PERFORMANCE OF PRESTRESSED CONCRETE CYLINDER PIPE (PCCP) IN WATER APPLICATIONS

by

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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

PERFORMANCE OF PRESTRESSED CONCRETE CYLINDER

PIPE (PCCP) IN WATER APPLICATIONS

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The analysis of water pipes field data is of great importance as it has a significant impact on society and the environment. These failures also have an overall impact on the financial burden of the water utilities.

This thesis consists of a detailed literature review on the previous studies conducted on prestressed concrete cylinder pipe (PCCP) performance. Moreover, a detailed national-level survey was conducted by the Center for Underground Infrastructure Research and Education (CUIRE) at UT Arlington to gather and analyze additional field performance data for large diameter pressure pipe including prestressed concrete cylinder pipe. Specifically, this thesis evaluates the field performance of PCCP, which is one of the most conventional and extensively used large diameter (24 in. and larger) rigid pipes in the U.S. water pipeline industry. This thesis explores different

failure parameters, such as pipe age, diameter, manufacturing process, type of joints and performance effectiveness of PCCP.

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CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1 History of Pipelines

Pipelines are assets of water utilities. Because they are underground, millions of miles of pipeline infrastructure are generally overlooked until there is a need for repair or replacement. Every single pipe has a history, such as, when it was installed, what its fail date was, and what caused its failure. There are thousands of public water utilities and only a few private water utilities, which serve safe drinking water.

According to the American Water Works Association (AWWA), a significant amount of water pipeline network is buried underground and is at the end of its useful life. This pipeline network will definitely require a large number of replacement pipes and/or repairs in the near future, which will cost billions of dollars (AWWA,[1] 2010). Water pipe ruptures cause 7 billion gallons of water to be lost in the US daily, which means that water utilities need to exceed their current annual budgets by at least $11 billion annually to keep up with the repair and replacement costs (ASCE, 2009). The costs of these pipe breakages have a significant impact on water utility's annual budget. These costs may be in the form of social, environmental, and replacement costs (Piratla and Ariaratnam, 2011; Higgins, 2010). To combat these issues, water utilities are looking

[1] http://www.awwa.org/files/GovtPublicAffairs/GADocuments/BuriedNoLongerCompleteFinal.pdf

for effective and sound solutions including statistical models that presents or predict future numbers of failure in pipeline based on historical data.

Based on the behavior of the pipelines with surrounding soils, pipes can be divided in three types: 1) rigid, 2) flexible and, 3) semi rigid.

1.1.1 Rigid Pipe

The Marston's load theory states that the load or the weight of the central column of soil above the buried pipe is modified by the pipe type, side soil column and, external prism along the central column. The external prism is more compressible than the pipe because of its inbuilt rigidity. The pipes take the load of central column plus the load due to shearing stresses and friction forces due to the differential settlement between external and central prism. Pipes behaving in this manner are called rigid pipes (Najafi and Gokhale, 2005), which include reinforced concrete non-cylinder pipe, PCCP, reinforced cement concrete (RCC) pipe, polymer concrete, vitrified clay, cast iron, and asbestos cement pipes. Figure 1.1(a) shows the adjusted load on a rigid pipe.

1.1.2 Flexible Pipe

Flexible pipe is capable of allowable vertical deflection without structural damage. The central soil column is above the pipe is allowed to settle in relation to the side soil column or external prisms. The actual load on pipe is less than the load of central prism (weight of soil above the pipe) found in rigid pipes described above due to shearing stresses and friction forces by differential settlements between external and central prisms. Pipes that behave in this manner are called flexible pipes (Najafi and

Gokhale, 2005). Thermoplastics, ductile iron pipe, steel pipe, reinforced fiberglass, high-density polyethylene (HDPE), and polyvinyl chloride (PVC) are some examples of flexible pipe. Figure 1.1(b) shows the adjusted load in flexible pipes.

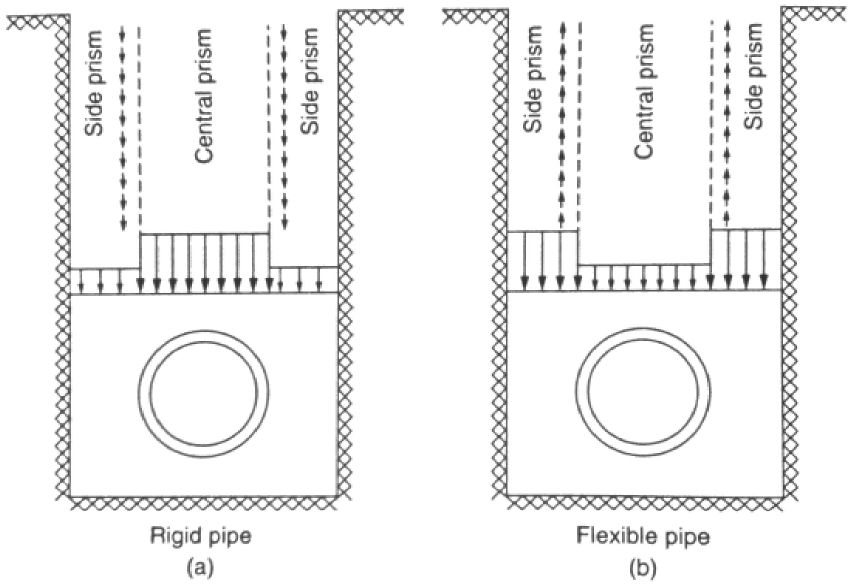


Figure 1.1 Trench Load Comparisons for (a) rigid (Marston load) and (b) flexible pipe (Najafi and Gokhale, 2005)

1.1.3 Semi-Rigid Pipe

Some pipe materials display characteristics of both rigid and flexible pipes. Since current designs are based on the concept of a rigid or flexible pipe, the term semi-rigid is used to describe pipes wherein the deflection range can be-between 0.1 and 3.0 percent without any structural damage (Najafi and Gokhale, 2005). Bar-wrapped concrete cylinder pipe falls under this classification.

1.2 Timeline of Prestressed Concrete Cylinder Pipe (PCCP)

PCCP is one of the rigid pipe types that are extensively used for water and wastewater transmission in the US and around the world. The first prestressed concrete cylinder pipe (PCCP) was manufactured and installed in 1942 in the United States (AWWA RF Study, 1995). The first tentative edition of PCCP (C301) was developed in 1949 by the American Water Works Association (AWWA), which introduced the first permanent edition/standard of PCCP in 1952. The first edition of AWWA Manual M9, published in 1979 provided guidelines establishing the minimum requirements for PCCP design. In year 2007, the latest edition of AWWA C301 was published. AWWA C301 standard describes the manufacture of circumferentially prestressed concrete pressure pipe with a steel cylinder and wire reinforcement (AWWA, 2007) and manual M9 is a comprehensive operations manual for water service explains the use of concrete pressure pipe. The manual provides all the supplemental information engineers and designers need to optimize field performance of concrete pressure pipelines (AWWA, 2008). AWWA PCCP history, publications and publication revisions are summarized in Table 1.1.

Table 1.1 Timeline of PCCP History and Publications (Romer et al., 2007)

Time	PCCP History, Publications, and Publication Revision
1942	First installation of LC-PCCP in U.S.
1949	First tentative edition of AWWA C301, allowable wire stress approximately 45% of ultimately strength and minimum mortar coating thickness 7/8 inch.
1952	First edition of AWWA C301.
1953	First installation of EC-PCCP in U.S.
1955	"Tentative" standard. Included minimum design basis.
1958	Second edition of AWWA C301, allowable wire stress approximately 70% of ultimately strength and minimum mortar coating thickness 5/8 inch.
1964	Third edition of AWWA C301, combined loading design procedure added: allowable wire stress 75% of ultimate strength.
1972	AWWA C301 revised.
1979	AWWA C301 revised.
1979	Manual M9, First edition.
1984	AWWA C301 revised, minimum mortar coating increased to ¾ inch; cast concrete coating deleted.
1992	AWWA C301 revised, design appendices deleted, minimum wire size increased to 0.192 in., minimum cylinder thickness increased to 16 gauge. First edition of AWWA C304.
1995	Manual M9, Second edition.
1999	AWWA C301 revised.
2007	AWWA C301 revised.
2007	Manual M9, third edition.

1.3 Types of PCCP

PCCP has been a very popular rigid pipe during the last fifty years due to its features, which include easy handling, installation, and durability. PCCP include a significant amount of the water utilities' underground inventory for larger diameter pipes in North America. The main components of PCCP are concrete core, steel cylinder, high tensile prestressing wires, and mortar coating. The concrete core makes effective use of concrete's compressive strength; steel cylinder provides tensile strength; prestressed wire gives compressive strength, and mortar coating provides weatherization protection against corrosion.

There are basically two types of prestressed concrete cylinder pipes produced by manufacturers. The first one is linear concrete prestressed concrete cylinder pipe (LC-PCCP). This pipe's diameter is generally less than or equal to 48 in. The second one is embedded concrete prestressed concrete cylinder pipe (EC-PCCP), which is greater than 48 in. diameter. Figure 1.2 shows PCCP types according to diameter size.

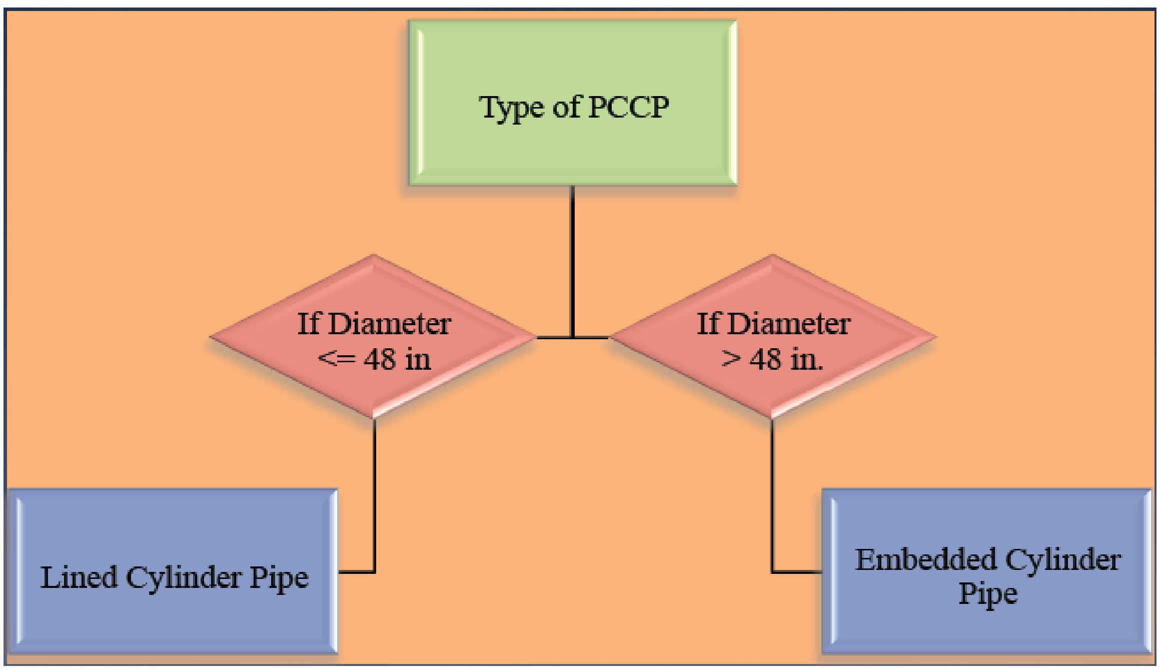


Figure 1.2 Classification of PCCP as per Diameter Size (Kola and Sinha, 2010).

1.3.1 Lined Cylinder Prestressed Concrete Cylinder Pipe (LC-PCCP)

Lined Cylinder Prestressed Concrete Cylinder Pipe was produced in 1942. In 1949 AWWA developed tentative standards for LC-PCCP, also known as AWWA C301 pipes. LC-PCCP is a composite structure of a concrete and lined steel cylinder in which the concrete is directly wrapped by prestressed wire on to the steel cylinder and coated with mortar. Prestressing is accomplished by helical wrapping of high tensile wire around the concrete-lined steel cylinder with precise tension at uniform spacing. It is manufactured in different diameters, ranging anywhere from 16 in. (410 mm) to 60 in. (1,520 mm). Figure 1.3 shows a detailed geometry of the LC-PCCP wall with all components.

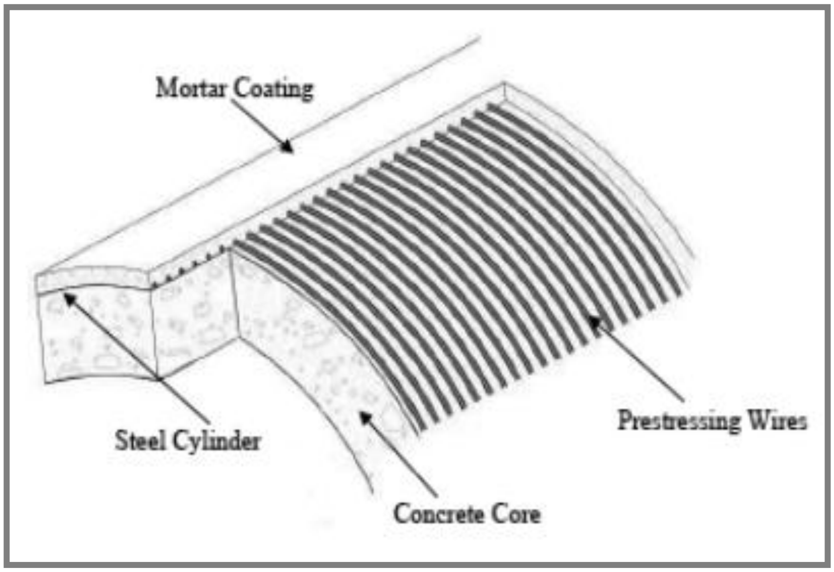


Figure 1.3 Cross-sectional View of Detailed Geometry of LC-PCCP Wall

(Alavinasab et al., 2011)

1.3.2 Embedded Cylinder-Prestressed Concrete Cylinder Pipe (EC-PCCP)

The first Embedded Cylinder Prestressed Concrete Cylinder Pipe (EC-PCCP) was installed in 1953. In that year, the AWWA published standard for C301. Embedded Cylinder-Prestressed Concrete Cylinder Pipe is a composite structure, which consists of a steel cylinder encompassed by concrete and prestressed wire, which is wrapped on the pipe's external concrete and coated with mortar. Prestressing is accomplished by helical wrapping of high tensile wire with precise tension at uniform spacing. The high compressive strength of concrete and steel's high tensile strength gives a combined form of elasticity. It is mostly manufactured in larger diameters or 48 in. (1,220 mm) and larger. Figure 1.4 shows all the component of the EC-PCCP.

