AN EVALUATION OF FAILURE MODES
FOR CAST IRON AND DUCTILE
IRON WATER PIPES

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 water 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 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 FAILURE MODES FOR CAST IRON AND DUCTILE IRON WATER PIPES

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The need to evaluate the performance of cast iron and ductile iron water pipes is of great importance since they are the most common pipe materials for water mains. The concern in the water industry is about the cost involved in repairs and replacement of water pipes due to failure. The rate of pipe failures increases as the design life ends and become a financial burden on the water industry.

This thesis evaluates the failure modes for the two most used pipe materials for water mains in the United States which are cast iron and ductile iron pipes. A study based on 15 survey responding water utilities on different failure parameters such as age of the pipe, diameter, manufacturing process, type of joints and type of failure will help in identifying future research areas.

This thesis consists of a detailed literature review and a limited survey conducted to gather failure data of from several water utilities in the United States.

The thesis concludes that stress failure is the most commonly occurring mode of failure followed by corrosion failure and joint failure for cast iron and ductile iron water pipes and

provides a limited prediction of water main problems only for the inventory water utilities which responded to the survey.

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CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1 History of Pipelines

Before the beginning of civilizations, ancestors in the Stone Age lived in caves and other camps which were close to drinking water sources such as lakes or springs. But, with the increase in human population along with the increase in wild animals, various diseases and dense vegetation posed difficulties in crop cultivation which drove some of these settlements to relocate to drier climates. Thus, the need arose to have a groundwater system (Cech, 2009).

The ancient Romans developed extensive water delivery systems. They stored the surface water and groundwater in underground reservoirs lined with clay or limestone formations. These reservoirs were called cisterns. Water was delivered by gravity through a network of conduits made of stone or brick. The first aqueduct was built in 312 B.C. This was followed by construction of more aqueducts and other water delivery structures such as canals. Romans also developed widespread water development systems in France, Italy, the Netherlands and Great Britain (Cech, 2009). From A.D. 100 to 300, the Romans used lead pipes and aqueducts to distribute the water to the mansions of the elite and their luxurious Roman baths (Najafi, 2010).

In A.D. 1236, the water from the river Thames and some nearby springs was carried into London with the help of a system of pipelines by the Romans made of lead or baked clay. In 1619, the water was delivered to every home in the city of London for the first time by a privately owned company called the New River Company (Cech, 2009).

The technology of pipelines saw a vast improvement with the introduction of cast iron pipes in the 1800s. Before that, most small diameter pipes were made of wood. Cast iron pipes gradually replaced the wooden pipes in the 1800s. These cast-iron pipes were cast vertically in pits and later replaced by centrifugally spun cast iron in the 1920s. In 1922, cement-mortar lining of pipes took place. Ductile iron pipe was first used in 1948 and the polyethylene encasement was first developed in 1951. Steel pipe has been in use since the 19th century and concrete cylinder pipe since the 1940s for water distribution (Walski, 2006). Bar-wrapped pipe was developed in 1942 with large-scale production starting in 1950 (Pure Technologies, 2012).

Modern piping materials such as polyvinyl chloride (PVC), high density polyethylene pipe (HDPE) and medium density polyethylene pipe (MDPE), glass-reinforced plastic pipe (GRP) and polymer concrete pipe (PC) have been used in North America for the last 40 years (Najafi and Gokhale, 2005).

1.2 Types of Piping Systems

There are four general types of piping systems used by water utilities which are transmission lines, in-plant piping systems, distribution mains and service lines.

1. Transmission Lines

Transmission lines are usually long and large in diameter (> 16-inch) and carry large quantities of water. They transmit raw water from source of supply to treatment plants and then carry the treated water from treatment plants and pumping stations to a distribution system. They generally have very few side connections and run in straight lines (Bhave and Gupta, 2006).

2. In-plant Piping Systems

In-plant piping systems are located in treatment plants and pumping stations. These systems generally have many valves, outlets and bends (AWWA, 2003). They are large in diameter and small in length (Bhave and Gupta, 2006).

3. Distribution Mains

Distribution mains carry water from transmission lines and service reservoirs and distribute it throughout the community. They have several side connections and are laid along streets for consumer services with 4-inch, 6-inch and larger diameters (Bhave and Gupta, 2006).

4. Service Laterals

Service laterals carry water from the distribution mains to the customer’s premises and are smaller (< 4-inch) in diameter (Bhave and Gupta, 2006).

1.3 Importance of Water

"Water promises to be to the 21st century what oil was to the 20th century: the precious commodity that determines the wealth of nations." – Fortune Magazine.

Freshwater is vital for life and a fundamental requirement for the economic, social and environmental well-being of humanity. However, 97% of all the water is in oceans and a meager 3% is fresh water. Out of this 3%, 69% is ice caps, 30% is groundwater and 1% exists in lakes and rivers. The distribution of water is highly uneven with large parts of the world having insignificant quantities of renewable water. Water consumption was predicted to exceed 70% of available supplies by 2005 (Weiner and Thenkabail, 2010).

Today, 780 million of the world's population lack access to clean water which is more than two and a half times the total population of the United States of America. A total of 200 million hours are consumed by people all over the world daily collecting water for their families. A child dies every 20 seconds from a water related disease, 3.41 million people die from water, sanitation and hygiene related causes. Hence, it is equally important to supply safe drinking water and not just water (Water Facts[1], 2012).

Even in the United States, people are at risk of contracting water-borne diseases due to the often murky supply of tap water in most cities and towns. Often, poor color, taste and odor, bacterial contamination, loss of hydraulic capacity and pressure, leaks, breaks, street cave-ins and adverse press coverage are problems related to water supply (Jeyapalan, 2007).

1.4 Failure of Water Pipelines

As per the "Report Card for America's Infrastructure" (ASCE, 2009), the nation's infrastructure is in poor condition and drinking water, wastewater have received very low grades compared to other infrastructure categories.

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[1] www.water.org/water-crisis/water-facts/water/

The U.S. public water systems have an average loss of 17 percent in their pipe systems. New York City has a daily water usage of more than one billion gallons and loses 10 percent of the water. Around 33 percent of drinking water is lost each year worldwide (Radoszewski, 2009). Due to leaks and breaks, water utilities in the United States lose 40 billion liters of water enrooted between treatment and tap everyday out of the processed 160 billion liters of water. The U.S. spent approximately $1.2 billion on water rehab in 2006 when the need was to spend $6 billion (Jeyapalan, 2007).

Water distribution networks form essential components of water supply systems in most urban centers. Water distribution network failure can lead to service interruptions, direct costs for repairs, property damage, lost water, indirect costs such as loss of production, damage to adjacent utilities and social costs such as discomfort, traffic and business disruptions (Rajani and Kleiner, 2010).

A number of professional organizations are concerned about the drinking water infrastructure and some have developed cost estimates for all drinking water infrastructure needs of the future including treatment plants. These cost estimates incorporate infrastructure needs due to regulation and deterioration of the drinking water infrastructure but do not cover new infrastructure. Organizations such as American Society of Civil Engineers (ASCE), United States Environmental Protection Agency (USEPA), American Water Works Association (AWWA), the Water Infrastructure Network (WIN) and the Help to Optimize Water (H2O) Coalition are working to make water utilities self-sustaining and not subsidized enterprises over the long term. A summary of cost estimates by these professional organizations related to drinking water infrastructure is provided in Table 1.1 (USEPA, 2002).

Table 1.1 Cost Estimates for Drinking Water Infrastructure Future Needs

(USEPA, 2002)

Professional Organization	**Cost Estimate**	**Period**	**Comments**
American Society of Civil Engineers (ASCE)	$11 B	Per Year	-
U.S. Environmental Protection Agency (USEPA)	$151 B	Next 20 Years	$83 B of this amount for transmission and distributing piping
American Water Works Association (AWWA)	$250 B	Next 30 Years	-
Water Infrastructure Network (WIN)	$460 B	Next 20 Years	Includes both water and wastewater
Help to Optimize (H2O) Water	None	None	Believes more analysis is needed

A study by the National Research Council of Canada (NRC) presented some statistics on water main breaks in 21 Canadian cities for the years 1992 and 1993. Cast iron pipe had average break rates of 56.16 breaks/ 100 miles/ year and 58.72 breaks/ 100 miles/ year in 1992 and 1993 respectively. Ductile iron pipe had average break rates of 14.88 breaks/ 100 miles/ year and 15.68 breaks/ 100 miles/ year in 1992 and 1993 respectively. Asbestos cement pipes had average break rates of 8.64 breaks/ 100 miles/ year and 9.76 breaks/ 100 miles/ year in 1992 and 1993 respectively. Lastly, polyvinyl chloride pipe (PVC) had average break rates of 1.44 breaks/ 100 miles/ year and 0.8 breaks/ 100 miles/ year in 1992 and 1993 respectively. The total number of breaks observed in these utilities was 3601 and 3773 for the years 1992 and 1993 respectively. The average annual total cost of these repairs was estimated to be $9.2 million (Rajani and McDonald, 1993).

A recent study by Utah State University Buried Structures Laboratory recorded the failure rates of different pipe materials over a 12 month period. The failure rate for cast iron pipe was 24.4 failures/ 100 miles/ year, ductile iron pipe was 4.9 failures/ 100 miles/ year, polyvinyl chloride pipe was 2.6 failures/ 100 miles/ year, concrete pressure pipe was 5.4 failures/ 100 miles/ year, steel pipe was 13.5 failures/ 100 miles/ year and asbestos cement pipe was 7.1 failures/ 100 miles/ year. Also, the failure rate for other pipe materials which include high density polyethylene, galvanized steel and copper pipes is 21.0 failures/ 100 miles/ year (Folkman, 2012).

The U.S. water pipe distribution network is over 9,320,600 miles and about 13,050 miles of new pipe is added every year. This national network of water pipes experiences 300,000 breaks per year. About $30 billion worth of water is lost every year due to the aging water pipes in most of the cities serving well beyond their design lives (Jeyapalan, 2007).

Thus, it is of great importance to study the failure of the water pipelines considering its impact on the social life, the financial impact it can have in the near future, the failure rates of the different pipe materials as well as the amount of water loss experienced worldwide.

1.5 Pipe Materials Used for Water Transmission and Distribution

1. Cast Iron Pipe (CIP)

Cast iron pipe (CIP) accounts for a large portion of buried water piping material throughout the North America. About 50% of the total length of installed water mains is cast iron pipe (Makar et al., 2001). Cast iron is also referred as gray cast iron and is a very strong but brittle material (Najafi and Gokhale, 2005). Pit cast gray iron and centrifugal cast gray iron are two types of cast iron pipe.

2. Ductile Iron Pipe (DIP)

Ductile iron pipe (DIP) was developed from cast iron pipe (CIP) by changing the distribution of graphite in a spherical form instead of a flake form with the addition of inoculants such as magnesium to the molten iron. This resulted in an improvement in strength, impact resistance and some other properties (Najafi and Gokhale, 2005).

3. Steel Pipe

Between 1850 and 1860, the Bessemer process for making steel was invented. This process was followed by open hearth process which made steel in large quantities available for use in railroads, factories, tools, equipment and steel pipe for water as well as gas, etc. (Cates, 1971). Use of steel pipe in the U.S. was observed as early as 1863 in San Francisco. Various developments in the technology over the years have made steel more versatile for piping applications (Najafi and Gokhale, 2005).

4. Asbestos Cement Pipe (AC)

AC was introduced in North America in the late 1920s and was used to carry water from the 1940s to 1970s. It was manufactured by mixing slurry of Portland cement (80-85%) with a mixture of chrysotile asbestos fibers (15-20%). Its use was discontinued in the early 1980s in North America (Pure Technologies, 2012).

5. Reinforced Concrete Pipe (RCP)

These concrete pipes can be reinforced with welded wire fabric, hot-rolled rod made of Grade 40 steel or cold-drawn steel wire made from hot-rolled rods. It can be used for pressure applications up to 55 psi (Najafi and Gokhale, 2005).

6. Prestressed Concrete Cylinder Pipe (PCCP)

This is a composite pipe manufactured using concrete and steel. It is used for high pressure applications and can handle up to 500 psi. Lined cylinder pipe and embedded cylinder pipe are the two types of PCCP (Najafi and Gokhale, 2005).

7. Polyvinyl Chloride Pipe (PVC)

PVC is an accidental discovery made by German scientists in the 19th century when the vinyl chloride was being observed and it resulted in the creation of an off-white accumulation of solid material when it got exposed to the sunlight. The technology was brought to United States in mid-1950s and by 2000 the use of PVC had reached 5 billion pounds (Najafi and Gokhale, 2005).

8. Polyethylene Pipe (PE)

In 1933, polyethylene was discovered and its use in pipe applications started in 1950. As a result of continuous development of polyethylene materials, its usage has increased significantly in the water industry from the early 1970s. A variety of materials which are low, medium, high or linear low density abbreviated as LDPE, MDPE, HDPE and LLDPE are used for PE pipes. PE pipes have solved the corrosion and leakage issues of the traditional iron, steel and concrete pipes. Also, PE pipes have shown a great durability with a leak free track record (Historical Developments of PE Pipe Materials, 2012).

9. Bar-wrapped Steel-cylinder Concrete Pipe (BWP)

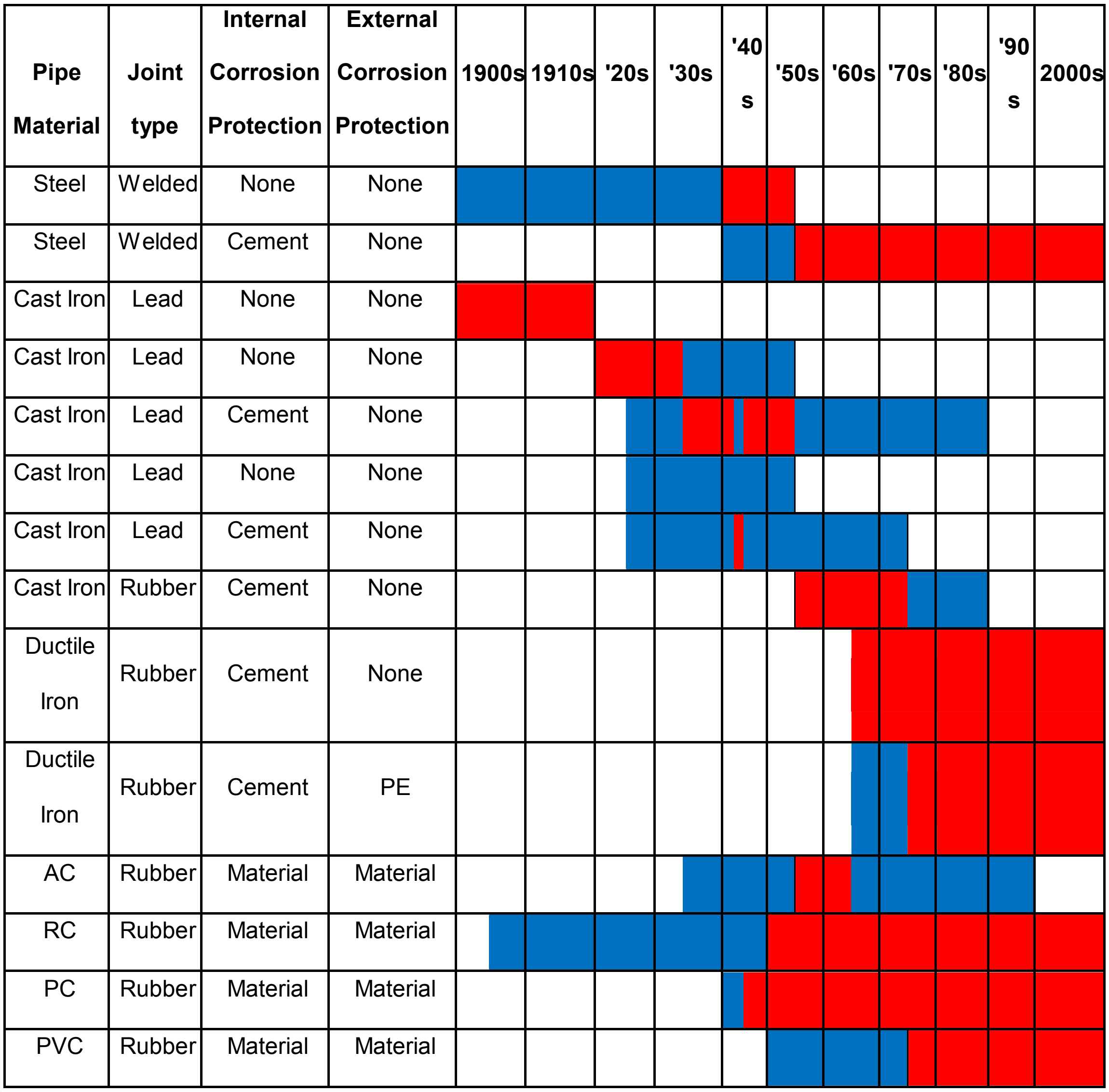
In BWP, steel reinforcing bars are wrapped around a welded steel cylinder to provide strength to the cylinder. The cylinder acts as a watertight membrane. It is typically used for pressures of 300 psi or less. It is produced in diameters of 10-72 inches (Pure Technologies, 2012).

10. Glass Reinforced Pipe (GRP)

This pipe is commonly known as fiberglass pipe. It was first manufactured in the United States in the 1950s. The fiberglass composites are made from glass fiber reinforcements, thermosetting resins and other additives such as fillers, catalysts, hardeners, accelerators and so on. Epoxy, polyester and vinyl ester are the types of resins used for its manufacturing. The use of GRP in large-diameter water applications is growing rapidly in North America (Najafi and Gokhale, 2005).

Table 1.2 represents the progression of pipe technology and the use of different pipe materials in the United States during the 19th and the 20th century followed by Table 1.3 explaining the applications of different pipe materials.

