161	3266	127	9819	4916	14736	1073	3.5279
49	15.10	1.280	3601	131	9950	4595	14545	1057	3.5220
50	16.52	1.414	3978	135	10085	4294	14379	1042	3.5168
51	18.08	1.564	4402	140	10225	4013	14238	1029	3.5124
52	19.82	1.734	4879	145	10370	3751	14120	1019	3.5085
53	21.74	1.925	5416	150	10520	3505	14025	1010	3.5054
54	23.88	2.139	6019	156	10676	3276	13952	1003	3.5028
55	26.26	2.380	6697	162	10838	3062	13899	997	3.5009
56	28.91	2.651	7460	169	11006	2861	13868	993	3.4995
57	31.87	2.956	8317	176	11182	2674	13856	991	3.4987
58	35.16	3.298	9282	183	11366	2499	13865	990	3.4984
59	38.85	3.684	10366	191	11557	2336	13893	991	3.4987
60	42.96	4.117	11586	200	11757	2183	13940	993	3.4994
61	47.57	4.605	12957	209	11966	2040	14006	996	3.5007
62	52.72	5.153	14500	219	12185	1907	14091	1001	3.5025
63	58.49	5.769	16234	229	12413	1782	14195	1008	3.5047
64	64.95	6.462	18184	239	12653	1665	14318	1016	3.5075

4.5 Summary

A methodology to determine the optimal time of replacement for a pipe is presented in this chapter. The distinct feature of this methodology is that the equivalent uniform annual cost (EUAC) is used as the basis for the model. The EUAC model delays the replacement in comparison with other models following the present worth approach. The EUAC theorem confirms this assertion. The optimal delayed replacement is also reflected in the new threshold break rate criterion, which modifies $Brk_{th,EUAC} = Brk_{ave} + Brk_{th,PW}$. The average break rate $Brk_{ave} = \text{EUAC per break cost}$ which results in the delayed replacement in comparison to the $Brk_{th,PW}$. Two numerical examples illustrate these conclusions.

Chapter 5 - Elements of the Comprehensive Decision Support System for Distribution System Piping

5.1 Overview

This chapter describes the various components of a comprehensive decision support system (CDSS) for pipe rehabilitation and replacement in water distribution systems. The users' manual for implementing the CDSS is provided as an appendix. The CDSS addresses the critical issues of a water main renewal program. The first two steps in the process are to identify candidate pipes and to prioritize their renewal. The methodology presented in Chapter 4 of this thesis can be used to prioritize pipe renewal. The CDSS steps in and identifies appropriate technologies based on the nature of the problem, the pipe, and site characteristics. Because the focus of the CDSS is on water distribution system pipes and not on transmission lines, the program applies only to pipes of diameter 24 inches or less. The selection of renewal technologies depends on pipe characteristics such as the diameter, material, structural condition of the pipe and the site characteristics including soil type, available space, length of drive, available workspace, and underground obstacles such as other utility connections. The selection also depends on the techniques (trench / trenchless) themselves in terms of accuracy, steerability, cost and time requirements, and abandonment when the procedure is to be terminated before completion due to unforeseen failure (*Iseley and Gokhale, 1997*).

The CDSS consists of two modules used sequentially:

- (1) Technology Selection Module (TSM)

The renewal technologies are selected in this module

- (2) Present worth cost analysis module.

Cost analysis module for the selected renewal technologies

Figure 5.1 presents the visual representation of the CDSS. The types of pipe problems that are presented in the model are grouped into structural, hydraulic, joint leakage, and water quality problems. Structural problems are the most serious. Typically, the pipe has to be replaced with a new pipe or lined with a structural liner to combat this problem. Hydraulic problems are related to insufficient supply of water. Increased demand and tuberculation of the inner surface of the pipe are some of the common causes for this problem. Lack of tight fitting and split bells lead to joint

leakage. Corrosion is one of the major culprits in degrading the water quality. Pipelining is commonly adopted to reduce corrosion. Based on the types of problems indicated by the user, the CDSS will present the appropriate renewal option categories (Table 5.1). With these categories, the program evaluates the pipe and site characteristic information presented in Table 5.2 and uses the knowledge base to select appropriate renewal technologies.

The renewal technologies that are available in the CDSS are presented in Table 5.3. Once the model has selected the appropriate renewal technologies, the user can proceed to the cost module portion of the CDSS to perform a present worth cost analysis of each technology to aid in the selection of the most appropriate pipe renewal technology from an economic standpoint.