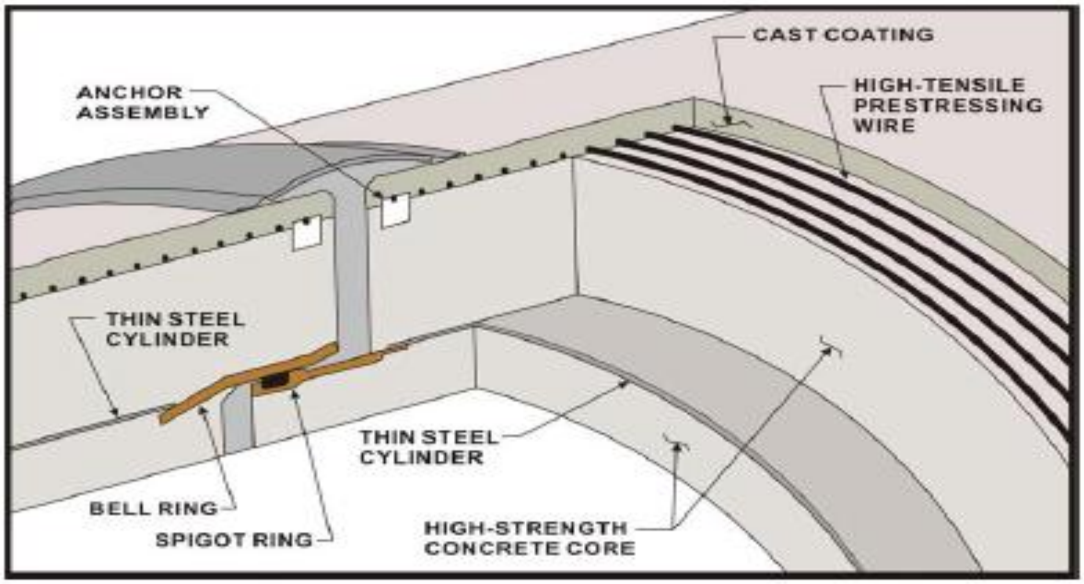


Figure 1.4 Cross-sectional View of EC-PCCP (Zarghamee, 2001)

Table 1.2 summarizes the differences between lined cylinders and embedded cylinders of PCCP as per the diameter size, type of construction or design, and prestressing wire.

Table 1.2 Differences between LC-PCCP and EC-PCCP (Romer et al., 2007)

Parameter	**LC-PCCP**	**EC-PCCP**
Diameter range	16 through 60 in.	30 through 256 in.
Design	Steel cylinder lined with in a cast concrete core	Steel cylinder embedded in a concrete core
Prestressing wire	Wrapped over steel cylinder	Wrapped over concrete core

1.4 PCCP Manufacturing Process

There are eight steps in the manufacturing process of prestressed concrete cylinder pipe, as described below (Arnaout, 2012):

Steps 1: A steel cylinder is fabricated and manufactured.

Step 2: A joint ring is attached to the steel cylinder.

Step 3: The cylinder assembly undergoes hydrostatic testing.

Step 4: The concrete core is embedded (placed) around the cylinder, which is slightly different than what takes place in a lined cylinder pipe. In lined cylinder pipe, the steel cylinder is lined with concrete, whereas in the embedded cylinder, the cylinder is encased in concrete to form the core. Vertical casting or a radial compaction method is used to line a cylinder pipe putting the concrete into place centrifugally. In the embedded cylinder pipe, vertical casting and the mechanical vibration method are used to encase the steel cylinder in the concrete.

Step 5: The concrete core is cured to give it added strength.

Step 6: Prestressing wire size is determined along with the tension and spacing needed to meet design requirement. Finally, the prestressing wire is wrapped around the concrete core to give it a high tensile strength. In the lined cylinder pipe the wire is wrapped onto the steel cylinder directly whereas in the embedded cylinder the prestressing wire is wrapped around the concrete core.

Step 7: Apply mortar coating.

Step 8: Cure mortar coating.

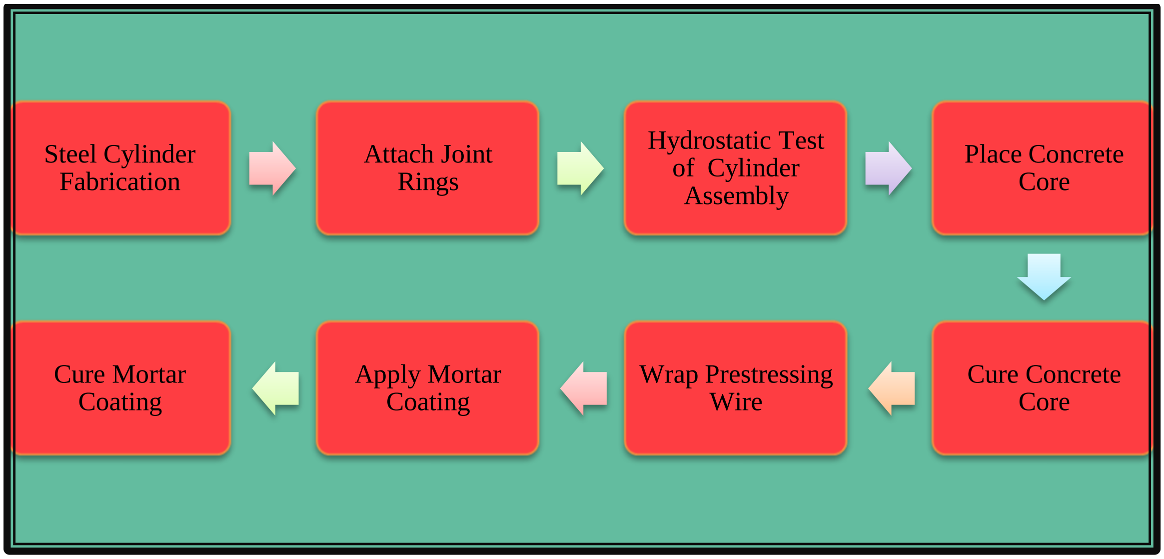


Figure 1.5 Manufacturing Process of PCCP (Arnaout, 2012)

Figure 1.5 shows the stepwise manufacturing process of prestressed concrete cylinder pipe. Each step of the manufacturing processes is explained in detail below.

1.4.1 Fabrication of Steel Cylinder

In the fabrication process of steel cylinder, a required material is cut, rolled and welded into a specified length, size and thickness by welding and shaping. After acquiring the desired shape and size of steel cylinder, the joints are welded to the pipe for testing. Butt welding or offset lap welding is used to wrap the prestressing wire on to the cylinder. Hydrostatic testing is also performed on this steel cylinder assembly to produce watertight pressure pipe. The test can be done in two ways, horizontally or vertically. When using a horizontal method, the hydrostatic test is conducted on pipe which has a thickness of 10-gauge (0.1345-in. or 3.42-mm) or less. The required pressure on the pipe needs to produce a minimum stress of 20,000 psi (138 MPa), but it cannot be greater than 25,000 psi (172 MPa). In the vertical hydrostatic test, the minimum required stress is

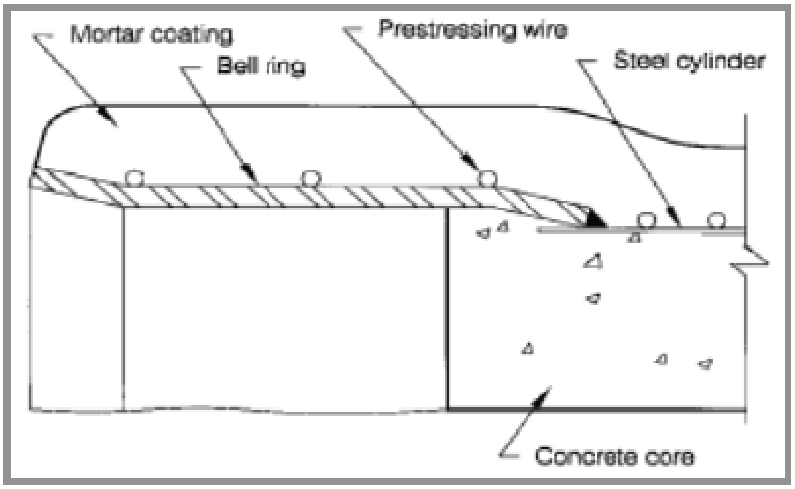
25,000 psi (172 MPa) at the lower end of the pipe. At every stage of these tests, all welds should be inspected and marked. If there is any leakage, the joint must be rewelded at the leakage point. The final product should be a watertight steel cylinder pipe with joint ring attached (AWWA C301, 2007).

1.4.2 Joint Rings

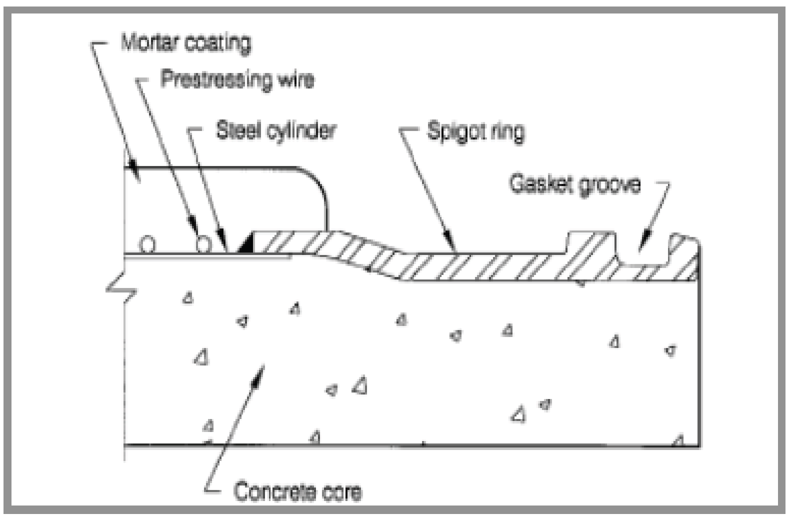
Water pipeline is an assembly of pipes, which transport drinking water to homes from water treatment plants, and the distance which translates to the length of the pipeline is measured in footage or miles. Since there is a limitation on manufacturing a single long pipe in meters or miles, only a single pipeline by joining two or more pipes together to transport water is possible.

The joint ring assembly used to join the pipes is made up of a steel bell ring, steel spigot ring and rubber O-ring gasket. The steel bell-and-spigot joint rings are welded to the end of the steel cylinder by butt-welding and the O-ring gasket is placed in between these two rings to make watertight seal. The welding should be smooth and flush to adjacent surface of gasket. During the pipe installation, the steel bell-and-spigot joint rings should be self-centering. A corrosion protection coating is applied to the exposed portion of steel at the joint rings, and Portland cement grout is also poured into the gap in between the steel bell-and spigot rings for additional corrosion protection. Figure 1.6 (a) and (b) is a cross-section of steel bell ring and steel spigot ring respectively. The steel spigot ring is projected to the end part of PCCP and the steel bell ring is joined at the receiving part of PCCP joints. As shown in Figure 1.7 (b) to groove the O-ring gasket in between the steel bell-and-spigot ring, a gasket groove portion is built in the spigot ring.

The joint rings should be pressed beyond their elastic limits before welded. The gap between the inside diameter of the steel bell ring and steel spigot ring should not be more than 3/16 in. or 4.8 mm if using a gasket, which has a diameter of 21/32 in. (16.7 mm) or less. The maximum out-of-roundness or the gap between those two rings for the pipe of 48 in. or 1,200 mm should not exceed 0.7 percent of the average of the maximum and minimum diameter of steel spigot ring and steel bell ring respectively or 3/16 in (4.8 mm), whichever is higher. In case of 48 in. or larger pipe, the out-of-roundness should not exceed 0.5 in. (12.7 mm) or 0.5 percent of the average of the maximum and minimum diameter of steel spigot ring and steel bell ring respectively, whichever is less. The thickness of bell rings should be 3/16 in. (4.8 mm) and ¼ in. (6.4 mm) for pipes with a diameter of 36 in. (910 mm) or smaller and pipes that have a diameter of 36 in. (910 mm) or larger respectively.



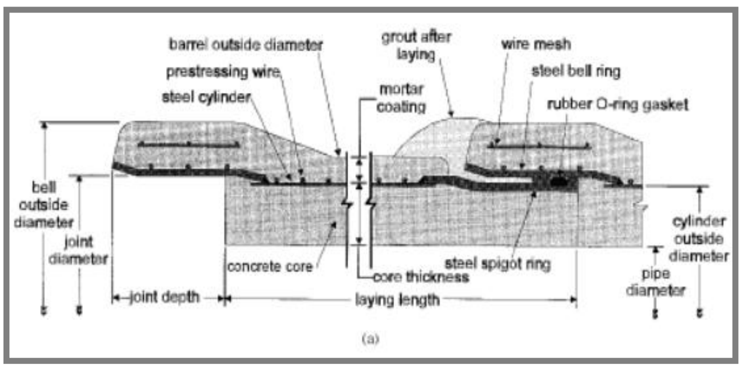
(a) Bell ring joint



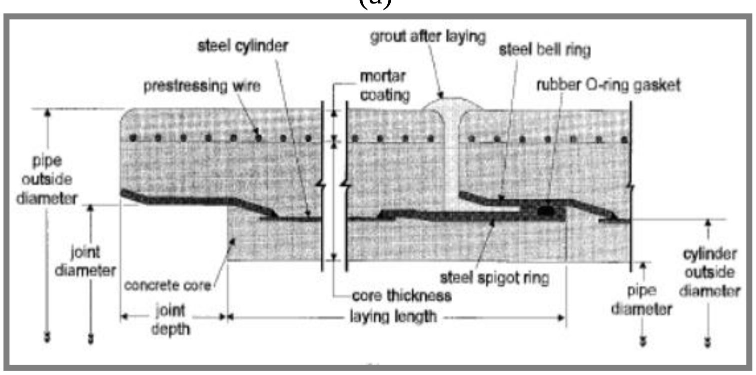
(b) Spigot ring joint

Figure 1.6 Joints in PCCP (a) bell ring joint and (b) spigot ring joint (Nayyar, 2000).

