AN EVALUATION OF LARGE DIAMETER
STEEL WATER PIPELINES

by

TUSHAR JOSHI

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November 20, 2012

DISCLAIMER

All pipe materials have advantages and limitations, and can deteriorate over time. Many project specific factors, operations and maintenance procedures of a specific utility, pipe manufacturing process, and site and soil conditions around the pipe affect the pipe performance. Since there is no national database of pipe inventory and performance in the U.S., and given the large number of utilities, it is difficult to gather data necessary for a comprehensive understanding of pipeline performance. Past literature do not consider all the factors affecting pipes, and, and the survey conducted as part of this thesis received limited responses. Therefore, this thesis cannot be used as basis for selection or rejection of any specific pipe material, and/or to make any design decisions on a project, which is responsibility of design professionals.

ABSTRACT

AN EVALUATION OF LARGE DIAMETER
STEEL WATER PIPELINES

Tushar Joshi, M.S.

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Supervising Professor: Mohammad Najafi

Steel water pipelines, as a part of America's underground infrastructure, play a key role in maintaining the quality of life and well-being of communities. Thousands of miles of steel water pipelines make up a huge and complex water transmission system. This complexity generates the necessity for research on underground infrastructure in general and steel pipelines in particular.

The objective of this research is to evaluate performance of large diameter (24 in. and larger) steel water pipelines. This research objective was achieved by use of a survey of various North American water utilities to provide details about their inventory. This data is processed graphically and statistically in order to arrive at useful results and sensible conclusions and also makes some recommendations for future researchers. The research is limited only to large diameter (24 in. and larger) steel water pipelines in the North America. This research highlights causes and modes of failures which affect performance of steel water pipelines.

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CHAPTER 1

INTRODUCTION

1.1 Background

Steel pipelines for water applications are used since late 1850's in the United States (Cates, 1971). They transport a large quantity of water, both potable and non-potable. This makes the steel water pipeline system critical to the social and financial well-being of many American communities. Many of these steel water pipelines have been underground for more than hundred years and are at the end of their useful life. Failure of these pipelines are costly and becomes inconvenient for the community that goes through disruption in water service, delays in traffic and health hazards. For better performance of pipelines, it is necessary to study their characteristics, strengths and limitations.

1.2 Water Transmission and Distribution Pipelines

In the U.S., there are three major categories of water pipe materials: metallic, plastic and cementitious. There are several types of pipes based on these materials. Each pipe has its own advantages and limitations. The selection of material depends on various factors such as construction methods, life expectancy, handling and installation, required dimensions of pipe, and types of soil as well as construction and operational stresses in the pipe (Najafi, 2010).

Figure 1.1 illustrates different pipes based on their materials. The following sections describe pipe materials used commonly for water transmission applications.

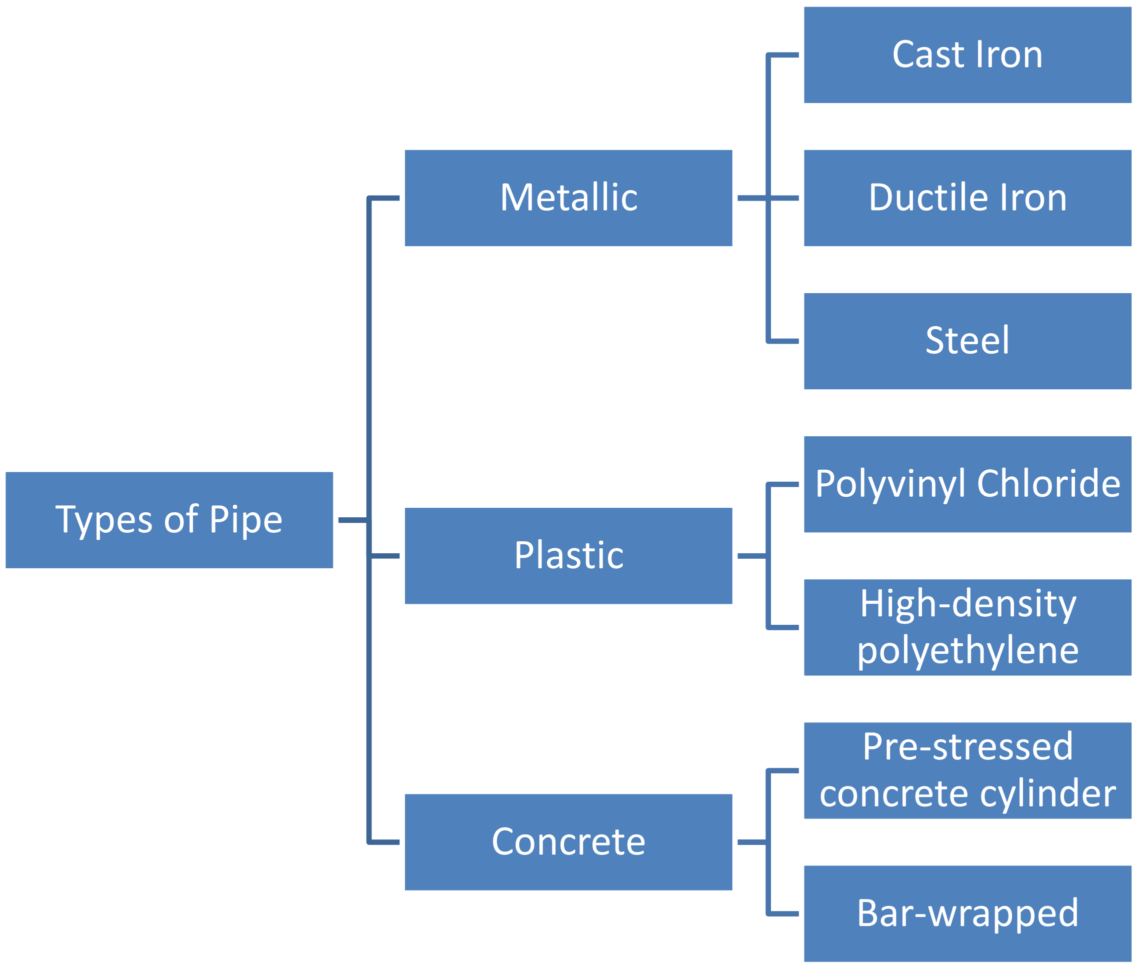


Figure 1.1 Types of Pipes for Water Transmission Based on Materials
(Adapted from Najafi, 2010)

1.2.1 Cast Iron (CI) Pipes

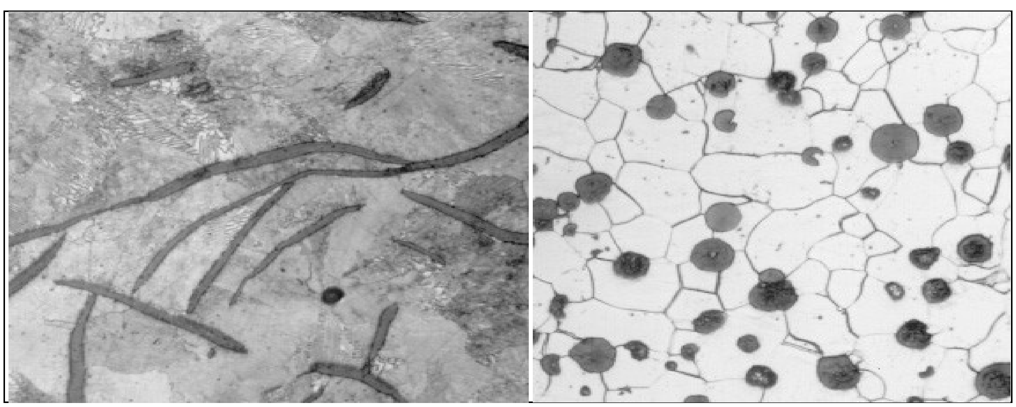
Cast iron pipes have been widely used for water transmission in the U.S. and in many other countries. Due to material strength, they are best suited for high pressure and heavy external loads. Since they are heavy in weight, it is difficult and expensive to transport them to jobsite. They are manufactured in sand molds and in short lengths. Production of cast iron pipes was started in early 1800’s in the North America. Scrapped ferrous material, such as iron or steel, is used as principal raw material in the production of cast iron pipes. They are available in diameters ranging from 4 in. to 64 in. (Najafi, 2010).

Figure 1.2 Cast Iron Pipe (Pure Technologies, 2012)

1.2.2 Ductile Iron (DI) Pipes

Ductile iron pipes were introduced in 1948 as advancement in cast iron pipes. Ductile iron pipes have a ductility that is missing in cast iron pipes, but have an additional strength and impact resistance over cast iron pipes. Ductile iron pipe is derived by distributing the flaky graphite of cast iron pipe into spherical form. Commercial production of ductile iron pipes started in the year 1955 and replaced cast iron pipes by the 1970s in municipal applications (Najafi, 2010).

(a)



(b)

Figure 1.3 Ductile Iron Pipe and Its Micrographic Structure: (a) Ductile Iron Pipe (Pure Technologies, 2012) and (b) Photomicrograph of Flaky Graphite in Grey Cast Iron Pipe (Left) and Spherical Graphite of Ductile Iron Pipe (Right)

1.2.3 Polyvinyl Chloride (PVC) Pipes

PVC pipes are widely popular material used in the water and wastewater industries. PVC is a thermoplastic material which softens when heated and hardens when cooled. The PVC pipe industry emerged out of necessity during World War II as a quick solution to restore pipelines damaged in the war. During 1950s and 1960s, considerable advancement was made in PVC technology (Handbook of PVC Pipe, 2001). Depending on the molecular structure, there are three types of PVC pipes available which are PVC-μ, PVC-O and PVC-M. These types are available in diameters ranging from 4 in. to 48 in. in size (Najafi, 2010).

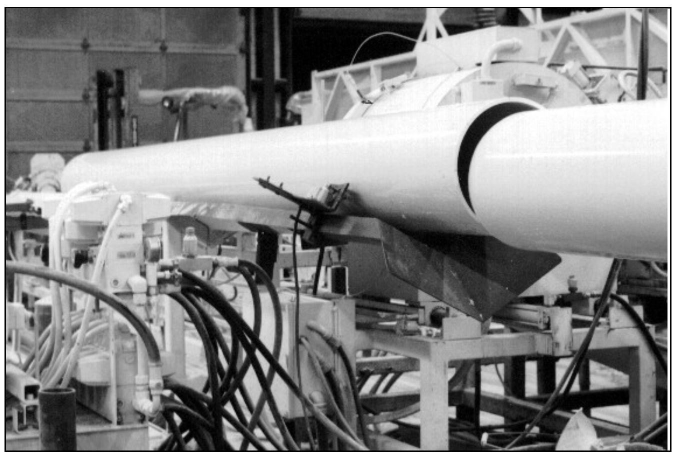


Figure 1.4 PVC Pipe (PVC Pipe Association, 2011)

1.2.4 High-Density Polyethylene (HDPE) Pipes

High-density polyethylene pipes have the highest stiffness in the category of polyethylene pipes. HDPE pressure pipes are applicable in gas, oil and water industries. Due to electrofusion it is possible to make a jointless HDPE pipe in the field. Although, primarily used as gas pipelines, its ability to withstand corrosion is gaining popularity for HDPE pipes in water industry too. They are available in diameters up to 63 in. (Najafi, 2010).

Figure 1.5 HDPE Pipe (Plastic Pipe Institute, 2012)

1.2.5 Prestressed Concrete Cylinder Pipes (PCCP)

PCCP pipes consist of a concrete core, a thin steel cylinder, high tensile pre-stressing wires and mortar coating. Each component has its own purpose. The innermost concrete core is the main load bearing structure of the pipe. The steel cylinder acts as a water barrier between two concrete layers. Pre-stressing wires produce compressive forces to counteract tensile stresses in the pipe created by internal water pressure. The outermost mortar coating protects pre-stressing wires from any physical damage. These pipes are highly resistant to physical damage and can withstand high internal pressure and external loading. They have a good corrosion resistance and can be installed rapidly and economically (Pure Technologies, 2012).

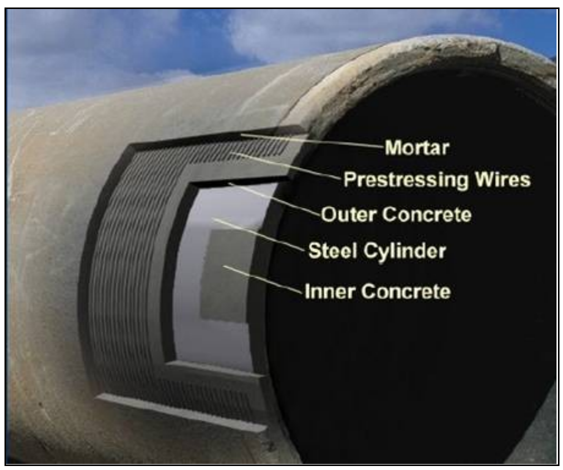


Figure 1.6 Interior of PCCP (Pure Technologies, 2012)

1.2.6 Bar-wrapped (BW) Pipes

Bar-wrapped pipe is a simplified term for Bar-wrapped steel cylinder concrete pressure pipe. It consists of a steel cylinder, steel bar reinforcement, concrete lining, and mortar coating with each having its own purpose. Steel cylinder acts as a membrane for water. Steel reinforcement is achieved by the cylinder being wrapped under tension to provide strength. Internal concrete lining and external mortar coating provide protection from corrosion to steel components. These pipes were first developed in 1942 and produced in large quantities during 1950's. They are available in diameter ranges starting from 10 in. to 72 in. (Pure Technologies, 2012).