Table 1.2 Timeline of Pipe Technology in U.S. (USEPA, 2002)



Pipe Material	Joint type	Internal Corrosion Protection	External Corrosion Protection	1900s	1910s	'20s	'30s	'40s	'50s	'60s	'70s	'80s	'90s	2000s
Steel	Welded	None	None	🟦	🟦	🟦	🟦	🟥	🟥⬜					
Steel	Welded	Cement	None					🟦	🟦🟥	🟥	🟥	🟥	🟥	🟥
Cast Iron	Lead	None	None	🟥	🟥									
Cast Iron	Lead	None	None			🟥	🟥🟦	🟦	🟦⬜					
Cast Iron	Lead	Cement	None			⬜🟦	🟦🟥	🟥🟦🟥	🟥🟦	🟦	🟦	🟦		
Cast Iron	Lead	None	None			⬜🟦	🟦	🟦	🟦⬜					
Cast Iron	Lead	Cement	None			⬜🟦	🟦	🟦🟥🟦	🟦	🟦	🟦⬜			
Cast Iron	Rubber	Cement	None						⬜🟥	🟥	🟥🟦	🟦		
Ductile Iron	Rubber	Cement	None							⬜🟥	🟥	🟥	🟥	🟥
Ductile Iron	Rubber	Cement	PE							⬜🟦	🟦🟥	🟥	🟥	🟥
AC	Rubber	Material	Material				⬜🟦	🟦	🟦🟥	🟥🟦	🟦	🟦	🟦	
RC	Rubber	Material	Material	⬜🟦	🟦	🟦	🟦	🟦	🟥	🟥	🟥	🟥	🟥	🟥
PC	Rubber	Material	Material					🟦🟥	🟥	🟥	🟥	🟥	🟥	🟥
PVC	Rubber	Material	Material						🟦	🟦	🟦🟥	🟥	🟥	🟥

Table 1.3 Applications of Different Pipe Materials (Adopted from: Najafi, 2010)

Pipe Material	Applications
Cast iron pipe	1. Mainly Potable water distribution 2. Few sewer systems
Ductile iron pipe	1. Mainly Potable water distribution 2. Few sewer systems
Steel pipe	1. Transports fluids such as natural gas, crude oil 2. Potable water transmission 3. Casing pipe in microtunneling, jacking, boring and pipe-ramming
Asbestos cement pipe	1. Water systems 2. Sewer systems
Reinforced concrete pipe	1. Non-pressure applications 2. Low-pressure applications
Prestressed concrete cylinder pipe	1. High pressure applications 2. Sewer systems 3. Industrial cooling systems
Polyvinyl chloride pipe	1. Water systems 2. Sewer systems
Polyethylene pipe	1. Gas distribution 2. Water systems 3. Sewer systems 4. Nuclear and industrial process piping 5. Electrical and communication duct
Bar-wrapped steel-cylinder concrete pipe	1. Pressure applications 2. Treatment plants
Glass reinforced pipe	1. Water systems 2. Sewer systems

1.6 Cast Iron Pipe (CIP) and Ductile Iron Pipe (DIP)

Cast iron pipe (CIP) is the most common pipe material used in the North American water systems. It is about 50% of the total length of installed water mains. From late 1800s till late 1960s, the water distribution piping installed in the United States was manufactured from cast iron (Makar et al., 2001). Table 1.4 summarizes the key events in the manufacturing of cast iron pipes.

Table 1.4 Key Events in Manufacturing of Cast Iron Pipe

(Rajani and Kleiner, 2010)

Period	Manufacturing Events	Comment
1800s	Volume production of pit cast (horizontally) pipes begin	Introduced wall thickness eccentricity as a result of mold sagging
1846	Patent granted for vertical casting process	-
1850s	Vertically cast pipes introduced	Vertically cast pipes produced largely concentric pipes with lengths up to 16 ft.
1914	Volume production begins of vertically cast pipes	Sand molds and cast vertically with bell at bottom
1920s	Centrifugally (spun) cast pipes introduced	Produced pipe of uniform wall thickness and higher strength
1930s	Volume production begins of centrifugally (spun) cast pipes	Centrifugally cast with sand or metal molds; pipes with metal molds require heat treatment

Ductile iron pipe (DIP) was first manufactured in 1948 on an experimental basis but the industrial production begun in late 1960s. About 19% of the total water mains are of ductile iron (Rajani and Kleiner, 2001).

1.7 History of Cast Iron Pipe

In 1562, the first use of cast iron pipe in Langensalza, Germany was recorded. It was used to supply water to a fountain. But, the first full-scale use of a cast iron pipe system for the distribution of water was in 1664 at the palace of Versailles in France. A cast iron main was constructed to carry water for about 15 miles (CISPI, 2006).

Immediately following this development, the cast iron pipe was used in many other distribution systems in France. In 1746, the Chelsea Water Company introduced cast iron in London, England. In 1785, the bell and spigot joint was invented by Sir Thomas Simpson, an engineer with a company of the same name. The bell and spigot joint represented marked improvement over the butt joints wrapped with metal bands used in the first cast iron pipe followed by joints held together with a version of flanges, a lead gasket and bolts (CISPI, 2006).

In the United States, the cast iron pipe was first used at the beginning of the nineteenth century. One of the first cast iron pipe installations (which was imported from England and Scotland) was at Bethlehem, Pennsylvania, where it replaced deteriorated wooden mains (CISPI, 2006). In 1817, the first cast-iron pipes were laid in Philadelphia, Pennsylvania (Walski, 2006). In 1819, production began at a number of charcoal furnace plants in New Jersey and at about the same time, a foundry located at West Point, New York, also started producing limited amounts of cast iron pipe. The production of cast iron was limited during the first half of the 19th century, but as the demand increased with cities continuing to install waterworks system at a rapid pace, the manufacturing of cast iron increased on a large scale (CISPI, 2006).

The cast iron pipe was classified in two types as “Pit Cast Gray Iron Pipe” and “Centrifugal Cast Gray Iron Pipe” as explained below.

1. Pit Cast Gray Iron Pipe

The first manufactured cast iron pipe was known as “pit” cast gray iron pipe. The manufacturing was done by pouring molten iron into a sand mold which was kept on end and lodged in a pit. The process was similar to pouring concrete into a form. The pipe was designed with greater wall thickness than required for the internal pressure and external loading expected which could have led to potential inconsistencies in the wall thickness. The performance of the pipe was well received within the industry in spite of it not having any kind of internal or external corrosion protection (USEPA, 2002).

2. Centrifugal Cast Gray Iron Pipe

In 1920, “spun” or “centrifugally” cast iron pipe was introduced which was manufactured by centrifugally casting pipe in a sand mold. The tensile strength of the pipe was improved due to the alteration of molecular composition of the metal because of the centrifugal forces experienced by the molten iron. The inconsistencies in the wall thickness were reduced to a great extent resulting in thinner walls. It also resulted in higher strength. Also, cement was used for interior lining to prevent against corrosion (USEPA, 2002).

In 1930, a significant improvement in the manufacturing process was made by using a water-cooled metal mold which allowed the pipe to be immediately withdrawn from the centrifuge. This process became known as the “deLavaud” process and it is still used for the manufacturing of ductile iron pipe (USEPA, 2002).

1.8 History of Ductile Iron Pipe

Ductile iron pipe is a major improvement over the cast iron pipe. In the U.S., 19% of its total water mains consist of ductile iron pipe. The first ductile iron pipe was produced experimentally in 1948 (Rajani and Kleiner, 2001). Minor but significant changes in chemistries and processing resulted in physical differences at the micro-structure level that resulted in a vastly improved fracture toughness and ductility making ductile iron piping products substantially more resistant to damage from impact or concentrated stresses (Makar et al., 2001).

The manufacturing process used for ductile iron pipe is the “deLavaud” process which is similar to the manufacturing of centrifugal cast gray iron pipe. Ductile iron pipe is a product of advanced metallurgy which offers unique properties for conveying water under pressure and other piping uses. It combines the physical strength of mild steel with the long life of gray cast iron. Ductile iron pipe has a greater margin of safety against service failures due to ground movement and beam stresses. It provides increased resistance to breakage caused by rough handling in shipping and installation. The corrosion resistance of ductile iron pipe has been proven in a wide variety of accelerated tests to be at least the equal of cast iron pipe (PSCIPCO, 2012).

Ductile iron pipe is produced by adding a closely controlled amount of magnesium alloy to a molten iron of low phosphorous and low sulfur content. Adding the magnesium alloy results in a remarkable change in the microstructure by causing the carbon in the iron to assume a spheroidal or nodular shape which is different than the flake form of graphite observed in cast iron pipe. A finer grained iron matrix in the surrounding ferrite structure is produced. As a result of this remarkable change in the properties, a stronger, tougher and ductile material is obtained (PSCIPCO, 2012).

Ductile iron pipe is stronger than cast iron pipe and is more resistant to corrosion. Ductile iron pipe is not susceptible to “graphitic” corrosion unlike cast iron pipe, which is an electrochemical reaction between the cathodic graphite component (flakes) and the anodic iron matrix resulting in metal loss. It also has approximately twice the strength of cast iron pipe. Its impact strength and elongation are also many times greater than cast iron pipe (USEPA, 2002).

1.9 Different Types of Joints Used for Cast Iron and Ductile Iron Pipes

As time passed by, materials used to make and join distribution system piping improved. During the late 1800s until the 1920s, pit cast iron was the most installed and manufactured pipe. To join these pipes, molten lead along with a rope (oakum) was used. Then from the 1920s up to the 1960s, centrifugal cast iron was primarily used. It was thinner as compared to the pit cast iron pipe and was stronger. Cement lining and leadite joining compound viz. plasticized sulfur cement were introduced in the same time period as joint materials. Leadite joints were eventually found to have increased splitting and corrosion compared to lead. Flexible rubber gasket joints were introduced in the 1950s as improved joints (Aging Infrastructure and Corrosion, 2012).

Following are the most common joints used for both cast iron and ductile iron pipes:

1. Bell and Spigot Joint

This joint was developed in 1785. This joint is generally made up of lead and oakum, sulfur compounds or cement. These joints are not used in ductile iron pipe (Nayyar, 2002). The joint making procedure included the caulking of yarn or braided hemp into the base of an annular bell cavity followed by the pouring of molten lead into the remaining space inside the bell. A watertight seal was obtained once the molten lead solidified (AWWA, 2009). Figure 1.1 represents a bell and spigot joint. The spigot end of the pipe is inserted in the bell of the adjoining pipe, leaving a space (A) to avoid metal to metal contact and the stress caused due to thermal expansion of the pipe. The yarn is inserted into the bell (C) and then hub (B) is completely filled by molten lead (Flowserve Corporation, 2012).

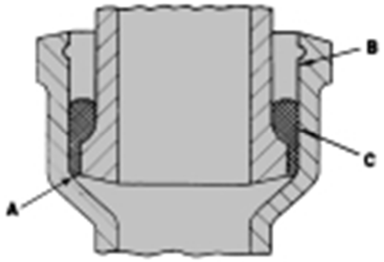


Figure 1.1 Bell and Spigot Joint (Flowserve Corporation, 2012)

2. Mechanical (Gland Type) Joint

This joint was an improvement to the bell and spigot joint. The lead and oakum of the conventional bell-and-spigot joint were replaced by a stuffing box in which a rubber or composition packing ring, with or without a metal or canvas tip or canvas backing, is compressed by a ductile cast-iron follower ring drawn up with bolts (Nayyar, 2002). Figure 1.2 represents a typical mechanical (gland type) joint.

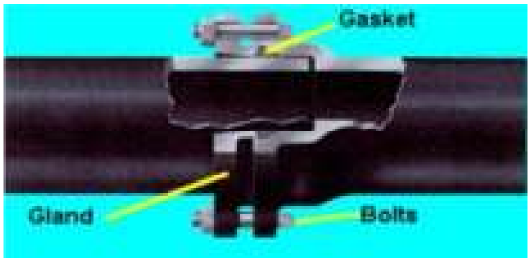


Figure 1.2 Mechanical (Gland Type) Joint (National Association of Pipe Fabricators, 2012)

3. Tyton Joint

The design of a Tyton joint contains an elongated grooved gasket. The inside contour of the socket bell provides a seat for the circular rubber in a modified bulb shaped gasket. An internal ridge in the socket fits into the groove of the gasket. The plain end of the pipe is slightly tapered which facilitates the assembly (Nayyar, 2002). Figure 1.3 illustrates a Tyton joint.

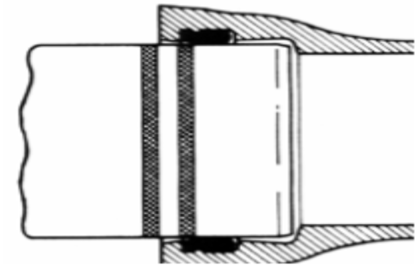


Figure 1.3 Tyton Joint (U.S. Pipe, 2010)

4. Mechanical Lock-Type Joint

This joint is similar to the mechanical (gland type) joint. The only difference is that in this type of joint, the spigot end of the pipe is grooved or has a recess to grip the gasket. For installations where the joints may tend to come apart owing to sag or lateral thrust in the pipeline, this joint is used to resist end pull (Nayyar, 2002).

5. Mechanical Push-On-Type Joint

In this type of joint, round rubber gasket is placed over the spigot end and is pulled into the bell by mechanical means, thus pulling the ring into place in the bottom of the bell. This joint is an improvement to the mechanical (gland type) joint. Outside the rubber gasket, braided jute is wedged behind a projecting ridge in the bell (Nayyar, 2002).

1.10 Failure of Cast Iron and Ductile Iron Pipes

The comparative studies about the failure rates for different pipe materials explained earlier had a failure rate of 56.16 breaks/100 miles/year and 58.72 breaks/100 miles/year for 21 Canadian cities (Rajani and McDonald, 1993). A study by Utah State University Buried Structures Laboratory presents a failure rate 24.4 failures/100 miles/year for cast iron pipes (Folkman, 2012). This study shows significantly higher than the failure rates of different pipe materials considered in previous studies. In accordance with above research studies, it can be concluded that cast iron pipes are most prone to failure when compared to other pipe materials.

The water industry is concerned about cast iron pipes installed prior to the 1960s. It was thought that the technology was continuously improving the performance of the pipe during this period; but it was ultimately found that the failure rate was increasing. There's a general opinion in the industry that the pipes installed in different time periods, may reach the end of their respective service lives at approximately the same time which will result in an increase in costs of replacement in a shorter period of time eventually increasing the overall financial burden (USEPA, 2002).

Though ductile iron pipe has been used since 1960's for U.S. water pipelines, it was the predominant material only in 1979. These pipes fail frequently due to age. Ductile iron pipe failures are repaired by water department crews who do not have evaluation expertise and cannot determine the cause of the failures. Often, the surface conditions of ductile iron pipe are misleading. Also, corrosion of the pipe material is frequently overlooked (Szeliga and Simpson, 2003).

1.11 Need Statement

Although cast iron pipe is not used for new installations anymore, it is still the most common material used in in-service water pipelines in North America (Makar, 1999). Cast iron and ductile iron pipes make up about 70% of the total water mains in North America (Makar et al., 2001). Even though studies calculating the failure rates for cast iron and ductile iron pipes are carried out along with detailed understanding of the different causes and modes of failure, certain parameters of failure such as age of the pipe, diameter size, manufacturing process and type of joints and the inter-relationships between these parameters have not been thoroughly investigated.

This research will help in collecting and evaluating information about the failure parameters of cast iron and ductile iron water. Also, information regarding the inventory of the pipe materials and the considerations on use of cast iron and ductile iron water pipes along with the type of failures observed will help in calculating number of water mains breaks which will be further used to predict the number of potential future breaks. The goal of this research is to help water utilities to better understand the failure of these pipe materials. Generally, the previous studies were for pipe diameter sizes smaller than 24-inch. This research is carried out for diameters smaller than 24-inch as well as for diameters that are 24-inch and larger.

1.12 Objectives

The objectives of this thesis are:

1. Evaluate the different causes and modes of failure in cast iron and ductile iron water pipes.
2. Itemize field performance of cast iron and ductile iron water pipes based on parameters such as:
    - Diameter of the pipe
    - Age of pipe materials
    - Different manufacturing processes
    - Type of joints

1.13 Methodology

The methodology of this thesis is summarized below:

1. Conduct a literature search to identify and review the past research regarding the failure of cast iron and ductile iron pipes.
2. Collect the historical failure data of cast iron and ductile iron water pipes from selected water utilities in the United States by a survey.
3. Compile the data obtained from the literature search and the survey questionnaires to understand the types of failure of cast iron and ductile iron water pipes.
4. Study the cast iron and ductile iron water pipes failures based on accumulated data by classifying the pipe materials per diameter, age, manufacturing process, joint materials and type of joints used as well as type of failure observed.

Figure 1.4 gives an overview of the strategy behind the research. This research's problem statement is about the failure of cast iron and ductile iron pipes. Finding an answer to this problem involved a literature search to understand and evaluate the failure of cast iron and ductile iron pipes. Along with the literature search, a survey questionnaire was prepared and sent out to U.S. water utilities to collect historical failure information on cast iron and ductile pipe materials. The research analyzes the failure of cast iron and ductile iron pipes as per diameter, age, manufacturing process, joints, different types of failure and failure rates. Finally, this research identifies some research topics for future investigations.