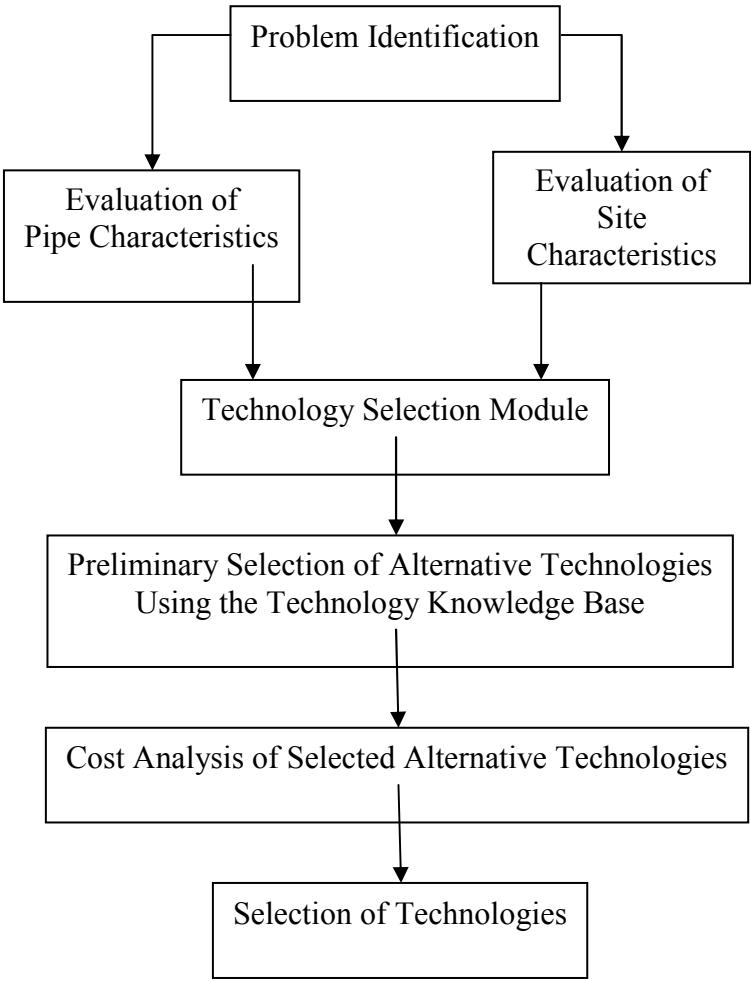


Figure 5.1 - CDSS logic diagram

Table 5.1 - Renewal option categories

Renewal option category
Replace with larger size pipe
Replace pipe
Add an additional parallel pipe
Insert structural liner
Insert semi-structural liner
Apply non-structural liner
Apply cathodic protection

Table 5.2 - Pipe and Site Characteristics

No.	Characteristic
1	Pipe material (existing and new)
2	Pipe diameter (existing and new)
3	Renewal length
4	Number of bends
5	Number of service connections
6	Number of service connections to be replaced
7	Number of isolation valves
8	Number of isolation valves to be replaced
9	Soil conditions
10	Presence of Hydrocarbons
11	Site conditions
12	Water table
13	Diameter change over pipe length
14	Major obstructions at site
15	Workspace
16	Water pH

Table 5.3 - Pipe renewal technologies

Pipe rehabilitation technologies	Pipe replacement technologies
Cement mortar lining	Open trench
Epoxy resin lining	Narrow trench
Close-fit sliplining	Pipe bursting
Cured-in-place pipe (CIPP)	Conventional sliplining
Cathodic protection	Horizontal directional drilling
	Jack and bore

5.2 Renewal Option Category Determination

Technology selection recommendations are made by the CDSS based on the nature of problems associated with the pipe under consideration; pipe and site characteristic information and technology limitations based on the pipe and site characteristics. The technology selection module (TSM) portion of the CDSS is where the knowledge base is used. Once the pipe to be renewed is selected, the types of problems that are associated with the pipe are evaluated to determine the types of renewal options that are available. The types of problems that are evaluated by the CDSS include structural, hydraulic, joint leaks and water quality. The TSM (logic presented in Figure 5.2) asks questions about the condition of the pipe in a hierarchically decreasing order of severity of the problem. If a pipe has multiple problems, the renewal option categories selected for the most severe problem will solve the less-severe problem(s) as well. For example, addressing the structural shortcomings of the pipe will, by default, also address any hydraulic, joint leak, and water quality needs of the same pipe. This first level of logic results in the selection of one or more renewal option categories