Figure 1.7 Bar-wrapped Pipe (Pure Technologies, 2012)

1.3 Steel Pipes

1.3.1 History of Steel Pipes

In the U.S., steel pipes have been used since the 1850's for water transmission. The design of steel pipe has been improved according to new techniques and methods of fabrication over time. In the early days, steel sheets were rolled and riveted at the seams to form a pipe. But, this technique did not allow engineers to design pipe for more than 10,000 psi yield strength. Over the years, steel quality improved and so did the riveting techniques, which allowed engineers to safely design the pipe for up to 15,000 psi. Diameters of these seam riveted pipes varied from 4 in. to 144 in., and their thickness from 0.16 in. to 1.5 in. By the time this technique began to gain popularity, a new technique was introduced in 1905. It involved two equal steel plates which were half of the intended circumference of the pipe, and an H-shaped lock bar. The longitudinal edges of the plates were set into the H-shaped lock bar to form a pipe. Pipes produced with such technique were able to handle stresses up to 55,000 psi (Watkins, 2006).

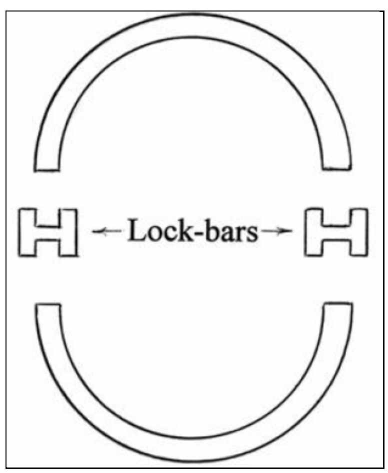


Figure 1.8 C/S of H-Shaped Lock-Bar Pipe (Watkins, 2006)

In the mid-1920, a revolutionary automatic welding technique was introduced, and by 1930s, outdated riveting and lock bar techniques (AWWA, 2004).

The development of steel pipes can be summarized into four major stages as follows:

- First Stage – The development of a furnace in the United States in 1831 to make wrought iron pipes
- Second Stage – The invention of steel in England in 1855 which converted iron into steel with Bessemer process.
- Third Stage – The development of lock-bar pipe technique in New York, USA
- Fourth Stage – The invention of automatic electric welding in the 1920s (Cates, 1971).

1.3.2 Types of Steel Water Pipes

1.3.2.1 Spirally Welded Steel Pipes

Spirally welded steel pipes are made by welding steel sheets spirally into a cylindrical shape. The angle of the de-coiled steel against the forming head determines the diameter of the pipe. Spirally welded steel pipes can be made up to 115 ft in length and 144 in. diameter. This method produces pipes at a slow rate, hence when large tonnage is required; it is not that useful (Buckland, 2005).

1.3.2.2 Electric Resistant Welded Steel Pipes

Electric resistance welded steel pipe involves a coiled steel plate of dimensions which will fit the pipe to be made. The edges of the plates are joined together to form a cylindrical shape. The edges are fused together by high voltage electric current. Pipes can be produced at a high speed by this method. One section of the pipe can be made as long as 115 ft (Buckland, 2005).

1.3.3 Properties of Steel Pipes

1.3.3.1 Strength

Compared to cast iron pipes of the same size, steel pipes are light in weight. This is because wall thickness of steel pipes can be reduced due to their high strength and toughness. Minimum yield strength of most grades of steel pipes is 42,000 psi or higher. Steel pipes perform well in unusual circumstances, such as non-uniform bedding, settling soils, or when subjected to external loads due to their longitudinal strength. Longitudinal strength is achieved by high strength steel, low Poisons ratio and coefficient of thermal expansion, or contraction. Since welding at the joints is possible, no thrust blocks are required at section ends (AISI, 2007).

1.3.3.2 Easy Installation

Easy installation of steel pipes is an advantage over cast iron pipes of similar strength. Stiffness of the pipe comes into account during the installation in order to adhere to its shape. Stiffness of the pipe is directly proportional to modulus of elasticity. Pipes with lower modulus of elasticity need to have higher wall thickness, which in turn causes an increase in weight and difficulty in transportation and installation. The modulus of elasticity of steel is 30,000,000 psi, which is good enough to produce required ring stiffness during the installation. Steel pipes have smooth outer surfaces which makes installation using micro-tunneling possible (AISI, 2007).

1.3.3.3 High Flow Capacity

Steel pipes have low frictional resistance to the flow of water. A typical designed steel pipe will have flow velocity of less than 15 ft per sec. The thin walls of steel pipe generate a larger inside diameter which allows greater flow capacity (AISI, 2007).

1.3.3.4 Leak Resistance

Risk of leaking mainly exists at the joints. Since steel pipes can be welded at the joints, the risk of leaking is much less. In case of gasketed joints, they should be designed within limits of pressure (AISI, 2007).

1.3.3.5 Long Service Life

Service life of steel pipes depends on rate of corrosion and internal abrasion. Research has been carried out in the past on corrosion control of steel pipes (Najafi and Gokhale, 2005). Many coatings available in the market and proper cathodic protection can reduce rate of corrosion. Impurities in water cause pipe abrasion to occur more rapidly. If pipe is properly lined from the inside, then it is possible to control abrasion. If required, service life of steel pipe can be extended beyond its designed life by proper maintenance (AISI, 2007).

1.3.3.6 Reliability

Reliability is a factor which can assure that pipe can tolerate any unprecedented event such as flood, soil movement, earthquake, etc. Reliability depends upon the toughness of the pipe. Steel is considered tough because of wide ductile range and ultimate stress resistance of over 65,000 psi for a typical design (AISI, 2007).

1.3.3.7 Versatility

Due to the growing population, demands of water supply may change in the future. This might require some changes and modification in the pipe. A versatile pipe material will easily adapt to these modifications. Steel pipes can be cut and welded if a special section has to be introduced in the pipeline. If there are any changes in the bedding of the pipe, the beam strength of the steel can compensate (AISI, 2007).

1.3.3.8 Economy

Economical pipe material is a material which is easy to transport and install and which costs less to maintain. Due to its light weight and longer sections, steel can be transported and installed cost-effectively. Welding allows steel pipes to often be repaired on site. Long pipe sections also reduce the cost of joining considerably (AISI, 2007).

1.3.4 Limitations of Steel Water Pipes

- Corrosion is the biggest limitation for any metallic pipe material (Cassa, 2011).
- Welding joints for steel water pipe are complicated and require skilled labor (Najafi & Gokhale, 2005).
- Steel pipe is susceptible to internal tuberculation and external corrosion, and is subjected to electrolysis, if not properly protected (Najafi & Gokhale, 2005).
- Use of anti-corrosion products increases the price of production and maintenance of steel pipe (Najafi, 2010).

- Air vacuum valves are necessary in large diameter pipes to prevent collapse, which adds to budgeted costs of installation (Najafi, 2010).

1.3.5 Uses of Steel Water Pipes

Following are applications of steel pipes:

- Transmission Mains – Transmission mains are used to carry water from water treatment plants to storage facilities. Transmission mains are designed to carry large volumes of water (Clear water solutions, 2007).
- Treatment Plant Piping – Water treatment plants are designed to remove bacteria, chemicals and suspended particles in water from surface and underground. Generally, spirally welded steel pipes are used to pipe this water to treatment plant (American, 2012).
- Distribution Mains – Distribution mains are the primary source of water supply from transmission mains to consumers (Clear water solutions, 2007).
- Force Mains – Force mains are pressurized pipes that carry wastewater (Wisegeek, 2012).
- Penstocks – A penstock is used to control the flow or level of water. It is used to supply water to hydraulic turbines (Wikipedia, 2012).

1.3.6 Standards and Specifications of Steel Pipe

Table 1.1 presents steel pipe standards and specifications (AISI, 2007).

Table 1.1 Standards and Specifications for Steel Pipe (AISI, 2007)

AWWA Standards	Title
C200-97	Steel Water Pipe
C203-02	Coal-Tar Coating and Lining
C205-00	Cement-Mortar Coating and Lining
C206-03	Field Welding
C207-01	Flanges
C208-01	Dimensions of Fabricated Fittings
C209-00	Cold-Applied Tape Fittings
C210-03	Liquid-Epoxy Coating and Lining
C213-01	Fusion Bonded Coatings
C214-00	Cold-Applied Tape-Piping
C215-04	Extruded Polyolefin Coatings
C216-00	Heart-Shrinkable Sleeves
C217-04	Petrolatum/Petroleum Coatings
C218-02	Coatings for Above Ground
C219-01	Bolted, Sleeve type Couplings
C220-97	Stainless Steel Pipe
C221-01	Fabricated Slip-Type Expansion Joints
C222-99	Polyurethane Coating and Lining
C223-02	Tapping Sleeves
C224-01	Polyamide Coatings
C225-03	Fused Polyethylene Coatings
C226(C2CC)	Dimensions of Stainless Steel Fittings
C227-07	Bolted Split Sleeve Couplings
C2BB	Stainless Steel Flanges
C2DD	Split Sleeve Couplings
C2EE	Fusion Bonded Polyethylene Coatings
C602-06	Cement-mortar Lining in-place
C604 (C6ZZ)	Installation
M-11 (5th Edition)	Steel Pipe Manual

1.3.7 Steel Pipe Joint Types

1.3.7.1 Bell and Spigot Joint with Rubber Gasket

This type of joint is used for steel water pipes with diameters up to 72 in., wall thicknesses through 3/8 in. and working pressures up to 250 psi (AISI, 2007). The main advantage of gasket joint is rapid installation. These are very popular for steel water pipes because of their water tightness and low cost. Since there is no need for welding linings, coatings on the pipe remain unharmed (Cates, 1971). Another advantage is they allow flexibility in pipeline which allows pipe for certain angular (approximately 4 degrees) and longitudinal movement in case of settling soil or earthquake. At the point of longitudinal thrust, joint should be supported by welding or by harnessing (AWWA, 2004). Requirements for this joint have been covered in AWWA standard C200.

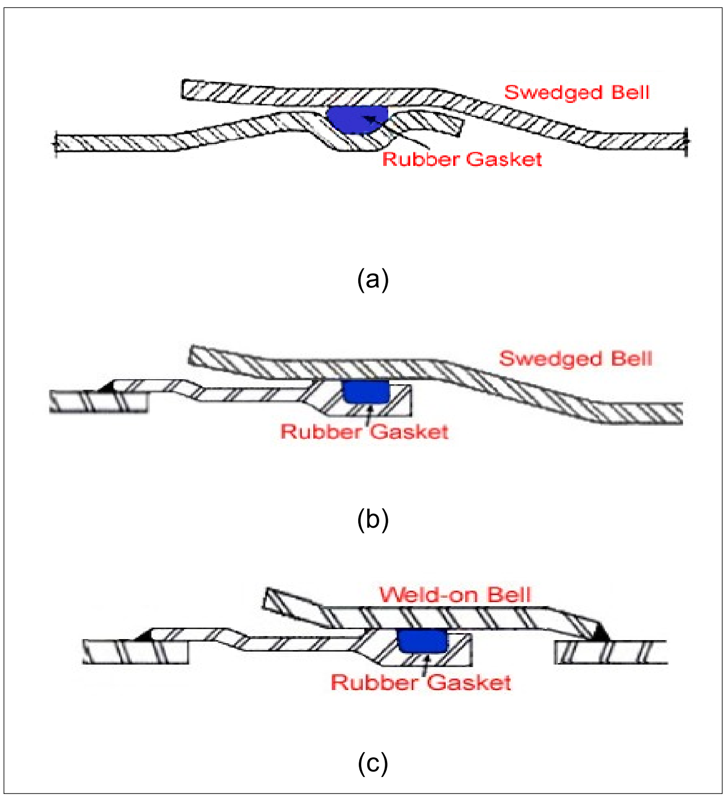


Figure 1.9 Different Types of Rubber Gasket Joints (a) Rolled-groove Joint, (b) Carnegie w/ Swedged Bell Joint and (c) Carnegie w/ Weld-on Bell Ring (Kelemen et al., 2011)

1.3.7.2 Welded Joints

Field welding is done for the steel water pipes which are 24 in. or larger in diameter with a working pressure up to 400 psi. There are two types of welded joints used for steel water pipe. One is Welded Lap Joint and another is Welded Butt Joint.

1.3.7.2.1 Welded Lap Joint

This type of joint is used when there is a flexibility requirement at the joint. It allows for some angular deflection and is usually welded on the outside. But, if required and pipe diameter is large enough for workers to enter the pipe safely, it can be welded from inside too. Requirements for the joint have been covered in AWWA C200 and requirements for the welding of the joints are covered in AWWA C206 (AISI, 2007).