The O-ring gasket is fabricated by hard rubber and used for water tightness in the pipe. It is a round ring, which should have diametric tolerance of ± 1/64 in. (± 0.40 mm). In the gasket rubber compound, polyisoprene or synthetic rubber should not be less than 50 percent of the total volume of gasket rubber. If it is tested according to ASTM D412, the tensile strength should not be less than 2,700 psi (18.6 MPa) for polyisprene rubber gasket and 2,000 psi (13.8 MPa) for synthetic rubber. The minimum density range for the gasket should 0.95 to 1.45 (mg/m^3) and ± 0.05 variations is allowed when it is tested according to ASTM D297. Figures 1.7 (a) and (b) show cross-sectional views of lined cylinder prestressed concrete pipe (LC-PCCP) and embedded cylinder prestressed concrete pipe (EC-PCCP) for the steel bell and spigot joints, respectively. The illustration clearly show how the gasket is grooved in between steel bell-and spigot rings for water tightness and the cement grout is grouted in place between those two rings for corrosion protection (AWWA C301 Standards, 2007).



(a)



(b)

Figure 1.7 Assembly of Joints and O-ring Gasket for (a) LC-PCCP and

(b) EC-PCCP (Nayyar, 2000).

1.4.3 Hydrostatic Test for Cylinder Assembly

Cement, fine aggregate, coarse aggregate, water and admixtures are the main components of concrete. There are basically three methods to place concrete in the pipe core: 1) centrifugal method, 2) vertical casting method, 3) radial compaction method. The minimum requirement of cement in the concrete is 560 lb (254 kg) for each cubic yard (0.76 m^3). If there is not a specified requirement by purchaser, the cement can be replaced with pozzolanic materials up to 20 percent of cement weight and up to 10 percent with silica fume. To achieve a high strength of concrete, the water-cement ratio in the concrete should be maintained and it should not exceed 0.5 for concrete placed by centrifugal method, or 0.45 for concrete placed by vertical casting and radial compaction method. The water-soluble chloride ion (cl-) should not exceed 0.06 percent of the weight of cement. The mixing of material and placing of concrete requires special attention. The aggregates should not be in frozen state at the time of mixing.

When concrete is pouring or placing, the temperature should not be below 40^0 F (4^0 C). While placing the concrete by vertical casting method or radial compacted method the temperature of the mix at the time of concrete placing should not be higher than 90^0 F (32^0 C) and 100^0 F (38^0 C) for centrifugally cast cores unless its specified in "HOT Weather Concrete" by the American Concrete Institute (ACI) Committee 305 (Romer et al., 2008).

1.4.4 Test of Concrete Cylinder

The testing of concrete cylinder is required to test the compressive strength of pipe concrete. The required minimum compressive strength of concrete core at the time of prestressing should be 3,000 psi (20.7 MPa) and 4,500 psi (31.0 MPa) at 28 days for vertical cast method. The required minimum compressive strength of concrete core at the time of prestressing should be 4,000 psi (27.6 MPa) and 6,000 psi (41.4 MPa) at 28 days for the centrifugal and radial compaction method (AWWA C301 standards, 2007).

1.4.5 Concrete Cure

Curing is a process of maintaining satisfactory moisture content at a certain temperature for a certain time period after placing and finishing the concrete to obtain desired properties or strength. Curing is very important for concrete and cannot overemphasize. Portland cement has some chemical properties and when it mixes with water a chemical reaction take place called "hydration." To overcome hydration effect, the curing of concrete is required (Siddique et al., 2007). According to ANSI/AWWA C301-07, curing of the concrete core should be done by an accelerated method, by water curing, and by the combination curing method.

In the accelerated curing method the concrete core should be kept in the curing facility or should be covered in a suitable enclosure to maintain appropriate air movement and steam. To maintain a moist environment for curing of the concrete core, the relative humidity should not be less than 85 percent. The temperature in the enclosure should not be less than 40^0 F (4^0 C) after placing the concrete. After placing the concrete the temperature in the enclosure for the next four hours should not exceed 95^0 F (35^0C). The temperature range in the enclosure should be maintained between 90^0 F (32^0C) and 125^0 F (52^0C) for at least 12 hours following the four-hour concrete placement procedure. Water curing should start after the concrete gains sufficient strength to prevent damage to its exposed concrete surface. The form should not be moved for at least 12 hours after placing concrete. The curing of a concrete core can be done by combining both an accelerated curing method and a water curing method (AWWA C301 Standards, 2007).

1.4.6 Wrap Prestressing Wire

The prestressing wire is wrapped around the concrete core in the helical form with uniform spacing and specified tension; however, in the pipe ends, the wire is applied in a circumferential manner at half of design tension. During wrapping of prestressing wire, the initial compression induced in the concrete core should be below 55 percent of the concrete core's compressive strength. Before wrapping the prestressing wire to the concrete core, the voids of 3/8 in. (10 mm) or larger in diameter and offsets larger than 1/8 in. (3 mm) on the exterior surface of the concrete core should be repaired. The prestressing wire should be rust free and capable of enduring minimum ultimate tensile strength. The tension in prestressing wire should be constantly measured during the wrapping process. The mean tension, which is applied for minimum required stress in the wire, should not fluctuate by ±10 percent. For multiple layers of circumferential prestressing wire reinforcing, each layer should be coated with cement mortar (AWWA C301 standards, 2007).

1.4.7 Apply Mortar Coating

Mortar coating is the outermost layer of prestressed concrete cylinder pipes. After wrapping prestressed wire on the concrete core, the minimum mortar coating thickness of ¾ in. (19 mm) should cover the prestressing wire. At the start of mortar coating the temperature of wrapped core should not be lower than 35 ^{0}F (2 ^{0}C). The batching portion of mortar consists of one portion of Portland cement and three portions of fine aggregate, by weight. The minimum contained moisture should be greater than 7 percent of total dry weight of mix (AWWA C301 Standards, 2007).

1.5 Advantages and Limitations of PCCP

PCCP is very thick when compared to other pipe materials, which in turn increases its resistivity to physical damage. The installation of the pipe is easy and economical. This pipe has a wide variety of diameter ranges from 16 to 256 in. Despite these advantages, this pipe has certain limitations. This pipe is heavy, which makes the handling difficult and an extra coating is required to protect the pipe from corrosion. Table 1.3 summarizes the advantages and limitations of PCCP.

Table 1.3 Advantages and Limitations of PCCP (Adapted from Romer et al., 2007)

Advantages	Limitations
Resistant to physical damage	—
Rapid and economical installation	Heavy, therefore shipped in shorter lengths.
Good Corrosion resistance compare to other pipe material like steel pipe, Ductile Iron Pipe and cast iron pipe.	Requires careful installation, e.g., considering suitability of bedding condition and soil type before installation.
Designed for the combination of internal pressure and external loading	—
Wide range of pipe diameter available (up to 256-in.)	—
Typically more economical than properly lined and coated ferrous pipes	—

1.6 Objectives

The objectives of this thesis are:

1. Using literature search, analyze the field performance of large diameter (24 in. and more) Prestressed Concrete Cylinder Pipe (PCCP) in water transmission applications.
2. Conduct and Analyze survey data to understand causes and modes of PCCP failures.

1.7 Methodology

The methodology of this thesis is summarized below:

1. Conduct a thorough literature search.
2. Collect the field performance data of PCCP from selected water utilities in the United States by a survey. A survey was conducted by Center for Underground Infrastructure Research and Education (CUIRE) at UT, Arlington. Thirteen water utilities have responded to this survey. The survey contained 13 questions on the area served by water utilities, total footage of PCCP according to the diameter, total length of inventory, and various causes and modes of failures.
3. Compile the data obtained from all the survey responses and carefully review in order to analyze and determine the field performance of PCCP according to age and location.
4. Study the failure patterns.

5. Conduct a statistical analysis on the field performance of PCCP pipe according to the pipe type, size of the diameters, and age.

1.8 Thesis Organization

The organization of this study is as follows. Chapter 1 presents a brief history of PCCP along with the PCCP manufacturing process. In the second chapter, literature on the topic is reviewed. The third chapter discusses methodology used for data gathering and analyzing the data. Chapter 4 discuses results as well as statistical analysis of survey data. The chapter builds a statistical model of pipe failure rates. Chapter 5 discusses the results as presented in the previous chapter. The final chapter offers a summary of conclusions and recommendations for future research.

1.9 Expected Outcome

This study will evaluate the use of 24 in. and larger diameter PCCP pipes in water distribution utilities in the U.S. for survey respondents. Failure rate of PCCP pipes per hundred miles, types of failures, footage, age, and failure comparison between diameters ranges, reported by water utilities, will be reported.

1.10 Chapter Summary

This chapter gave a brief history of pipeline infrastructure and types followed by the introduction of PCCP which is used extensively as the water and wastewater pipeline in the US and around the world. It also presented the types of PCCP, timeline, and a step-by-step analysis of the PCCP manufacturing process. It also reviewed the objectives and methodology of this research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter consists of findings from previous research on PCCP performance and provides better knowledge of causes of pipe failures, which could be due to internal as well as external damage. This chapter covers causes of failures, consequences of pipeline failures, and the failure patterns of PCCP.

2.2 Failure Causes

Causes of the pipe failures can be internal as well as external cracks. The possible reasons of failure are due to deterioration and internal corrosion (Ojdrovic et al., 2011). Other internal problems are decay due to the quality of material, construction methods, and operational parameters, while external factors could be related to environmental conditions (Marshall and Fisk, 2010); wire breaks (Bell, 2010) etc. This thesis discusses the most common causes of PCCP failure, which adversely affect the service life of PCCP; five of these reasons are discussed below:

2.2.1 Failure due to Corrosive Environment

External corrosion is a well-known reason for pipe failures in the water pipelines Rostum, 2000; Folkman, 2012). The basic reason behind corrosion is metal's electrochemical process, which precedes the degradation of material. Properties of the surrounding environment, e.g., acidic soil, sour gas created during oil production, accidents involving natural gas transmission, etc. Uncontrolled corrosion means less service life of pipe and higher cost. If proper corrosion control technology is used in water pipelines a significant operations and maintenance savings can be made (Romer and Bell, 2004).

A 2001 study by Romer and Bell broadly characterizes failures in five categories, listed below:

1) *Corrosive soil* condition is the most common cause of external corrosion. More than 2,000 ppm sulfates concentrated and 350 ppm chloride concentrated in soil can be damaging for cement mortar coating or concrete pipe. Industrial wastewater and mine tailings contain acidic minerals that make surrounding soil high in acidic properties, which react with cement mortar and corrode it.

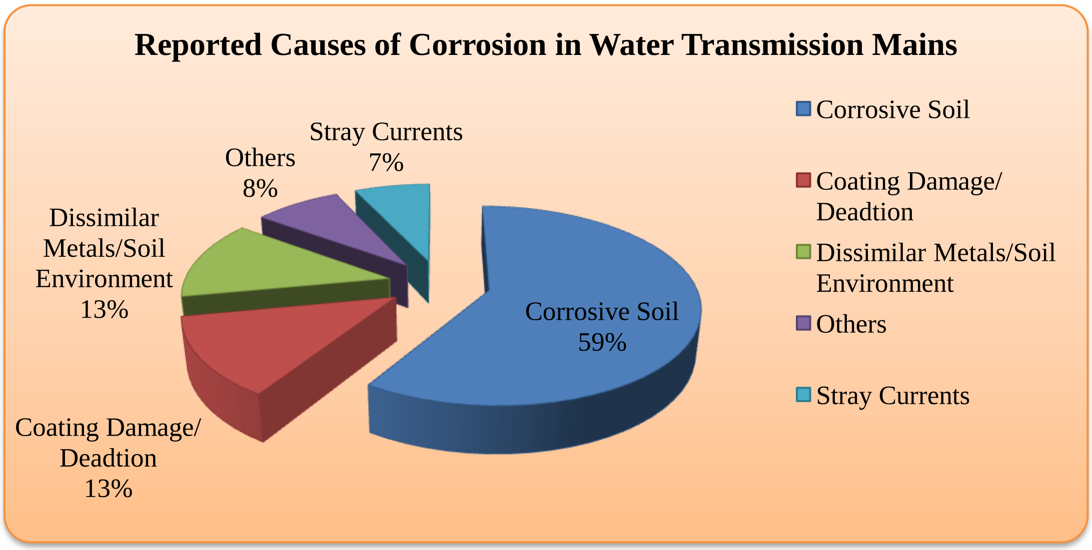
2) *Dissimilar metals* include copper service lines directly connected to the unprotected metallic lines, i.e., two pipelines connected without electrical isolation.

3) *Coating damage* includes cement-mortar coatings damaged by physical handling, omission of coating at joints prior to back fill, disbandment of coatings by misapplication of cathodic protection and inappropriate repairs of coatings.