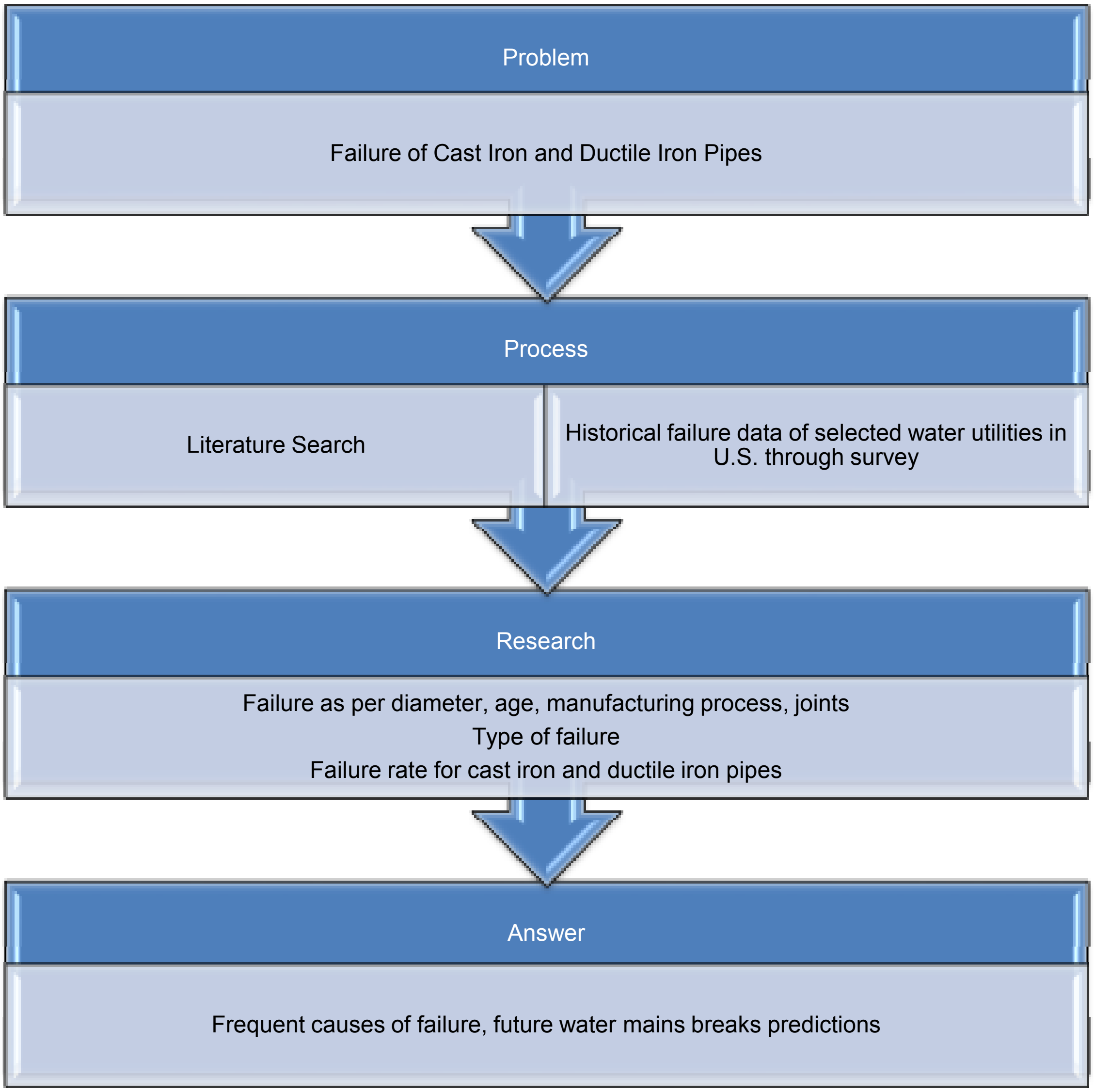


Figure 1.4 Methodology Overview

1.14 Expected Outcome

The results from this study are expected to create awareness for future research on cast iron and ductile iron pipes' repairs and replacements. The survey questionnaire for water utilities was designed to provide answers about the field performance of these pipe materials over the years and help find the modes of failures and failure rates for cast iron and ductile iron pipes. This study of these two pipe materials based on parameters such as, pipe age, manufacturing process, diameter size and inventory of pipe materials will help in identifying future research and development.

1.15 Thesis Organization

Chapter 1 presents an overall idea of the whole research. It contains the history of pipelines, importance of water distribution pipelines, failure of water pipelines, pipe materials used for water distribution and their applications followed by a brief history about cast iron and ductile iron pipes, type of joints used for cast iron and ductile iron pipes, failure of cast iron and ductile iron pipes, problem statement, objectives, methodology and expected outcome of this research. Chapter 2 provides a literature review on failure of cast iron and ductile iron pipe materials. Chapter 3 explains the methodology used for this thesis in detail by outlining a step by step description of the research performed. Chapter 4 outlines results of the research. Chapter 5 discusses the literature search carried out and the thesis research done with the help of the survey questionnaire. Chapter 6 draws conclusions and offers recommendations for further study. Appendices and references are provided at the end of this research.

1.16 Chapter Summary

This chapter gave a brief introduction about the pipe materials used for water distribution and their applications, the importance of water followed by a brief introduction about cast iron and ductile iron pipes. Types of joints used for cast iron and ductile iron pipes and an introduction to the failure modes of cast iron and ductile iron pipes were presented. Additionally, this chapter reviewed the problem statement, objectives, methodology and expected outcome of this research.

CHAPTER 2

LITERATURE SEARCH

2.1 Introduction

This chapter consists of a detailed review of findings from an extensive literature search. Literature search was used as one of the tools to understand more about existing research work on the failure of cast iron and ductile iron pipes and to get a better knowledge of causes and modes of failure of cast iron and ductile iron pipes. The subjects covered in this chapter include the consequences of pipeline failures, causes of failure, various types of failure in cast iron and ductile iron pipes over the years and the risk assessment of pipeline failure. The chapter concludes with information about the regression models used to predict future mains breaks.

2.2 Consequences of Water Pipeline Failures

Water supply lines are a link between the water treatment plants and users. Water lines transmit and distribute water. Water supply pipeline breakages cause inconvenience to consumers along with economic losses to treatment plants and water utilities (Zheng, et al., 2011). The consequences of failure of pipelines can be assessed in terms of direct costs, indirect costs and social costs.

1. Direct Costs (Zlokovitz and Juran, 2005)
    - Planning
    - Design
    - Contracting cost
    - Permanent reinstatement
    - Professional charges
2. Indirect Costs (Zlokovitz and Juran, 2005)
    - Disruptions to businesses

- Increase in road maintenance requirements
- Damage to adjacent property
- Diversion of existing facilities
- Reduction in road pavement life

3. Social Costs (Najafi and Gokhale, 2005)
    - Vehicular traffic disruption
    - Road damage
    - Noise and vibrations
    - Pedestrian safety
    - Citizen complaints
    - Environmental impact

2.3 Causes of Failures

The common problem among water utilities in North America is the aging of water pipes manifesting breaks and leaks. Corrosion of these pipes has led to an advanced state of deterioration (Seica and Packer, 2004). The failure causes include physical loads applied to the pipe, deterioration due to usage, limited structural resistance because of construction practices during installation and decline in the resistance over the years (Wood and Lence, 2009).

A range of factors such as physical, environmental and operational conditions must be considered while studying the pipeline failure mechanism. Also, the manufacturing quality of pipes and their installation are also important. The factors that influence the failure are (Vipulanandan et al., 2012):

1. Internal and external loads exerted by the soil pressure, traffic loads, frost loads, operation pressure and third party interference.
2. Characteristics of pipe such as age, material and diameter.
3. Internal and external temperature.
4. Internal and external corrosion.

Some of the factors affecting the failure of pipelines are mentioned in Table 2.1.

Table 2.1 Factors Affecting Failure of Pipelines (Adopted from Najafi, 2010)

Pipe Factors	**Environmental Factors**
Type and material of pipe	Manufacturing defects
Location of pipe	Transportation, handling and installation damage
Diameter	Soil loads
Length	Point loads from projecting rocks, etc.
Type of soil and embedment	Internal pressure loads
Joining method	Axial loads due to temperature, water hammer, etc.
Internal and external corrosion protection	Frost loads in soils
Wall thickness	Freezing and expansion of water
Depth of installation	Loads due to expansion of soils
Bedding conditions	Third-party damage
Foundation conditions	Traffic loads

2.4 Types of Failures

The types of failures can be classified into three major categories: 1) corrosion and environment, 2) failure due to excessive stresses and, 3) failure at the joints. Table 2.2 summarizes these types of failure.

Table 2.2 Classification of Failures

(Adopted from: Vipulanandan et al., 2012 and Doyle, 2000)

Type of Failure	Modes of Failure	Causes of Failure
Corrosion and Environment	Pitting Holes	Corrosive soils, microbiological influence, stray currents.
	Graphitization	Corrosive soils, hydrogen embrittlement, stray currents, anaerobic bacteria.
	Secondary Effects	Hydrogen embrittlement, chlorides from water, coating damage, dissimilar soils, ground movements.
Stress Failure	Transverse Break	Circumferential stress, thermal stresses, transient conditions, mechanical stresses, soil swelling or settlements.
	Split Pipe	Ambient temperature differences, transient conditions.
Joint Failure	Brittle Failure	Graphitization, hydrogen embrittlement, coating damage.
	Connection Failure	Defects in welding, thermal stresses, fatigue weakening.
	Joint Burst	Soil swelling/settlements, differential thermal expansion/contraction.

The following types of failures are considered in this research:

1. Corrosion Failure

Water utility personnel agree that the majority of the pipe breaks occur at locations where the pipe wall has been weakened. This weakening of the pipe wall is as a result of pipe corrosion (Fitzgerald III, 1968).

Corrosion can occur both the inside and outside of the pipe. External corrosion can occur as a result of stray currents that pipe conducts from the ground or as a result of misapplication of cathodic protection causing hydrogen embrittlement. Internal corrosion happens when water properties and its chemical composition interact with the inner pipe wall (Vipulanandan et al., 2012).

Two types of corrosion processes are observed in a cast iron pipe: 1) A simple corrosion pitting and, 2) graphitization. In graphitization, some of the iron is removed leaving behind a matrix of graphite flakes which are held together by iron oxide. Graphitization forms a solid substance on the pipe, which is misleading because it appears to be an undamaged pipe. Sometimes, this product is strong enough to resist internal water pressure temporarily. Thus, it is important to recognize the extent of corrosion damage to the pipe material frequently by using sand blasting or other similar methods (Makar et al., 2001).

Unlike cast iron pipe, ductile iron pipe does not have a matrix of cast iron flakes which can lead to the false assumption that graphitization cannot occur in ductile iron pipe (Makar et al., 2001). However, a paper by Szeliga and Simpson lists the two failure mechanisms of ductile iron pipe as graphitization and pitting corrosion which are similar to that observed in cast iron pipe. Figure 2.1 explains the different types of corrosion. The failure observed on the right is the corrosion through-hole whereas that on the left is chain corrosion pitting.

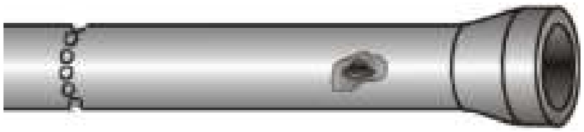


Figure 2.1 Corrosion Failures (Makar et al., 2001)

The design, operation and maintenance of every element of a water system are affected by corrosion. Piping systems are very vulnerable to accelerated deterioration from corrosion. Some of the impacts of corrosion are summarized below (Kroon, 2004):

- Costly System Repairs and Replacements
- Disruption of Service
- Expensive Loss of Water
- Structural and Environmental Damage
- Reduced Water Quality
- Improper Treatment
- Decreased system capacity

2. Transverse Break

This type of failure is observed most commonly in small diameter pipes, i.e., pipes with a diameter of less than 16-inches. Generally, the bending forces experienced by the pipe are the main cause of this type of failure. The failure crack proceeds across the circumference of the pipe. Sometimes, the movement of soil may exert tensile forces on the pipe, which can also lead to this type of failure. Figure 2.2 shows a typical transverse break observed in a pipe (Makar et al., 2001).

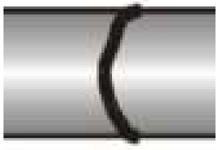


Figure 2.2 Transverse Break (Makar et al., 2001)

3. Split Pipe

As explained earlier, the joints in cast iron pipe were originally sealed using rope (oakum) packed between the bell of one pipe and the spigot of the other. Then molten lead was poured into the joint which sealed it completely. Later, leadite viz. a rigid, sulfur based compound was used in the 1930s and 1940s instead of lead. However, because leadite is a non-metallic compound, its thermal coefficient of expansion is different than lead. Therefore, at very cold temperatures, the pipe can cause the bell to split as shown in Figure 2.3. The crack terminates just below the bell of the pipe once the stresses produced by the thermal expansion have been relieved (Makar et al., 2001). Sometimes, this crack is introduced when lead is hammered into place or due to excessive hammering in cast iron and ductile iron pipes (Rajani and Kleiner, 2010).

Figure 2.3 Split Pipe (Makar et al., 2001)

4. Joint Failure

Joint failure is a gradual process. Due to the deterioration of joints over a period of time, leaks in the distribution system caused by pipe breaks are usually observed near the joint. This may have an impact on the water quality. These failures are often undetected and not acted upon as they are not catastrophic most of the time. The failure of sealing used in lead joints is the most problematic failure. It is observed due to the degradation and corrosion of bolts and backing rings (Reed et al., 2006).

Ground movement can lead to a change in joint alignment. A large change to the alignment can lead to a leakage and ultimately joint failure. Also, the joint can be displaced without undergoing any change in the alignment (Liu, et al., 2012).

2.5 Risk Assessment of Failure

“Risk can be defined as the product of the likelihood of pipeline failure and the consequence of such a failure (Thorne, 1992).”

While analyzing the failure of pipe, it is also important to assess the risk involved in the failure. The consequences of failure include flooding, loss of service, transportation delays, liability and sometimes health hazards. A risk matrix was prepared by Grigg, Fontane and Van Zyl (2011) which explains the various scenarios of pipe failure as illustrated in the four quadrants in Figure 2.4 matrix below ranging from high-likelihood and high consequence situations which require immediate attention to pipes that will require little or no attention. High and low risk funding areas are also marked for attention (Grigg et al., 2011).

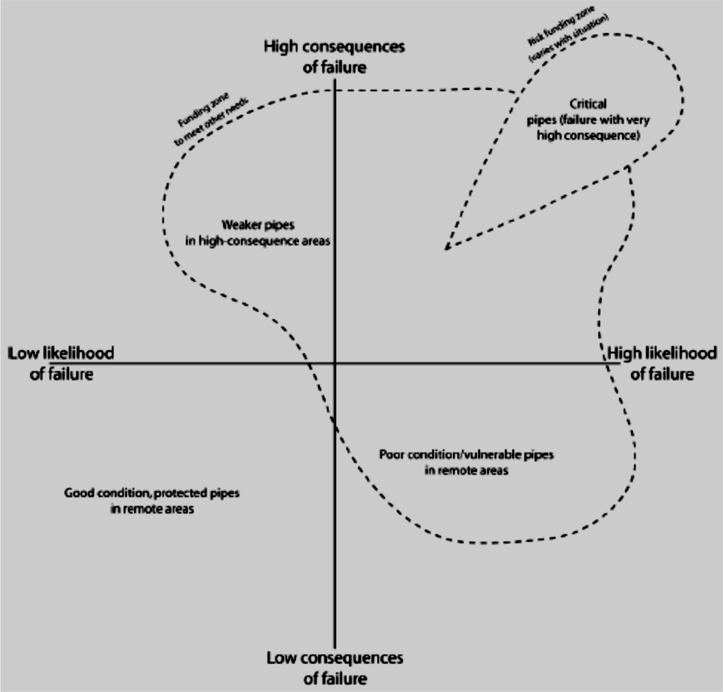


Figure 2.4 Risk Matrix for Pipe Failure (Grigg et al., 2011)

2.6 Regression Analysis

The relation between a predictor variable and a response variable is utilized in regression analysis. Regression analysis is used to predict the response variable "*y*" based on its relation with the predictor variable "*x*" (Kutner et al, 1996). The various terms and definitions used for this analysis are explained below:

1. Relation between Two Variables

The two variables are the response variable "*y"* which is also called as the dependent variable or the outcome variable and "*x*" which is the predictor variable or the independent variable. General form of the relationship between these two variables is represented by Equation 2.1 (Kutner et al, 2004).

$$y = f(x)\ldots \text{ Eq. 2.1}$$

2. Coefficient of Determination (R^2)

The coefficient of determination is represented by "R^{2}" and is interpreted as the proportionate reduction of total variation in the response variable "*y*" associated with the use of the predictor variable "*x*." Thus, the larger the "R^2" is, the more the reduction in total variation of "*y*" because of "*x*" (Kutner et al, 2004).

3. Scatter Plots

It is the graphical representation of the bivariate (two variables) data before working out a correlation or fitting a regression line (Lacy, 2012). The scatter plots can be used to get the following different regression models and relationships between "*y*" and "*x*."

a. Linear Model

This is a basic regression model with one predictor variable and linear regression function. It is represented by Equation 2.2 (Kutner et al, 2004).

$$E(y) = \alpha + \beta x_i + \varepsilon_i \dots \text{Eq. 2.2}$$

where,

$E(y)$ … Value of response variable in the i^{th} trial

α … Intercept of the regression line

β … Slope of the regression line

x_i… Value of predictor variable in the i^{th} trial

i... 1,..., n

ε_i… Random error term

b. Logarithmic Model

This model is used to linearize a nonlinear relationship. The natural log of Equation 2.2 is taken and transformed in Equation 2.3 for this model. The change in "*y*" is the proportionate change for a one-unit change in "*x*" (Kahane, 2008).

$$E(y) = \alpha + \beta \ln(x_i) + \varepsilon_i \dots \text{Eq. 2.3}$$

c. Quadratic Model

Polynomial regression model for a response variable "*y*" and single predictor variable "*x*" is represented by Equation 2.4.

$$E(y) = \alpha + \beta_1 x + \beta_2 x^2 + \cdots + \beta_i x^i + \varepsilon_i \dots \text{Eq. 2.4}$$

In this model, "i" is the degree of the polynomial function. The second-degree polynomial function is known as the quadratic regression model represented by Equation 2.5.

$$E(y) = \alpha + \beta_1 x + \beta_2 x^2 + \varepsilon_i \ldots \text{Eq. 2.5}$$

The graph of this model is parabolic with a single bend, either increasing and then decreasing or decreasing and then increasing (Model Building with Multiple Regression, 2012).

d. Exponential Model

Exponential regression model for a response variable "y" and single predictor variable "x" is represented by Equation 2.6.

$$E(y) = \alpha\beta^x \ldots \text{Eq. 2.6}$$

Exponential model only considers positive values of the predictor variable. It has a convex shaped graph either continually increasing or continually decreasing (Model Building with Multiple Regression, 2012).

e. Power Model

Power regression model improves the estimation of "y" while retaining the simplicity of the standard log-linear relationship. Power regression model for a response variable "y" and single predictor variable "x" is represented by Equation 2.7. This is also called as the Power Law (Valiantzas, 1991).

$$E(y) = \alpha x^\beta \ldots \text{Eq. 2.7}$$

2.7 Chapter Summary

This chapter reviewed the existing literature search on failure of cast iron and ductile iron pipes. The impact of pipeline failure in terms of direct, indirect and social costs was explained. Also, the causes and modes of failures are discussed. A short explanation on the risk assessment of pipeline failure followed by information about regression analysis concludes this chapter.