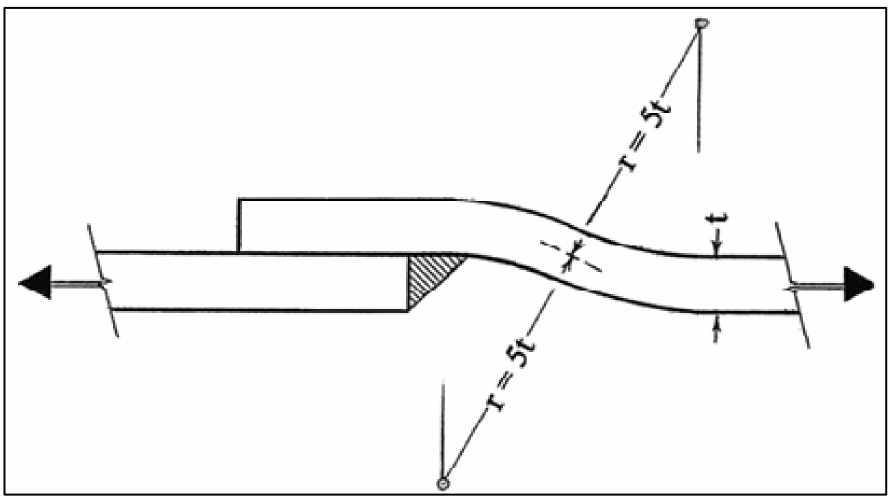
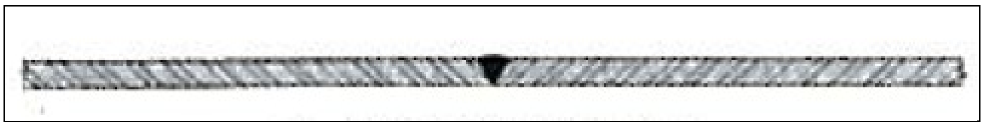


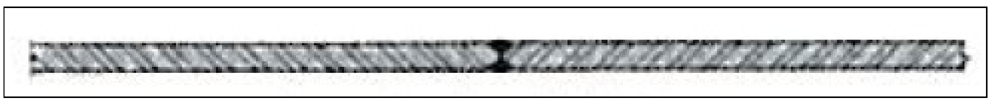
Figure 1.10 Welded Lap Joint (Watkins, 2006)

1.3.7.2.2 Welded Butt Joint

This joint does not allow any angular or longitudinal movement. It can be welded from outside or inside or both. It develops a good strength at the joint. Fitting up the joint is more difficult and expensive than that which is required by the Welded Lap Joint. The requirements for the joint and the welding of the joint have been covered in standards AWWA C200 and C206 respectively (AISI, 2007).



(a)



(b)

Figure 1.11 Types of Welded Butt Joint (a) Single Welded Butt Joint and (b) Double Welded Butt Joint (AWWA, 2004)

1.3.7.3 Butt-Strap Joint

This joint is useful when temperature stress control is desired on the butt-welded pipelines. The butt strap can be welded on site or in the factory to one end of the pipe. Depending upon the situation, the strap can be welded inside or outside or both. The standards for this joint have been covered by AWWA C206 (AISI, 2007).

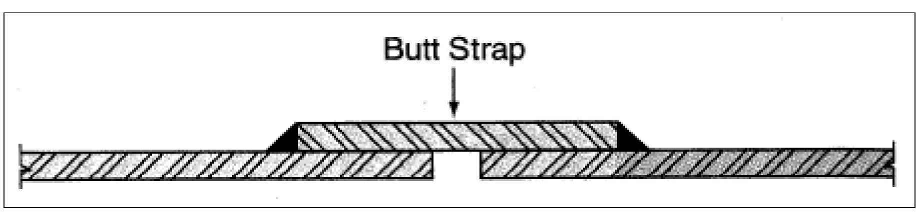


Figure 1.12 Butt-strap Joint (AISI, 2007)

1.3.7.4 Mechanical Couplings

Mechanical couplings can be used for steel water pipes of all sizes and pressure. They provide pipe with required strength and tightness with flexibility by relieving expansion and contraction forces in a pipeline. Rubber gaskets are used for the firmness between the coupling parts and between the pipe sections. Maximum allowed axial movement in the couplings is 3/8 in. If greater movement is needed, then it is advisable to use expansion joints rather than mechanical couplings (Cates, 1971). The requirements for the mechanical couplings are covered by Standard AWWA C219.

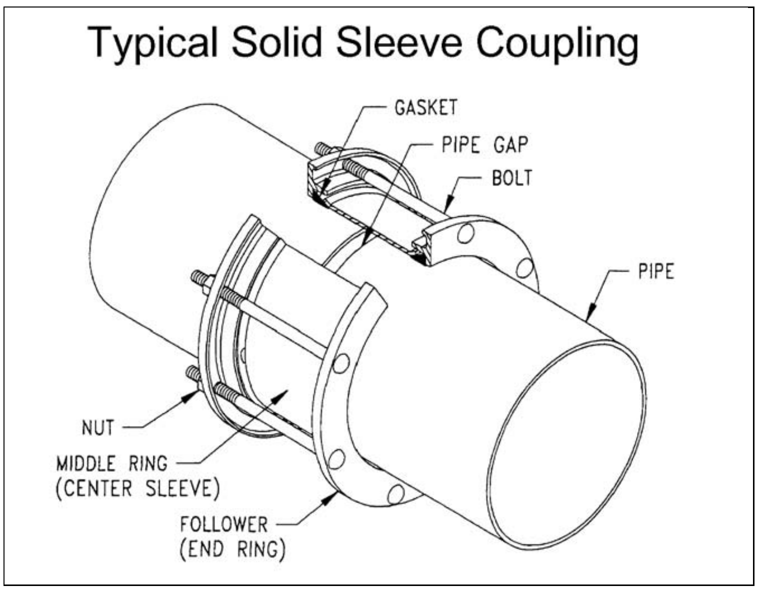


Figure 1.13 Mechanical Couplings (AISI, 2007)

1.3.7.5 Split-sleeve Couplings

A split sleeve coupling can be designed for steel water pipes with barrel deflection. It allows for axial movement greater than 3/8 in. The requirements for the split-sleeve couplings have been covered in AWWA C227 (AISI, 2007).

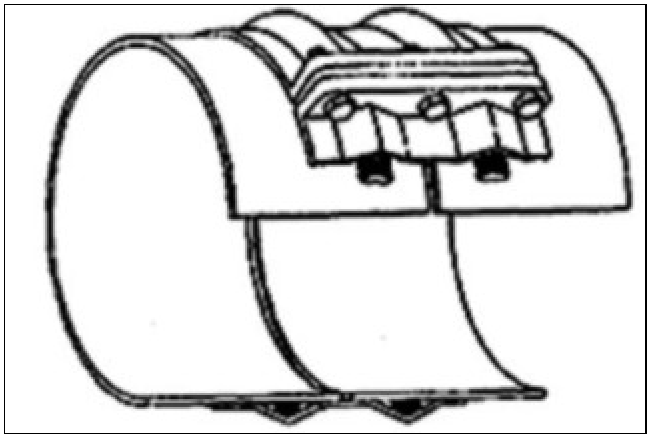


Figure 1.14 Split-sleeve Couplings (AISI, 2007)

1.3.7.6 Flanged Joints

Flanged joints are not flexible and are a bit expensive. Hence, generally they are avoided for large diameter steel water pipes. They are useful in special situations such as gate valves, meters, bridge crossings etc. (Cates, 1971).

1.3.8 Types of Linings and Coatings for Steel Water Pipes

1.3.8.1 Cement-Mortar Protective Coatings and Linings

These types of linings and coatings have been in use since late 1800s in the United States. A practical method to apply such linings and coatings was discovered in the 1920s. When cement-mortar linings and coatings are applied on steel water pipelines, the strength of steel and protective qualities of cement mortar together make a good and long lasting water transmitting unit. When used as internal lining it provides a smoother surface which increases coefficient of flow of water which in turn increases service life of the pipe. As a coating it provides a good protection from corrosion. Minimum requirements for cement-mortar linings and coatings are covered in AWWA standard C205 (AWWA, 2008).

1.3.8.2 Polyurethane Coatings

Initially in the 1970s, polyurethane coatings were used for oil and gas steel pipelines. Later due to research development, they started being used for steel water pipelines. The coating consists of fast-setting, high solids polyurethane. It is applied in one coat using spray technique. Coatings offer good abrasion resistance and high corrosion resistance. AWWA standard C222 covers minimum requirements for this type of coating (AWWA, 2008).

1.3.8.3 Tape Coating Systems

Prefabricated polyolefin tapes are applied as a three-layer system which consists of liquid adhesive, corrosion preventive tape as an inner layer and mechanical protective tape as an outer layer. Tape Coating systems are used for exterior of steel water pipeline in the potable water supply industry. AWWA C214 describes the materials and applications of tape coating systems (AWWA, 2007).

1.3.8.4 Heat-shrinkable Cross-linked Polyolefin Coatings

Heat-Shrinkable coatings can be field or shop applied. These coatings have polyolefin which is cross-linked by electron beam or chemicals. The product is available in three types, tubular sleeves, wrap-around types and tape type. AWWA C216 describes material, application and field procedure requirements for these coatings (AWWA, 2007).

1.3.8.5 Liquid-epoxy Coating Systems

Such coating systems are used when protection against corrosion is needed for both the interior and exterior of steel water pipes, fittings and special sections installed underwater or underground. The coating is applied by spraying it on the pipe. AWWA standard C210 covers minimum requirements for this type of coating system (AWWA, 2008).

1.3.8.6 Liquid Coating for Exterior of Aboveground Steel Water Pipelines and Fittings

Due to adverse atmospheric conditions sometimes aboveground steel water pipes are also subjected to corrosion. With the increasing rate of corrosion of aboveground steel pipes emerges the need for a good protective coating system. AWWA C218 has covered standards for liquid coating the exterior of aboveground steel water pipelines and fittings (AWWA, 2008).

1.3.8.7 Coal Tar Protective Coatings and Linings

Coal tar enamel is used for protection against corrosion and has been in use since the 1930s. It is used both externally and internally. While applying externally it is usually reinforced with glass fiber. When applied internally it is used without reinforcement. Minimum requirements for this coating/lining have been covered in AWWA standard C203 (AWWA, 2009). This type of coatings and linings are hardly used anymore.

1.3.8.8 Cold Applied Tape Coatings

Cold applied tape coatings are easy in application and suitable only for external application. They do not require any special equipment and can be applied over a broad range of application temperatures. AWWA C209 describes protective exterior coatings which are cold applied (AWWA, 2007).

1.4 Pipeline Failures

All the pipe materials mentioned in Section 1.2 have their own different modes or causes of failures. Principle modes are circumferential break, longitudinal break, bell split or joint failure, material softening, holes due to corrosion. Behavior of a pipe generally depends on pipe size, material, stresses on the pipe and the soil it’s buried in, internal and external loads such as water pressure and load due to traffic respectively, and bio-chemical and electro-chemical environment (Rajani & Kleiner, 2001).

1.5 Problem Statement

ASCE 2009 report card “Americas Infrastructure” gave D-minus to drinking water infrastructure. “America's drinking water systems face an annual shortfall of at least $11 billion to replace aging facilities that are near the end of their useful life and to comply with existing and future federal water regulations. This does not account for growth in the demand for drinking water over the next 20 years. Leaking pipes lose an estimated seven billion gallons of clean drinking water a day (ASCE, 2009).”

TABLE A ★ 2009 *Report Card for America's Infrastructure*

Aviation	D
Bridges	C
Dams	D
Drinking Water	D-
Energy	D+
Hazardous Waste	D
Inland Waterways	D-
Levees	D-
Public Parks and Recreation	C-
Rail	C-
Roads	D-
Schools	D
Solid Waste	C+
Transit	D
Wastewater	D-
AMERICA'S INFRASTRUCTURE G.P.A.	D

Figure 1.15 ASCE Report Card (ASCE, 2009)

Almost two-thirds of all water pipes in the US are metallic and out of date which includes approximately 48% of the cast iron pipeline inventory and 19% of the ductile iron pipeline inventory nationwide (Rajani & Kleiner, 2001). To assume the remaining metallic pipes are steel, it means approximately 30% of metallic pipe footage for water is steel. Most of this infrastructure is at the end of its useful life. According to a report issued by American Society of Civil Engineers (ASCE) in 2009, more than one million pipelines are at the end of their useful life. Because pipes are underground, they do not attract any attention. When they fail, it not only interrupts service but costs much more than it would have if properly maintained.

In May 2001, the American Water Work Association (AWWA) issued a facts explaining report called "Dawn of Replacement Era: Reinvesting in Drinking Water Infrastructure" (AWWA, 2001). The report determined that a significant investment will be required for our underground water infrastructure to work efficiently throughout its useful life. Restoring the existing water system as per the population growth will require an investment of at least $1 trillion over the next 25 years. Delaying this will only aggravate the circumstances.

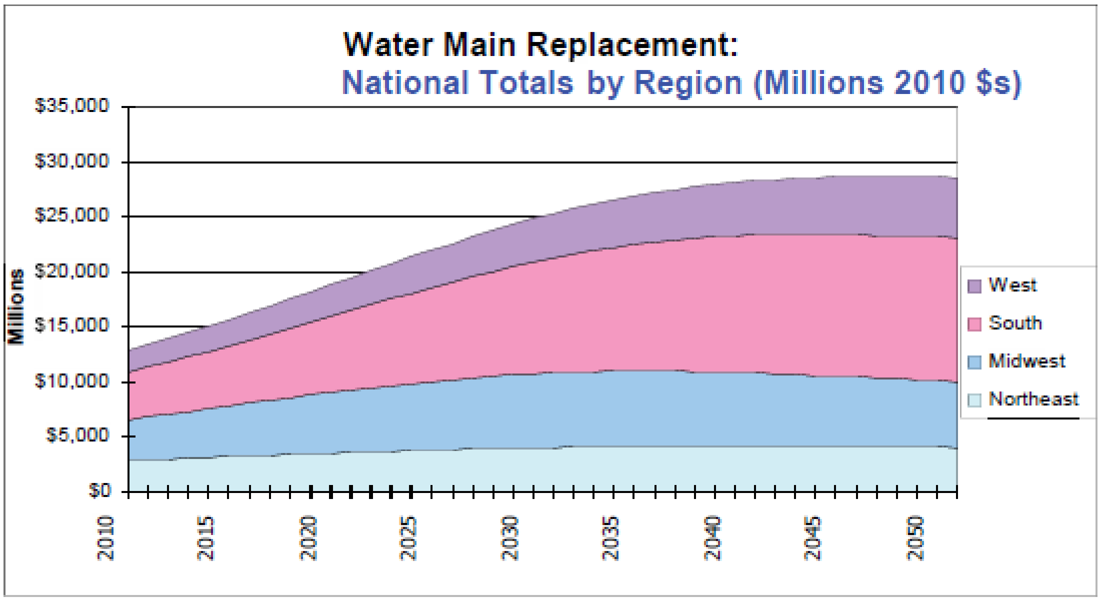


Figure 1.16 Water Main Costs per Region (AWWA, 2012)

The North America has a huge network of steel water pipelines. These are one of the oldest pipelines installed underground. For more than a century, the pipelines have served efficiently. But their condition deteriorated with time. The current circumstances will be aggravated by simply waiting until a repair is mandated with the ensuing chaos of flooded streets and traffic delays. There should be a way to prevent such occurrences from happening. This research studies steel water pipelines by carrying analysis on the data provided by 14 water utilities. The results may not be same for all water utilities, but they will help in making decisions for these water utilities about repair or rehabilitation of steel water pipelines.