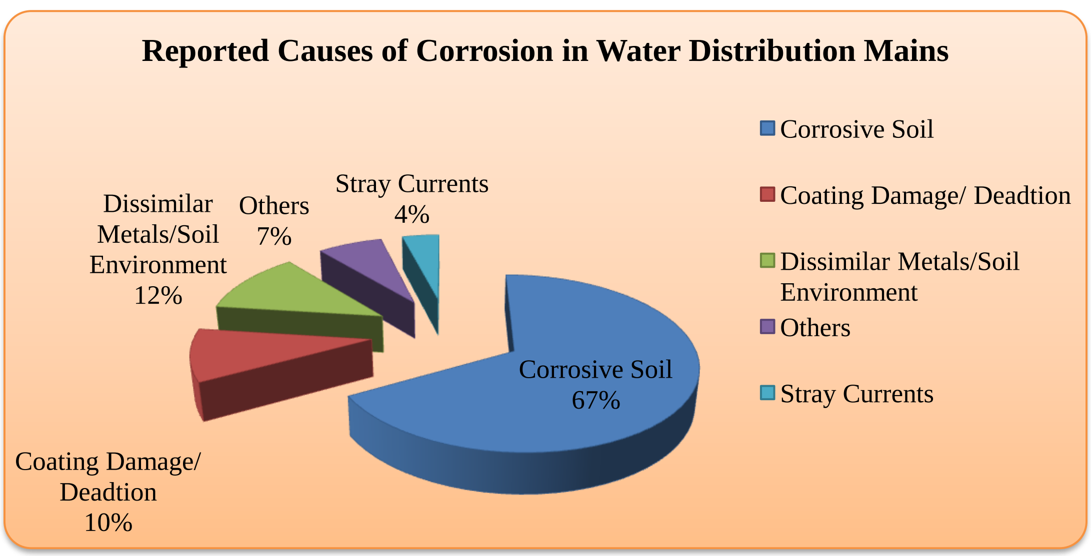
4) *Secondary effects* include biochemical or bacterial action, hydrogen embrittlement of prestressing wire, metallic coating, and stress or crevice corrosion.

5) *Stray current* is a common cause of external pipe corrosion. It happens when the buried pipeline reacts like an anode and the ground or another structure behaves like a cathode causing the current to flow from pipe to ground or another structure, resulting in

corrosion. The causes of stray current are electric power transmission lines, direct current from other pipelines' cathodes protection systems, and lighting.



(a)



(b)

Figure 2.1 Causes of Corrosion in PCCP due to (a) water transmission mains and (b) water distribution mains (Romer and Bell, 2001).

Figure 2.1 shows (a) corrosion from transmission mains, and (b) reported causes of corrosion from distribution mains. In Figure 2.1 (a) a maximum 59% of corrosion during water transmission is due to the corrosive soil and the minimum corrosion percentage is due to stray currents, while in Figure 2.1 (b) the causes of corrosion in distribution mains are due to the corrosive soil (67%), which is 8% higher than what is found in transmission mains.

2.2.2 Failure due to Wire Breaks

Failure depends on a number of factors including broken wire, location of broken wire, original pipe design, and maximum pressure likely to occur in the future (Zarghamee and Ojdrovic, 2001; Zarghamee et al., 2011; Parks et al., 2001). Overloading of the highly stressed and longitudinally cracked prestressing wire can be a cause of most common types of rupture (Uyeda et al., 1994; Bell and Paulson, 2010).

As per Margevicius and Haddad, prestressed concrete cylinder pipe fails because of the failure in prestressed reinforcing wires. Defective prestressing wire, carbonation of the concrete core, incomplete encasement of the prestressing wire with Portland cement slurry and mortar coating are may be some primary reasons for wire breaks (Margevicius and Haddad, 2002; Holley and Rittenhouse, 2008). Figure 2.2 shows wire breakage in 36-in. and larger PCCP diameters due to corrosion of prestressing wire.

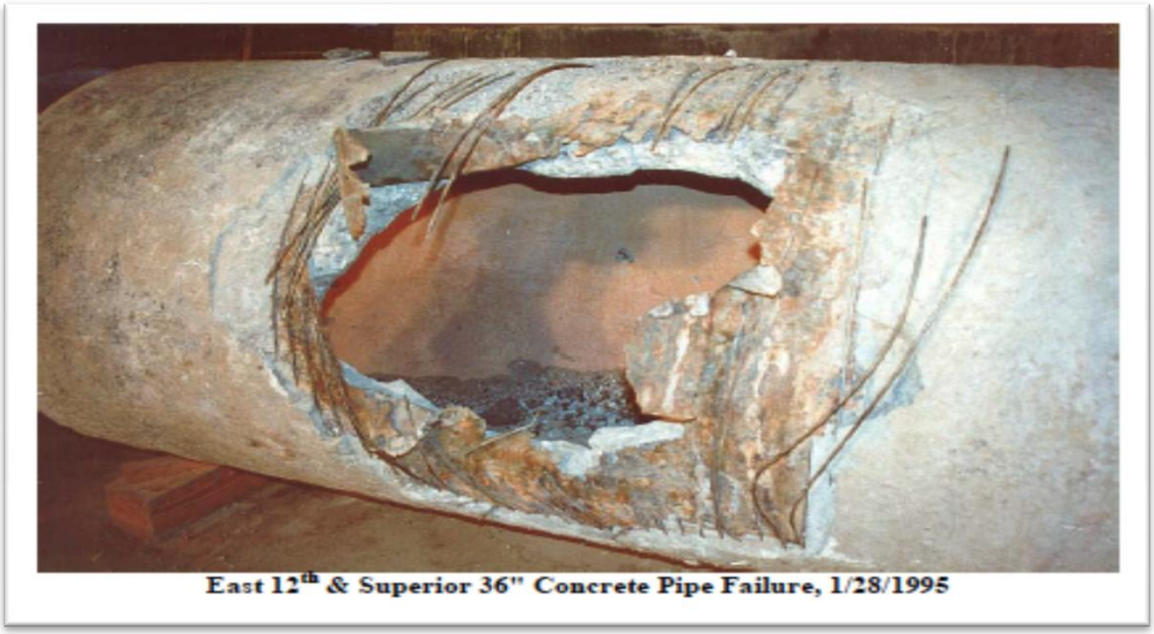


Figure 2.2 PCCP Rupture Failure due to Wire Break in 36-in. Diameter Size Pipe (Margevicius and Haddad, 2002)

2.2.3 Defective Manufacturing Materials and/or Manufacturing Methods

Manufacturing defects could be due to the utilization of low quality of mortar during manufacturing of pipe, leaking in joints due to out-of-roundness, poor quality of alkali-silica, wire manufacturing problem, excessive core creep and shrinkage due to high water cement ratio, excessive fine aggregate ratio, and improper curing of the concrete (Romer et al., 2007). Similarly, Uyeda points to defective wire and longitudinal cracks in prestressing wire during pipe manufacturing causing high stress during the winding operation resulting in fractures in the prestressing wire (Uyeda et al., 1994; Marshall and Fisk, 2010).

2.2.4 Failure Due to Improper Design

Design of PCCP is a very complex procedure, and the owner/engineer should review it prior to its implementation. Improper design can lead to pipe failures and ruptures. Pipe failure can be caused by inadequate joint restraints and dissimilarity in bedding stiffness that can lead to differential settlement and circumferential cracks Coating cracks due to excessive operational pressure and operational surge pressure, and cracking of the core and coating can all occur during the pipe load (Romer et al., 2007).

2.2.5 Failure Due to Construction Damage

As noted by Romer, failure by construction damage includes third party damage, settlement of soil or structure, wrong pipe class, wrong wire size, structural distress, and others (Romer et al., 2007).

Third party damage is an accidental damage during construction of pipeline from other workers' construction or mechanical equipment. PCCP is designed for specific location and suitable bedding condition. If a wrong pipe class is used at an unsuitable condition, the pipe strength will reduce and may be result in pipe failure. Damages and defects in PCCP may be due to wire breaks and cracks (Alavinasab et al., 2011).

2.3 Consequences of Pipeline Failures

Prestressed concrete cylinder pipes are manufactured in large diameters to transport thousands of gallons of water from sources such as water reservoirs, lakes, and rivers to water treatment plants. Every day, thousands of gallons of water are lost due to water pipeline failures in the United States. Failure of PCCP is measured in pipe breakage due to ruptures as well as leaks, deterioration, structural weakness, and loss of service.

The American Water Work Association defines failure of PCCP as:

"Failure was indicated as requiring action after installation to correct a pipe deficiency – repair, replacement, or both repair and replacement of the affected units" and "The term failure is synonymous with repair and replacement rate."

The existing literature shows a variety of factors that can affect PCCP failure patterns. As said previously, different types of failures in pipes can lead to rupture or other problems, which can affect water pipeline performance underground. These failures vary widely from modest to substantial as shown in the data research conducted in earlier studies. Some of the causes of failures are summarized in Table 2.1.

Table 2.1 Comparison of Results from Prior Studies

Study	**Date**	**Conclusion**
Marshall and Flak	2010	PCCP fails by the poor quality of material, construction damage, operational parameter and environmental condition
Bell et al.	2010	PCCP fails due to wire breakage
Romer and Bell	2004	PCCP Fails due to corrosive environment
Zarghamee and Oidrovic	2001	Rupture failure in PCCP due to wire breaks
Margevicius and Haddad	2002	Rupture failure in PCCP due to defective prestressing wire
Romer et al.	2007	PCCP failure due to defective manufacturing materials, methods and improper design
Uyeda et al.	1994	Longitudinal cracks in PCCP during prestressing

2.4 Chapter Summary

This chapter examined the existing literature on failure of PCCP pipes. The pipeline failure can have a significant impact on the society and environment. Various causes of PCCP failures were discussed. This chapter presented a comparative analysis of prior studies.

CHAPTER 3

METHODOLOGY

This chapter discusses the methodology to analyze the performance of Prestressed Concrete Cylinder Pipe (PCCP) in water transmission and presents survey data to analyze the failure rate of PCCP pipe.

3.1 Introduction

This research is divided into two parts. The first part begins with a data representation of survey responses. The second part presents the statistical analysis of the performance data by diameter and years. The methodology is explained further in this chapter.

3.2 Use of Surveys

A survey was created to identify the cause of failure of large diameter pipelines including prestressed concrete cylinder pipe in water transmission. This study was conducted at UT Arlington. Survey data was synthesized by the Center for Underground Infrastructure Research and Education (CUIRE). The survey was designed in an effective way to get maximum information or data on large diameter pipelines including PCCP pipe failure. The process followed in completion of the survey is shown below:

- Set goals and objectives of survey
- Create questionnaire – what to ask
- Disperse the survey to water utilities

- Collect responses
- Analyze the survey responses

The email method was used in dispersing the survey and some telephone interviews were followed. The survey sample is included in Appendix B.

3.2.1 Data Collection

Various methods of data collection were adopted including personal interviews, telephone interviews, and email surveys to collect the data from various water utilities. There were some multiple-choice questions, and essay questions.

3.2.1.1 Personal Interviews

Some of the survey questions were asked from the representatives of water utilities in the Underground Construction Technology (UCT) 2012 conference in San Antonio, Texas, and ASCE Pipelines Conference 2012 in Miami Beach, Florida. Good responses from personal interviews were received. The personal interview approach helped to comprehend the questions clearly and create new ideas.

3.2.1.2 Telephone Interviews

Telephone interviews with some water utilities personnel were conducted. It was also used in to gather data that was unclear or not provided in the responses.

3.2.1.3 Email Surveys

An email surveys is a convenient method. It is the fastest and most economical of all methods utilized. The responder can reply whenever it’s convenient to them and send their response back momentarily. In this study the emailing method was utilized the most.

For the convenience of responders, the survey was sent in two formats, Microsoft Word and PDF.

3.2.2 Survey Analysis

The original survey was sent to more than 300 water utilities and 13 utilities responded to the PCCP part. Figure 3.1 presents the geographical location of those water utilities that responded back. Some questions were partially answered and to fill the gap, some respondents sent their pipe reports in Excel spreadsheet. Those utilities that populated their survey partially or sent Excel sheets were later contacted via telephone or email to get more information.

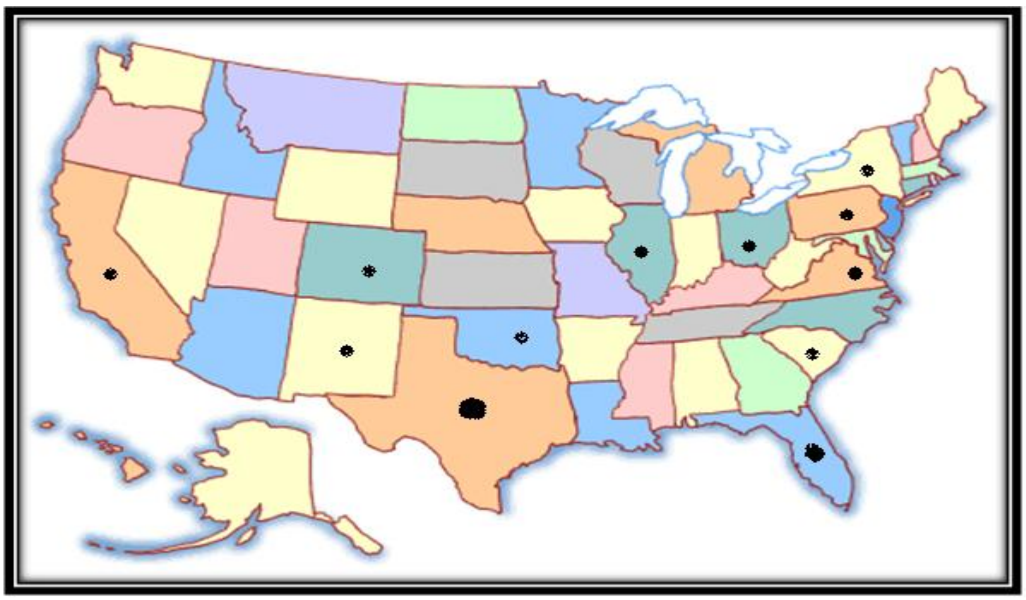


Figure 3.1 Geographical Locations of Water Utilities

3.3 Methodology

This part of research introduces statistical analysis for the year of pipe installation, diameter ranges, and the types of failures observed.

3.3.1 Dependent Variable

The dependent variable, $FailureRate_{dt}$, is constructed by dividing the number of failures across each diameter category ($Failures_d$) to total number of failures in a year ($TotalFaliures_t$).