CHAPTER 3

METHODOLOGY

This chapter discusses the research methodology used to study the failure of cast iron and ductile iron pipes.

3.1 Introduction

This research was divided in two parts as per diameter ranges of “Smaller than 24-inch” and “24-inch and Larger.” For diameters smaller than 24-inches, the use of a failure data of more than 30,000 pipe section failures from a single utility was considered whereas for diameters larger than 24-inches, a survey was carried out of selected water utilities across U.S. The methodology for both of these is explained later in this chapter. Figure 3.1 represents an overview of this research.

3.2 Use of Surveys

A survey is a systematic method of collecting data from a population of interest. A survey collects quantitative information through the use of a structured and standardized questionnaire (Conducting Survey Research, 2012). A survey questionnaire was used in this thesis to collect historical data of cast iron and ductile iron pipes from select water utilities across U.S. This questionnaire was sent out to various professionals in these water utilities who were asked to respond based on the historical data of their water utility as well as their experience.

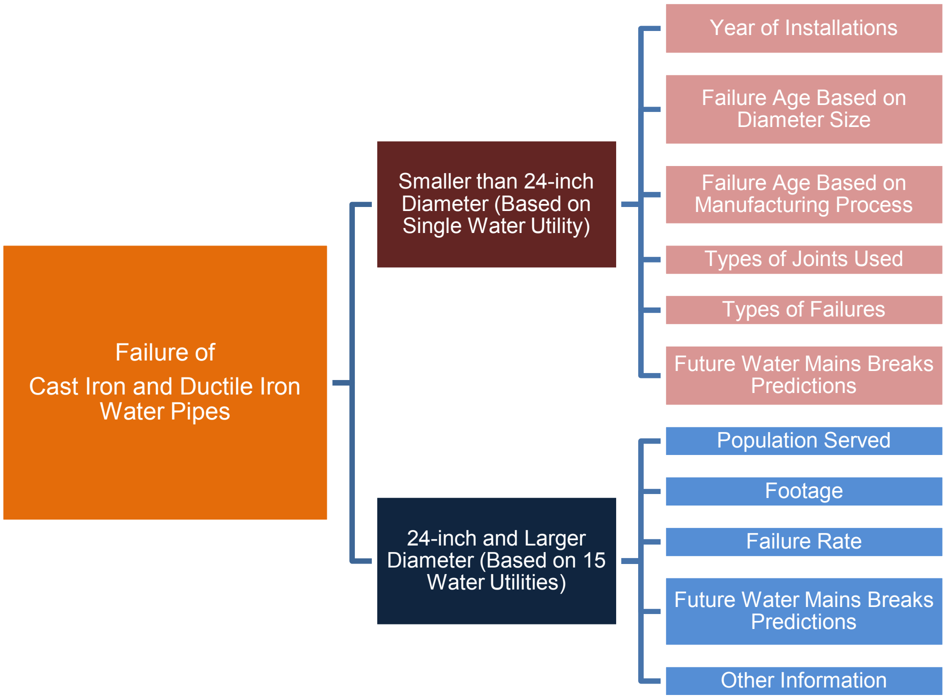


Figure 3.1 Research Details

3.3 Smaller than 24-inch Diameter Size

This part of research considered the year of pipe installation, diameter ranges, different manufacturing processes, types of joints used and the types of failures observed. The pipe sections of varying length from a single water utility are considered for this part of the research.

A graph was plotted based on the date of installations from 1872 to 1972. Then, the failures as per different diameter sizes, e.g., 4-inch, 6-inch, 8-inch, 12-inch,16-inch and 20-inch, were studied and based on the date of installations and date of failures, the failure ages for the diameter sizes were categorized into four different categories of less than 25 years old, between 25 years to 50 years old, between 50 and 75 years old and more than 75 years old which helped in comparing the service life of cast iron and ductile iron pipes.

Furthermore, similar to failure ages for the diameter sizes, failure ages for the different manufacturing processes were studied based on the date of installations and the date of failures. This was followed by an overview about the use of different types of joints in cast iron and ductile iron pipes.

The types of failures were then studied based on three different categories of corrosion: 1) failure, 2) stress failure (transverse failure and split pipe) and, 3) joint failure. These types of failures were further classified based on the manufacturing processes such as pit cast gray iron pipe, centrifugal cast gray iron pipe and ductile iron pipe. Corrosion failure for these three manufacturing processes was studied. The stress failure was classified for these manufacturing processes according to transverse failure and split pipe failure. Similarly, joint failure was classified into four categories of 1) bell and spigot - lead joint, 2) bell and spigot - leadite joint, 3) mechanical lock-on type joint and, 4) mechanical pus-on type joint.

Lastly, the scatter plots of different models such as linear, logarithmic, quadratic, exponential and power were plotted for different manufacturing processes with number of failures as the response variable *"y"* and the year of failure as the predictor variable *"x."* The relationships gave a proper significant trend equation and the relationship ratio R-squared (R^2). The higher the "R^2," the more accurate is the trend line. The trend equation obtained can be used to get an idea about future water mains breaks for this one particular water utility.

3.4 24-inch and Larger Diameter Size

A survey questionnaire was prepared by the Center for Underground Infrastructure Research and Education (CUIRE) and sent out to more than 250 U.S. water utilities to collect the historical failure data of cast iron and ductile iron pipes for 24-inch and larger diameter sizes. A total of 15 survey responses were received from these water utilities with cast iron and ductile iron pipe's information. Appendix B includes the survey questionnaire. Follow up with these utilities for more information was done by calling the respective personnel. Also, the utilities were given a choice of sending the failure record sheets maintained over the years instead of answering the survey questions.

The participating water utilities answered questions regarding the population served by the large diameter pipelines, the footage of the pipelines and the inventory of pipe materials. Inventory questions covered the age of the inventory and the use of different pipe materials.

The footage of the pipe materials along with the failure data available was used to calculate the failure rates of these pipes based on Equation 3.1:

$$Failure\ Rate\ (Per\ 100\ Miles) = \frac{Number\ of\ Failures}{Total\ Footage\ (miles)}(100) \ldots \text{Eq. 3.1}$$

The above equation provided information regarding the number of failures per 100 miles of the pipes based on the historical failure data collected. It helped in studying the failure rates for cast iron and ductile iron pipes.

Similar to the research for smaller than 24-inch diameter size, the scatter plots of different models such as linear, logarithmic, quadratic, exponential and power were plotted for cast iron and ductile iron pipes with number of failures as the response variable *"y"* and the year of failure as the predictor variable *"x*." The relationships gave a proper significant trend equation and the relationship ratio R-squared (R^2).

Other questions such as the type of failures, percentage of failure rates for these pipe materials and any considerations on use of these pipe materials were also included in the survey questionnaire.

3.5 Chapter Summary

This chapter introduces the research methodology. The research was divided in two parts covering 1) diameter sizes smaller than 24-inch and, 2) pipes with diameters of 24-inch and larger. The study of the failure of cast iron and ductile iron pipes and the execution of the survey questionnaire to water utilities achieved the objectives of this research.

CHAPTER 4

RESEARCH RESULTS

This chapter presents the results of the research. These results have been divided according to results as they apply to diameter ranges of smaller than 24-inch and larger than 24-inch.

4.1 Smaller than 24-inch Diameter Size

A total of 31,560 pipe section failures spanning over a period of 110 years from 1872 to 1982 obtained from a water utility located in Wisconsin were considered in this study of cast iron and ductile iron water pipes. The length of the pipe sections was not available and hence was not considered for the research.

1. Year of Installation

Figure 4.1 represents the year in which the 31,560 water mains were installed from a single water utility. These water mains include both cast iron and ductile iron pipe sections of varying lengths. The length of individual pipe sections was not available and hence is not considered. There was a sudden increase in pipe section installations in 1937 when a small town named “Lake” was annexed and the water system was brought in under the ownership and maintenance of this water utility in Wisconsin. A total of 2,576 pipe sections were authorized for installation by the utility for the town of Lake. Up to 1945, only “Pit Cast Iron Pipe” was used in the water system. Beginning in 1946, the use of “Centrifugal Cast Iron Pipe” was introduced and used until 1964. From 1949 till 1959, there were a significant number of centrifugal cast iron pipe installations. Ductile iron pipe has been in use since 1964.

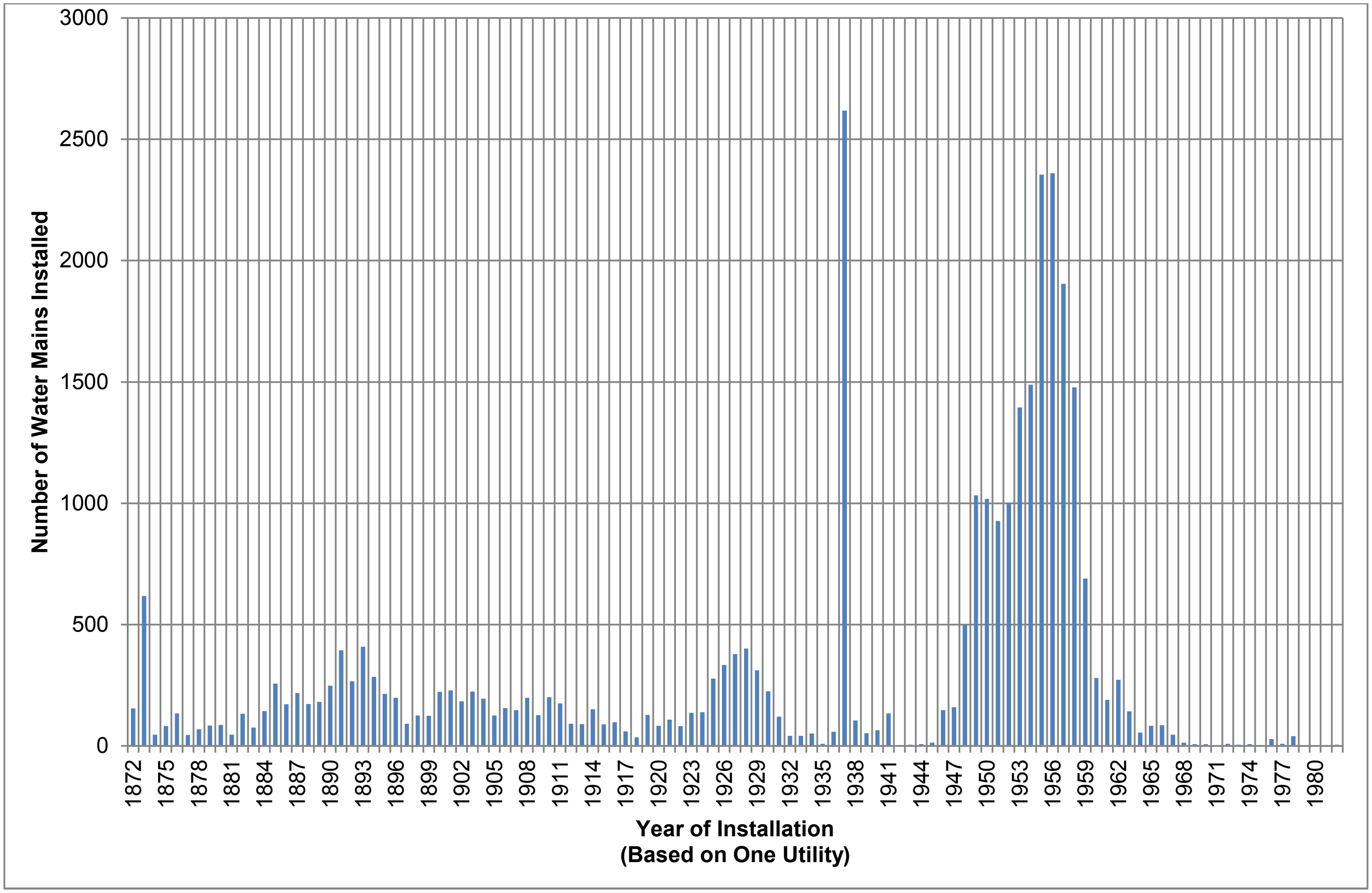


Figure 4.1 Number of Water Main Installations Each Year

2. Failure Age of Water Mains Based on the Diameter Size

A total of 16,841 pipe section failure readings are considered in this section out of the 31,560 due to insufficient data from a single water utility. The failure of both cast iron and ductile iron water pipes are categorized as per the diameter size in Figure 4.2. Diameter size of 6-inch had the most number of failures followed by 8-inch, 12-inch, 16-inch, 4-inch and 20-inch diameter pipes. Table 4.1 summarizes the failure ages in four different categories.

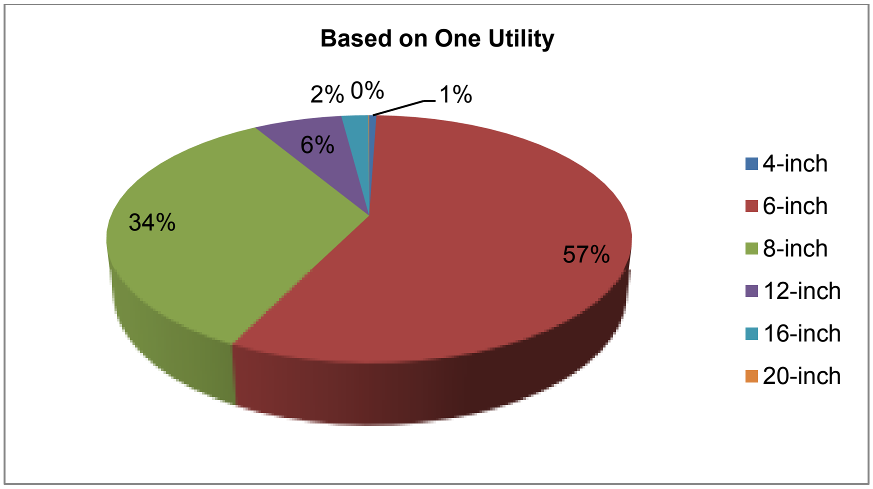


Figure 4.2 Water Main Pipe Failures Based on Diameter Size

Table 4.1 Failure Age of Water Mains Based on Diameter Size

Diameter Size	**Number of Failures (Based on One Utility)**				
	Total	**Less than 25 years old**	**Between 25 years to 50 years old**	**Between 50 years to 75 years old**	**More than 75 years old**
4-inch	103	1	15	13	74
6-inch	10,414	210	4,824	2,286	3,094
8-inch	4,984	42	2,851	1,677	414
12-inch	1,087	4	677	387	19
16-inch	254	0	150	97	7

3. Failure Age of Water Mains Based on the Manufacturing Process

The failure of two types of cast iron pipe, i.e., pit cast gray iron and centrifugal cast gray iron and the ductile iron water pipes are shown in Figure 4.3. The maximum number of failures observed is 17,364 in centrifugal cast gray iron followed by 13,797 in pit cast gray iron and 399 in ductile iron water pipes.

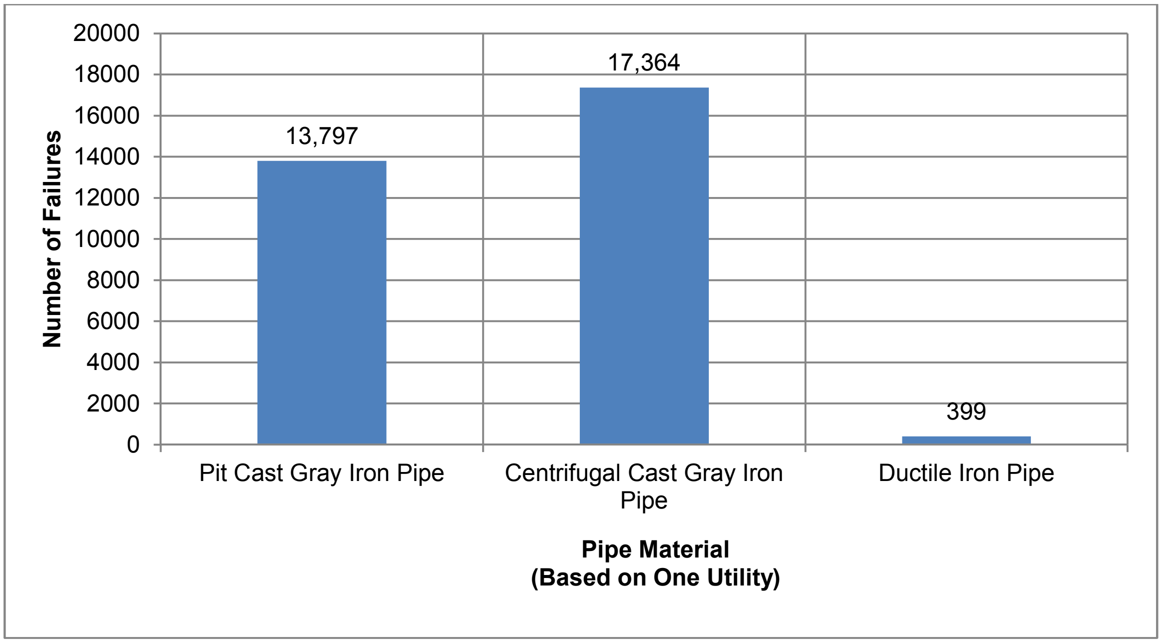


Figure 4.3 Water Main Pipe Failures Based on Different Manufacturing Processes

Table 4.2 explains the failure age of the water mains based on the same manufacturing processes. Only, 16,846 pipe section failures were considered due to insufficient data.