1.6 Objectives and Scope

The main objective of this thesis is to evaluate large diameter (24 in. and larger) steel water pipelines. Research also aims to achieve the following:

- Determine failure causes and modes that affect most steel water pipelines.
- Determine the range for average age for steel water pipelines.
- Calculate the rate of failure for steel water pipelines.
- Evaluate the change in the behavior of steel pipelines with outside temperature.
- Compare the analysis of steel water pipelines in this study with some of the past studies.

The scope of this thesis is limited to steel water pipeline evaluation of 24 in. and larger diameter size in the U.S. This research does not compare behavior of steel pipeline with any other pipe material. It does not suggest any preventive majors to improve performance of steel water pipelines. A very good study of different water pipe materials was recently done by Dr. Steven Folkman of Utah State University (Folkman, 2012).

1.7 Methodology

To fulfill the proposed objectives, the author of this thesis used the following methodology.

- Collecting information about steel water pipes through a literature search.
- Preparing a survey for water utilities in order to collect data on large diameter (24 in. and larger) steel water pipe.
- Analyzing this data in order to evaluate performance of steel water pipe.

1.8 Expected Outcome

This research is expected to contribute in better understanding of performance of steel water pipelines (24 in. diameter and larger) based on the data provided by 14 water utilities in the U.S.

1.9 Organization of Thesis

The thesis consists of five chapters. The first chapter contains introduction of the topic and need for the research. The second chapter explores the literature about the problem, past studies that helped during the actual analysis. The third chapter explains the research's methodology. The fourth chapter contains analysis and results of the research and discussion on results. The fifth chapter provides conclusions derived from the results, limitations of the research, and recommendations for future researchers.

1.10 Chapter Summary

This chapter introduced the topic of this thesis. An overview of several types of pipe materials was presented and the need for this research was discussed. It also briefly explained objectives and scope of the thesis, its methodology and expected outcome.

CHAPTER 2

STEEL PIPE LIMITATIONS

2.1 Introduction

The first steel water pipeline in United States were was installed underground in 1858 when the Francis Smith Company laid the first riveted wrought steel water lines in Railroad Flats, CA. The pipe was 11 in. to 22 in. in diameter and the pipe wall had a depth of 1/16 in.; it was put together by slipping the sections together "like stove pipes (Cates, 1971)." According to Walter Cates, author of "History of Steel Water Pipe, its Fabrication and Development," the pipe was still in use at the time of his writing in 1971. Steel pipes have an average life span of 50-75 years. However, as for any other type of pipe, they have their own benefits and limitations. When a pipeline exceeds its design life, and/or not properly installed and maintained, it may become subject to failure. . This chapter briefly discusses the causes and modes of failures of steel water pipelines.

2.2 Causes of Steel Water Pipelines Failures

2.2.1 External Corrosion

There are numerous forms of corrosion. However, external corrosion is mostly electrochemical in nature in the case of buried steel water pipelines. Electrochemical process is a tendency of metals to reverse back into the ore from which they are derived (AWWA, 2004). There are four major components involved in electrochemical corrosion.

- Cathode, an electrode at which reduction occur

- Anode, an electrode at which oxidation occurs
- Electrolyte, a chemical environment
- A metallic path, in this case steel water pipeline

Together these components make a corrosion cell, also called an Electrochemical Cell, having a potential energy difference between cathodes and anodes. Negatively charged anode repulses the electrons towards cathode and metal ions from the electrolyte (in this case mostly moist soils) enter the anode, which causes anode to corrode (AWWA, 2004).

Corrosion is divided into following general types:

- Galvanic Corrosion – It involves galvanic cells and electrodes of different metals in homogeneous electrolyte (AWWA, 2004).
- Electrolytic Corrosion – Many industries, e.g., transportation industries, use DC currents for their operations. Some of these currents go away from their paths in order to search the least resisting path. If there are metallic pipes in the path of these stray currents, they travel through pipes and make their way back to the generator. The area of pipe at which currents enter becomes the cathode and the area at which they leave becomes the anode. The area which becomes the anode is the one where electrolytic corrosion occurs (AWWA, 2004).
- Biochemical Corrosion – Certain anaerobic bacteria in the soil produce active pseudo galvanic cells which may result in corrosion (AWWA, 2004).
- Stress and Fatigue Corrosion – Stress corrosion is caused by some tensile stresses produced in the pipe due to a static loading. These stresses are built up in a corrosive atmosphere when pipe's yield stress is exceeded. Fatigue corrosion occurs from cyclic loading (AWWA, 2004).

2.2.2 Internal Corrosion

Internal corrosion is considered even worse than external corrosion since it affects the water quality. Extent of internal corrosion depends upon whether pipe is internally lined and corrosivity of water. Internal corrosion forms tubercles of ferric hydroxide on the pipe wall. This process is called tuberculation. Tuberculation gradually reduces inner diameter of the pipe and affects the flow capacity of pipe (AWWA, 2004).

2.2.3 Handling and Storage of Pipes

Improper handling and storage of steel pipes is one of the major causes which may lead to poor performance after the installation. Steel pipelines are coated with anticorrosion materials. If they are not handled or stored properly, it can damage the coating.

2.2.4 Layout of Pipes

As much as possible, avoiding alignments with improper soil conditions may reduce possibility of excessive deflections, and unpredicted point loads acting on the pipe.

2.2.5 Jointing of Pipes

Use of defective jointing material can affect pipe's performance. Every pipe is vulnerable at the joints. Displacement at joints can lead to poor performance of pipeline. Hence, proper care during fitting the joint is also very necessary (Repair of Pipeline, 2012).

2.2.6 Soil Characteristics

Soil embedment is of great importance in the case of steel pipes. Steel, being a metal, is prone to corrosion. Hence, corrosive soils are an issue when the pipeline is not properly protected..

2.2.7 Temperature Changes

Extreme temperature changes can cause stresses in the steel pipe due to contraction and expansion. These thermal stresses can weaken the joints (Repair of Pipeline, 2012).

2.2.8 Aggressive Water

Raw water with impurities and high mineral content can create biofims and possibly damage internal lining of the pipeline which may lead to flow capacity problems.

2.3 Modes of Failure of Steel Water Pipelines

2.3.1 Blowout Holes due to Corrosion

Blowout holes due to Corrosion are common modes of failures observed in steel water pipelines. Sometimes corrosion causes thinning of pipe wall until the point water blows out through the thin wall. Size of the hole depends on area of the pipe wall covered by corrosion and internal water pressure (Cassa, 2011).

2.3.2 Circumferential Break

Circumferential break is mainly a result of longitudinal stresses. Longitudinal stresses are governed by thermal contraction due to low water temperature, bending stresses due to movements of soils, third party damages, and inadequate trench and bedding practices. However, circumferential break has mainly been observed in small diameter pipes (Rajani & Kleiner, 2001).

2.3.3 Longitudinal Break

Longitudinal break is rarely seen in steel water pipelines. Transverse stresses are the cause of longitudinal breaks in a pipe. These transverse stresses are governed by hoop stresses due to internal pressure in pipe, ring stresses due to soil cover load and increase in ring load due to expansion of moisture in the ground (Rajani & Kleiner, 2001).

2.4 Chapter Summary

This chapter discussed limitations of steel water pipelines. All pipe types deteriorate over time, and their applicability for specific conditions of a project must be investigated on a case by case basis.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter introduces the method adopted for this research to achieve the desired results. It explains the literature search process, and what steps were followed during survey preparation and how the analyses were done.

3.2 Methodology

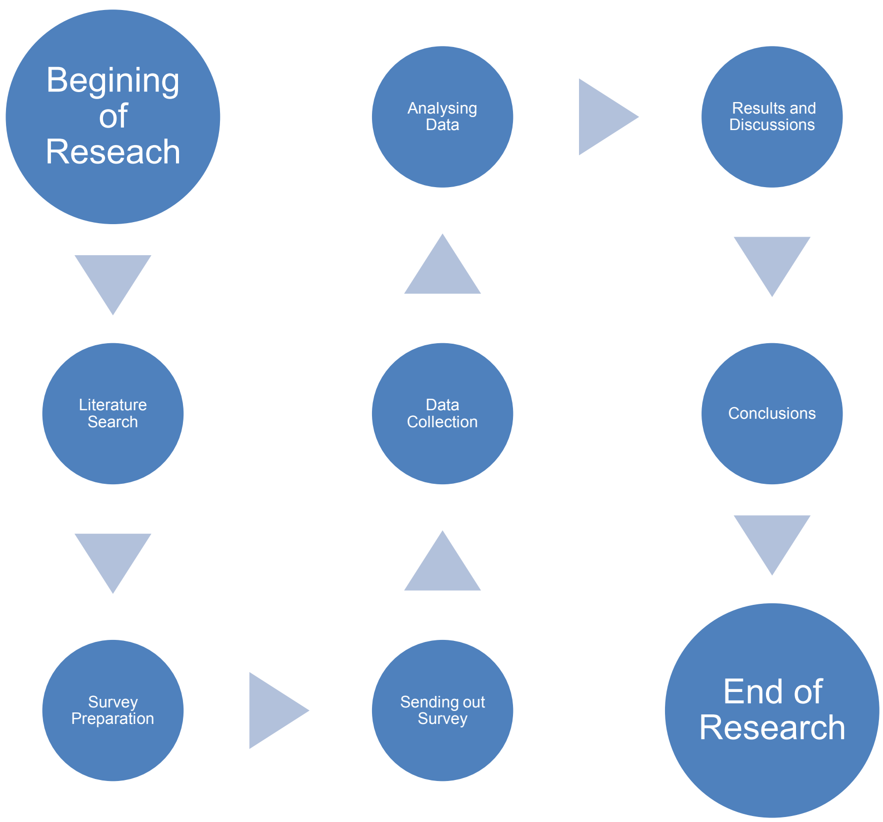


Figure 3.1 Research Methodology

3.3 Research Method

The main objective of the thesis is to study the performance of 24 in. and larger steel pipe for water transmission applications. This objective was achieved by following tasks:

- Collecting information about steel water pipes through a literature search.
- Preparing a survey for water utilities in order to collect data on large diameter (24 in. and larger) steel water pipes.
- Analyzing this data in order to evaluate performance of steel water pipe.

3.4 Literature search

This thesis was started with a literature search to gather information on steel water pipes. The literature search further expanded to present an overview of various water pipe materials. History and characteristics of steel pipes were investigated. Through various databases, past studies related to the subject were found. The literature search helped in understanding behavior of steel water pipelines.

3.5 Survey Preparation

Survey preparation was the most critical step of this research. In order to do analysis with conclusive results it was necessary to have a survey which provides proper data. The following is some basic guidelines about survey preparation, which made the whole procedure efficient and effective:

- Review basic objectives of the study,
- Visualize the output,
- Prioritize the output and define the sequence of the topics,
- Think through the respondent's perspective and how easy will it be to provide information,
- Determine the type of questions best suited for the research,
- Prepare the questions,

- Sequence the questions,
- Estimate the time length it will take to fill out the survey,
- Pretest the survey with a few people, and
- Send out the survey (QuestionPro, 2012).

The survey shown in Appendix A was prepared with 8 questions. The survey was sent out to over 300 water utilities across the U.S. Fourteen (14) water utilities from different states responded with good data which was used in this research.

In this survey, questions were essay as well as multiple choices. Focus was kept in that all the answers should relate to performance of pipelines. Survey began with a question asking water utilities about the population they serve. Utilities were also asked about the pipe footage of their water system, its dimensions and ages. It was important to know if any pipe material had not been considered in the city and the reasons behind it. In the next part of the survey, water utilities were asked to give data about the pipe performance.

3.6 Analyzing Survey Data

Once surveys were received, the next step was to analyze the data for study of steel water pipes. The data in the survey was prepared graphically for quick perception. The graphs were analyzed with different aspects to explore the most influential factors that play a key role in steel pipe performance

3.7 Chapter Summary

This chapter discussed methodology, explaining the step by step process adopted to carry out this research. From studying of steel water pipe performance and collecting data through the survey from water utilities, research objectives were achieved. Results obtained from the research will give better understanding about performance of large diameter (24 in. and larger) steel pipes.

CHAPTER 4

RESEARCH RESULTS

4.1 Introduction

Previous chapter discussed the methodology used to derive the results of this thesis. This chapter discusses how the methodology was implemented using the survey data.