3.3.2 Independent variable

Independent variables include:

(1) Three dummy variables: A dummy variable is a variable that takes on the values of 1 and 0 in the regression model, for diameter category (*Diameter*) - (A) between 24 in. and 36 in., (B) between 42 in. and 48 in., and (C) 54 in. and larger. Diameter range of 24 in. and 36 in. is used as the base case or the comparative case.

(2). Another variable used in the model is the dummy variable for year (*Time*) that represents the time period from 1971 to 2011 with the base case of 1971.

Table 3.1 below provides the definition and descriptive statistics for the variables collected in the survey and used in the analysis:

Table 3.1 Descriptive Summary Statistics

Variables	Definition	Mean	Std. Deviation	Min	Max
$Failures_d$	Failures across each Diameter Category	1.83	1.12	1	6
$TotalFaliures_t$	Total Number of Failures in a Year	3.82	2.64	1	9
$Diameter_d$	Dummies for Diameter Range (3)				
	Between 24 in. and 36 in. (Base Case)			0	0
	Between 42 in. and 48 in.			0	1
	54 in. and larger			0	1
$Time_t$	Year Dummies				
	1971 (Base Case)			0	0
	1972 – 2011			0	1

Number of Observations = 92

3.3.3 Model

A categorical regression model is presented. This model quantifies the data by assigning numerical values to the categories, resulting in an optimal linear regression equation.

The model presents the failure rate as a function of explanatory variables, years and diameter categories. The complete model has the following form:

$$FailureRate_{dt} = \alpha + \beta_d Diameter_d + \beta_t Time_t + \varepsilon rror_{dt}$$

And, $FailureRate_{dt} = Failures_d / TotalFaliures_t$

Where, *FailureRate* is a ratio of number of Failures across each diameter category by total number of failures in that year. *Diameter* represents dummy variable for the diameter categories- between 24 in. and 36 in., between 42 in. and 48 in., and 54 in. and larger, and *Time* denotes dummies for year from 1971 to 2011.

3.4 Chapter Summary

This chapter introduced the research methodology. This chapter further explained the research process of data presentation. Also, statistical model used to analyze the survey data was discussed.

CHAPTER 4

RESEARCH RESULTS

4.1 Introduction

This chapter presents the results and statistical analysis of the failure data. Results are separated into two groups: 1) data representation of the failure data, and 2) statistical model of failure rate by diameter size over multiple years.

4.2 Data Presentation

4.2.1 Total Population Served

The total population of the area served by water utilities is very important. It gives a good idea about the size of water utilities. Figure 4.1 presents population of 13 water utilities with PCCP in their inventory. The lowest population among those water utilities is 11,529 and the highest is about 3 million. The total population reported is 13,892,508.

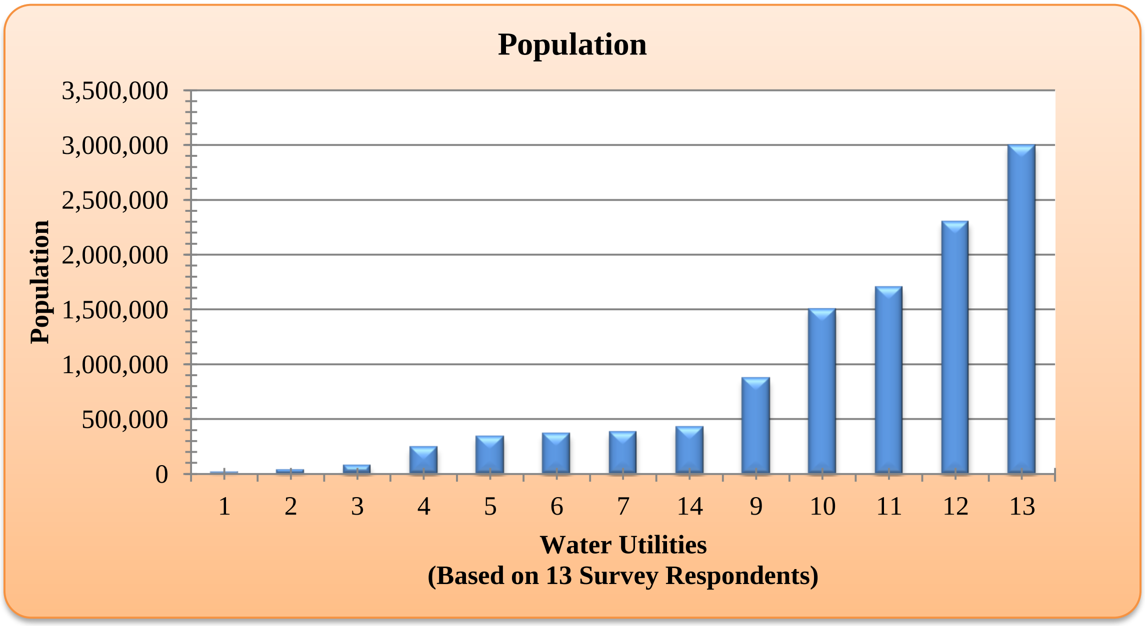


Figure 4.1 Population of all Water Utilities

4.2.2 Total Footage

One of the questions in the survey was to provide the total footage of 24 in. and larger pipes in their water utility but some water utilities gave total pipe length they serve including less than 24 in. Those water utilities were contacted again to update their survey results. The total footage of 24 in. and larger pipes (including PCCP and others as shown in Figure 4.2) reported by survey respondents is 1,987 miles. Figure 4.2 shows the total pipe length of 24 in. and larger for every individual in their water utilities system. The highest footage is 432 miles for Water Utility 13, and the lowest footage is served by Water Utility 1, which is 3 miles.

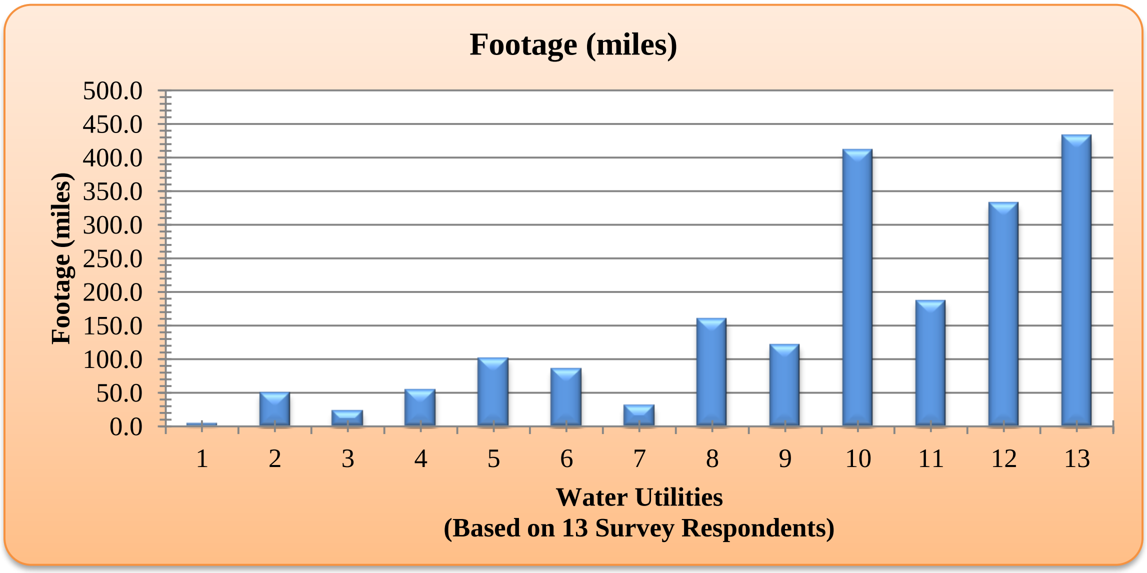


Figure 4.2 Footage of 24 in. and Larger Pipe in Water Utilities.

4.2.3 Population Served per Mile

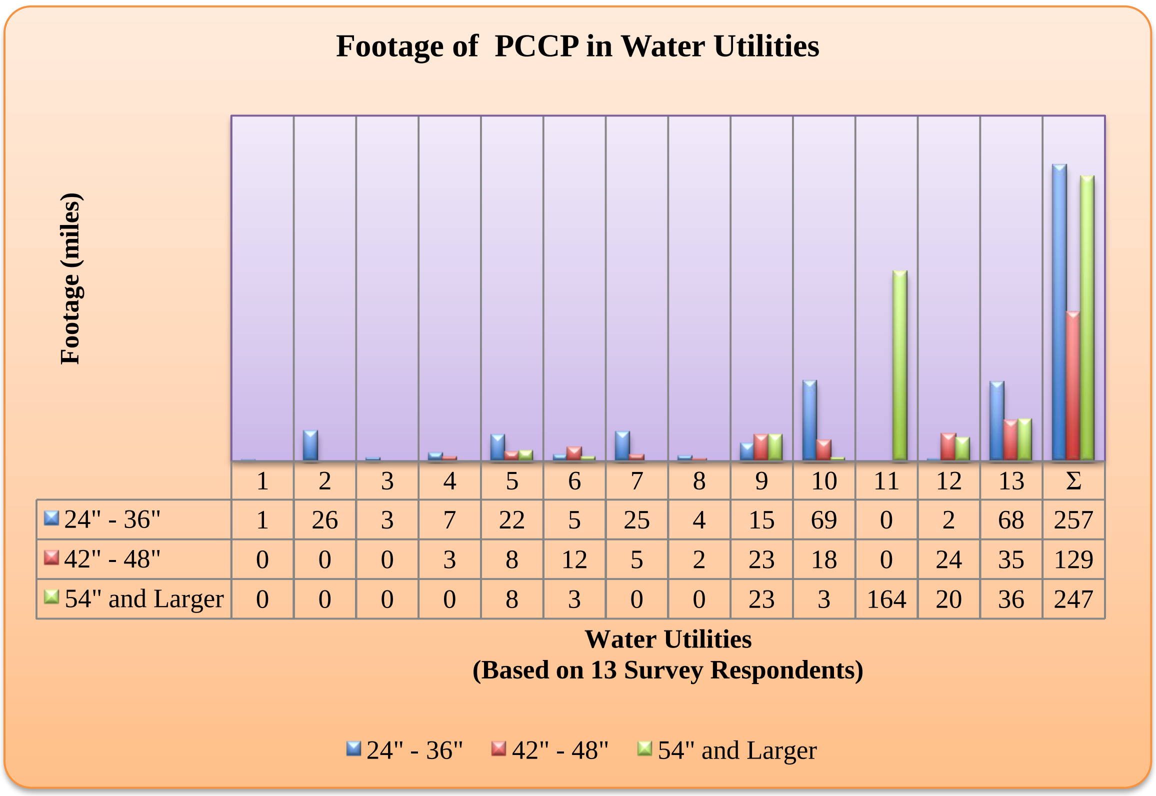
Population served per mile is a ratio of total population served by a utility to total footage (miles) of 24 in. and larger pipes of that water utility. Table 4.1 shows population served per mile.

Table 4.1 Population Served per Mile (Based on 13 Survey Respondents)

Survey Respondents	Population Served	Footage (miles)	Population Served per mile	Survey Respondents	Population Served	Footage (miles)	Population Served per mile
1	11,529	3	3,792	8	420,000	159	2,633
2	34,400	49	694	9	867,599	120	7,182
3	78,000	22	3,482	10	1,500,000	410	3,651
4	240,000	54	4,444	11	1,700,000	187	9,091
5	340,758	100	3,381	12	2,300,000	331	6,936
6	365,438	85	4,299	13	3,000,000	432	6,944
7	380,000	30	12,667	Total	11,237,724	1,986.5	69,196

4.2.4 Diameter Size

As discussed in the previous chapter, Prestressed Concrete Cylinder Pipe (PCCP) is commonly used in large diameter sizes. Figure 4.3 (a) explains diameters of PCCP pipes in each water utilities based on footage length. The total footage of PCCP for all of the water utilities is 632.2 miles with 246.1 miles of 24 in. to 36 in. diameter, 128.9 miles of 42 in. to 48 in. diameter and a remaining 257.2 miles of 54 in. and larger.