Table 4.2 Failure Age of Water Mains Based on Manufacturing Processes

Manufacturing Process	**Number of Failures (Based on One Utility)**				
	Total	**Less than 25 years old**	**Between 25 years to 50 years old**	**Between 50 years to 75 years old**	**More than 75 years old**
Pit Cast Gray Iron	7,125	20	1,676	1,818	3,611
Centrifugal Cast Gray Iron	9,683	230	6,812	2,641	0
Ductile Iron Pipe	38	7	30	1	0

4. Types of Joints

Four types of joints were used by the water utility with the Lead Joint showing as the most used. Until 1929, the only type of joint used was that of Lead. Then, from 1930-1937, both Lead and Leadite Joints were used. Leadite Joints were the predominant type of joint used from 1930 until 1945. Then again, when the “Centrifugal Cast Gray Iron” pipe was introduced, Lead Joint became the most used type of joint. Its usage continued until 1960. Though usage of the Mechanical Lock-Type Joints is observed in the early 1900s, it was not used on a frequent basis until the year 1955. Around the same time, the use of Mechanical Push-On-Type Joints began. Cast iron pipes have all of the type of joints used while ductile iron pipe either has the Mechanical Lock-Type Joint or the Mechanical Push-On-Type Joint only. Figure 4.4 illustrates the distribution of types of joints used by the water utility in the installations of cast iron and ductile iron pipes.

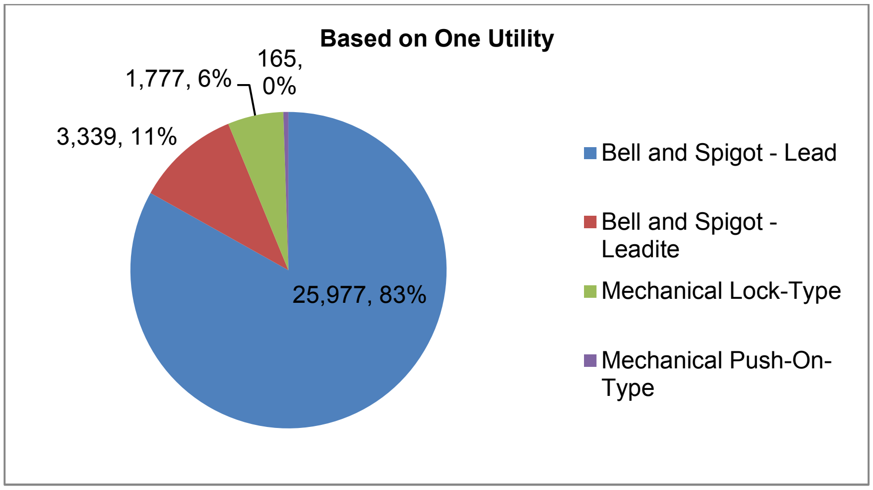


Figure 4.4 Types of Joints

5. Types of Failures

The failure of water mains sections is categorized into three different types: 1) corrosion failure, 2) stress failure (transverse break and split pipe) and, 3) joint failure. Figure 4.5 represents the different types of failures observed in water mains.

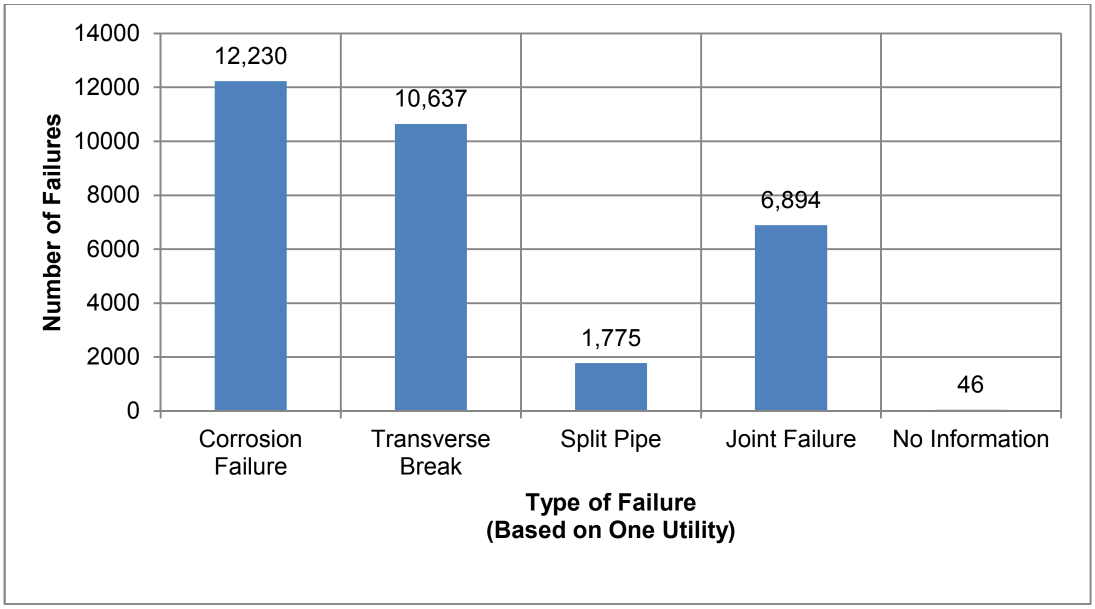


Figure 4.5 Types of Failures

Figure 4.6 to Figure 4.8 categorizes these different types of failures as per the different manufacturing processes.

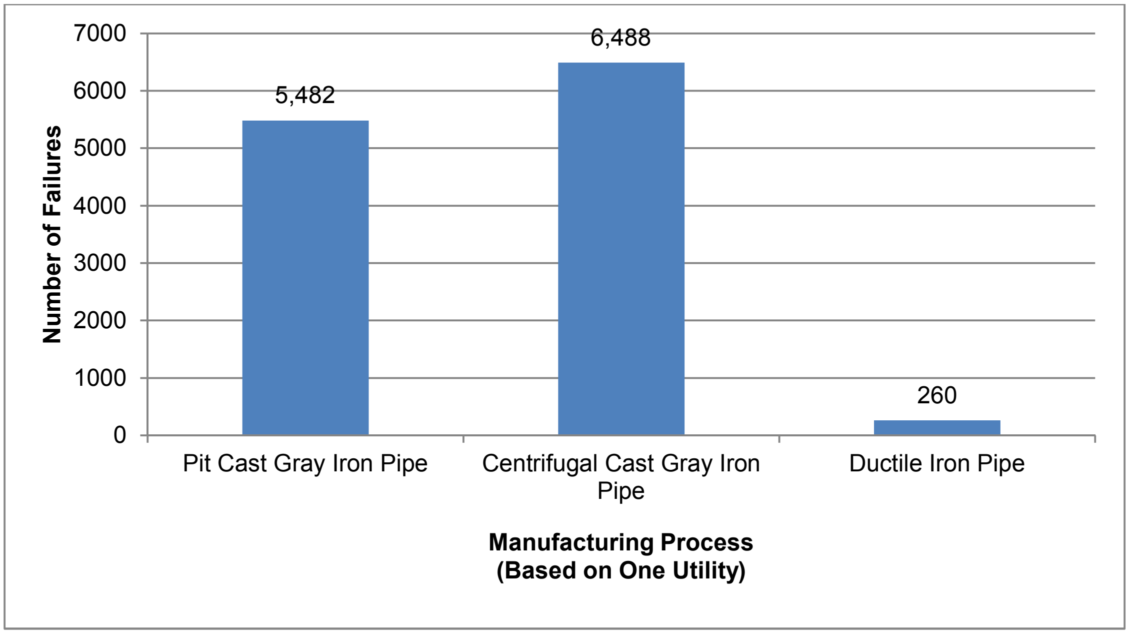


Figure 4.6 Corrosion Failures as per Different Manufacturing Processes

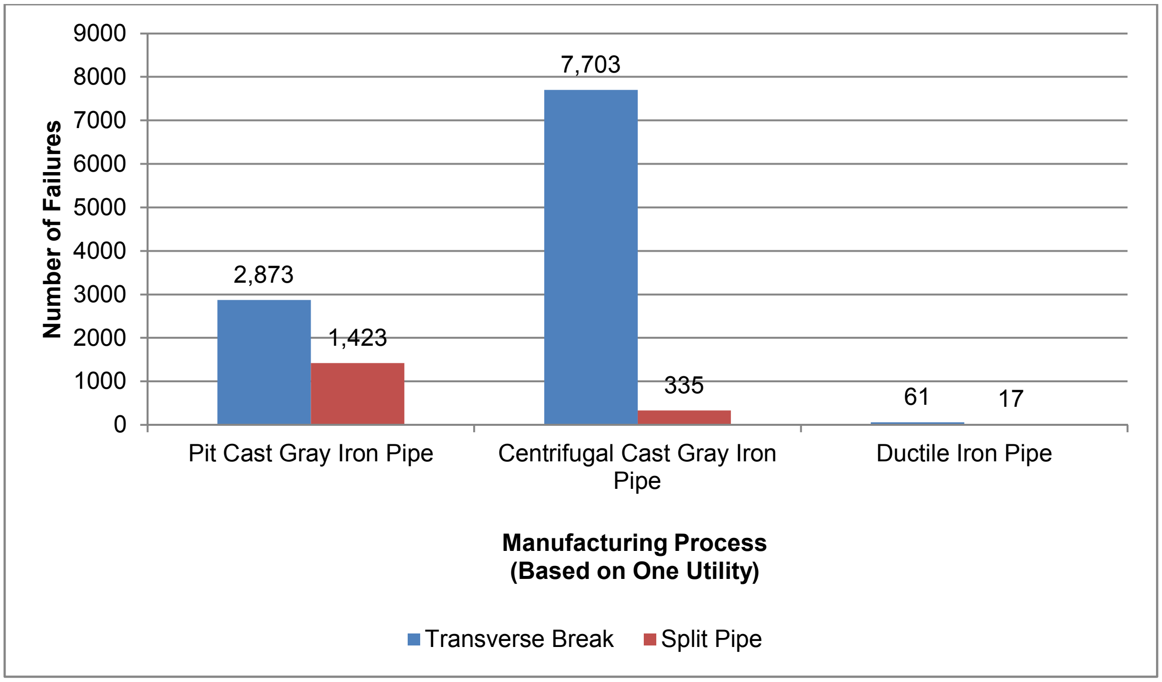


Figure 4.7 Stress Failures as per Different Manufacturing Processes

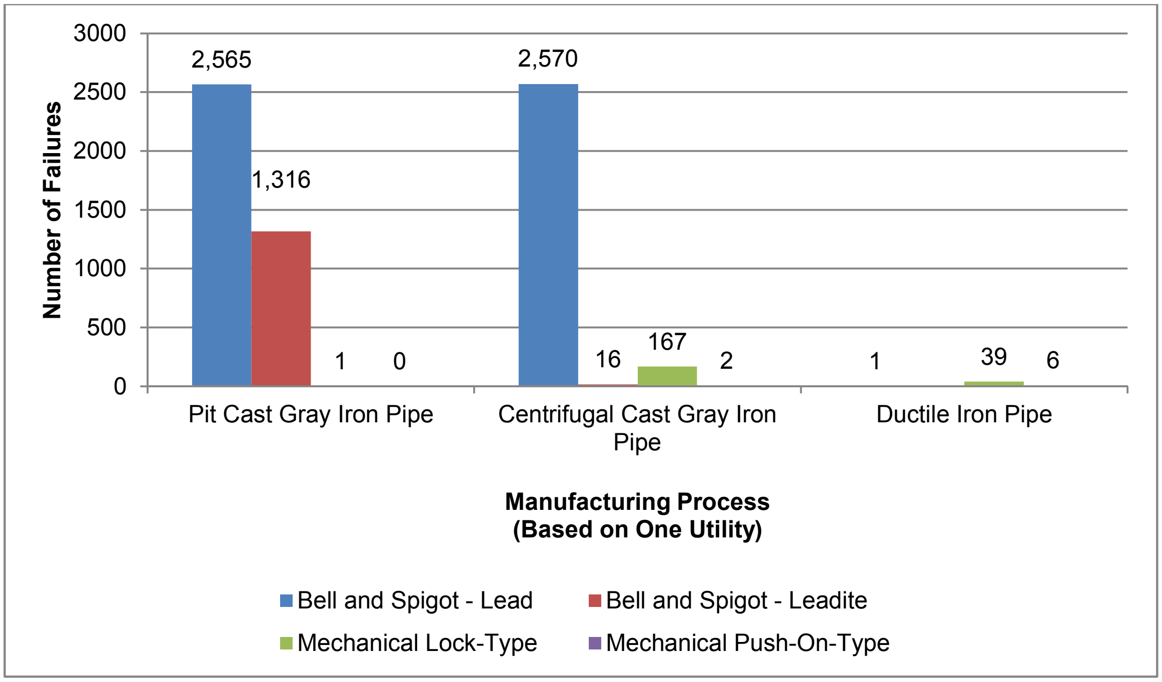


Figure 4.8 Joint Failures as per Different Manufacturing Processes

6. Future Water Mains Breaks Predictions

Figure 4.9 represents the different regression models such as linear, logarithmic, quadratic, exponential and power for pit cast gray iron pipe fitted on the number of pipe section failures per year based on failure data from a single water utility. The criteria to find out the best fitted trend line would be dependent on the relationship between the two variables which is explained by “R^2.” The relationship between the response variable (*y*) and the predictor variable (*x*) is the strongest for the highest value of “R^2.” Table 4.3 compares the line equations for all four of these models and the respective “R^2” values.

Figure 4.10 represents the different models for centrifugal cast gray iron pipe sections followed by comparisons of line equations and “R^2” values in Table 4.4 followed by similar models in Figure 4.11 for ductile iron pipe sections and comparisons in Table 4.5.

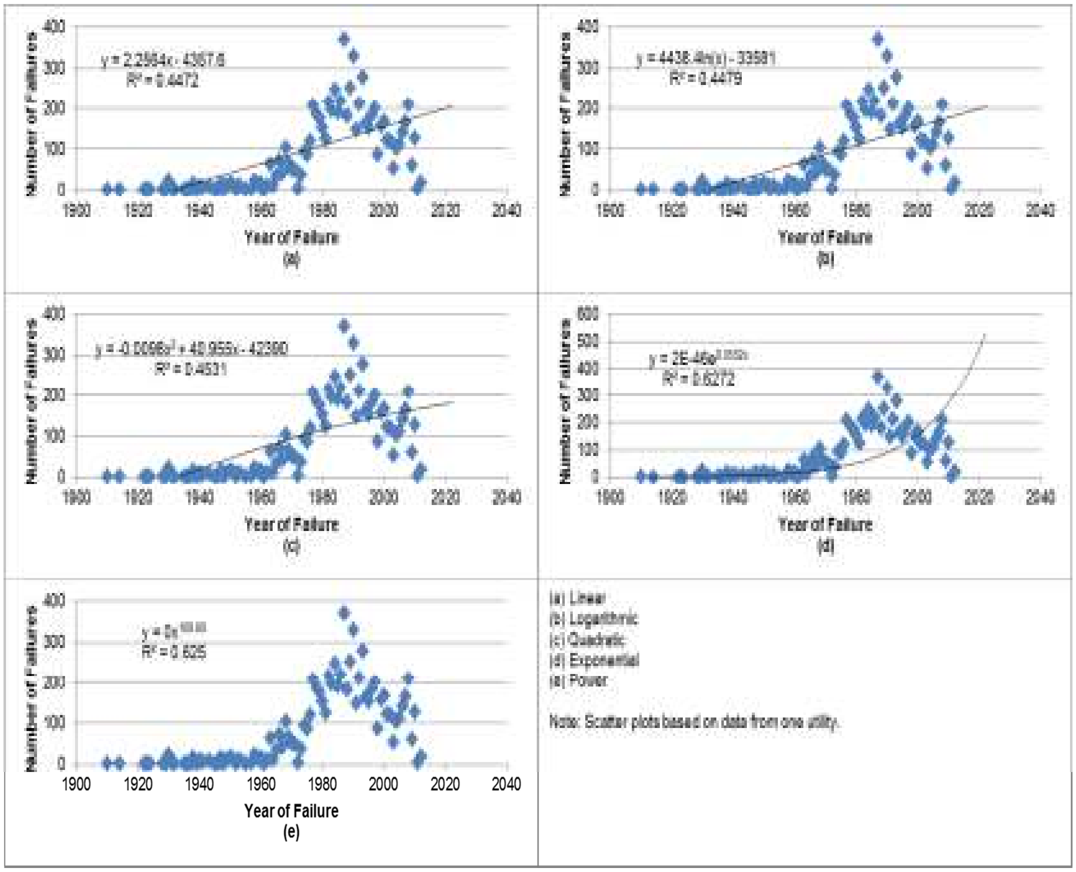


Figure 4.9 Fit Trend Line for Different Models for Pit Cast Gray Iron Pipe

Table 4.3 Comparison of Regression Models for Pit Cast Gray Iron Pipe

Relationship	**Line Equation**	**Coefficient of Determination (R^2)**
Linear	$y = 2.2564x - 4357.6$	0.4472
Logarithmic	$y = 4438.4\ln(x) - 33581$	0.4479
Quadratic	$y = -0.0098x^2 + 40.955x - 42390$	0.4531
Exponential	$\mathbf{y = 2E - 46e^{0.0522x}}$	**0.6272**
Power	$y = 0x^{108.69}$	0.625