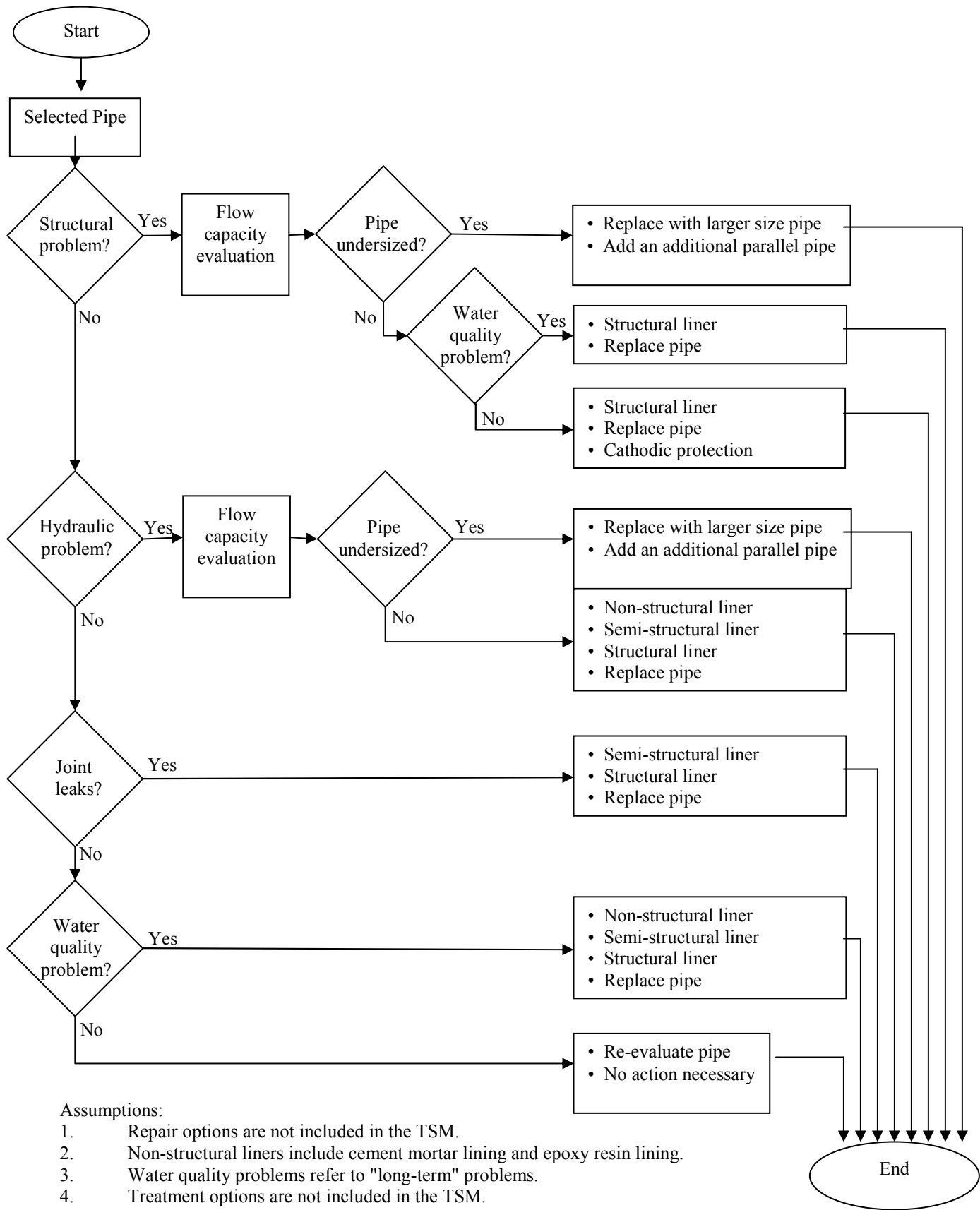


Figure 5.2 - Preliminary selection of alternative technologies in the TSM

In the second level of screening, site-specific information about the pipe and its environment are used to select one or more specific renewal technologies. Comparative costs are then calculated for the specific technologies by the cost model. A brief overview of the various problems related to water distribution pipes is presented in the next section

5.3 Problem Identification

5.3.1 Structural Problems

At the top level of the TSM, the structural condition of the pipe is addressed and a determination of whether the pipe is undersized or not is made.

- 1) If the pipe lacks structural strength, it immediately becomes a candidate for pipe replacement or sliplining with a structural liner. To decide whether a new, larger diameter pipe is necessary, the user is prompted to decide whether the capacity of the replacement pipe is sufficient or not. If the existing pipe's original capacity is insufficient, a larger size pipe and the addition of a new parallel pipe to the existing pipe are selected as two options. As the energy slope of the existing pipe is in general not known, it is assumed the same for both existing and new pipe. Then, from the Hazen-Williams formula we have:

$$Q_o = 1.318 \left[\frac{\pi D_o^2}{4} \right] C_o \left[\frac{D_o}{4} \right]^{0.63} S^{0.54} \quad (5.1)$$

and

$$Q_e = 1.318 \left[\frac{\pi D_e^2}{4} \right] C_e \left[\frac{D_e}{4} \right]^{0.63} S^{0.54} \quad (5.2)$$

and

$$Q_n = 1.318 \left[\frac{\pi D_n^2}{4} \right] C_n \left[\frac{D_n}{4} \right]^{0.63} S^{0.54} \quad (5.3)$$

Where
 Q = discharge (cfs)
 D = diameter (ft)
 C = Hazen-Williams C-value
 S = energy slope
 o = original condition
 e = existing condition

n = new pipe.

From the above three equations we obtain the flow ratios as:

$$\frac{Q_e}{Q_o} = \left[\frac{D_e}{D_o} \right]^{2.63} \left[\frac{C_e}{C_o} \right] \quad (5.4)$$

and

$$\frac{Q_n}{Q_o} = \left[\frac{D_n}{D_o} \right]^{2.63} \left[\frac{C_n}{C_o} \right] \quad (5.5)$$

It is further assumed that the reduction in the Hazen-Williams Coefficient (C_o to C_e) accounts for both tuberculation and subsequent loss in the internal diameter of the existing pipe. One should note that even when Q_n/Q_o ratio is 1 (100% restoration), the pipe might be considered undersized due to an increase in demand. Because only new pipes are considered, the selected options also remedy any previous hydraulic, joint leak and water quality problems.

- 2) If the capacity of the existing pipe were adequate, a new pipe of the same diameter and a structural liner that adds strength to the old pipe would be recommended. These options rectify any previous joint leak and water quality problems as well.
- 3) If there are no water quality problems and adequate capacity is available with the same diameter pipe, cathodic protection is recommended to overcome the structural strength deficiency and prevent external corrosion. In addition, structural liner and replacement with the same diameter pipe options are also recommended.

5.3.2 Hydraulic Problems

At the next level of the TSM, hydraulic problems are addressed. It is assumed that any hydraulic problem will demonstrate itself as insufficient flow due to an increase in demand.

- 1) If a new pipe of the same size has insufficient capacity, a larger pipe or a parallel pipe to the new one is recommended.

- 2) If the new pipe is not undersized but only a smooth pipe with a higher Hazen-Williams C-value is required, non-structural and semi-structural liner options are added to the structural liner and replacement by the same diameter new pipe options.

5.3.3 Joint Leaks

All pipes are manufactured in discrete lengths and must be assembled on site to span the length of the line required. Pipes are connected by joints of various types (*AWWA*, 1996). Over a period, these joints may start to leak, resulting in wastage of water and diminished pipe support by eroding the bedding material. Liners can prevent these leaks by spanning the joints with a new wall.