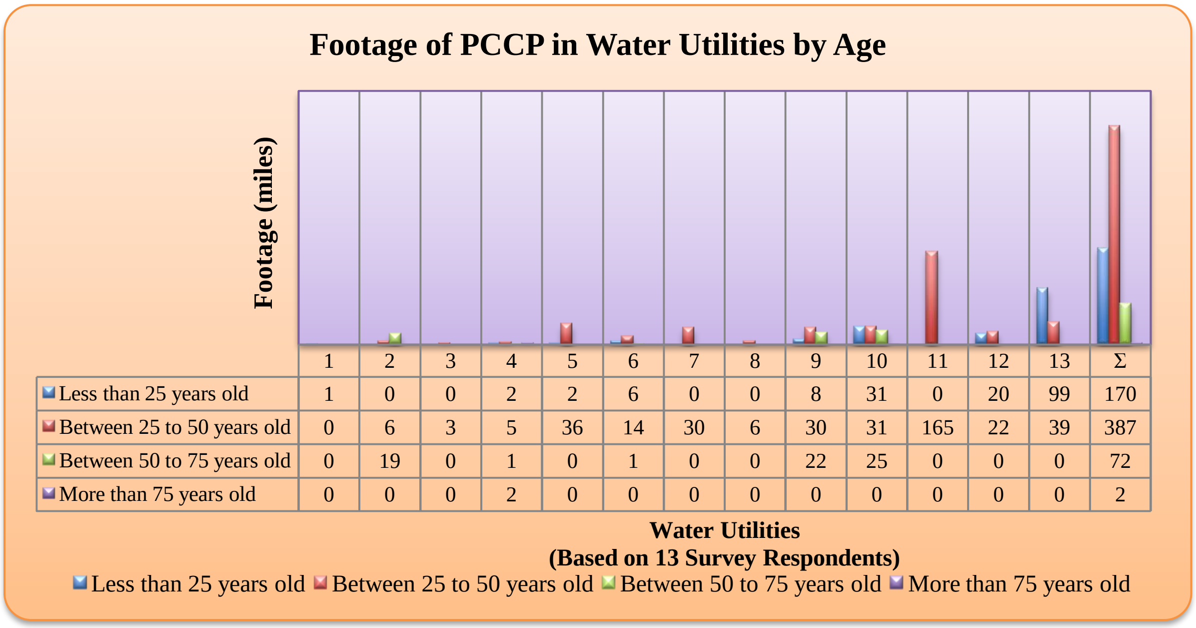
	1	2	3	4	5	6	7	8	9	10	11	12	13	Σ
24" - 36"	1	26	3	7	22	5	25	4	15	69	0	2	68	257
42" - 48"	0	0	0	3	8	12	5	2	23	18	0	24	35	129
54" and Larger	0	0	0	0	8	3	0	0	23	3	164	20	36	247

Figure 4.3 PCCP in Water Utilities by Footage

4.2.5 Age of PCCP

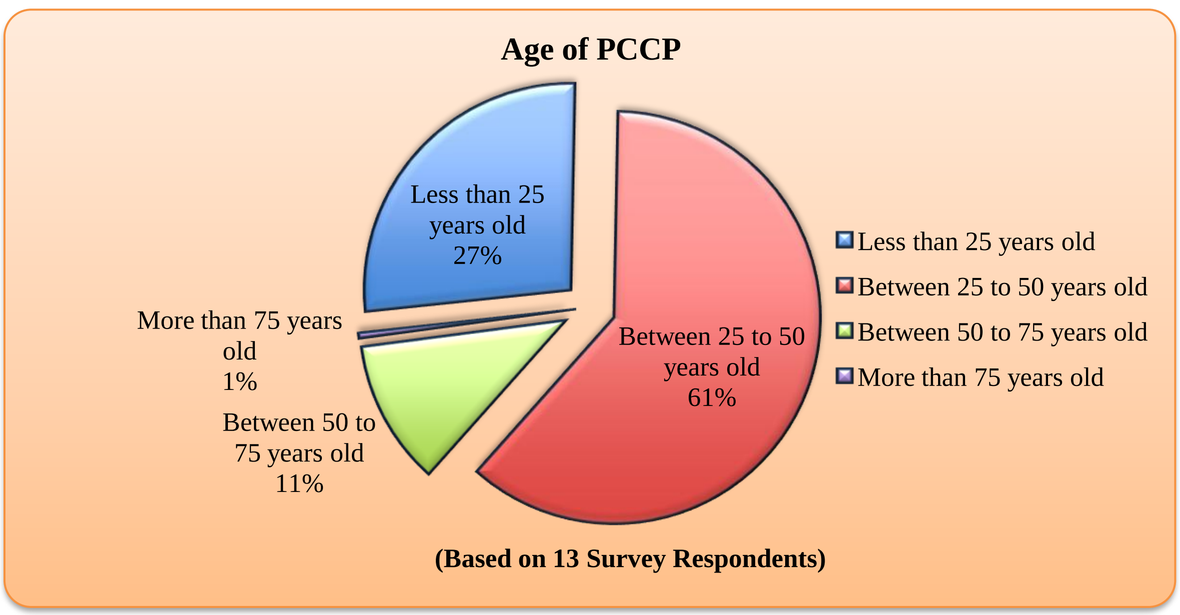
Both literature review and survey data suggest that majority of PCCPs in service is between 25 and 50 years. Figure 4.4 (a) represents the total footage in miles of PCCP in four different age categories of less than 25 years old (170 miles), between 25 to 50 years old (387 miles), between 50 to 75 years old (72 miles) and more than 75 years old (2 miles), based on the inventory of survey respondents. The maximum age of PCCP for these water utilities is between 25 to 50 years (see Figure 4.4b).

Figure 4.4 (b) shows percentage of PCCP pipe based on age for the surveyed water utilities.



	1	2	3	4	5	6	7	8	9	10	11	12	13	Σ
Less than 25 years old	1	0	0	2	2	6	0	0	8	31	0	20	99	170
Between 25 to 50 years old	0	6	3	5	36	14	30	6	30	31	165	22	39	387
Between 50 to 75 years old	0	19	0	1	0	1	0	0	22	25	0	0	0	72
More than 75 years old	0	0	0	2	0	0	0	0	0	0	0	0	0	2

(a)



(b)

Figure 4.4 Age of PCCP in Water Utilities by (a) footage and (b) percentage in inventory

4.2.6 Number of Failures

This section discusses failures reported by the surveyed water utilities. Figure 4.5 (a) shows the failures by diameter range. There were a total of 13 water utilities that reported a total of 92 failures in which there were 47 failures in the pipe diameter range between 24 in. and 36 in., 12 failures in the pipe diameter range between 42 in. and 48 in., and 33 failures in the pipe diameter range of 54 in. and larger. No failures were reported for other PCCP diameter ranges.

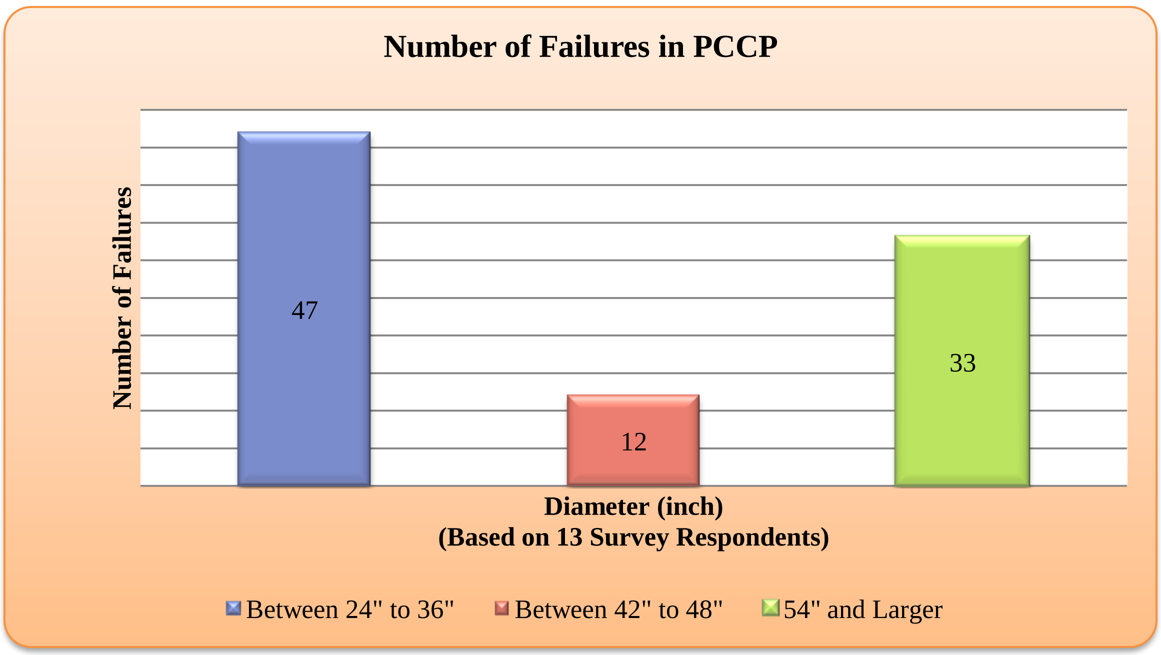


Figure 4.5 Numbers of Failure by the Water Utilities.

4.2.7 Failure Rate of PCCP

This section discusses the failure rates of all the pipe materials from all the survey respondents for all diameter sizes. The failure rate is calculated using the following formula:

Failure rate per 100 Miles = {Number of failure/ total footage (Miles)} x 100

= {(25+3+1+2+14+29+14+3)/632} x100 = 15 failure per hundred mile

Average Failures = Sum of all the number of failures / total water utilities

= 92/13 = 7 failures per utility

The failure rates by each water utility are summarized in Table 4.2.

Table 4.2 Failure Rate of PCCP (Based on 13 Survey Respondents)

Water Utility	Number of Failures	Footage (miles)	Failure Rate per mile	Failure Rate per 100 miles
1	0	1	0	0
3	0	25.6	0	0
6	0	2.6	0	0
9	25	9.8	2.551	255
11	3	38.5	0.078	8
12	1	20.3	0.049	5
13	2	30	0.067	7
14	0	6	0	0
16	0	60.5	0	0
18	14	90	0.156	16
19	29	164	0.177	18
20	14	45	0.311	31
21	3	139	0.022	2
Total	**92**	**632.3**	**0.146**	**15**

As per survey results, the total number of failures in PCCP was 92, and the total length of PCCP was 632 miles. The total failure rate for PCCP, therefore, is 15 per 100 mile. Figure 4.6 presents the failure rates per hundred miles for each individual water utility. It should be noted that this failure rate is only valid for the PCCP inventory of survey respondents, and cannot be regarded as expected as an overall PCCP failure rate.

For example, Romer et al (2008) reported a failure rate of 2.65 per 100 miles per year for embedded cylinder PCCP and 25.4 per 100 miles per year for lined cylinder PCCP.

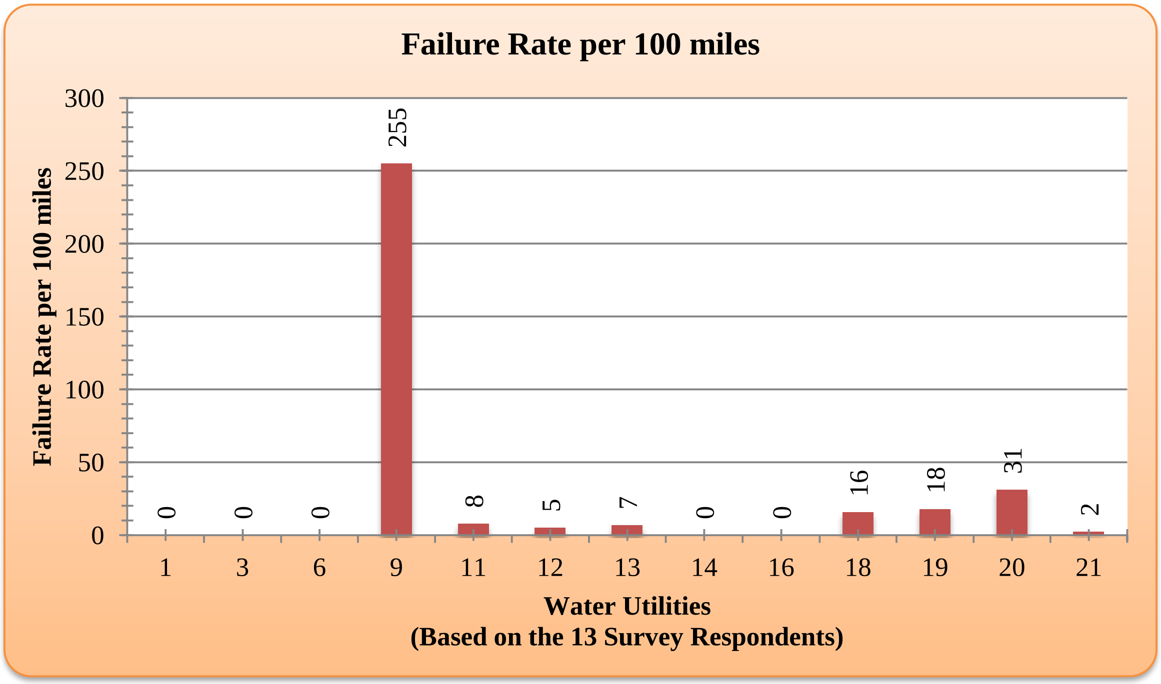


Figure 4.6 Failure Rates per 100 Miles Reported by Survey Respondents

The failure rates were further analyzed based on the different regions in the U.S. The responding water utilities based on their locations were categorized in 4 regions. A total of 92 failures were reported by 13 different water utilities. Table 4.3 summarizes failure rates in these different regions.

Table 4.3 Failure Rate by Region (Based on 13 Survey Respondents)

Region	Failure	Footage (miles)	Failure Rate per 100 miles
Northeast	2	6	33
Midwest	40	160	24
Mid-south	47	368	12
Southwest	3	38	7

4.3 Statistical Analysis

To analyze the performance of PCCP, this analysis covers the failure rate across various diameter ranges over multiple years from 1971 to 2011. The literature offers little guidance to answer this question and whether these changes vary by type of diameter or by year. Failure rate, a continuous dependent variable, is hypothesized to be a function of categorical independent variables including years and diameter size. This thesis presents the failure rate by dividing total failures in each diameter range by total failures in that year. For the diameter size, the pipe diameters were classified in three categories as follows:

- Category 1: between 24 in. and 36 in.
- Category 2: between 42 in. and 48 in.
- Category 3: 54 in. and larger.

Figure 4.7 summarizes the rate of failure, by diameter size over the time spans designated in the study. Failure rate was calculated by dividing the number of failures across each diameter category by total number of failures in a year. For example, in the year 1982, the failure rate for the diameter range 24 in. to 36 in. was calculated to be 80%. It was calculated by dividing 4 failures that occurred in that year for that diameter divided by the total failures (5) in that year. The failure rate calculated from the sample data was graphed against the years, from 1971 to 2011, for all diameter ranges. By graphing calculated failure rate against each year, notable high points were in the years 1982 and 2010 for the diameter range between 24 in. and 36 in., which may suggest that this range continues to experience a higher failure rate. For the diameter range, 42 in. to

48 in., there seems to be a downward trend since 2009. A similar trend is observed for the diameter range, 54 in. and larger, where failure rates have started to decline in last few years. This analysis is based on 8 responding utilities and may not be valid for other water utilities. However, same procedure can be applied to investigate failure trends for other utilities.