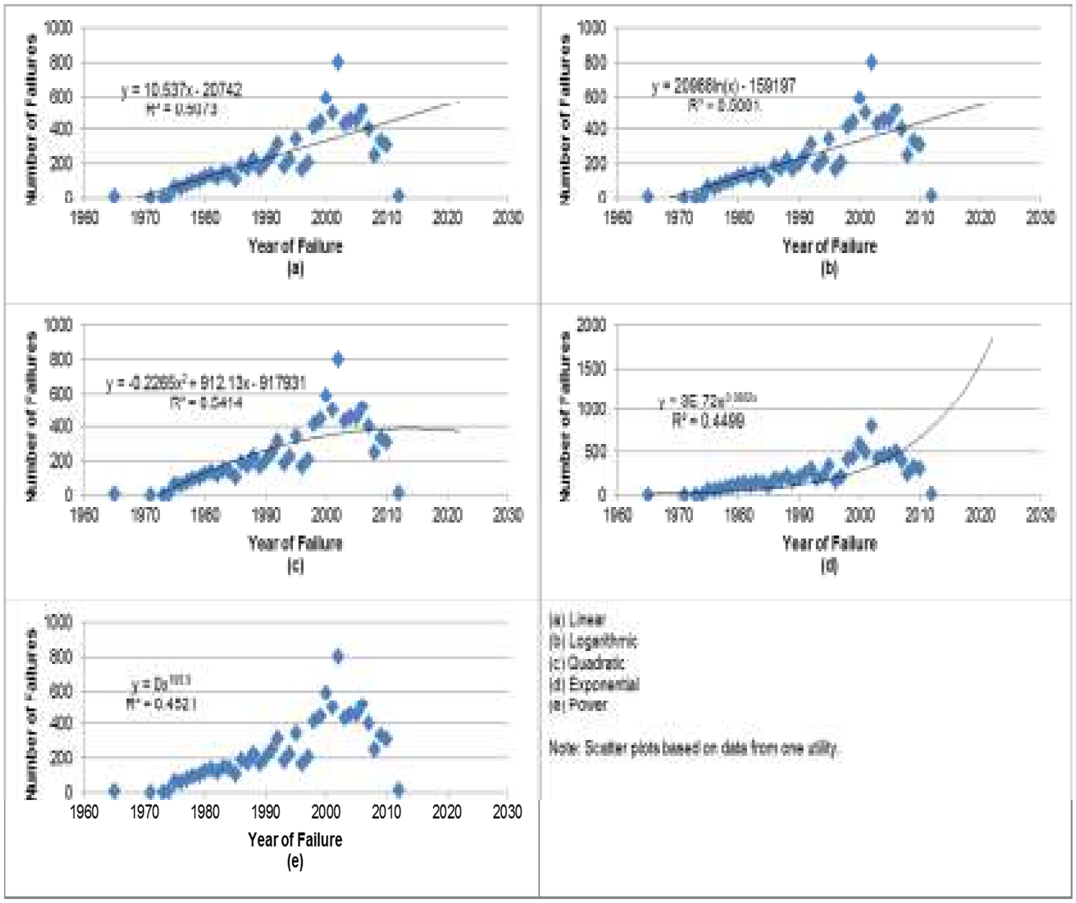


Figure 4.10 Fit Trend Line for Different Models for Centrifugal Cast Gray Iron Pipe

Table 4.4 Comparison of Regression Models for Centrifugal Cast Gray Iron Pipe

Relationship	**Line Equation**	**Coefficient of Determination (R^2)**
Linear	$y = 10.537x – 20742$	0.5073
Logarithmic	$y = 20988\ln(x) – 159197$	0.5081
Quadratic	$\boldsymbol{y = -0.2265x^2 + 912.13x - 917931}$	**0.5414**
Exponential	$y = 3E – 72e^{0.0852x}$	0.4499
Power	$y = 0x^{169.9}$	0.4521

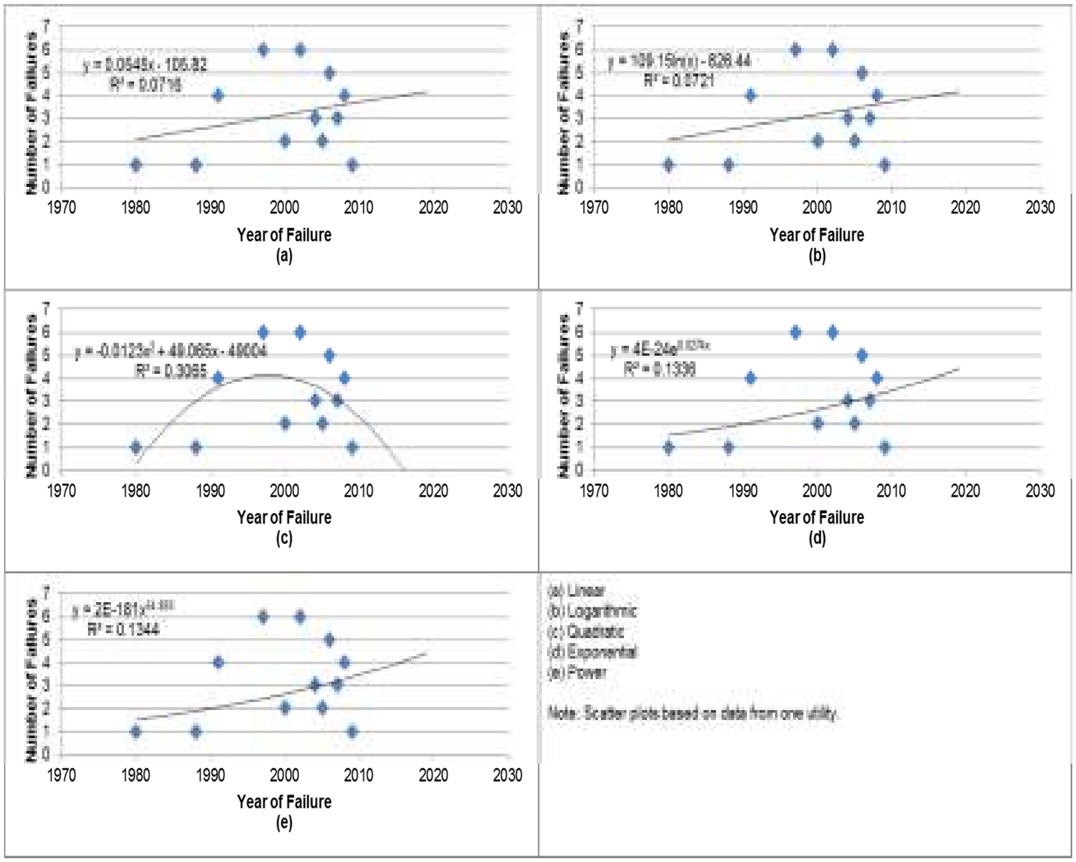


Figure 4.11 Fit Trend Line for Different Models for Ductile Iron Pipe

Table 4.5 Comparison of Regression Models for Ductile Iron Pipe

Relationship	**Line Equation**	**Coefficient of Determination (R^2)**
Linear	$y = 0.0545x – 105.82$	0.0716
Logarithmic	$y = 109.15\ln(x) – 826.44$	0.0721
Quadratic	$\boldsymbol{y = -0.0123x^2 + 49.065x - 49004}$	**0.3065**
Exponential	$y = 4E – 24e^{0.0274x}$	0.1336
Power	$y = 2E – 181x^{54.893}$	0.1344

4.2 24-inch and Larger Diameter Size

As a second part of this research, a survey was carried out to get failure information for cast iron and ductile iron pipes for 24-inch and larger diameter sizes. The respondents of the survey were spread out over nine states in the U.S. The survey respondents are the water distribution utilities from cities in these states. Figure 4.12 represents the geographic location of the survey participants. The survey respondents are assigned identifications numbers for simplicity in the further analysis.

Figure 4.12 Geographic Location of Participating Utilities

1. Population Served

Figure 4.13 shows the total population served by each of the survey respondent. The numbers on the X-axis represent the water utilities who responded to the survey.

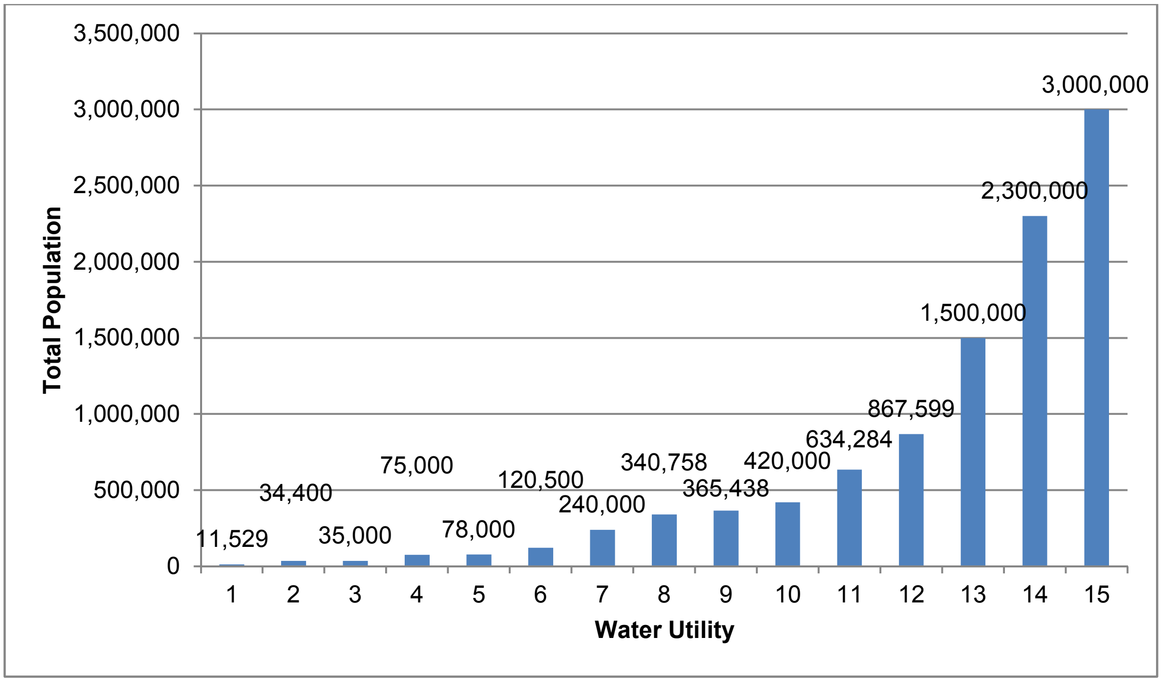


Figure 4.13 Population Served by Survey Respondents

2. Total Footage of Cast Iron and Ductile Iron Pipes

Figure 4.14 represents the total footage in miles of the installed cast iron pipe based on the survey results. It shows the footage for three different diameter ranges of 24-inch to 36-inch, 42-inch to 48-inch and 54-inch and larger. The survey respondent number 15 has the highest footage of 60 miles in the 24-inch to 36-inch diameter range while survey respondent number 12 has the highest footage of 7.1 miles and 12.3 miles in the 42-inch to 48-inch and 54-inch and larger diameter ranges respectively.

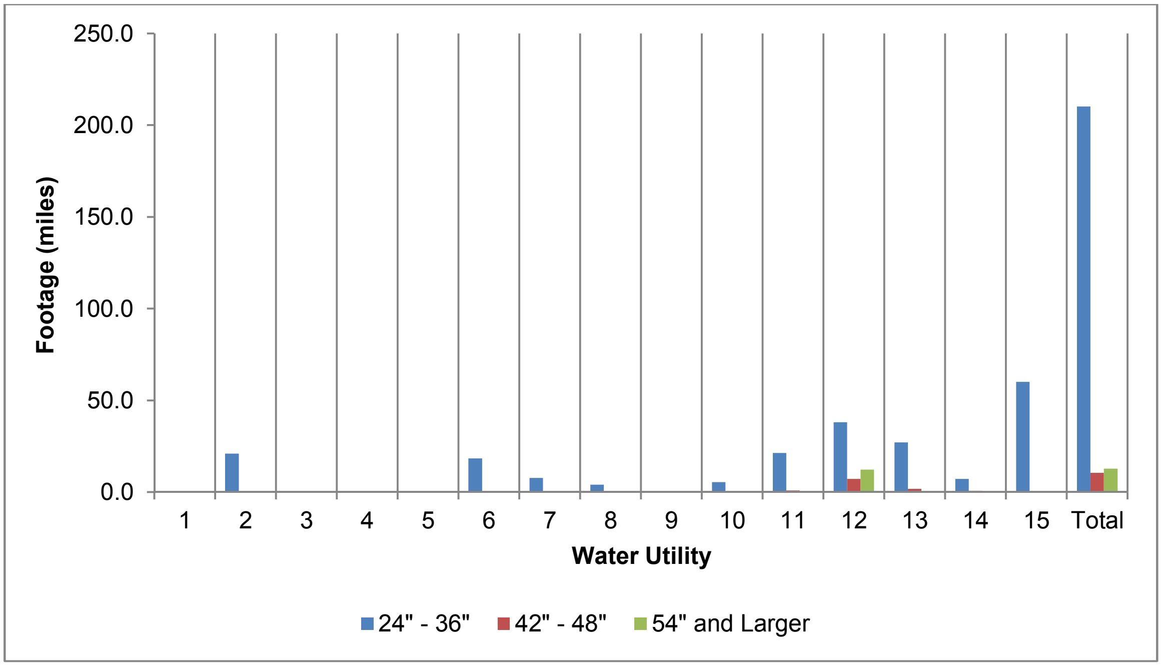


Figure 4.14 Total Footage of Cast Iron Pipe

Figure 4.15 represents the overall percent distribution of the footage of cast iron pipe as per the three diameter ranges of 24-inch to 36-inch, 42-inch to 48-inch and 54-inch and larger.

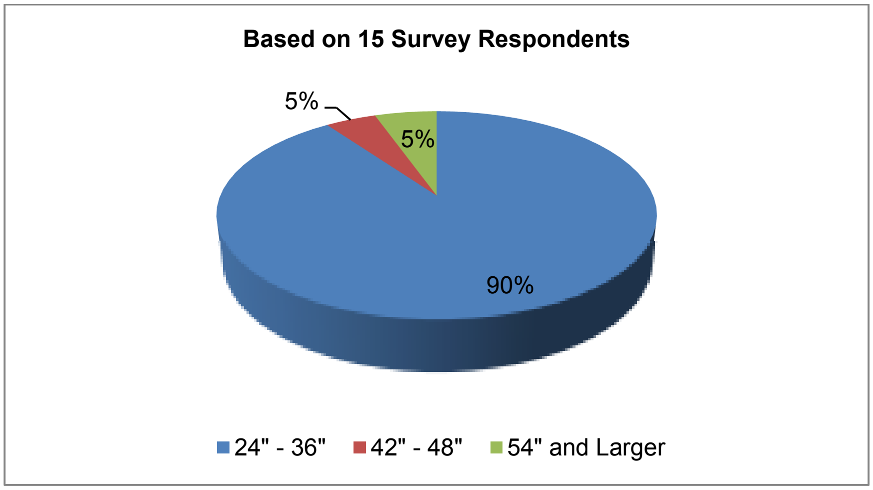


Figure 4.15 Percent Distribution of Total Footage of Cast Iron Pipe

Similar to Figure 4.14, Figure 4.16 represents the total footage in miles for ductile iron pipe in the same diameter ranges of 24-inch to 36-inch, 42-inch to 48-inch and 54-inch and larger. The survey respondent number 14 has the highest footage of 113.3 miles in the 24-inch to

36-inch diameter range while survey respondent number 9 has the highest footage of 6.5 miles and 2.3 miles in the 42-inch to 48-inch and 54-inch and larger diameter ranges respectively.

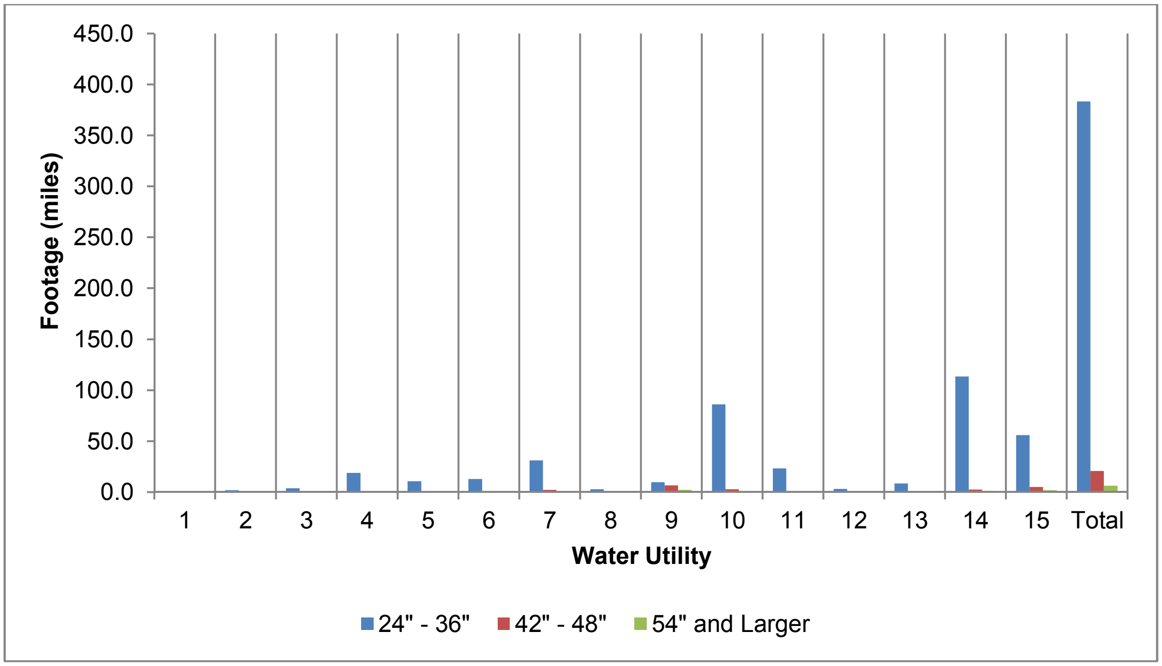


Figure 4.16 Total Footage of Ductile Iron Pipe

Figure 4.17 represents the overall percent distribution of the footage of ductile iron pipe as per the three diameter ranges of 24-inch to 36-inch, 42-inch to 48-inch and 54-inch and larger.