- For joint leaks, the CDSS recommends semi-structural liner, structural liner or replacement by the same diameter new pipe.

5.3.4 Water Quality

Finally, water quality issues are considered. Generally, water quality problems can be addressed by flushing and disinfection. Other occasions require modifications to the treatment process. The CDSS addresses problems due to internal corrosion associated with metallic pipes.

- The CDSS recommends non-structural liner, semi-structural liner, structural liner and replacement by the same diameter new pipe options for rectifying internal corrosion.

If none of the four problems, namely (1) structural, (2) hydraulic, (3) joint leaks, and (4) water is present, the pipe is considered to be in good condition and no action is necessary at the present time. This first level of logic results in the selection of one or more categories of renewal technologies. In the second level of screening, site-specific information about the pipe and its environment are used to select one or more specific renewal technologies. Comparative costs are then calculated for the specific technologies by the cost model as shown in Figure 5.1.

5.4 Renewal Technologies in the CDSS

As mentioned earlier, pipe renewal includes both rehabilitation and replacement. In the CDSS, five rehabilitation and six replacement technologies are included. These are presented in Table 5.3. A detailed discussion of the technologies is presented in the preceding chapters. It is

assumed that all rehabilitation technologies require cleaning prior to application. Once the problems with the pipe have been identified, and the CDSS recommends renewal option categories, the model will select specific technologies based on both existing and new pipe properties, and site conditions. The site conditions include major obstructions, limited workspace, water table level, soil properties, and water pH. While the number of bends, isolation valves, and service connection pose difficulties, it is assumed that they will not eliminate the selection of a particular technology. Table 5.4 lists the technologies that are applicable for each of the renewal option categories provided in Figure 5.2. Depending on the pipe and soil characteristics information entered by the user and the technology limitations, some of these technologies may not appear in the final list of recommended renewal alternatives.

5.4.1 Rehabilitation Technologies

Rehabilitation technologies involve placing a liner inside of an existing pipe, which may be experiencing hydraulic, joint leak or water quality problems. In situations where structural strength deficiencies exist on the outside of the existing pipe, cathodic protection is considered as a rehabilitation technology to prevent external corrosion. Tables 5.5 and 5.6 are provided to assist the user in determining the values of each pipe and site characteristic that can be entered by the user without limiting the selection of a particular rehabilitation technology.

5.4.2 Replacement Technologies

Replacement becomes crucial when structural defects are present in the pipe or the existing pipe can no longer meet the hydraulic capacity requirements. Usually replacement technology has two stages: removal of the old pipe, and installation of the new pipe. Sometimes the old pipe is abandoned in place and the new pipe is laid parallel to the old one. The CDSS does not make any specific recommendations on the removal of the old pipe unless the renewal technology makes use of the existing old pipe. Also, as a general guideline for soils with significant existing or potential hydrocarbon contamination, the CDSS issues a warning in using PVC and HDPE pipes, due to the potential permeation of organic chemicals into the pipe. The following pipe replacement technologies are available in the CDSS. Tables 5.7 and 5.8 are provided to assist the user in determining the values of each pipe and site characteristic that can be entered by the user and will not limit the selection of a particular replacement technology.

Table 5.4 - Renewal option categories and applicable technologies

Renewal Option Category	Applicable technologies
Replace with larger size pipe	Open trench, narrow trench, pipe bursting, horizontal directional drilling, jack and bore
Add an additional parallel pipe	Open trench, narrow trench, pipe bursting, horizontal directional drilling, jack and bore
Add an additional parallel pipe	Open trench, narrow trench, pipe bursting, horizontal directional drilling, jack and bore
Structural liner	Conventional sliplining, close-fit sliplining
Replace pipe	Open trench, narrow trench, pipe bursting, horizontal directional drilling, jack and bore
Cathodic protection	Cathodic protection
Non-structural liner	Cement mortar lining, epoxy resin lining
Semi-structural liner	Close-fit sliplining, CIPP

Once the applicable renewal and/or replacement technology selections have been made based on the rules contained in the knowledge base, the CDSS user can utilize the cost module to compare the costs of selected technologies. The user can then make his/her final selection of technology.

Table 5.5 - Rehabilitation methods – acceptable values for pipe specific information

Problem	Cement mortar lining		Epoxy resin lining		Close-fit sliplining		CIPP		Cathodic protection	
	Hydraulic and Water Quality	Hydraulic and Water Quality	Hydraulic and Water Quality	Hydraulic and Water Quality	Structural, Hydraulic, Joint leaks and Water quality	Structural, Hydraulic, Joint leaks and Water Quality	Structural, Hydraulic, Joint leaks and Water Quality	Structural	Structural	Structural
Existing pipe material	CI, DI, steel	CI, DI, steel and prestressed concrete	All	All	All	All	CI, DI, steel and prestressed concrete	CI, DI, steel and prestressed concrete	CI, DI, steel and prestressed concrete	CI, DI, steel and prestressed concrete
Existing pipe diameter*	4" - 24"	4" - 12"	4" - 24"	4" - 24"	4" - 24"	4" - 24"	4" - 24"	4" - 24"	4" - 24"	4" - 24"
Replacement pipe material†	NA	NA	HDPE	NA	NA	NA	NA	NA	NA	NA
Replacement pipe diameter†	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Renewal length	This value will not influence the selection of renewal technologies, but will affect the cost									
No. of bends	This value will not influence the selection of renewal technologies, but will affect the cost									
No. of service connections	This value will not influence the selection of renewal technologies, but will affect the cost									
No. of service connections to be replaced	This value will not influence the selection of renewal technologies, but will affect the cost									
No. of isolation valves	This value will not influence the selection of renewal technologies, but will affect the cost									
No. of isolation valves to be replaced	This value will not influence the selection of renewal technologies, but will affect the cost									

* CDSS applies in the diameter range 4"-24".