4.2 Survey Data

The survey included in Appendix A was prepared to gather data about steel water pipelines. It was sent out to approximately 300 water utilities across the U.S. Fourteen (14) water utilities responded back with a good amount of data which has been used in the analysis. The identity of water utilities is not revealed as they were promised that their identity would be kept confidential. Hence they are designated with numbers, 1, 2, 3...up to 14, according to the population they serve. Number 1 is assigned to the water utility with the lowest population and so on up to number 14 which represents the highest population serving water utility. Throughout the research, each survey respondent retains the same number. The survey started with population served by the utility, and continued with footage of their inventory, any reasons for not considering use of steel water pipelines, and other details about performance of large diameter (24 in. and larger) steel pipelines.

4.2.1 Population Served by Water Utilities

Figure 4.1 shows the population served by each water utility. Average population per utility is 866,782. The lowest population served is 34,400 while the highest population served is 3 million. Total population served by all the utilities is 12 million. Due to this variation in population, it will give a better idea of impact of population on pipe performance.

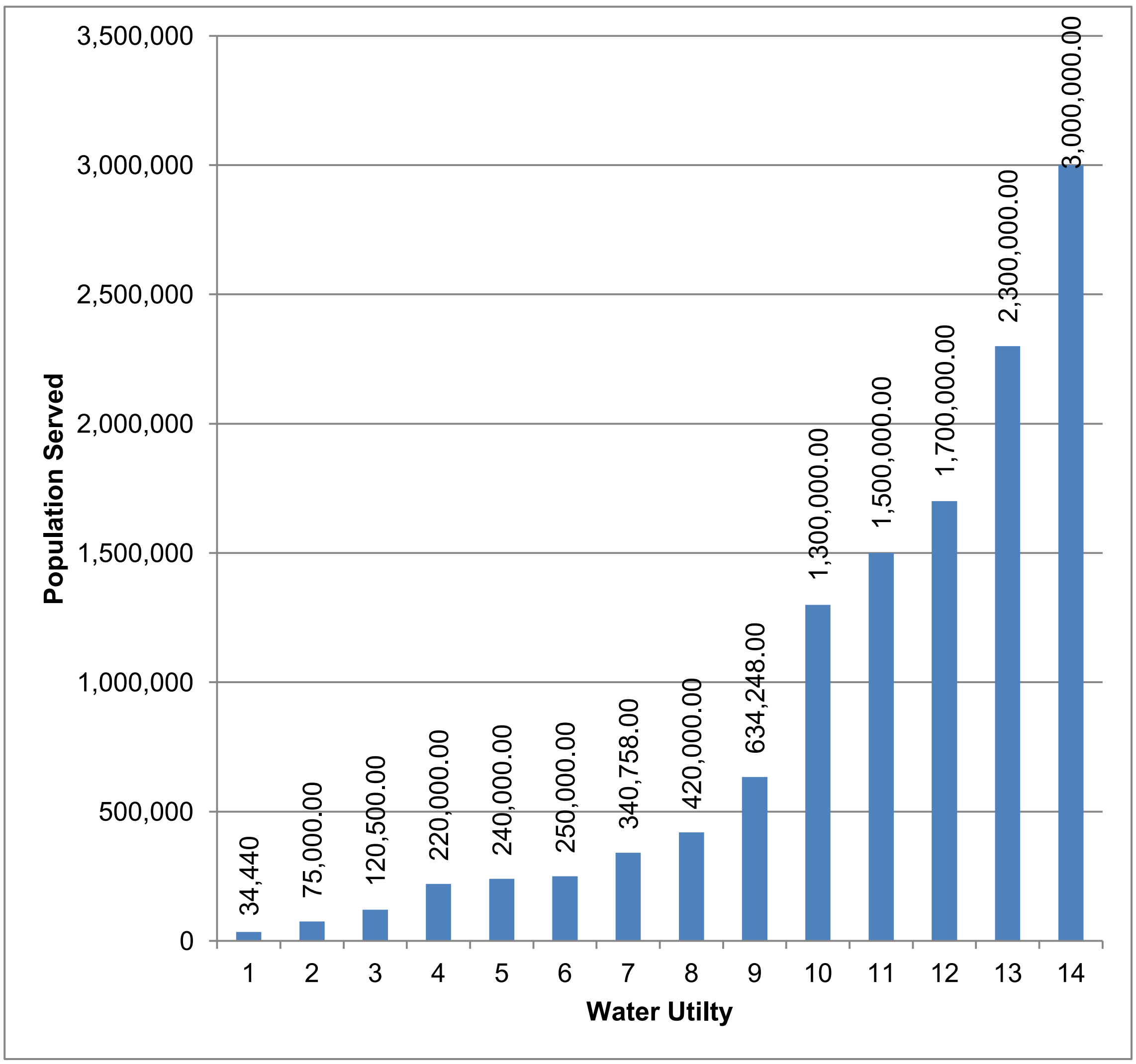


Figure 4.1 Population Served by Each Water Utility

(Based on 14 Survey Respondents)

4.2.2 Steel Pipeline Footage

Figure 4.2 shows the steel water pipeline mileage covered by each water utility. Average distance covered by pipelines per utility is 41 miles, considering 14 utilities. The utility with lowest footage served has 0.1 mile, and the utility with highest footage has 231 miles. It can be seen that there is lot of variation among utilities when it comes to large diameter steel pipeline footage. Some utilities are almost fully dependent on steel pipelines for water transmissions, while some barely use steel pipelines.

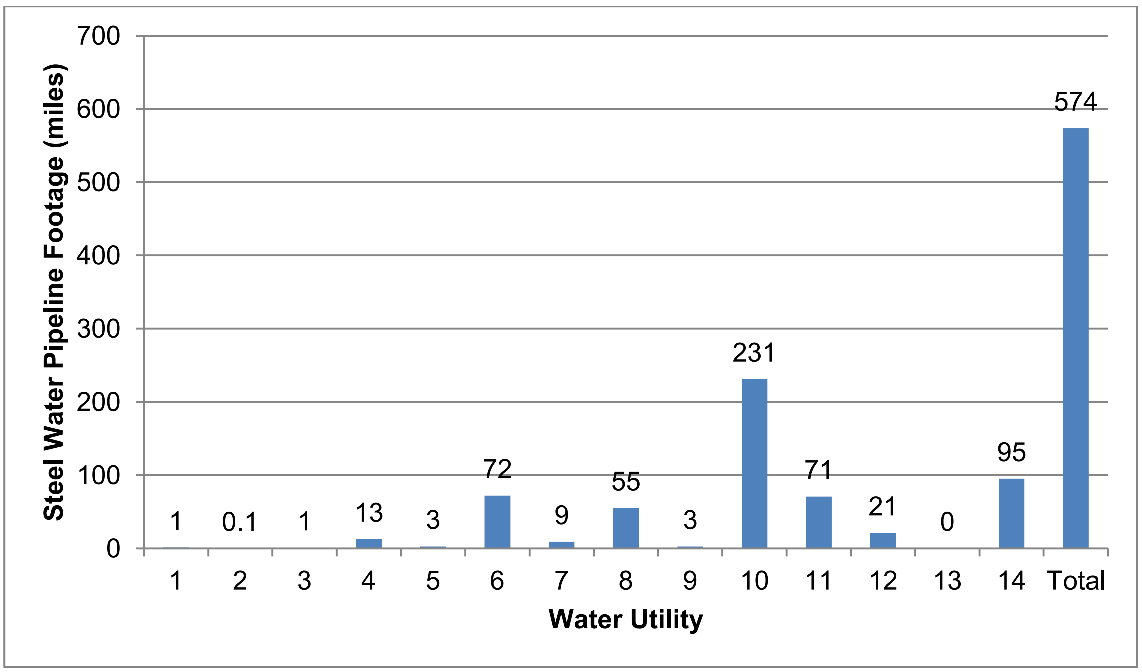


Figure 4.2 Steel Water Pipeline Footage for Each Water Utility

(Based on 14 Survey Respondents)

4.2.3 Mileage Distribution

Figure 4.3 shows that almost half of total large diameter steel pipeline mileage in the inventory of 14 water utilities responded, serves pipelines with a diameter of 24 in. to 36 in. The remaining mileage is almost equally divided among pipes with diameters between 42 in. and 48 in. and pipes with diameters that are 54 in. and larger.

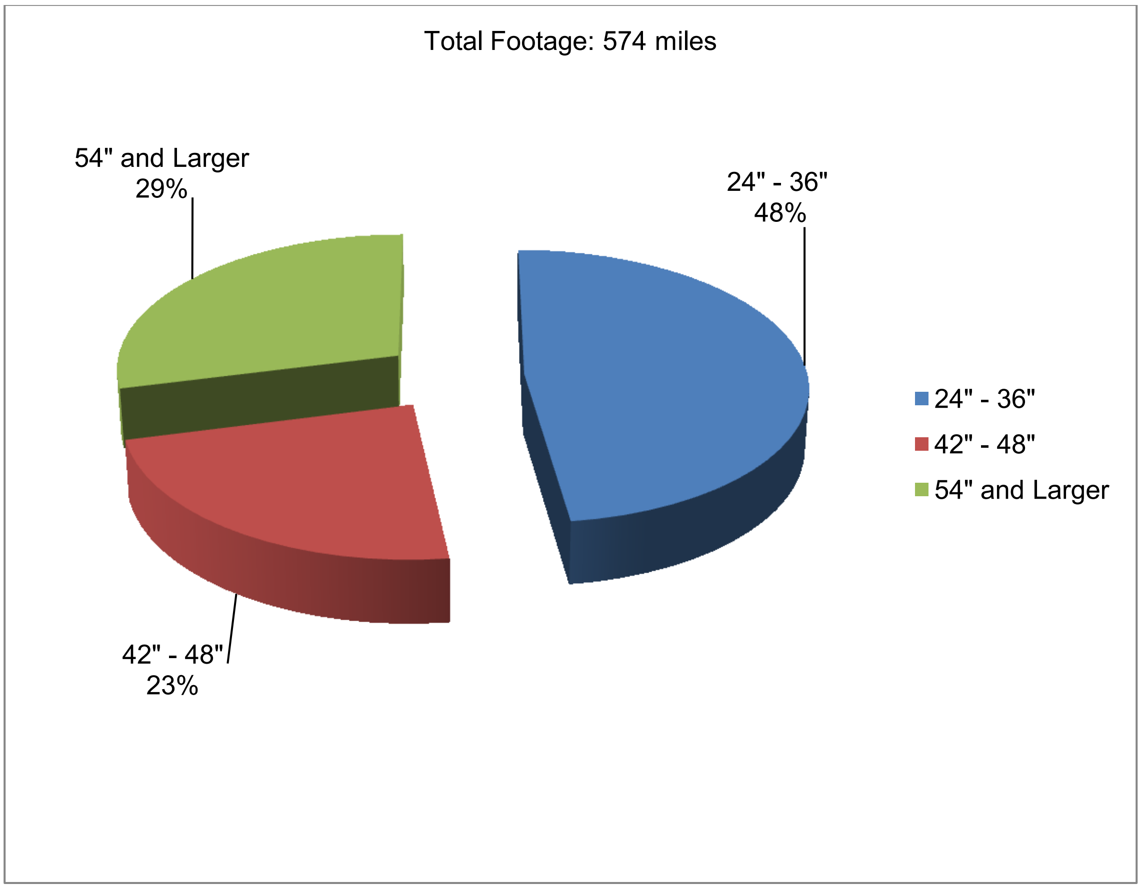


Figure 4.3 Steel Water Pipeline Footage Distribution according to Size of Diameter

(Based on 14 Survey Respondents)

4.2.4 Age Distribution

Figure 4.4 shows the large diameter steel pipeline mileage distribution in terms of age. Chapter 1 discussed that steel pipes for water transmission were used since 1850s. Use of steel pipes was at its peak during the 1930's when automatic welding was invented. This is reflected in the survey results too. It can be seen that the highest percentage of large diameter steel pipe footage (inventory) is 50 to 75 years old. Due to increased use of plastic pipes for water transmissions, use of steel pipe were reduced (or at least not replaced with steel pipe) after the 1970s. Thus the "less than 25 years old" category has the least percentage of steel pipes installed. This is true only for 14 utilities that responded to the survey, and may not be a national trend.