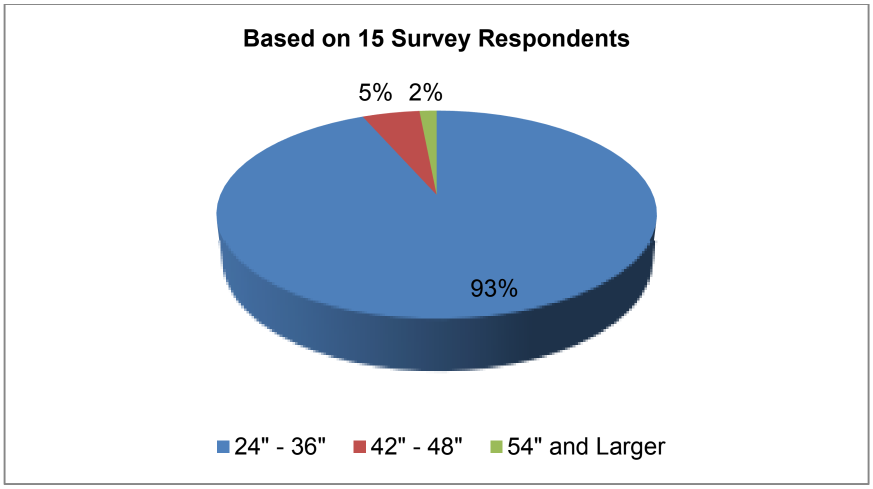


Figure 4.17 Percent Distribution of Total Footage of Ductile Iron Pipe

3. Failure Rate

Failure rates for cast iron and ductile iron pipes are calculated based on the survey responses per 100 miles of pipe length. Table 4.6 explains the failure rates for different diameter ranges for both the pipe materials for all the survey respondents calculated using Equation 3.1.

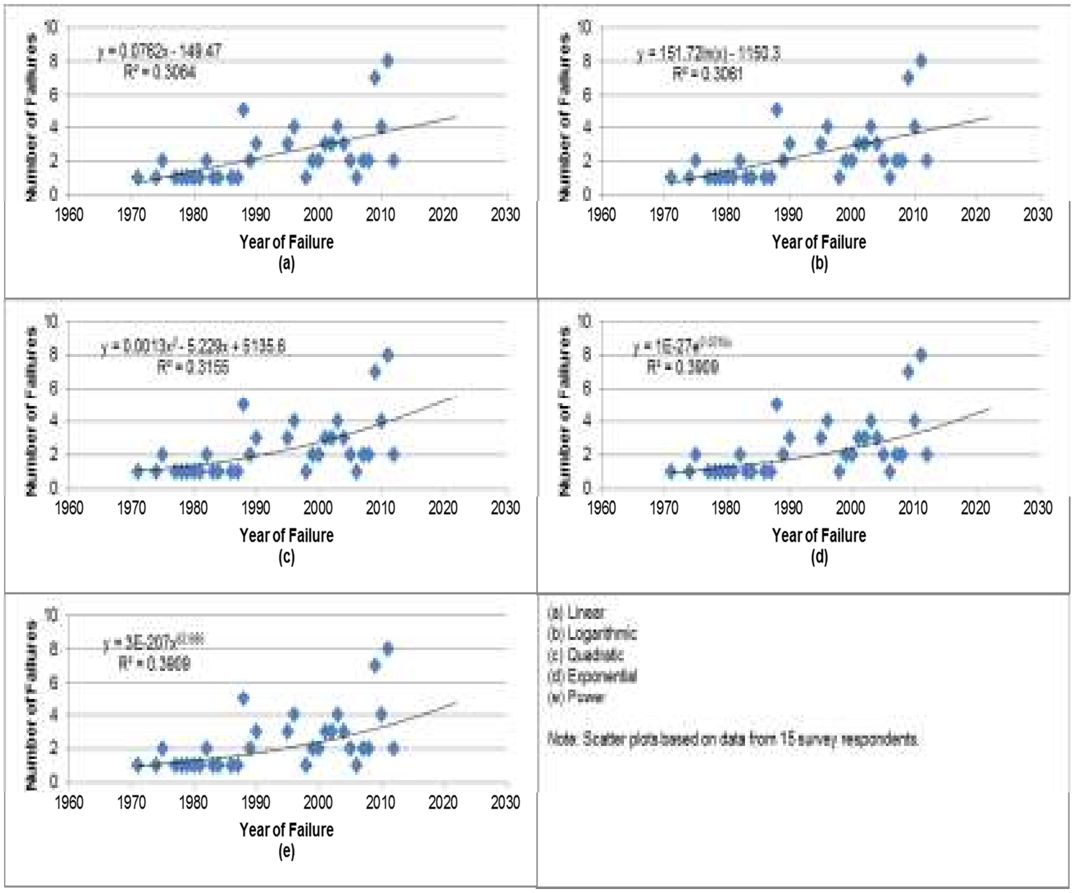
4. Future Water Mains Breaks Predictions

This is similar to the research carried out for the smaller than 24-inch diameter size. The only difference is that the data used to plot scatter plots here is from the selected 15 water utilities in the United States unlike the data which was from a single water utility for the smaller than 24-inch diameter size. Also, only two categories of cast iron and ductile iron pipes are considered as data was not available separately for pit cast gray iron and centrifugal cast gray iron pipe.

Figure 4.18 represents the different regression models such as linear, logarithmic, quadratic, exponential and power for cast gray iron pipe fitted on the number of failures-year of failure data from the 15 water utilities. The criteria to find out the best fitted trend line would be dependent on the relationship between the two variables which is explained by "R^2." The relationship between the response variable (y) and the predictor variable (x) is the strongest for the highest value of the "R^2." Table 4.7 compares the line equations for all these four models and the respective "R^2" values for cast iron pipe. Similarly, Figure 4.19 represents the different models for ductile iron pipe followed by comparisons of line equations and "R^2" values in Table 4.8.

Table 4.6 Failure Rates for Cast Iron and Ductile Iron Pipes

Survey Respondent No.	Cast Iron Pipe									Ductile Iron Pipe								
	Total Footage (miles)			No. of Failures			Failure Rate (per 100 miles)			Total Footage (miles)			No. of Failures			Failure Rate (per 100 miles)		
	24-inch to 36-inch	42-inch to 48-inch	54-inch and Larger	24-inch to 36-inch	42-inch to 48-inch	54-inch and Larger	24-inch to 36-inch	42-inch to 48-inch	54-inch and Larger	24-inch to 36-inch	42-inch to 48-inch	54-inch and Larger	24-inch to 36-inch	42-inch to 48-inch	54-inch and Larger	24-inch to 36-inch	42-inch to 48-inch	54-inch and Larger
1	0.0	0.0	0.0	-	-	-	-	-	-	1.1	0.0	0.0	1	-	-	93.5	-	-
2	21.0	0.0	0.0	11	-	-	52.3	-	-	1.9	0.0	0.0	3	-	-	158.7	-	-
3	0.0	0.0	0.0	-	-	-	-	-	-	3.8	0.0	0.0	1	-	-	26.4	-	-
4	0.0	0.0	0.0	-	-	-	-	-	-	19.0	0.0	0.0	-	-	-	-	-	-
5	0.2	0.0	0.0	-	-	-	-	-	-	10.7	0.0	0.0	3	-	-	28.0	-	-
6	18.4	0.0	0.0	3	-	-	16.3	-	-	13.0	0.0	0.0	0	-	-	0.0	-	-
7	7.6	0.1	0.0	20	0	-	263.5	0.0	-	31.2	2.1	0.5	19	3	0	60.9	143.5	0.0
8	4.0	0.0	0.0	12	-	-	301.5	-	-	2.9	0.0	0.0	2	-	-	70.2	-	-
9	0.0	0.0	0.0	-	-	-	-	-	-	9.7	6.5	2.3	1	0	0	10.3	0.0	0.0
10	5.5	0.0	0.0	0	-	-	0.0	-	-	86.2	2.9	0.1	3	0	0	3.5	0.0	0.0
11	21.3	0.9	0.0	6	0	-	28.1	0.0	-	23.1	0.6	0.0	1	0	-	4.3	0.0	-
12	38.0	7.1	12.3	2	0	0	5.3	0.0	0.0	3.0	0.0	0.0	0	-	-	0.0	-	-
13	27.0	1.7	0.1	50	10	0	184.9	595.2	0.0	8.6	1.0	0.1	1	0	0	11.6	0.0	0.0
14	7.1	0.7	0.3	0	0	0	0.0	0.0	0.0	113.3	2.6	1.2	0	0	0	0.0	0.0	0.0
15	60.0	0.0	0.0	1	-	-	1.7	-	-	56.0	5.0	2.0	1	0	0	1.8	0.0	0.0
Total	210.1	10.4	12.7	105	10	0	50.0	96.2	0.0	383.4	20.7	6.2	36	3	0	9.4	14.5	0.0
Combined Failure Rate	**49.3**									**9.5**								



Note: Scatter plots based on data from 15 survey respondents.

Figure 4.18 Fit Trend Line for Different Models for Cast Iron Pipe

Table 4.7 Comparison of Regression Models for Cast Iron Pipe

Relationship	**Line Equation**	**Coefficient of Determination (R^2)**
Linear	$y = 0.0762x – 149.47$	0.3064
Logarithmic	$y = 151.72\ln(x) – 1150.3$	0.3061
Quadratic	$y = -0.0013x^2 – 5.229x + 5135.6$	0.3155
Exponential	$\mathbf{y = 1E – 27e^{0.0315x}}$	**0.3909**
Power	$\mathbf{y = 3E – 207x^{62.685}}$	**0.3909**

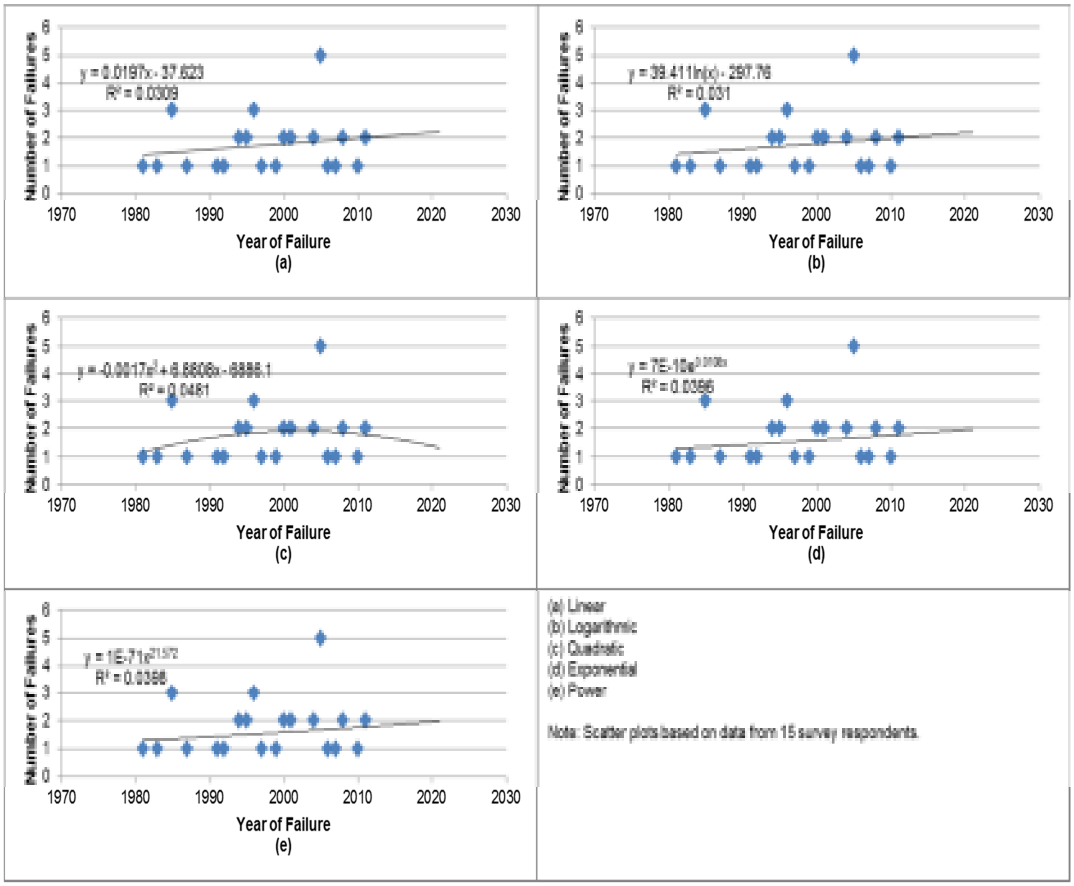


Figure 4.19 Fit Trend Line for Different Models for Ductile Iron Pipe

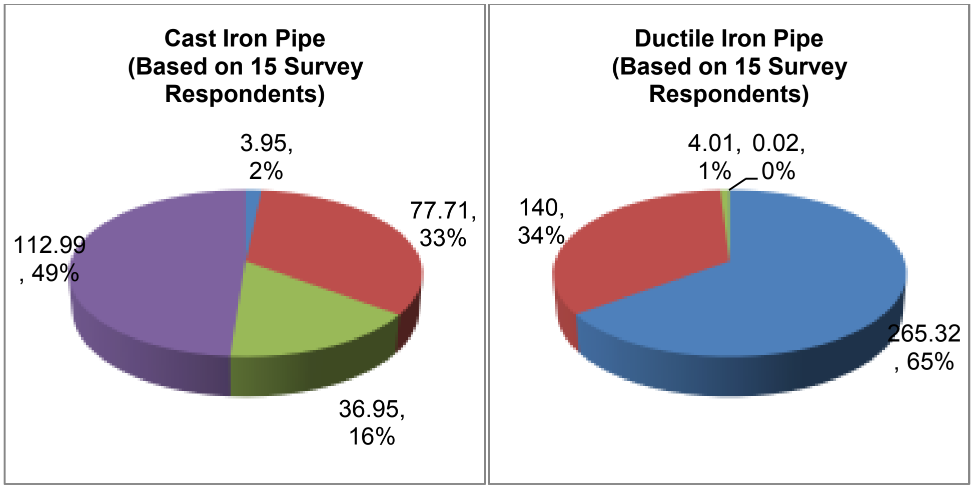
Table 4.8 Comparison of Regression Models for Ductile Iron Pipe

Relationship	**Line Equation**	**Coefficient of Determination (R^2)**
Linear	y = 0.0197x – 37.623	0.0309
Logarithmic	y = 39.411ln(x) – 297.76	0.031
Quadratic	**y = -0.0017x2 + 6.8808x – 6886.1**	**0.0481**
Exponential	y = 7E – 10e0.0108x	0.0396
Power	y = 1E – 71x21.572	0.0398

5. Other Information

The remaining survey questions provided answers about various things such as the age of the inventory of the water utilities, the considerations for use of cast iron and ductile iron pipes in the water system of some utilities, frequent type of failures and the failure rates of these pipe materials with respect to the total pipe inventory of the utilities.

Figure 4.20 explains the age of the inventory of both cast iron and ductile iron pipes. The water utilities were asked to provide the age of the pipe materials in their water utilities in the four categories of Less than 25 years, Between 25 years and 50 years, Between 50 years and 75 years and More than 75 years.



Legend:

- 🟦 Less than 25 years old
- 🟥 Between 25 to 50 years old
- 🟩 Between 50 to 75 years old
- 🟪 More than 75 years old

Figure 4.20 Age of the Inventory

Furthermore, survey respondents were asked a question related to the considerations on the use of cast iron and ductile iron pipes in the respective water utilities. Table 4.9 summarizes the reasons for considerations as well as some advantages and disadvantages mentioned by the respondents on these two pipe materials.

Table 4.9 Advantages and Considerations

Based on 15 Survey Respondents	
Cast Iron Pipe	**Ductile Iron Pipe**
Advantages	
Good history	Strong and forgiving
Reliable	Easy to use
Considerations	
Corrosion	Corrosive soil conditions
High weather failure rates	--
No longer manufactured	--

The survey respondents had joint failure as the main type of failure for these pipe materials followed by corrosion. A particular water utility mentioned age as the reason for the leaks at the joints and blowout holes. The failure rates for these pipe materials are less than 10% of the total inventory of these pipe materials in all of the water utilities.

4.3 Chapter Summary

This chapter presented performance of cast iron and ductile iron pipes based on the data from a single water utility for pipe diameters of less than 24-inch. Also, the second part of this chapter presented results from the survey questionnaire of the responding 15 water utilities.

CHAPTER 5

DISCUSSIONS OF RESULTS

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

5.1 Smaller than 24-inch Diameter Size

As many as 300 water mains breaks can be experienced by a large water utility per year (Makar, 1999). A study of 31,560 water main pipe section failures of cast iron and ductile iron pipes in a period of 110 years from a single specific water utility are a focal point of this research.

The first ever cast iron pipe manufactured was of pit cast gray iron pipe in the 1800’s and volume production of this pipe began in 1914 (Rajani and Kleiner, 2010). The featured survey respondent, a water utility in Wisconsin, installed pit cast gray iron pipe from 1872 till 1945 with a significant number of installations from 1925 to 1931. A total of 13,797 pipe sections of varying lengths were installed. Complete data on 7,125 failures of these pipe sections was available for this research’s analysis. The length of the pipes was not considered due to data unavailability. Failure analyses revealed that 3,611 pipe section failures had a service life of more than 75 years followed by 1,818 with a service life of 50-75 years; 1,676 had 25 to 50 years of service life and only 20 failures had less than 25 years of service life.