† Not applicable for rehabilitation but values are still required for replacement options.

Table 5.6 - Rehabilitation methods – Acceptable values for site specific information

Technology	Cement mortar lining		Epoxy resin lining		Close-fit slip lining		CIPP		Cathodic protection	
	All	Either Yes/No	All	Either Yes/No	All	Either Yes/No	All	Either Yes/No	All	Either Yes/No
Soil conditions	All	Either Yes/No	All	Either Yes/No	All	Either Yes/No	All	Either Yes/No	All	Either Yes/No
Hydrocarbons	Either Yes/No	Either Yes/No	Either Yes/No	Either Yes/No	Either Yes/No	Either Yes/No	Either Yes/No	Either Yes/No	Either Yes/No	Either Yes/No
Site conditions	Either Rural/Urban	Either Rural/Urban	Either Rural/Urban	Either Rural/Urban	Either Rural/Urban	Either Rural/Urban	Either Rural/Urban	Either Rural/Urban	Either Rural/Urban	Either Rural/Urban
Water table	Either High/Low	Either High/Low	Either High/Low	Either High/Low	Either High/Low	Either High/Low	Either High/Low	Either High/Low	Either High/Low	Either High/Low
Diameter change over pipe length	Either Yes/No	Either Yes/No	Either Yes/No	Either Yes/No	Either Yes/No	Either Yes/No	Either Yes/No	Either Yes/No	Either Yes/No	Either Yes/No
Major obstructions	Either Yes/No	Either Yes/No	Either Yes/No	Either Yes/No	Either Yes/No	Either Yes/No	Either Yes/No	Either Yes/No	Either Yes/No	Either Yes/No
Cover Depth	No limits †	No limits †	No limits †	No limits †	No limits †	No limits †	No limits †	No limits †	No limits †	No limits †
Workspace	Either Limited/Unrestricted	Either Limited/Unrestricted	Either Limited/Unrestricted	Either Limited/Unrestricted	Either Limited/Unrestricted	Either Limited/Unrestricted	Either Limited/Unrestricted	Either Limited/Unrestricted	Either Limited/Unrestricted	Either Limited/Unrestricted
Water pH	Select 7-12	Select 7-12	Select 7-12	Select 7-12	Select 7-12	Select 7-12	Select 7-12	Select 7-12	Select 7-12	Select 7-12

† Will depend on local conditions.

Table 5.7 - Replacement technologies – Acceptable values for pipe specific information

Technology	Open trench	Narrow trench	Pipe bursting	Conventional Sliplining	HDD	Jack and bore
Problem	Structural, Hydraulic, Joint leaks and Water quality	Structural, Hydraulic, Joint leaks and Water quality	Structural, Hydraulic, Joint leaks and Water quality	Structural, Hydraulic, Joint leaks and Water quality	Structural, Hydraulic, Joint leaks and Water quality	Structural, Hydraulic, Joint leaks and Water quality
Existing pipe material	All	All	CI, PVC, prestressed concrete	All	All	All
Existing pipe diameter*	4”- 24”	4”- 24”	4”- 24”	4”- 24”	4”- 24”	4”- 24”
Replacement pipe material	All	All	All	All	PVC, HDPE, steel	All
Replacement pipe diameter	4”- 24”	4”- 24”	Existing or larger diameter	Existing or smaller diameter	4”- 24”	4”- 24”
Renewal length						This value will not influence the selection of renewal technologies, but will affect the cost
No. of bends						This value will not influence the selection of renewal technologies, but will affect the cost
No. of service connections						This value will not influence the selection of renewal technologies, but will affect the cost
No. of service connections. to be replaced						This value will not influence the selection of renewal technologies, but will affect the cost
No. of isolation valves						This value will not influence the selection of renewal technologies, but will affect the cost
No. of isolation. valves to be replaced						This value will not influence the selection of renewal technologies, but will affect the cost

* CDSS applies in the diameter range 4”-24”.

Table 5.8 - Replacement technologies – Acceptable values for site specific information

Technology	Open trench		Narrow trench		Pipe bursting		Conventional Sliplining		HDD		Jack and bore	
	All		Clay		Clay, Sandy	All		All		All		All
Soil conditions	All		Clay		Clay, Sandy	All		All		All		All
Hydrocarbons	Either Yes/No		Either Yes/No		Either Yes/No	Either Yes/No		Either Yes/No		Either Yes/No		Either Yes/No
Site conditions	Either Rural/Urban		Either Rural/Urban		Either Rural/Urban	Either Rural/Urban		Either Rural/Urban		Either Rural/Urban		Either Rural/Urban
Water table	Either Low/High		Low		Low	Either Low/High		Either Low/High		Either Low/High		Either Low/High
Diameter change over pipe length	Either Yes/No		Either Yes/No		Either Yes/No	Either Yes/No		Either Yes/No		Either Yes/No		Either Yes/No
Major obstructions	Either Yes/No		option 'No'		option 'No'	Either Yes/No		Either Yes/No		Either Yes/No		Either Yes/No
Cover Depth	No limits †		No limits †		No limits †	No limits †		No limits †		No limits †		No limits †
Workspace	Either Limited/Unrestricted		Either Limited/Unrestricted		Either Limited/Unrestricted	Either Limited/Unrestricted		Either Limited/Unrestricted		Either Limited/Unrestricted		Either Limited/Unrestricted
Water pH	1-12		1-12		1-12	1-12		1-12		1-12		1-12

† Will depend on local conditions.