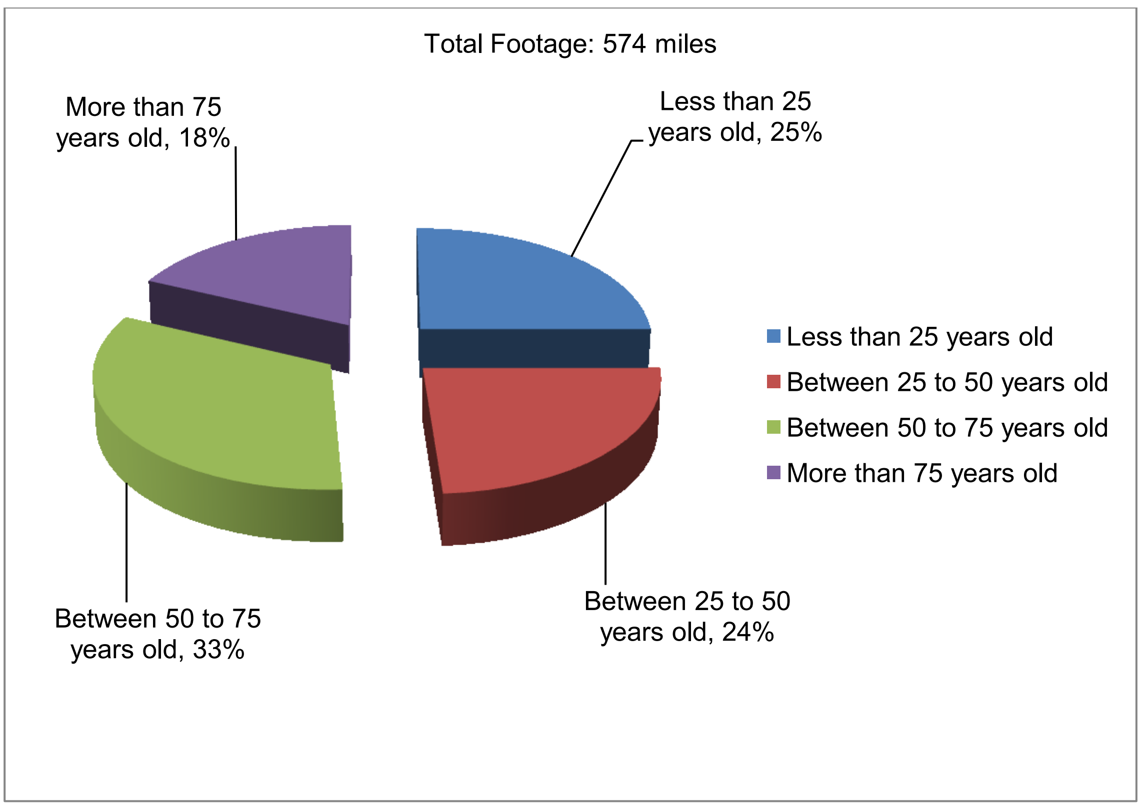


Figure 4.4 Steel Water Pipeline Footage Distribution According to Age

(Based on 14 Survey Respondents)

<u>4.3 Research Analysis</u>

4.3.1 Diameter Size

Figure 4.5 illustrates the percent of steel pipe failure in different diameter ranges according to 14 survey respondents. Since most of the pipeline inventory of these 14 water utilities falls under the range of 24 in. to 36 in. diameters, almost 90% of failed pipelines in this range. The remaining 10% is equally divided between the 42 in. to 48 in. diameter pipelines and the 54 in. and larger diameter pipelines.

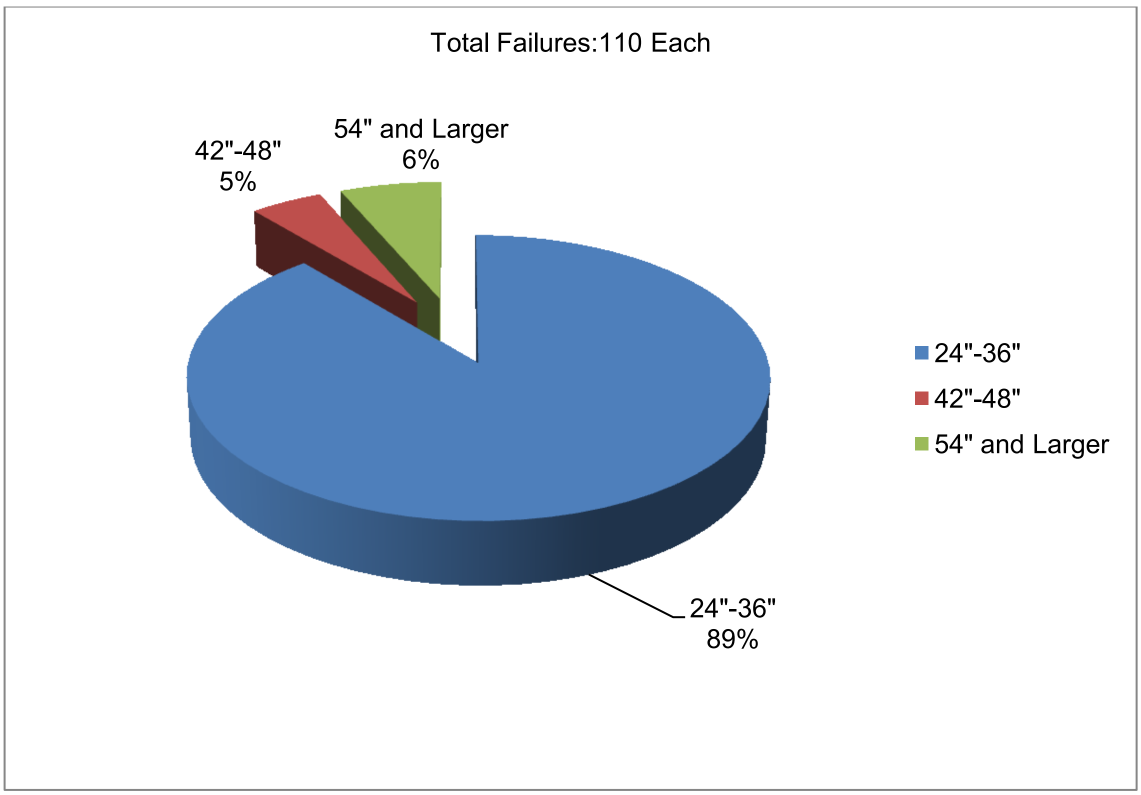


Figure 4.5 Failure with Respect to Diameter Size

(Based on 14 Survey Respondents)

4.3.2 Steel Pipe Failure Modes

Figure 4.6 illustrates that blowout hole due to corrosion is the highest occurring steel pipe failure mode for the inventory of 14 water utilities. Water utilities were unable to identify the mode for 20% of their steel pipelines. A beam break usually happens very rarely which relates to steel toughness and ability to handle stresses. About 5% pipelines had circumferential breaks and longitudinal split.

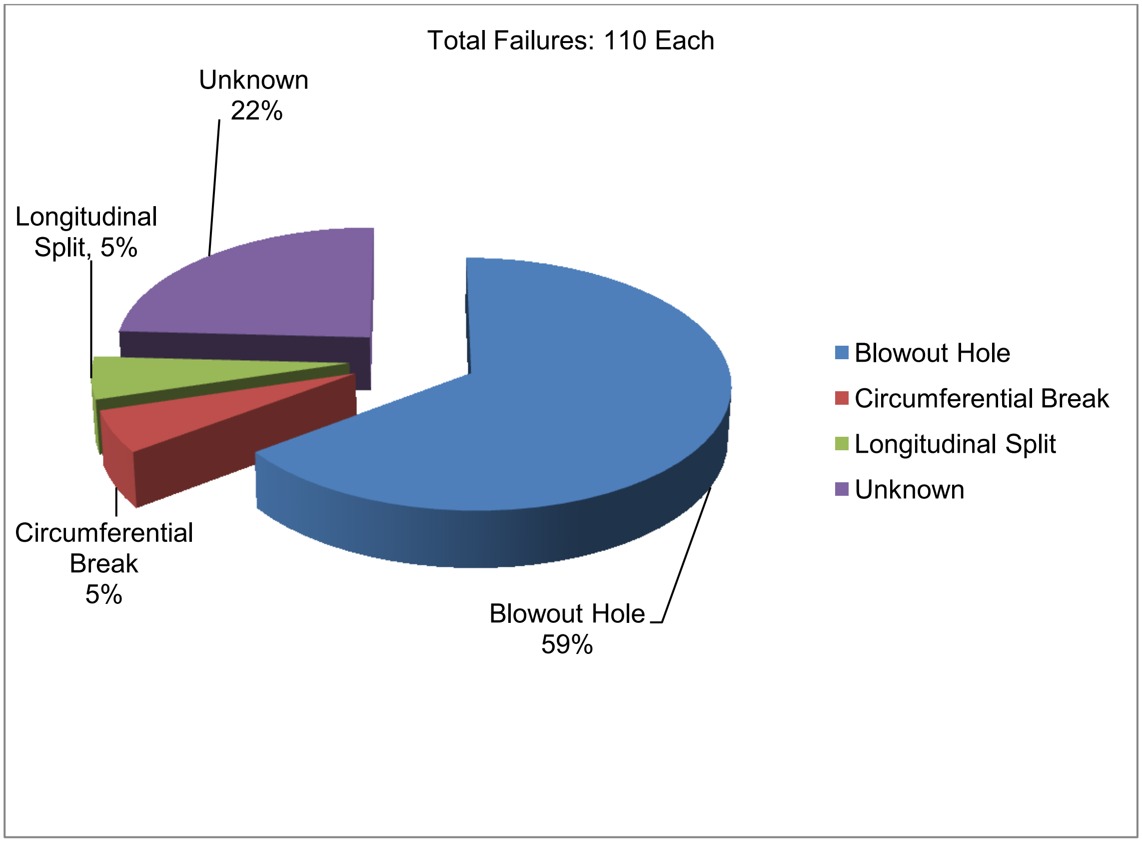


Figure 4.6 Large Diameter Steel Pipe Failure Modes

(Based on 14 Survey Respondents)

4.3.3 Causes of Steel Pipe Failure

Figure 4.7 illustrates the percent distribution of causes of steel pipe failures according to data provided by 14 survey respondents. The main cause in the data provided by 14 survey respondents was corrosion. Almost 60% of pipes in the inventory of 14 water utilities failed due to corrosion followed by 9% at joint, 6% of pipelines due to ground movement and 1% due to third party damage.

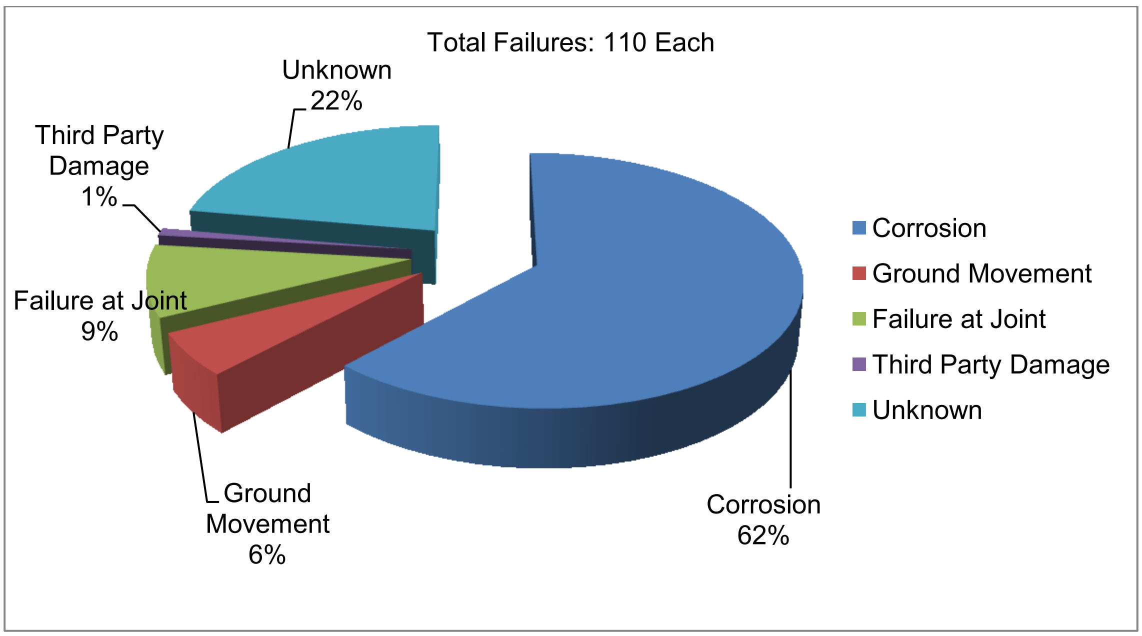


Figure 4.7 Causes of Large Diameter Steel Pipe Failures

(Based on 14 Survey Respondents)

4.3.4 Type of Joints

Figure 4.8 explains that the bell and spigot joint had 70% failures. It was followed by 20% pipelines with riveted joints in the data provided by 14 respondents. No joint failures with welded joints were observed.

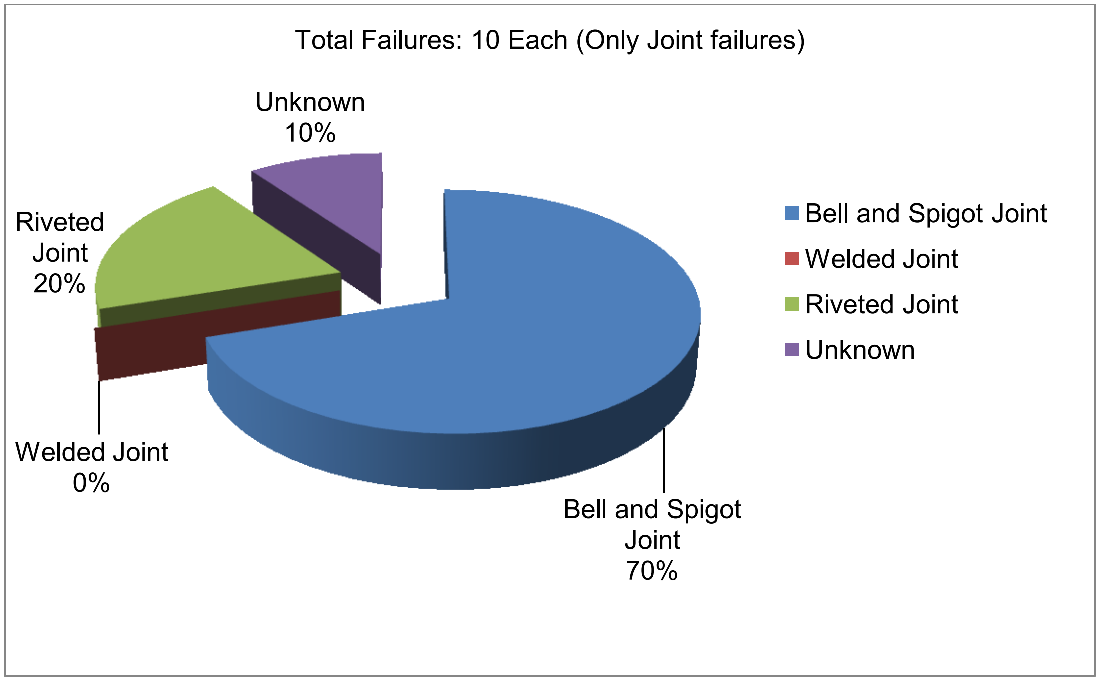


Figure 4.8 Failure with Respect to Type of Joints

(Based on 14 Survey Respondents)

4.3.5 Types of Coatings

Figure 4.9 illustrates the performance of steel pipeline in percentile with respect to the type of coating only. Largest number (92%) of steel pipelines that failed in the inventory of 14 water utilities was coated with coal tar enamel/tape. However, this type of coating is hardly in use today. The remaining 8% of pipelines used some sort of insulating (coating) material as a protection against corrosion, but did not specify. Nothing was reported in cement mortar coatings use.