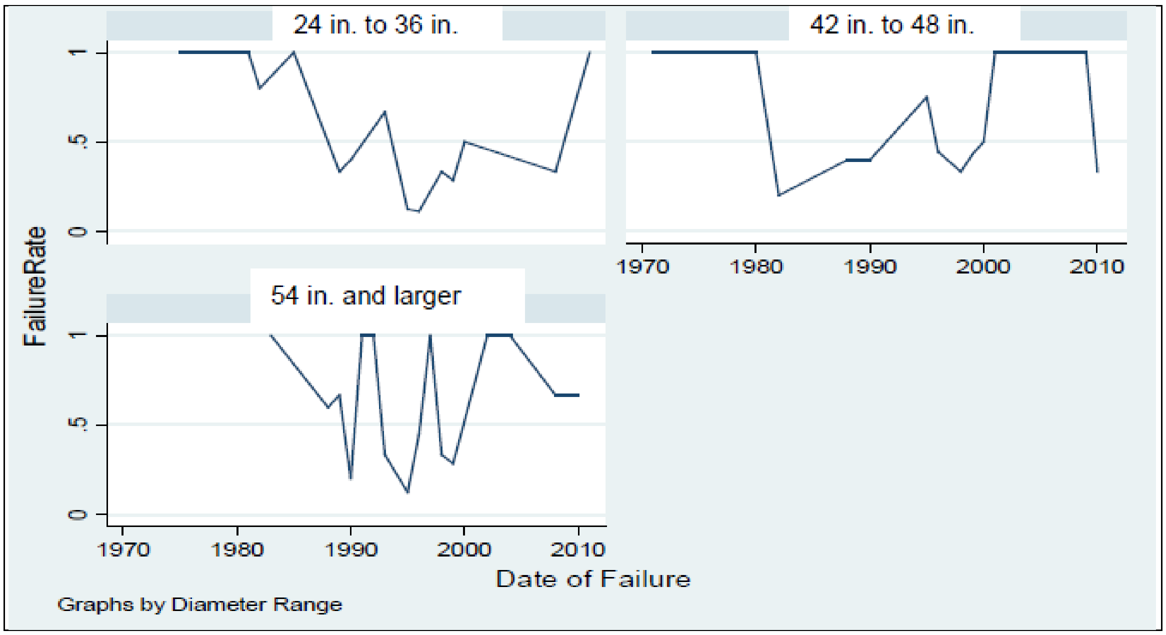


Figure 4.7 Failure Rate (Measured in Percentage) by Diameter Range

To present a hypothesis that failure rate varies by diameter size and years, this study regressed failure rate on year dummies with 1971 and diameter sizes 24 in. to 36 in. as base cases. The results are presented in Table 4.4.

Table 4.4 Estimated Failure Rate by Year and Diameter Size

Variables	Coefficients	Std. Errors	Probability
Intercept	0.953*	0.160	0.000
1975	0.047	0.160	0.772
1976	0.047	0.160	0.772
1977	0.000	0.000	1.000
1980	0.000	0.000	1.000
1982	-0.476	0.421	0.276
1983	-0.001	0.146	0.995
1985	0.047	0.160	0.772
1988	-0.501*	0.147	0.004
1989	-0.477*	0.229	0.055
1990	-0.651*	0.137	0.000
1991	-0.001	0.146	0.995
1992	-0.001	0.146	0.995
1993	-0.477	0.281	0.110
1996	-0.651*	0.161	0.001
1998	-0.651*	0.096	0.000
1999	-0.651*	0.115	0.000
2000	-0.476*	0.085	0.000
2001	0.000	0.000	1.000
2002	-0.001	0.146	0.995
2003	-0.001	0.146	0.995
2004	-0.001	0.146	0.995
2006	0.000	0.000	1.000
2008	-0.477*	0.229	0.055
2009	0.000	0.000	1.000
2010	-0.501*	0.225	0.042
2011	0.047	0.160	0.772
42 in. to 48 in.	0.047	0.160	0.772
54 in. and Larger	0.048	0.125	0.706

Notes:

1. Year 1971 and diameters 24 in. to 36 in. are base cases
2. Failure Rate is given in percentage.
3. $^{*}p < 0.05$

The overall model is statistically significant as indicated by the statistically significant intercept (α = 0.953). Table 4.4 illustrates failure rates for various diameter ranges and years. It uses the year 1971 and the diameter range between 24 in. to 36 in. as base cases. For example, the coefficient for the year 1988 is significant as indicated by the p-value of less than 0.05 ($p < 0.05$) which implies that with 95% confidence level, and the failure rate for the year 1988 is about 50% less than the base case of 1971. For other coefficients where the p-value is greater than 0.05($p > 0.05$) no statistically significant linear dependence was detected between dependent (failure rate) and independent variables.

The greatest coefficient is for the base case, year 1971, which implies the failure rate, was highest in that year. Since 1988, there is a downward trend in the failure rate and a significant reduction in the failure rate compared to the base case of 1971. It may be due to the improvements introduced as a result of AWWA standards in early 1980s. These improvements included amendments made to the PCCP AWWA C301 Standards such as increasing the minimum diameter range of prestressing wire from 0.125 in. to 0.192 in., increasing the improving the wire testing requirements including the introduction of hydrogen embrittlement susceptibility testing and improving the mortar coating absorption as well as testing for mortar coating. In 1955, for the prestressing wire which fails due to hydrogen embrittlement sensitivity (environmental deterioration), AWWA mandated hydrogen embrittlement qualification testing as part of the AWWA Standards, and allowed only the class II and class III wires in the manufacturing process of PCCP.

No identifiable differences were found between the two diameter ranges, 42 in. to 48 in. and 54 in. and larger in regards to the failure rate. The coefficients for these diameter ranges are insignificant (P- value >0.05). The base case diameter range of 24 in. to 36 in. seems to have the highest failure rate when compared to other ranges, which could be due to operational damage, external corrosion, prestressed wire breakage, embrittlement, and joint failure. Another reason for the failure rate to be high in this range could be attributed to the fact that this diameter range is most commonly utilized.

4.4 Chapter Summary

This chapter presented the failure rate results based on the survey data from 13 water utilities for PCCP pipes. The analysis for survey respondents suggests that failure rates have started to come down in recent years.

In terms of the diameter range variability, 42 in. to 48 in. and 54 in. and larger, have achieved lower failure rates compared to the diameter range 24 in. to 36 in. The results of the analysis support the hypothesis that there are variations in failure rate by diameter size and by years. All results are limited to 13 survey respondents, and may not represent overall PCCP performance.

CHAPTER 5

DISCUSSION OF RESULTS

This chapter presents discussion of results in Chapter 4. This discussion synthesizes both survey results and information gained from literature search.

5.1 Yearly Trend

To analyze the performance of Prestressed Concrete Cylinder Pipe (PCCP) in water transmission applications, a model was formulated by diameter range and year to identify diameter types with a reduction in failure rates from 1971 to 2011. The results of 13 utility survey shows that failure rates after 1988 have been reduced. This is the year when improvements to AWWA standards were made new standard include a number of provisions that focus on cost-effective measures to reduce the failure rates and improve the manufacturing process. AWWA has played a significant role by promoting improved quality of material and design in PCCP by implementing standards and continues to provide revised standards over time.

5.2 Diameter Size

The diameter range of 24 in. to 36 in. has the highest failure rate, which may be due to the fact that it is most commonly used. Also, it may be due to operational damage, external corrosion, prestressed wire breakage, embrittlement, and joint failure, as may be common to other diameter ranges.

5.3 Survey Results

As per the survey results, corrosion and wire breaks are the most common causes of failure in PCCP reported by 13 water utilities. About 61% of PCCP inventory is between 25 and 50 years old. Total number of failures in PCCP was 92 and the total length of pipe was 632 miles. The overall failure rate of PCCP is 15 percent per 100 miles. The Northeast region of the U.S. had highest failure rate of 33.11 percent with the lowest failure rate recorded in the Southwest region, which is 7.8 percent. The failure difference between these two locations might be due to many parameters, such as total footage in each region, and operational, environmental, and installation factors. Table 5.1 shows a comparison of failure rates from current research with previous studies.

Table 5.1 Comparisons of Current and Previous Research Studies

Study	Author	Year	Methodology	Failure Rate	Limitations
Failure of Prestressed Concrete Cylinder Pipe	Romer et al.	2008	Survey and workshop were conducted, failure data base had total 592 entries representing a diverse collection from 35 states	26 failures per 100 miles per year	The failure rate is per year, failure rate is for lined cylinder prestressed concrete cylinder pipe
Water Main Breaks Rate in the USA and Canada: A Comprehensive Study	Folkman	2012	Survey were conducted, total 180 survey responses from U.S. and Canada	6 failures per 100 miles per year	Less than 24 in. diameter size, Failure rate for each utility not given
Large Diameter (24 in. and larger) Water Pipe Questionnaire	CUIRE	2012	13 Survey responses from U.S., 8 out 13 water utilities have at least one failure in their water pipe	15 failures per 100 miles	Larger than 24 in., Diameter size, Failure rate for each year not given

5.4 Chapter Summary

This chapter briefly discussed results of this research. A comparison of survey results with past research was made.

CHAPTER 6

CONCLUSIONS, LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 Introduction

This chapter summarizes conclusions of this thesis. It also recommends some topics for future research.

6.2 Conclusions

The following conclusions can be derived from this thesis based on 13 survey respondents.

1. The total footage of PCCP from all survey respondents is 632 miles and the overall failure rate for PCCP is 15 percent per 100 miles.
2. The most common cause of failure reported in PCCP is external corrosion, prestressing wire breaks, joint failure and age of pipe.
3. The most used diameter range of PCCP is between 24 in. and 36 in., which is about 41% of total PCCP inventory.
4. The total population served by survey respondent water utilities is 13,892,502.
5. About 61% of PCCP inventory is between 25 and 50 year old.
6. Based on 13 survey respondents, the overall failure rate of PCCP are 15 per 100 miles.

7. Based on 13 survey respondents, which have at least one failure, the overall failure rate of North East region is the highest and west region is the lowest.

6.3 Limitations of Research

1. This thesis results are based on 13 survey respondents, for 24 in. and larger, so data availability was limited to only those survey respondents.
2. Parameters such as soil conditions, depth of installation, internal loads (operating and surge pressure), external loads (traffic and soil), class of prestressing wire, temperature changes, bedding conditions and so on can influence failure rate, but are not considered in this research.

6.4 Recommendations for Future Research

The following is a list of recommendations to expand this study:

1. Develop a database of U.S. water pipe inventory.
2. Involve a larger sample size for the research can improve the quality results.
3. A regional survey of water utilities to compare environmental and operational factors can be helpful.
4. A compressive of comparison different pipe materials (costs, ease of installation, carbon footprint, maintenance requirements, and so on) will be an important topic to investigate.

APPENDIX A

ABBREVIATIONS

ACI – American Concrete Institute

ANSI - American National Standards Institute

ASCE - American Society of Civil Engineers

AWWA - American Water Works Association

BWP - Bar-wrapped Steel-cylinder Concrete Pipe

CIP - Cast Iron Pipe

CUIRE - Center for Underground Infrastructure Research and Education

DIP - Ductile Iron Pipe

EC-PCCP - Embedded Cylinder Prestressed Concrete Cylinder Pipe

GRP - Glass Reinforced Pipe

HDPE – High Density Polyethylene

LC-PCCP - Lined Cylinder Prestressed Concrete Cylinder Pipe

NRC - National Research Council of Canada

PCCP - Prestressed Concrete Cylinder Pipe

PE - Polyethylene Pipe

PVC – Polyvinyl Chloride

RCC - Reinforced Cement Concrete

UCT- Underground Construction Technology

APPENDIX B

LARGE DIAMETER (24 IN. AND LARGER)

WATER PIPE QUESTIONNAIRE

THE UNIVERSITY OF TEXAS AT ARLINGTON

Center for Underground Infrastructure Research and Education (CUIRE)

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

E-mail: najafi@uta.edu

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 45 minutes****
If you have any questions or concerns, please feel free to contact CUIRE at 817-272-9177 or Chandan Venkatesh, CUIRE Graduate Research Student, at 817-682-4404 or chandan.venkatesh@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	Brian Haemmerle, PE		Position:	Distribution Engineering Manager			
b) Name of the organization	City of Columbus, Division of Power and Water	City	Columbus	State	Ohio	Zip	43215
c) Address	910 Dublin Road						
d) E-mail	bmhaemmerle@columbus.gov						
e) Phone:	614.645.0856			Fax:	614.645.6165		

1. What is the population of the area served by your water pipes?
(1,100,000_(includes suburban community populations which have pipes that are owned by suburban community, but operated and maintained by the City of Columbus)______

The above answer is accurate within: ☐ *±5%* ☒ *±10%* ☐ *±15%*

2. **What is the total length of your water pipelines? ______ft or _3,615_mi.**

The above answer is accurate within: ☒ ±5% ☐ ±10% ☐ ±15%

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

The below answer is accurate within: ☒ ±5% ☐ ±10% ☐ ±15%

Type of Pipe	% Total Inventory			
	Less than 25 years old	Between 25 to 50 years old	Between 50 to 75 years old	More than 75 years old
PCCP*	0.69	2.43	0.38	0
Steel*	0	0	0	0
PVC*	0	0	0	0
HDPE*	0	0	0	0
DIP*	1.08	0.51	0	0
CIP*	0	0.003	0.08	0.57
Bar-wrapped*	0	0.03	0.26	0
Asbestos Cement*	0	0	0	0
Other (Please Specify):				
UNKNOWN	0.01	0.06	0.01	0.03

Type of Pipe	Footage (mile)		
	24" – 36"	42" – 48"	54" and larger
PCCP*	81.6	43.7	1.4
Steel*	0	0	0
PVC*	0	0	0
HDPE*	0	0	0
DIP*	52.8	2.5	0
CIP*	23.6	0.1	0
Bar-wrapped*	5.8	4.4	0.4
Asbestos Cement*	0	0	0
Other (Please Specify):			
UNKNOWN	4.0	0.2	0

4. **In your large diameter* water pipe (24 in. and larger) inventory, what percentage is:**
The below answer is accurate within: ☒ *+5%* ☐ *+10%* ☐ *+15%*

Type of Pipe	**% of Total Inventory**		
	24" – 36"	**42" – 48"**	**54" and larger**
PCCP*	2.26	1.21	0.04
Steel*	0	0	0
PVC*	0	0	0
HDPE*	0	0	0
DIP*	1.46	0.07	0
CIP*	0.65	0.003	0
Bar-wrapped*	0.16	0.12	0.01
Asbestos Cement*	0	0	0
Other (Please Specify):			
UNKNOWN	0.11	0.006	0

5. **Not considering *environmental*, *operational*, *design*, *construction*, *material* and *other conditions*, please provide your ranking (high, medium or low) of failure rates for the following pipe materials.**

High (H) = 25% or more of your total pipe inventory.
Medium (M) = between 10% to 25% of your total pipe inventory.
Low (L) = less than 10% of your total pipe inventory.