5.5 Present Worth Cost Analysis

The cost module is an integral part of the CDSS. It provides the means to perform a comprehensive cost analysis for selected pipe renewal technologies. The cost module portion of the CDSS asks the user project specific information regarding the technologies that were selected by the TSM. This information along with the pipe and site characteristic information that was entered by the user in the TSM is written to a cost spreadsheet that calculates the present worth cost of each selected technology.

The cost spreadsheet is organized into a number of worksheets, each of which performs cost computation for a specific cost category. Each worksheet has a name at the bottom of the screen, which indicates the cost category. The following discussion provides a brief description of each worksheet that is in the cost spreadsheet so that the user can understand the nature of the costs involved.

1. ***Input worksheet*** - This worksheet stores all of the data inputs provided by the user during the CDSS session. These data are used by the spreadsheet to calculate costs for each of the cost categories. This worksheet will be hidden from view by the user during the CDSS session, however, if the user wishes to use the cost spreadsheet without the CDSS interface all worksheets can be viewed by the user.
2. ***Unit costs worksheet*** – This is where the user provides unit cost data for equipment, pipe (by material and diameter) and other material, and labor.
3. ***Pre-Construction Survey worksheet*** – Includes survey of ground conditions, groundwater measurements, locating other services and “C-Value” testing, when necessary.
4. ***Mob & Demob worksheet*** – Includes the mobilization and demobilization costs associated with bringing associated equipment to work site and removing it upon project completion.
5. ***Site Preparation worksheet*** – Includes costs for clearing and grubbing of site, if necessary.
6. ***Permit Fees worksheet*** – Includes all permitting costs associated with the project.
7. ***Flushing Cost Details worksheet*** – Includes cost of labor and water used in the flushing process.

8. ***Cleaning Cost Details worksheet*** – Includes cleaning costs associated with mechanical scraper, hydraulic scraper or pigs.
9. ***Bypassing Cost Details worksheet*** – Includes costs for bypassing of water services including temporary bypass lines and ramping material for driveways, where necessary.
10. ***Traffic Control Cost Details worksheet*** –Includes costs for cones, barriers, direction signs and flagmen.
11. ***Excavation – Trench; Excavation – Entrance & Exit; and Excavation - Service worksheets*** – Include costs for trenching, sheeting and shoring, dewatering, and pavement removal where necessary for applicable excavation sites (open or narrow trench, entrance/exit pits or service connections).
12. ***Reconnection – Water main and Reconnection Service worksheets*** – Include reconnection costs for tapping service connections, fittings and valves.
13. ***Restoration – Trench; Restoration – Entrance & Exit; and Restoration - Service worksheets*** – Include costs for backfill, and pavement replacement for associated excavations.
14. ***Pressure Test worksheet*** – Includes costs for equipment and personnel necessary to perform pressure test.
15. ***Disinfection worksheet*** – Includes costs for equipment and chemicals necessary for disinfection.
16. ***Rehabilitation/Replacement*** (Cost Detail Sheets) – Includes the costs associated with the actual installation/renewal technology selected. (Worksheet names: Cement Lining Cost Details, Epoxy Lining Cost Details, Conventional Sliplining, Close-fit Sliplining, CIPP, Cathodic, Open Trench Cost Details, Narrow Trench Cost Details, Pipe Bursting Cost Details, Horiz Dir Drill, and Jack & Bore)
17. ***Rehabilitation/Replacement*** (Cost Summary Sheets) – Includes the total cost calculations for each technology. These are the costs that are displayed in the CDSS.

5.5 Summary and Future Development

A comprehensive decision support system for distribution water piping (with diameters not more than 24 inches) has been developed. The CDSS is capable of evaluating trench/trenchless technologies for pipe renewal projects. A cost analysis module is also included to evaluate technologies from an economic standpoint. A knowledge base, which takes into

account the pipe, site characteristics, and individual technology limitations, is used to make the decisions. It should be noted that the various constraints are in sync with the current practices of the trenchless industry. Advances in technology however are expanding the scope of each technology and bringing down the associated costs. Newer technologies are able to perform the same tasks quickly and economically. These factors tend to control the useful life of any decision support system geared towards trenchless technologies. To increase the useful life of a decision support system, importance should be given to two aspects. Firstly, the framework of the DSS should be flexible enough to accommodate newer technologies. Secondly, the developers should remain in constant touch with the industry and adjust the various constraints in accordance with technological advances.

Chapter 6 – Thesis Summary

6.1 General Introduction

Renewal of damaged water mains is necessary to ensure adequate supply of pure water. For water mains, both the initial and repair costs are high. With time, they deteriorate, not only losing strength but also the water they deliver may not be of the best quality and hydraulic capacity is also lost. Utilities do consider average main life. Significant liability costs and indirect costs also prompt the need for an optimal replacement time. Hence a decision support system has been developed to address the issue of optimal pipe replacement with the most appropriate renewal technology for water distribution systems with diameter less than 24 inches.