The centrifugal cast gray iron pipe installations followed the pit cast gray iron pipe of the 1920s and began volume production in the 1930s (Rajani and Kleiner, 2010). The water utility installed centrifugal cast gray iron pipe from 1946 until 1964 with a total of 17,364 installations which exceeded the pit cast gray iron pipe in a relatively shorter period of time. Complete data of 9,683 failures was available. Considering these failures, there are no pipe sections having a service life of more than 75 years old. 2,641 had a service life between 50 and 75 years. A significant 6,812 centrifugal gray iron pipes had 25 to 50 years of service life and there were only 7 failures which had less than 25 years of service life.

Ductile iron pipe was introduced to the pipe industry in 1948 and was the predominant pipe material by year 1979 (Simpson, et al., 2003). The installations for ductile iron pipes observed in from the primary utility in this thesis report are in between 1953 to 1982. The research in this thesis analyzed a total of 399 installations. Complete data for only 38 failures was available. Considering these failures, no pipe sections had a service life of more than 75 years. Only one failure was observed to have a service life of 50-75 years, while 30 had a service life of 25-50 years. Finally, seven failures had less than 25 years of service life. The pit cast gray iron pipe performed better than the centrifugal cast gray iron pipe and ductile iron pipe as far as the service life is concerned.

The 4-inch diameter cast iron and ductile iron pipe sections had the most number of failures after 75 years. Meanwhile, 6-inch, 8-inch, 12-inch and 16-inch cast iron and ductile iron pipe had the most number of failures during a 25-to-50-year service life. From the available data of different types of joints used for 31,258 cast iron and ductile iron pipes combined, an incredible amount of 25,977 bell and spigot - lead joints representing about 83% of all joints used in the utility. Bell and spigot - leadite joints were the next most used for 3,339 cast iron and ductile iron pipes representing about 11% followed by 1,777 (6%) mechanical lock-type joint and an insignificant 165 (~0%) mechanical push-on-type joints.

Cast iron and ductile iron pipe failures were combined when averaging failures. The three major categories: 1) corrosion failure, 2) stress failure and 3) joint failure were evaluated. Stress failure was divided in two types of failure, transverse break with 10,637 failures and split pipe with 1,775 failures adding up to 12,412--the most observed failure--followed closely by corrosion failure at 12,230 failures. Joint failure had the least incidents with only 6,894 failures in both cast iron and ductile iron pipes. Furthermore, these types of failure were categorized based on the three manufacturing processes of pit cast gray iron, centrifugal cast gray iron and ductile iron pipes.

Pit cast gray iron has corrosion as the main cause of failure followed by transverse break failure, bell and spigot – lead joint failure, split pipe failure and then lastly bell and spigot – leadite joint failure. For centrifugal cast gray iron pipe, transverse break failure is the main cause of failure followed by corrosion, bell and spigot – lead joint failure and split pipe failure. Some failure in mechanical lock-type and push-on type of joint was observed as well. Corrosion is the main cause in ductile iron pipe failure followed by transverse break failure and then mechanical lock-type joint failure. Some failures were observed in mechanical push-on-type joints as well as split pipes.

Thus, it is safe to say that the two major types of failures observed in all pipe materials were corrosion failure and stress failure which includes transverse break failure which was about 6 times higher than split pipe failure.

- Regression Models

Using the regression models, we can predict the number of failures (y) for the corresponding year of failure (x) for this single water utility. The relationship criteria to determine the best fit model is dependent on the value of "R^2." The higher the value of "R^2," the stronger is the relationship between these two variables.

For pit cast gray iron pipe, from Table 4.3, we have the "R^2" value of 0.6272 for the exponential model as the highest value amongst all the models. Thus, the best fitted trend line equation for pit cast gray iron pipe is $y = 2E - 46e^{0.0552x}$. For a given value of "*x,*" the value of "*y*" can be predicted using this equation for this single water utility.

For centrifugal cast gray iron pipe, from Table 4.4, we have the "R^2" value of 0.5414 for the quadratic model as the highest value amongst all the models. But, the value of "*y*" cannot be negative as it is the number of failures the utility might experience. Thus, the model is rejected.

Also, the second highest value of “R^{2}” is for the power model but as the intercept of this model is zero, this model is rejected too. The best available model for this pipe is the logarithmic model with “R^{2}” value of 0.5081 and the best fitted trend line equation is $y = 20988\ln(x) - 159197$. For a given value of “*x*,” the value of “*y*” can be predicted using this equation for this single water utility.

For ductile iron pipe, from Table 4.5, again though the highest “R^{2}” value is for the quadratic model, as the number of failures cannot be zero, we have to reject this model. The second highest “R^{2}” value of 0.1344 is for the power model. Thus, the best fitted trend line equation for this pipe is $y = 2E - 181x^{54.893}$. For a given value of “*x*,” the value of “*y*” can be predicted using this equation for this single water utility. The relationship between the variables is very weak as only a few data points were available and more data is needed to get a better trend line equation.

5.2 24-inch and Larger Diameter Size

The second part of the research dealt with the failure of 24-inch and larger diameter cast iron and ductile iron water pipes. This research was based on a survey of 15 water utilities from nine states in the United States. The diameter ranges considered for the survey were 24-inch to 36-inch, 42-inch to 48-inch and 54-inch and larger.

A total population of 10,022,508 people is served by the responding water utilities. The total footage reported for cast iron pipe was 233.2 miles and ductile iron pipe was 410.3 miles. The distribution of cast iron pipe footage for 24-36 inches diameter range was 210.1 (90%) miles, 42-48 inches diameter range was 10.4 (~5%) miles and 54-inches and larger diameter range was 12.7 (~5%) miles. Similarly, for ductile iron pipe, footage for 24-36 inches diameter range was 383.4 (93%) miles, 42-48 inches diameter range was 20.7 (5%) miles and 54-inches and larger diameter range was 6.2 (2%) miles.

The failure rate per 100 miles of pipe footage was calculated for both cast iron and ductile iron pipes. These rates were the most interesting and important finding of the second part of the research.

For cast iron pipe, a total of 115 failures were reported by this study's survey respondents representing 15 water utilities. The diameter range of 24-36 inches had 105 failures and 42-48 inches had 10 failures. The utilities did not report any pipe failures in the 54-inch and larger diameter range. The failure rate for pipe with a diameter range of 24-36 inches was 50 failures per 100 miles of pipe footage. The failure rate for pipe with a diameter range of 42-48 inches was 96.2 failures per 100 miles of pipe footage. The failure rate for pipe with 24-inch and larger diameter sizes combined was 49.3 failures per 100 miles of pipe footage.

For ductile iron pipe, a total of 39 failures were reported by survey respondents representing 15 water utilities. Ductile iron pipe with a diameter range of 24-36 inches had 36 failures and pipe with the 42-48 inches diameter range had 3 failures. Again, the utilities did not report any failure for pipes with diameters in the 54-inch and larger diameter range. The failure rate for the diameter range of 24-36 inches was 9.4 failures per 100 miles of pipe footage, whereas for pipe with a diameter range of 42-48 inches, the failure rate was 14.5 failures per 100 miles of pipe footage. The failure rate for 24-inch and larger diameter sizes was 9.5 failures per 100 miles of pipe footage. The failure rates are influenced by various factors like soil conditions, depth of installation, internal loads (operating and surge pressure), external loads (traffic and frost), temperature changes and, bedding conditions. The information about all of these factors was not considered in calculating the failure rates due to lack of data. The failure rates provide limited information about the performance of these pipe materials. All the influencing factors need to be considered to get accurate failure rates.

The comparison between the failure rates of cast iron and ductile iron pipes clearly identifies the better performing material. Ductile iron pipe has a failure rate of 9.5 failures per 100 miles of pipe footage which is far below the failure rate of cast iron pipe which is 49.3 failures per 100 miles of pipe footage. Also, comparison of failure rates from current research was compared with the previous studies. Table 5.1 summarizes the methodology used, the failure rates as well as some of the limitations of each of these studies.

Table 5.1 Comparison of Current Research with Previous Studies

Study	Year	Methodology	Failure Rate		Unit	Limitations
			Cast Iron Pipe	Ductile Iron Pipe		
Rajani and McDonald	1992	21 survey responses from Canada	56.2	14.9	Failures/100 miles/year	Diameter size, age of pipe, failure rate for each utility, regression analysis of failure not given
Rajani and McDonald	1993		58.7	15.7		
Weimer	2001	500 survey responses from Germany	43.2	4.8		Most pipes of diameter size 2-inch and less, regression analysis of failure not given
Davis et al.	2007	22 survey responses from UK and Australia and 55 from U.S. and Canada	32.2	8.5		Type of failure, diameter size, age of pipe, failure rate for each utility, regression analysis of failure not given
Folkman	2012	188 survey responses from U.S. and Canada	24.4	4.9		Less than 24-inch diameter size, failure rate for each utility not given
CUIRE (Current)	2012	21 survey responses from U.S.	49.3	9.5	Failures/ 100 miles	Larger than 24-inch diameter size, failure rate for each year not given

The utilities were also asked questions regarding the underground inventory of pipe materials currently in use. Almost half (49%) of the total inventory of cast iron pipe is more than 75 years old. About 33% of its inventory is between 25 years and 50 years old and 16% is between 50 years and 75 years old. Only 2% of the total inventory of cast iron pipe is less than 25 years old which explains the stoppage in manufacturing of cast iron pipe. For ductile iron pipe, 65% of the inventory is less than 25 years old, 34% is in between 25 years and 50 years old and 1% is between 50 years and 75 years old.

- Regression Models

Similar to the smaller than 24-inch diameter size regression models, we can predict the number of failures (*y*) for the corresponding year of failure (*x*) for the 15 survey responding water utilities. The relationship criteria to determine the best fit model is dependent on the value of "R^2." The higher the value of "R^2," the stronger is the relationship is between these two variables.

For cast iron pipe, from Table 4.7, we have the "R^2" value of 0.3909 for two models as the highest value. Thus, we have two different best fitted trend line equations for this pipe. The exponential equation of $y = 1E - 27e^{0.0315x}$ and the power equation of $y = 3E - 207x^{62.685}$ can be used to predict the value of "*y*" for a given value of "*x*" for 15 water utilities responded to survey.

For ductile iron pipe, as shown in Table 4.8, the highest "R^2" value is the quadratic model. However, as number of failures cannot be zero; this model is not acceptable. The second highest "R^2" value of 0.0398 is for the power model. Thus, the best fitted trend line equation for this pipe is $y = 1E - 71x^{21.572}$. For a given value of "*x*," the value of "*y*" can be predicted using this equation for these 15 water utilities. The relationship between the variables is very weak as only a few data points were available and more data is needed to get a better trend line equation.

5.3 Chapter Summary

This chapter discussed survey results conducted for this thesis and compared with previous literature. The cast iron and ductile iron pipes were compared based on various factors, such as, age and, manufacturing processes. In addition, different statistical models for performance of pipe inventory within utilities responded to survey were presented.

CHAPTER 6

CONCLUSIONS, LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

This chapter includes the conclusions from the research discussed in the previous chapters. It also recommends topics for future research in this area.

6.1 Conclusions

The following conclusions can be derived from this thesis:

6.1.1 Smaller than 24-inch Diameter Size

All the conclusions are based on data from one specific water utility in this section.

1. The centrifugal cast gray iron pipe is the most used pipe followed by pit cast gray iron pipe and then ductile iron pipe.
2. Centrifugal cast gray iron pipe has the highest number of failures followed by pit cast gray iron and ductile iron pipes.
3. Pit cast gray iron pipe is the longest lasting pipe with more than half of the installations lasting for more than 75 years of service life.
4. Bell and spigot joints with lead sealant is the most used type of joint with 83% of total installations having this joint.
5. Stress failure which includes transverse failure and split pipe failure, is the most frequently observed failure in cast iron and ductile iron pipes followed by corrosion failure and then joint failure.

6. The numbers of failures for pit cast gray iron pipe are expected to increase exponentially over the years for this single water utility.
7. The numbers of failures for centrifugal cast gray iron pipe are expected to increase logarithmically over the years for this single water utility.
8. The numbers of failures for ductile iron pipe are expected to increase exponentially over the years for this single water utility.
9. The numbers of failures for ductile iron pipe are expected to vary as a power of the year of failure for this single water utility.

6.1.2 24-inch and Larger Diameter Size

All the conclusions are based on survey responses from 15 water utilities in this section.

1. The total footage reported by the survey respondents for cast iron is 233.2 miles and for ductile iron pipes is 410.3 miles. The diameter range of 24-36 inches is most commonly used for cast iron encompassing 90% of the total footage in miles and for ductile iron pipes with 93% of the total footage in miles.
2. 49% of the pipe inventory of cast iron pipe is more than 75 years old.
3. 65% of the pipe inventory of ductile iron pipe is less than 25 years old.
4. The failure rate for cast iron pipe is 49.3 failures per 100 miles of pipe footage.
5. The failure rate for ductile iron pipe is 9.5 failures per 100 miles of pipe footage.
6. The numbers of failures for cast iron pipe are expected to increase exponentially over the years based on the data from these 15 survey respondents.
7. The numbers of failures for ductile iron pipe are expected to vary as a power of the year of failure for these 15 survey respondents.

6.2 Limitations of Research

1. Smaller than 24-inch diameter size research results are based on only one specific water utility.
2. 24-inch and larger diameter size research results are based on 15 survey respondents.
3. The results achieved in this thesis are from a very small limited number of survey respondents. Also, the data available from the survey respondents was incomplete.
4. Parameters such as soil conditions, depth of installation, internal pressures (operating and surge), external loads (traffic and soil), temperature changes, bedding conditions, installation processes, manufacturing standards and so on can influence failure rate, but are not considered in this research.

6.3 Recommendations for Future Research

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

1. Include other parameters such as soil conditions, depth of installation, internal loads (operating and surge pressure), external loads (traffic and frost), temperature changes and bedding conditions.
2. Involve a larger sample size for the research to improve the accuracy of the results.
3. Study the condition assessment of cast iron and ductile iron pipes.
4. Evaluate availability of repairs and rehabilitation methods such as pipe lining, pipe bursting, etc. for cast iron and ductile iron pipes.
5. Compare failure modes of cast iron and ductile iron pipes with other pipe materials used for water pipelines.

APPENDIX A

ABBREVIATIONS

AC - Asbestos Cement Pipe

A.D. - Anno Domini

ANSI - American National Standards Institute

ASCE - American Society of Civil Engineers

AWWA - American Water Works Association

B.C. - Before Christ

BWP - Bar-wrapped Steel-cylinder Concrete Pipe

CIP - Cast Iron Pipe

CISPI - Cast Iron Soil Pipe and Fittings Handbook

CSIRO - Common Scientific and Industrial Research Organization

CUIRE - Center for Underground Infrastructure Research and Education

DIP - Ductile Iron Pipe

GRP - Glass Reinforced Pipe

H2O - Help to Optimize Water

NRC - National Research Council of Canada

PCCP - Prestressed Concrete Cylinder Pipe

PE - Polyethylene Pipe

PSCIPCO - Pacific States Cast Iron Pipe Company

PVC - Polyvinyl Chloride Pipe

RCP - Reinforced Concrete Pipe

USEPA - United States Environmental Protection Agency

WIN - Water Infrastructure Network

APPENDIX B

SURVEY QUESTIONNAIRE FORM

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

Cast Iron Pipe (CIP) and Ductile Iron Pipe (DIP) 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 project regarding types of failures of CIP and DIP water pipelines. The below national survey is critical as a first step to learn more about the CIP and DIP failures, since it will provide valuable information regarding the inventory and conditions of CIP and DIP. 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 15 minutes****

If you have any questions or concerns, please feel free to contact Ameya Paradkar, CUIRE Graduate Research Student, at 817-313-0767 or ameya.paradkar@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:**
   CIP - ______ft or ______mi.
   DIP - ______ft or ______mi.

3. **Please provide us the footage of the water system.**

Type of Pipe	**Footage (mile)**					
	Less than 10”	**10”- 12”**	**16”- 20”**	**24” – 36”**	**42” – 48”**	**54” and larger**
CIP						
DIP						

4. **Please provide information for past water pipe failures.**

Type of Pipe	**Pipe ID***	**Date of Installation**	**Pipe Diameter***	**Location**	**Date of Failure**	**Soil Conditions***

5. For the pipe ID's* mentioned in <u>Question 4</u>, please provide causes of failure, modes of failure, type of joint and type of water for pipe failure.

Pipe ID*	**Cause of Failure**	**Mode of Failure**	**Type of Joint***	**Type of Water (Treated or Untreated)**

6. Rank the following causes of failure for CIP according to their frequency of occurrence.

Please rank with <u>#1 being the highest frequency of occurrence</u>

Causes of Failure	**Rank**	
	CIP	**DIP**
Age of Pipe*		
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		

7. **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 Ameya Paradkar, CUIRE Graduate Research Student, at 817-313-0767 or ameya.paradkar@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.
- **Diameter:** Diameter here refers to the outer dimension of the pipe.
- **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. The term “excessive” is used if it results in pipe failure.
- **Excessive Live Loads:** Live loads change in position or magnitude, e.g., vehicular loads. The term “excessive” 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**: Corrosion, Transverse break, Split pipe, Joint failure, etc.
- **Installation Problems:** The difficulties faced during the laying of pipe in the ground.
- **Joint:** The means of connecting sectional length of pipeline system into a continuous line using various types of jointing materials.
- **Manufacturing Defects:** An error or flaw in a pipe introduced during the manufacturing rather than the design phase.
- **Pipe ID:** Unique identity of pipe.
- **Population:** The whole number of people or inhabitants in a region or country.
- **Third Party Damage:** Damage caused by someone other than pipeline operator and owner.

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