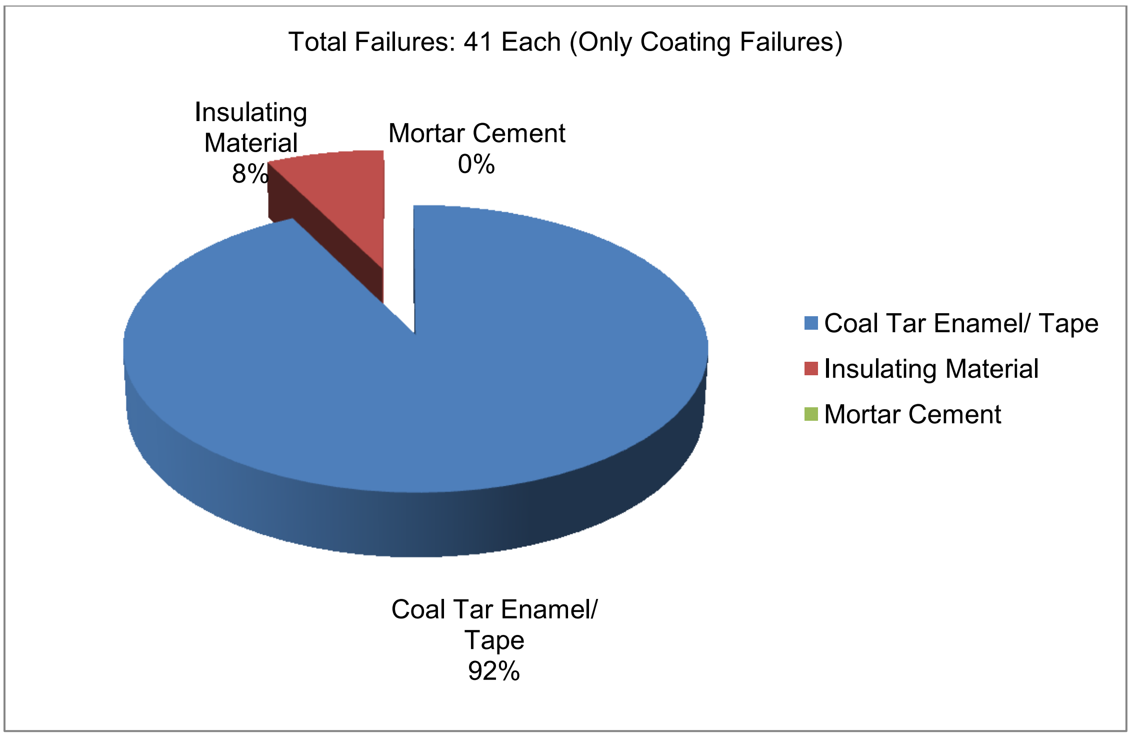


Figure 4.9 Failure with Respect to Type of Coatings

(Based on 14 Survey Respondents)

4.3.6 Average Age of Steel Pipelines

Many utilities did not provide the year of installation of the pipeline. Out of 110 pipelines only seven pipelines provided their year of installation.

Table 4.1 Calculation of Average Age of Steel Pipelines

(Based on 14 Survey Respondents)

<table>
<tr><th>Pipe Diameter</th><th>Year of Installation</th><th>Year of Failure</th><th>Age of the Pipeline</th><th>Average Age of Pipelines</th><th>Standard Deviation</th></tr>
<tr><td>36</td><td>1925</td><td>2001</td><td>76</td><td rowspan="7">54</td><td rowspan="7">11</td></tr>
<tr><td>36</td><td>1957</td><td>2010</td><td>53</td></tr>
<tr><td>36</td><td>1957</td><td>2011</td><td>54</td></tr>
<tr><td>42</td><td>1938</td><td>1979</td><td>41</td></tr>
<tr><td>42</td><td>1938</td><td>1980</td><td>42</td></tr>
<tr><td>48</td><td>1924</td><td>1974</td><td>50</td></tr>
<tr><td>60</td><td>1923</td><td>1986</td><td>63</td></tr>
</table>

Table 4.1 shows the average age of large diameter steel pipelines in the inventory of utility respondents. The average age for steel water pipelines is 54 years. The earliest pipeline failure occurred after 41 years of service while the pipeline that survived the longest served for 76 years before replacement. With the standard deviation 11, large diameter steel water pipelines in the survey respondents' inventory had an age between 43 and 65 years.

4.3.7 Reasons for Considerations Large Diameter Steel Pipes

Water utilities with no steel pipeline footage were asked the reasons for not using it. Following are the reasons considered by surveyed water utilities:

- Steel pipes require a welder and contractor to perform repair which would mean a longer time to get pipe back in service.
- The pipes are more susceptible to damage during installation.
- Proves costly due to cathodic protection requirement.
- Not suitable for in shop repairs.
- Not suitable for grounds with high watertable
- Not economical
- Difficult to tap or repair
- Unfamiliar with the pipe material and its usage

4.3.8 Performance of Steel Water Pipes

The following calculation for total footage of steel water pipeline is based on 14 survey respondents only. The number may not be true for every water utility in the U.S.

Failure Rate $= \frac{Number\ of\ Failures*100}{Miles}$ (Folkman, 2012).

Failure Rate of Steel Water Pipeline $= \frac{110*100}{573.54}$

= 19 Failures per 100 miles

4.3.9 Behavior of Steel Water Pipelines with Respect to Change in Outside Temperature

To check if there is a direct correlation between the outside temperature and behavior of steel water pipeline, the water utilities are divided into three different zones according to their location. The zones are separated by the average annual temperature. Thus the average annual temperature for a location of a particular water utility will decide which zone it falls under. Zone 1 is comprised of the coldest locations in the U.S. with average annual temperature of less than 50°F. Zone 2 will have the location with moderate average annual temperature between 50°F to 60°. Lastly, Zone 3 has the hottest locations with average annual temperature greater than 60°F. The information about average annual temperatures of different states was adopted from a Website (Current Results, 2012).

Table 4.2 Divisions of Water Utilities

(Based on 14 Survey Respondents)

Zone	Average temperature (°F)	Utilities
Zone 1	<50	1,6,7,8
Zone 2	50-60	2,3,5,9,10,11
Zone 3	>60	4,12,13,14

Table 4.2 shows the divisions of water utilities according to the particular range of average annual temperatures they fall under.

Table 4.3 Zone Wise Performance with Respect to Temperature
(Based on 14 Survey Respondents)

Zone	Number of Failures	Footage (miles)	Failure Rate (per 100 miles)
Zone 1	55	137.29	40
Zone 2	54	307.66	18
Zone 3	1	128.59	1

Table 4.3 shows variation in performance of steel water pipelines among different temperature zones separated by average annual temperature. Since there is a variation in the

rate of failure of steel water pipelines for different temperature zones, it can be said that there is a direct correlation between outside temperature change and performance of steel water pipelines of 14 water utilities responded to the survey. Obviously, other impacting factors, such as, soil, operational, and loading conditions, joint type, quality of installation and maintenance, and so on, may have impacted the failure rates, and were not considered in Table 4.3.

4.3.10 Comparison with Past Studies

Figure 4.10 shows the comparison between the analysis of steel water pipeline in this research, and some of the past studies. However, this research considers only 24 in. and larger steel water pipelines, while other studies have considered pipelines with all diameter sizes.

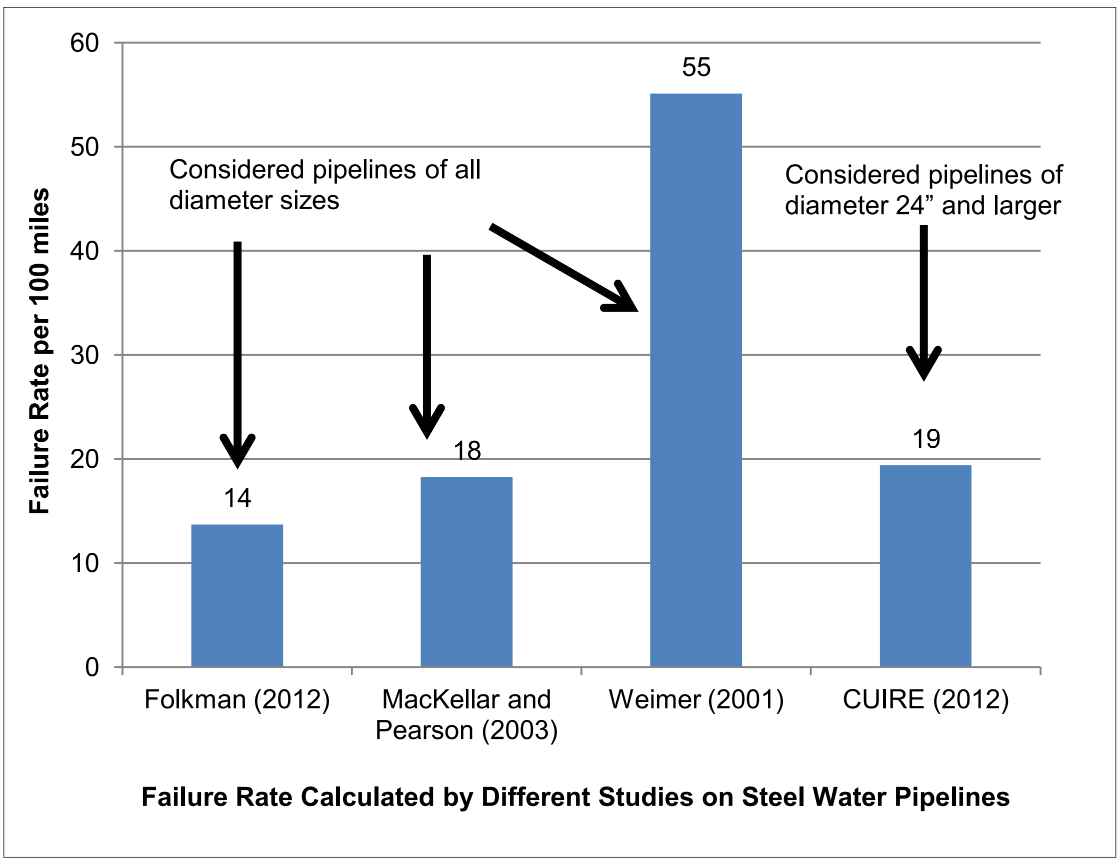


Figure 4.10 Comparison of Different Studies on Steel Water Pipelines

4.4 Discussion of Results Based on 14 Utility Respondents

From section 4.3.1, steel pipes with diameter ranges between 24 in. and 36 in. were more common (approximately 50% of total footage), and had the largest failure rate compared to other diameters. In the remaining 11%, 5% had diameters between 42 in. and 48 in. and the remaining 6% of steel water pipelines had diameters of 54 in. and larger.

Section 4.3.2 shows 59% of pipelines had blowout holes. This means that blowout holes are responsible for failure of more than half of the total steel water pipe inventory. Nine percent of steel pipelines fail at their joints. It happens either if designer does not consider all the forces acting on the joint, improper joint design and installation, or because water utilities have not properly trained their maintenance personnel to take care of the problem. Since steel is a material with high strength and toughness, the other modes such as longitudinal splits or circumferential breaks rarely occur.

Section 4.3.3 analyzed performance of steel water pipelines of 14 water utilities responded according to cause of failure. Corrosion counted for 60% of steel water pipe failures. More than half of this corrosion is due to wear and tear or damage to coating on the pipeline. Wear and tear of pipeline coating occurs due to negligence of guidelines during application and installation. Improper application of coating causes pipe to corrode in less time than normally it would take. With proper coatings and linings[1], and use of cathodic protection, corrosion of steel pipelines can be eliminated or reduced. Ground movements due to earthquake or soil settling can bring additional stresses to pipes which are not considered during the design. Due to reliability of steel as a pipe material, steel water pipes can withstand such forces. Only six percent of large diameter steel pipelines have failed due to ground movements, which prove the reliability of steel as a good pipe material.

[1] Coating is considered to be on the outside and lining is in the inside of the pipe.

To analyze behavior of steel water pipelines at the joints, only those pipelines were considered which failed at joint. From section 4.3.4, automatic welded joint were determined to be the most reliable joint with zero percent failures. It is one of the latest technologies of all the steel pipe jointing methods. In fact automatic welding made steel pipes a very popular material. Bell and Spigot joints have highest number of failures with seventy percent. This type of joint is the oldest of all. It was invented in 1785 for cast iron pipes (CISPI, 2006). Later they were used for steel water pipes installed in the 1800s. Twenty percent of pipelines failed at riveted joints. These joints were used from the 1900s until the late 1930s when the invention of automatic welding took place.

Coating wear and tear is a dominating factor for the cause of corrosion in steel water pipeline. Steel water pipelines corroded due to wear and tear of coatings is analyzed in section 4.3.5. Ninety-two percent of steel water pipelines of 14 water utilities responded was coated with coal tar enamel tape. However, such type of coating is hardly in use anymore. No pipeline coated with cement mortar coating was found. About 8% of pipelines that corroded had other (not specified) insulating materials as a coating.