6.2 Contributions of this thesis

In this thesis the optimal replacement time of pipes (for water distribution systems) is addressed by minimizing the EUAC (equivalent uniform annualized cost). The newly derived threshold break rate formula to minimize cost performs well and shows improvement over the present worth analysis. Examples have been provided to illustrate the advantage of the annualized cost approach and the new threshold break rate equation. Also, for the first time a unified, comprehensive review of pipe renewal and installation technologies is made available. This review forms the knowledge base of the comprehensive decision support system (CDSS). The CDSS is very user friendly and provides appropriate technology selection for water distribution systems with pipes of diameter less than 24 inches. It also yields a task-by-task cost report for the pipes concerned and thus becomes a true practitioner's tool.

6.3 Future Research

Reliable cost data of pipe repair are available because the costs are of direct concern to the utilities. The proposed threshold break rate uses the cost database to suggest what break rate is most economically sustainable. Assessing a pipe's actual break rate is a growing area for research. Both statistical and physically based approaches may be followed. Considering thousands of miles of pipes involved in water distribution systems and advances in information / computing technology, it is prudent to maintain an

accurate break rate inventory. An accurate break and environment database will contribute significantly to the development of break rate prediction models.

Chapter 7 - Bibliography

Agbenowosi, N. (2000) "A mechanistic analysis based decision support system for scheduling optimal pipeline replacement", *PhD Dissertation*, Virginia Tech, 160-174.

American Water Works Association (1987) *Cleaning and Lining Water Mains. Manual of Practice* AWWA M28..

American Water Works Association Research Foundation. (1988), *Demonstration of Innovative Water Main Renewal Techniques*.

American Water Works Association Research Foundation (1990), *Assessment of Existing and Developing Water Main Rehabilitation Practices*..

American Water Works Association (1996), *Water Transmission and Distribution*, Second Edition, Denver, Colorado

American Water Works Association (1999), *Mainstream*. 43(2), 3.

Annual Book of ASTM Standards. (1992), American Society for Testing and Materials, Section 4, Philadelphia, Pa.

Ariaratnam, S.T., Lueke, J.S., and Allouche, E.N. (1999) "Utilization of Trenchless Construction Methods by Canadian Municipalities." *Journal of Construction Engineering and Management*, 125(2), 76-86.

Certified Foundations Inc. <http://www.cfi-1.com>

Chapman, D.N., and Ichioka, Y. (1999) "Prediction of Jacking Forces for Microtunneling Operations." *Trenchless Technology Research*, 14(1), 31 –41.

Coller, P., Staheli, K., Bennett, D., and Post, R. (1996) “Review of Jacking Forces in Theory and Practice, Part I” *No-Dig Engineering*, 3(5), 17-23.

Coller, P., Staheli, K., Bennett, D., and Post, R. (1996) “Review of Jacking Forces in Theory and Practice, Part II” *No-Dig Engineering*, 3(6), 16-20.

Corrosion Source <http://www.corrosionsource.com>

CSIRO Built Environment <http://www.dbce.csiro.au>

Dakota Pipelining corporation <http://www.dakotapipelining.com>

Deb, A.K., Hasit, Y., Grablutz, F. and Herz, R. (1998) *Quantifying Future Rehabilitation and Replacement Needs of Water Mains*. Denver, Colorado, American Water Works Association Research Foundation

Deb, A.K., Hasit, Y., Snyder, J., Schoser, H, Loganathan, G.V and Khambhammettu, P. (2000) *Draft report for project 2519*, American Water Works Association Research Foundation

Digging –Deep <http://www.catflap.net/digging-deep>

Directional Crossing Contractors Association (DCCA),
<http://www.dcca.org/guidelines/dccaguidemidsize.htm>

Doherty, D.J. (1997) “Design and Administration of Utility Projects Utilizing Multiple Trenchless Methods” *No-Dig Engineering*, 4(3), 17-18.

Envirobore Corporation, <http://www.envirobore.com/faqs/default.htm#Question4>

Fabrycky, W.J and Blanchard, B.S. (1991) *Life-cycle cost and economic analysis*, Prentice Hall Inc., New Jersey.

Fabrycky, W.J., Thuesen, G.J., and Verma, D. (1998) *Economic Decision Analysis*, Prentice Hall Inc., New Jersey.

Grant, E.L., Ireson, W.G., and Leavenworth, R.S. (1982) *Principles of Engineering Economy (7th edition)*, John Wiley & Sons, New York.

Griffin, J. (1995). "Remediation Meets Trenchless Technology." *Construction Equipment*, March, pp-628.

Haas, C., Fowler, D., Conegliano, B., Wright, C., and Bauhan, T. (1995) "Evaluation of Underground Infrastructure Maintenance Technologies" *Journal of Infrastructure Systems*, 1(4), 17-21.

Hastak, M., and Gokhale, S. (1999) "System for Evaluating Underground Pipeline Renewal Options" *Journal of Infrastructure Systems*, 6(3), 105-113.

Heavens, J.W. "The Trenchless Renovation of Potable Water Pipelines." Insituform® Technologies, Inc., Chesterfield, MO.

Herbert, H. "Technical and Economic Criteria Determining the Rehabilitation and/or Renewal of Drinking Water Pipelines." Stadtwerke Innsbruck, Innsbruck.

Inrock <http://www.inrock.com>

Insituform <http://www.insituform.com>

International Aramoon Corporation <http://www.aramoon.com>

International Society for Trenchless Technology, Working Group No.3 (Microtunneling). (1994). "Microtunneling Jacking Force," draft report.

Iseley, T. and Gokhale, S.B. (1997) "Trenchless Installation of Conduits Beneath Roadways", Synthesis of Highway Practice 242, NCHRP, National Academy Press, Washington, D.C.