Type of Pipe	**Footage (mile)**		
	24" – 36"	**42" – 48"**	**54" and larger**
PCCP*	low	low	low
Steel*	n/a	n/a	n/a
PVC*	n/a	n/a	n/a
HDPE*	n/a	n/a	n/a
DIP*	low	low	low
CIP*	low	low	low
Bar-wrapped*	low	low	low
Asbestos Cement*	n/a	n/a	n/a
Other (Please Specify):			

6. **Check (✓) the following pipe materials which are limited or restricted* for use in your large diameter* (24 in. and larger) water system?**

Pipe Material	Range of Diameter		
	24" – 36"	**42" – 48"**	**54" and larger**
PCCP*	☐	☐	☐
Steel*	☐	☐	☐
PVC*	☒	☒	☒
HDPE*	☒	☒	☒
DIP*	☐	☐	☐
CIP*	☒	☒	☒
Bar-wrapped*	☒	☒	☒
Asbestos Cement*	☒	☒	☒
Other (Please Specify):			
	☐	☐	☐
	☐	☐	☐

7. **Why is the type of pipe material (24 in. and larger) mentioned in the <u>Question #7</u> banned or restricted*?**

Pipe Material	Reason for Restriction
PCCP*	
Steel*	
PVC*	Not included in city specifications
HDPE*	Not included in city specifications
DIP*	
CIP*	Not included in city specifications
Bar-wrapped*	Not included in city specifications
Asbestos Cement*	Not included in city specifications
Other (Please Specify):	

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

Pipe ID*	Pipe Type	Pipe Diameter *	Location	Date of Failure	Cathodic Protection* (Y/N)	Soil Conditions*
		SEE ATTACHED				

Note: The majority of large diameter pipe do not have cathodic protection. Soil conditions were not documented during those failures and therefore that information was not available.

9. **For the pipe ID's* mentioned in <u>Question 9</u>, please provide causes of failure, modes of failure, type of joint, type of coating and type of water for pipe failure.**

Pipe ID*	Cause of Failure	Mode of Failure	Type of Joint*	Type of Coating*	Type of Water (treated or untreated)
		SEE ATTACHED SPREADSHEET			

10. **In <u>Question #9,</u> is there any causes for pipe failures other than <u>Age of the Pipe*</u>?**

☒Yes ☐No

If Yes, please proceed to **<u>Question #12</u>**. If No, please proceed to **<u>Question #13.</u>**

11. **Rank the following causes of failure for each of the pipe materials according to their frequency of occurrence.**
Please rank with <u>#1 being the highest frequency of occurrence</u>

Note: The majority of failure modes were not documented during the repairs, so no data was readily available for this question.

PCCP*

Causes of Failures	Range of Diameter*		
	24” – 36”	**42” – 48”**	**54” and larger**
Water Temperature			
External Corrosion*			
Internal Corrosion*			
Manufacturing Defects*			
Installation Problems*			
Third Party Damage*			
Soil Conditions*			
Excessive Dead Loads*			
Excessive Live Loads*			
Excessive Internal Pressure*			
Joint* Failure			
Operation Related			
Other			

Steel*

Causes of Failures	Range of Diameter*		
	24” – 36”	**42” – 48”**	**54” and larger**
Water Temperature			
External Corrosion*			
Internal Corrosion*			
Manufacturing Defects*			
Installation Problems*			
Third Party Damage*			
Excessive Dead Loads*			
Excessive Live Loads*			
Excessive Internal Pressure*			
Joint* Failure			
Coating Problems*			
Over Deflection*			
Other			

PVC*

Causes of Failures	Range of Diameter*		
	24" – 36"	42" – 48"	54" and larger
Water Temperature			
Manufacturing Defects*			
Third party Damage*			
Excessive Internal Pressure*			
Joint* Failure			
Longitudinal Failure			
Ultraviolet Radiation			
Oxidation*			
Permeation*			
Buckling*			
Other			

HDPE*

Causes of Failure	Range of Diameter*		
	24" – 36"	42" – 48"	54" and larger
Water Temperature			
Manufacturing Defects*			
Third party Damage*			
Excessive Internal Pressure*			
Joint* Failure			
Longitudinal Failure			
Ultraviolet Radiation			
Oxidation*			
Permeation*			
Buckling*			
Other			

DIP*

Causes of Failure	Range of Diameter*		
	24" – 36"	42" – 48"	54" and larger
Water Temperature			
External Corrosion*			
Internal Corrosion*			
Manufacturing Defects*			

Installation Problems*			
Third Party Damage*			
Excessive Dead Loads*			
Excessive Live Loads*			
Excessive Internal Pressure*			
Joint* Failure			
Coating Problems*			
Soil Conditions*			
Other			

CIP*

Causes of Failure	Range of Diameter*		
	24" – 36"	42" – 48"	54" and larger
Water Temperature			
External Corrosion*			
Internal Corrosion*			
Manufacturing Defects*			
Installation Problems*			
Third Party Damage*			
Excessive Dead Loads*			
Excessive Live Loads*			
Excessive Internal Pressure*			
Joint* Failure			
Coating Problems*			
Soil Conditions*			
Other			

Bar-wrapped*

Causes of Failure	Range of Diameter*		
	24" – 36"	42" – 48"	54" and larger
Water Temperature			
External Corrosion*			
Internal Corrosion *			

Manufacturing Defects*			
Installation Problems*			
Third Party Damage*			
Soil Conditions*			
Excessive Dead Loads*			
Excessive Live Loads*			
Excessive Internal Pressure*			
Joint* Failure			
Coating Problems*			
Other			

12. 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 Summer 2012.

If you have any questions or concerns, please feel free to contact Rahul Manda, CUIRE Graduate Research Student, at 817-682-4404 or rahul.manda@mavs.uta.edu or the Principal Investigator of this project, Dr. Mohammad Najafi at 817-272-0507 or najafi@uta.edu

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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 Defects**: 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.

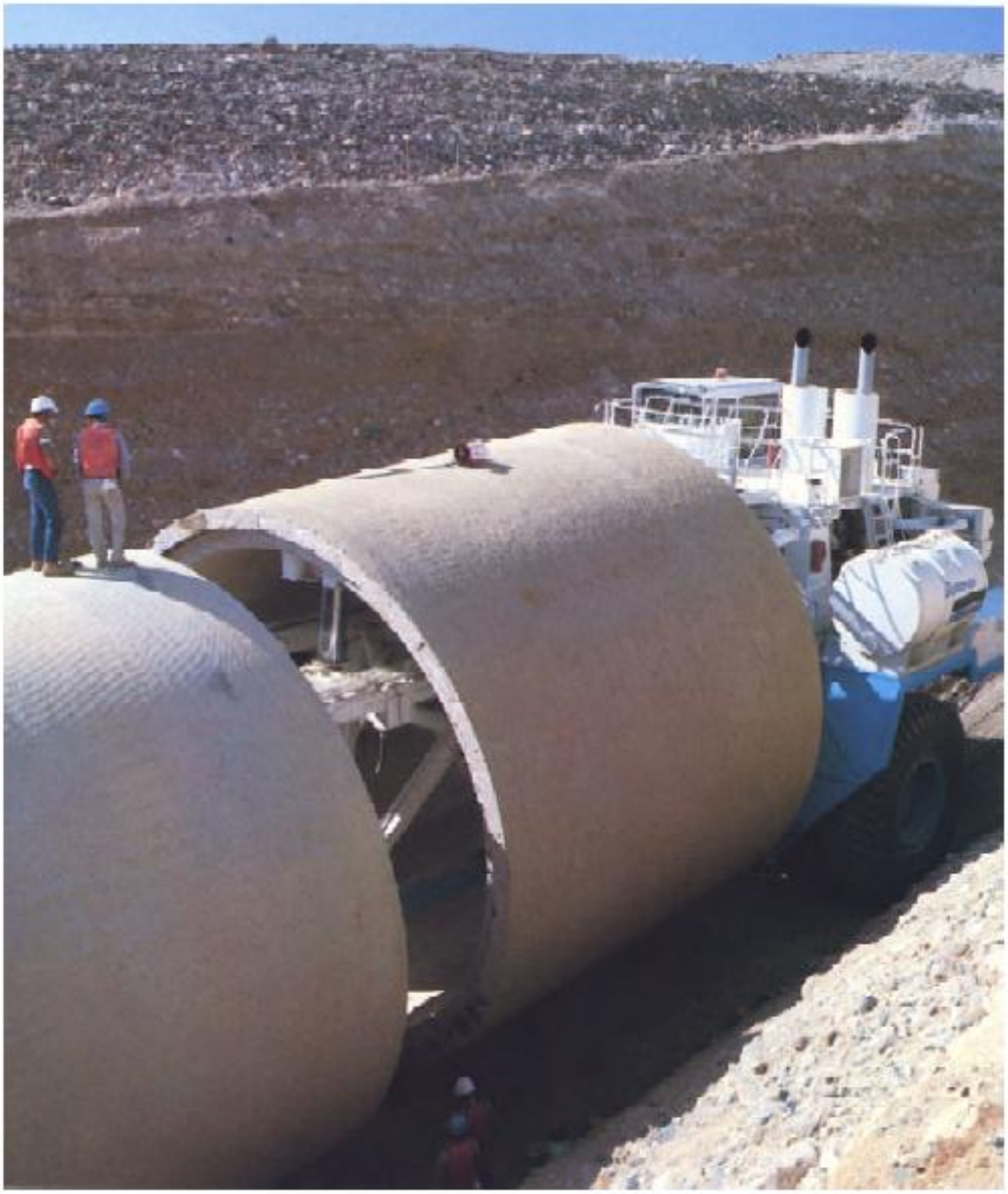
APPENDIX C

PHOTOGRAPHS OF PRESTRESSED CONCRETE CYLINDER PIPE

Ten miles of 96-inch diameter prestressed concrete cylinder pipe, part of the San Diego Aqueduct, will transport potable water to large metropolitan area (Ameron International).

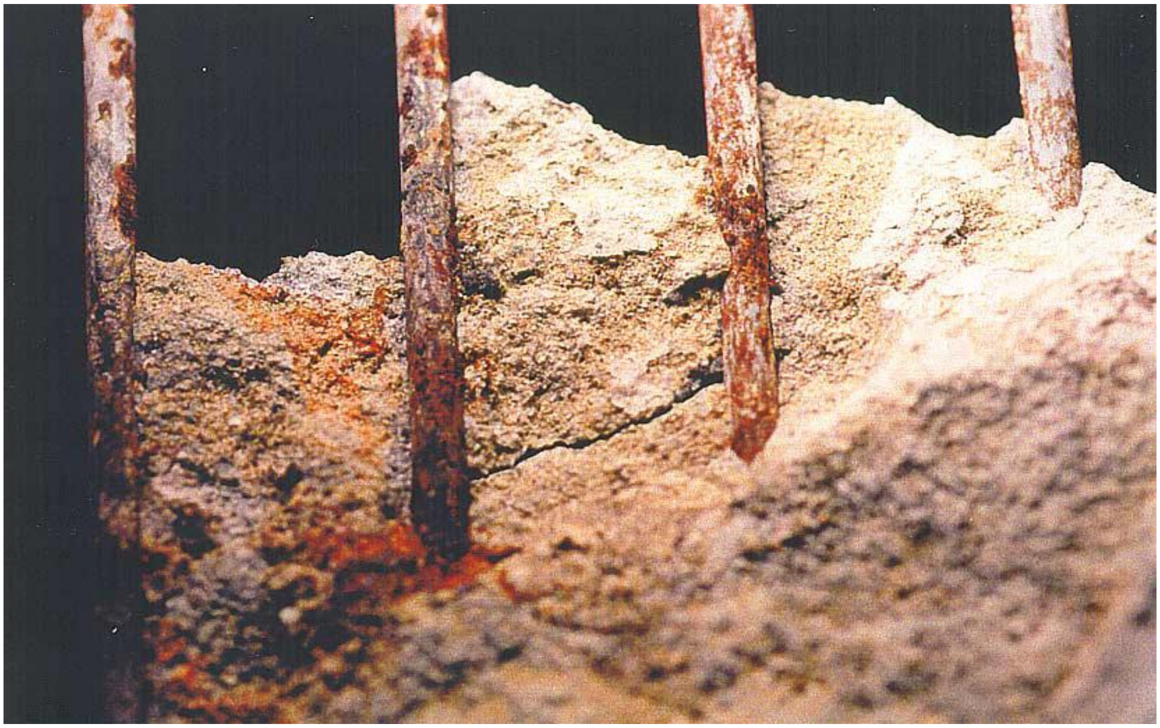
PCCP Handling

PCCP Handling (Ameron International)



In trench, the pipe mobile's forward wheels enter the preceding pipe action and move forward to make joint. Joining of large diameter pipe sections is accomplished with controls that can maneuver the pipe in 1/16 inch increments. (Ameron International).

Special pipe sections and custom fittings are part of prestressing concrete cylinder pipe system at a power station (Ameron International).



Corroded wires on 36-inch concrete mains (Margevicius and Haddad 2002).

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BIOGRAPHICAL INFORMATION

Rahul Manda was born in Bikaner, India, on September 6, 1986, the son of Ram Gopal Manda and Laxmi Manda. He graduated in 2010 from University of Pune with a bachelor's degree in civil engineering. He has held several positions in different student organizations at the University of Texas at Arlington including vice president of the Texas Society of Professional Engineers (TSPE) Student Chapter. He also received a graduate student civil engineering scholarship for academic year 2011-12 awarded by the University of Texas at Arlington and a CUIRE scholarship for the Spring 2012 semester awarded by the Center for Underground Infrastructure Research and Education (CUIRE).