In section 4.3.6, a range for average age of steel water pipelines of 14 water utilities responded to the survey is calculated. Age of Pipelines with known year of installation and year of failure was first calculated separately. Then the mean of ages of all these pipelines was subtracted and added from the standard deviation of ages to find out a range. Obviously, the actual age of steel water pipelines for each responding utility may or may not fit in the range. It should be noted that depending upon environmental conditions, pipe dimensions, external loads, internal water pressure, burial depth, type of water, and so on; life expectancy of a pipeline may change.

In sections 4.3.8, failure rate of steel water pipelines is calculated based on the responses from 14 water utilities. To better understand the performance of large diameter steel water pipelines, Section 4.3.10 compared results of this research with other studies on steel pipelines..

In section 4.3.9 the 14 water utilities were divided into three separate zones. Each zone was assigned a particular temperature range. The water utilities put in a specific zone on the basis of average annual temperature of their location. The performance of steel water pipelines was analyzed separately for each zone. Zone 1 with the coldest localities showed the highest rate of 40 failures per 100 miles. Zone 2 with the localities having moderate temperature had the rate of 18 failures per 100 miles. Zone 3 with hottest localities showed the lowest rate of only 1 failure per 100 miles. Such a temperature variation of each zone showed that there are some outside temperature impacts on the performance of steel water pipelines. However, outside temperature is not the only parameter affecting the performance of steel water pipelines.

There are some past studies about steel pipelines in water application. In section 4.3.10 performance of steel water pipeline in this study was compared to other studies for validation of this research. Table 4.4 shows comparison among different parameters in various studies considered in Figure 4.10

Table 4.4 Comparison of Various Studies on Steel Water Pipeline

Parameters	Studies on Steel Water Pipelines			
Source	Folkman (2007)	MacKellar & Pearson (2003)	Weimer (2001)	CUIRE (2012)
Failure Rate per 100 miles	14	18	55	19
Location of Study	U.S.A.	U.K.	Germany	U.S.A.
Survey Respondents	188	17	500	14
Diameter Size	All	All	All	24 in. and Larger

4.5 Chapter Summary

This chapter presents results and analysis on the data for large diameter steel water pipelines provided by 14 water utilities across the U.S. A discussion of behavior of steel water pipelines for 14 responding water utilities was presented.

CHAPTER 5

CONCLUSIONS, LIMITATIONS, AND RECOMMENDATIONS FOR FUTURE RESEARCH

5.1 Introduction

After research analysis, this chapter briefly discusses conclusions drawn from literature review and research results. This chapter also discusses the limitations of this study and suggests some recommendations for future research.

5.2 Conclusions Based on 14 Respondent Utilities

Following is the conclusions drawn from results of this research, based on 14 respondent utilities:

- Steel water pipelines with diameter range 24 in. to 36 in. are most common.
- Corrosion is the major cause of steel water pipe failures.
- Most frequent failure mode for steel water pipe is blow-out holes due to corrosion.
- Steel water pipes with bell and spigot joints have largest percent of joint failure.
- Steel water pipes with coal tar enamel/tape have largest failure rates..
- Steel water pipes approximately have 19 failures per 100 miles.
- Steel water pipe performance may fluctuate with the variance in outside temperature.
- Average age limits for steel water pipes may range between 43 to 65 years from the date of their installation. These limits can vary depending upon environmental conditions, pipe dimensions, external loads, internal water pressure, type of water, and other factors.

5.3 Limitations of Research

- Steel water pipes smaller than 24 in. diameter sizes were not considered.
- This research was conducted with limited and incomplete data availability (provided by only 14 water utilities).
- Parameters such as soil conditions, depth of installation, internal loads (operating and surge pressure), external loads (traffic and frost), manufacturing processes of pipes, bedding and embed conditions, and so on, can influence performance of steel water pipelines, but are not considered in this research.

5.4 Recommendations for Future Research

- Involve larger survey sample size in order to improve accuracy.
- Investigate impacts of other parameters, such as soil-pipe interaction, friction coefficient, effects and prevention of biofilms, and burial depth of pipe on performance of steel water pipelines.

5.5 Chapter Summary

This chapter discussed conclusions and limitations of this research and also suggested some recommendations for future research.

APPENDIX A

SURVEY QUESTIONNAIRE FORM

Center for Underground Infrastructure Research and Education (CUIRE)

Phone: 817- 272- 0507 Fax: 817- 272- 2630

E-mail: najafi@uta.edu; Web site : www.cuire.org

Large Diameter* (24 in. and Larger) Water Pipe Questionnaire

Project Overview

The Center for Underground Infrastructure Research and Education (CUIRE) at The University of Texas at Arlington is working on a major project regarding failure modes, causes and rates of 24 in. and larger water pipelines. The primary objective of this project is to gain an understanding of pipe material performance under different environmental, loadings and operational conditions.

The below national survey is critical as a first step to achieve these objectives, since it will provide valuable information regarding the inventory and conditions of 24-in. and larger water pipes. To show our appreciation for your time and efforts to complete this survey, we will send you a copy of the research findings upon completion, scheduled for Summer 2012.

Alternatively, instead of completing the survey; you may send us a report or

a database file of your water pipe inventory, conditions and failure rates

****The average time to complete this survey is estimated to be 20 minutes****

If you have any questions or concerns, please feel free to contact CUIRE at 817-313-9177 or Tushar Joshi, CUIRE Graduate Research Student, at 817-313-0735 or tushar.joshi@mavs.uta.edu or the Principal Investigator of this project, Dr. Mohammad Najafi at 817-272-0507 or najafi@uta.edu.

a) Contact Person's Name		Position:		
b) Name of the organization	City		State	Zip
c) Address				
d) E-mail				
e) Phone:		Fax:		

1. What is the population of the area served by your water pipes? _____________

2. What is the total length of your 24 in. and larger water pipelines?
   ___________ ft or ___________ mi.

3. Please provide us the footage of the water system (24 in. and larger).

Type of Pipe	Footage (mile)		
	24” – 36”	42” – 48”	54” and larger
Other (Please Specify):			

4. In your large diameter* water pipe (24 in. and larger) inventory, what footage is:

Type of Pipe	Total Inventory (mile)			
	Less than 25 years old	**Between 25 to 50 years old**	**Between 50 to 75 years old**	**More than 75 years old**
PCCP*				
Steel*				
PVC*				
HDPE*				
DIP*				
CIP*				
Bar-				
Other (Please Specify):				

5. Please provide information for past water pipe failures (24 in. and larger).

Pipe ID*	Pipe Type	Pipe Diameter*	Location	Date of Installation	Date of Failure	Cause of Failure	Mode of Failure	Type of Joint*	Type of Coating*	Type of Water (treated/ untreated)	Cathodic Protection* (Y/N)	Soil Conditions*

6. **Why, if any, of the following type of pipe materials (24 in. and larger) not considered for use in your water system?**

Pipe Material	Reason(s) for Consideration
PCCP*	
Steel*	
PVC*	
HDPE*	
DIP*	
CIP*	
Bar-wrapped*	
Other (Please Specify):	

7. **List the most frequently observed causes of failure* for each of the pipe materials in your water utility.**

Pipe Material	1	2	3	4	5	6
PCCP*						
Steel*						
PVC*						
HDPE*						
DIP*						
CIP*						
Bar – wrapped*						

8. **Please provide any comments/suggestions, or feel free to send us any case study or pipeline failure report.**

Once again, thank you very much for your time. We will get back with you with the survey results in Fall 2012. If you have any questions or concerns, please feel free to contact Tushar Joshi, CUIRE Graduate Research Student, at 817-313-0735 or tushar.joshi@mavs.uta.edu or the Principal Investigator of this project, Dr. Mohammad Najafi at 817-272-0507 or najafi@uta.edu

Dr. Mohammad Najafi, P.E., F. ASCE
CUIRE Director
Editor-in-Chief, ASCE Journal of Pipeline Systems
Department of Civil Engineering—The University of Texas at Arlington
Box 19308—428 Nedderman Hall
Arlington, TX 76019-0308
CUIRE Office: 817-272-9177
Fax: 817-272-2630
Email: najafi@uta.edu
www.cuire.org

DEFINITIONS

- **Age of the Pipe:** The number of years the pipe has been installed.
- **Asbestos Cement Pipe:** A concrete pipe made of mixture of Portland cement & asbestos fiber.
- **Bar Wrapped:** Bar-wrapped Cylinder Concrete Pipe combines the strength of steel with the corrosion resistance and durability of concrete. It is comprised of a welded steel cylinder that serves as a watertight membrane and works together with steel reinforcing bars wrapped under tension around the cylinder to provide strength.
- **Buckling:** Unpredictable deformation observed in the pipe as a result of instability of pipe due to the increasing loads which might lead to complete loss in carrying capacity of pipe.
- **Cast Iron Pipe:** A hard, brittle, nonmalleable iron-carbon alloy, cast into shape, containing 2 to 4.5 percent carbon, 0.5 to 3 percent silicon, and lesser amounts of sulfur, manganese, and phosphorus.
- **Cathodic Protection:** Preventing corrosion of pipeline by using special cathodes (and anodes) to circumvent corrosive damage by electric current.
- **Coating:** Coating is applied to the surface of the pipe to protect it from corrosion. For e.g. Three layer PE (3LPE), three layer PP (3LPP), fusion bonded epoxy (FBE or Dual FBE), coal tar enamel (CTE), asphalt enamel and polyurethane (PUR).
- **Corrosion:** The destruction of materials or its properties because of reaction with its (environment) surroundings.
- **Diameter:** Diameter here refers to the outer dimension of the pipe.
- **DIP:** Ductile Iron Pipe is an improvement to the Cast Iron Pipe. In DIP, the majority of the pools of graphite are in the form of spheroids. This distinctive shape significantly reduces the occurrence of points of stress concentration.

- **Excessive Dead Loads:** Weight of all materials on pipe. Generally expressed in terms of weight per unit length. Static load throughout the design life of the pipe. For large pipes with full flow, the contents can be considered to be dead loads because their weights and locations are very predictable. E.g. Soil load. Excessive term is used if the dead loads result in pipe failure.
- **Excessive Internal Pressure:** Force exerted circumferentially on the pipe from inside per square unit area of the pipe is internal pressure. Excessive term is used if it results in pipe failure.
- **Excessive Live Loads:** Live loads change in position or magnitude. E.g. Vehicular loads. Excessive term is used if the live loads result in pipe failure.
- **External Corrosion:** Corrosion observed in pipe due to external sources like soil, groundwater.
- **Failure of Pipe**: Fracture, Breakage, Upset, Lining/Coating problems, Loss of Capacity, Leakage.
- **HDPE:** A plastic resin made by the copolymerization of ethylene and a small amount of another hydrocarbon. The resulting base resin density, before additives or pigments, is greater than 0.941 g/cm.
- **Installation Problems:** The difficulties faced during the laying of pipe in the ground.
- **Internal Corrosion:** Corrosion observed in pipe due to the materials it carries.
- **Joint:** The means of connecting sectional length of pipeline system into a continuous line using various type of jointing materials.
- **Manufacturing Defect**s: An error or flaw in a pipe, introduced during the manufacturing rather than the design phase.
- **Over Deflection**: Deflection is the vertical or horizontal curvature or combination of both observed in pipe. Over deflection is defined as the deflection at which the pipe fails.
- **Oxidation**: The erosion damage observed in the pipe due to its surrounding environment.

- **PCCP:** Pre-stressed Concrete Cylinder Pipe (PCCP) consists of a concrete core, a thin steel cylinder, high tensile pre-stressing wires and a mortar coating.
- **Permeation:** Permeation of piping materials and non-metallic joints can be defined as the passage of contaminants external to the pipe, through porous, non-metallic materials, into the drinking water. The problem of permeation is generally limited to plastic, non-metallic materials.
- **Pipe ID:** Unique identity of pipe.
- **Population:** The whole number of people or inhabitants in a region or country.
- **PVC:** A polyvinyl chloride (PVC) is made from a plastic and vinyl combination material. The pipes are durable, hard to damage, and long lasting.
- **Repair:** Fixing a section of pipeline to make the pipeline back in working condition without increasing the design life.
- **Replacement:** The act of installing a new pipeline in the place of old pipeline or renewing the pipeline with new design life.
- **Restricted**: The pipe material could not be used due to certain difficulties.
- **Steel Pipe:** Steel pipe is a material made from an alloy of iron and carbon.
- **Third Party Damage:** Damage caused by someone other than pipeline operator and owner.

APPENDIX B

LIST OF ABBREVIATIONS

AISI - American Iron and Steel Institute

ASCE - American Society of Civil Engineers

AWWA - American Water Works Association

BW - Bar-wrapped Steel-cylinder Concrete Pipe

CI - Cast Iron

CISPI - Cast Iron Soil Pipe and Fittings Handbook

CUIRE - Center for Underground Infrastructure Research and Education

DI - Ductile Iron

PCCP - Prestressed Concrete Cylinder Pipe

HDPE – High-Density Polyethylene

PVC - Polyvinyl Chloride

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BIOGRAPHICAL INFORMATION

Tushar Joshi currently has a bachelor's degree in civil engineering from Datta Meghe College of Engineering affiliated with Mumbai University, India. He is in pursuit of a Master of Science degree in Civil Engineering at the University of Texas at Arlington (UTA). His area of concentration is Construction Engineering and Management. Since Fall of 2010, Mr. Joshi has achieved high degrees of academic development at UTA including the CUIRE's scholarship award for Master's students received in Spring of 2012 and Fall 2012.