Kleiner, Y., Adams, B.J. and Rogers, J.S., (1998a). "Long-term planning methodology for water distribution system rehabilitation." *Water Resources Research*, vol.34: 2049-2051

Kramer, S.R., McDonald, W.J., and Thomson, J.C. (1992) *An Introduction to Trenchless Technology*, Van Nostrand Reinhold, New York.

Kurtz, M., (1984) "Handbook of Engineering Economics." McGraw-Hill, Inc, New York.

Lang, H.J., Merino, D.K., (1993) "The Selection Process for Capital Projects" John Wiley & Sons, New York.

Loganathan, G.V., and Park, S (2000) "An Optimal Pipeline Replacement Scheduling Model for Water Distribution Systems", Final report submitted to the US Geological Survey.

Lueke, J.S., Ariaratnam, S.T., and AbouRizk, S.M. (1999) "Application of Simulation in Trenchless Renewal of Underground Urban Infrastructure." *Proceedings of the 1999 Winter Simulation Conference P.A Farrington, H.B. Nembhard, D.T. Sturrock, and G.W.Evans, eds.* 929-936.

Luger, H.J., and Hegarden, H.M.A.M. (1988) "Directional Drilling in Soft Soil: Influence of Mud pressures." *Proceedings of the third international conference on trenchless technology, NO-DIG 88*, 155-163, Water Pollution Control Federation, Alexandria, VA, USA.

Lys, R. Jr., and Garrett, T.M. (1995) "Microtunneling Forces: The Pipe's Perspective." *Proceedings of second international conference: Advances in underground pipeline engineering*, 627-634, American Society of Civil Engineers, New York.

Mast, V.A., and Koerner, K.E. (1996) "Environmental Horizontal Directional Drilling Technology." *No-Dig Engineering*, 3(2), 17-21.

Multimedia Encyclopedia of Trenchless Technology, Trenchless Data Service.
(<http://www.trenchlessdataservice.com>)

McKim, R.A. (1997) "Selection Methods for Trenchless Technologies" *Journal of Infrastructure Systems* 3(3), 119-125

Najafi, M., and Iseley, D.T. (1991) "Stress/Strain Analysis of Forces Resulting from Horizontal Earth Boring Utilizing Pipe Jacking Techniques." *Proceedings, Conferences on Shaft Drilling Technology: Las Vegas, Nevada, (April 24-26)*.

Najafi, M., Iseley, D.T, and Bennett, D. (1994) "New Developments in Trenchless Pipeline Rehabilitation." *Proceedings, 11th International NO-DIG '94: Copenhagen, Bella Center, (May 31 – June 2)*.

NDI Focus (1990) "Directional Control" *No-Dig International*, October

Newman, D.G. (1980). *Engineering Economic Analysis*. Engineering Press, Inc., San Jose, CA.

O'Brien & Gere (1998), "Notebook on Trenchless Technology", Web site on Trenchless Technology. <http://www.obg.com/trenchless.html>

Park, S. (2000). “An Optimal Pipeline Replacement Scheduling Model for Water Distribution Systems” *Ph.D Dissertation*, Virginia Tech

PM Construction <http://www.pmconst.com>

Rogers, C.D.F. (1996) “Comparison of Ground Disturbance for Trenching and Pipe Bursting Operations, Part II” *No-Dig Engineering*, 3(1), 16-20.

Rycom Instruments, <http://www.rycominstruments.com>

Southwest Contractor (1989), February.

Shamir, U., Howard, C.D.D., (1979) “An analytic approach to scheduling pipe replacement.” *Journal of American Water Works Association*.

Smith, G.W. (1987) *Engineering Economy –Analysis of Capital Expenditures* Iowa State University Press, 4th edition, Ames, Iowa.

Stephens, P.J. (1996) “Project Guidelines for Slipline Grouting” *No-Dig Engineering*, 3(2), 2-4.

Stice, L., R.T. Thompson, and T. Isley. (1995) “The Time Has Come for Trenchless Technology”, *Environmental Etcetera*, www.rfweston.com/allenv/etc/trenchle.htm

Tanwani, R. (1996) “Pipe Jacking: An Overview and Case Study” *No-Dig Engineering*, 3(2), 22-24.

Tanwani, R., and Iseley, D.T. (1994) “Tracking and Steering Systems in Trenchless Construction” *Journal of Construction Engineering and Management*, 120(1), 65-76.

Thompson, J., T. Sangster, and S. Kramer (1998) “Overview of the Economics of Trenchless Technology.” *No-Dig Engineering*, 3rd and 4th Quarter Issue.

Tighe, S., Lee, T., McKim, R., and Haas, R. (1999) “Traffic Delay Cost Savings associated with Trenchless Technology” *Journal of Infrastructure systems*, 5(2), 45-51.

Trenchless Data Service, <http://www.trenchlessdataservice.com>

Trenchless Technology Center (TTC) (1998) “The Effect of Pipe Bursting on Nearby Utilities, Pavement and Structures.” Technical Report # TTC-98-01.

TT Technologies Inc., 2020 East New York Street. Aurora, IL.

Walski, T.M. (1987b) “Replacement Rules for Water Mains” *Journal of American Water Works Association*, 79(11), 33-37.

Walski, T.M. and A. Pellicia. (1982.) “Economic Analysis of Water Main Breaks” *Journal of American Water Works Association*, 74(3), 140-147.

Young, O.C., and Trott, J.J. (1984) *Buried rigid pipes – Structural design of pipelines* Elsevier Applied Science Publishers, New York, NY