DEVELOPMENT OF A PERFORMANCE ANALYSIS FRAMEWORK FOR WATER PIPELINE INFRASTRUCTURE USING SYSTEMS UNDERSTANDING

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THESIS SUBMITTED TO THE FACULTY OF VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

ENVIRONMENTAL ENGINEERING

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DECEMBER 12TH, 2018

BLACKSBURG, VIRGINIA

KEYWORDS: SYSTEMS APPROACH, WATER PIPELINE PERFORMANCE ANALYSIS, FAILURE MODES, AND MECHANISMS, SOIL CORROSIVITY

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ABSTRACT

The fundamental purpose of drinking water distribution systems is to provide safe drinking water at sufficient volumes and optimal pressure with the lowest lifecycle costs from the source (treatment plants, raw water source) to the customers (residences, industries). Most of the distribution systems in the US were laid out during the development phase after World War II. As the drinking water infrastructure is aging, water utilities are battling the increasing break rates in their water distribution system and struggling to bear the associated economic costs. However, with the growth in sensory technologies and data science, water utilities are seeing economic value in collecting data and analyzing it to monitor and predict the performance of their distribution systems. Many mathematical models have been developed to guide repair and rehabilitation decisions in the past but remain largely unused because of low reliability. This is because any effort to build a decision support framework based on a model should rest its foundations on a robust knowledge base of the critical factors influencing the system, which varies from utility to utility. Mathematical models built on a strong understanding of the theory, current practices and the trends in data can prove to be more reliable. This study presents a framework to support repair and rehabilitation decisions for water utilities using water pipeline field performance data.

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GENERAL AUDIENCE ABSTRACT

The fundamental purpose of drinking water distribution systems is to provide a safe and sufficient volume of drinking water at optimal pressure with the lowest costs to the water utilities. Most of the distribution systems in the US were established during the development phase after World War II. The problem of aging drinking water infrastructure is an increasing financial burden on water utilities due to increasing water main breaks. The growth in data collection by water utilities has proven to be a useful tool to monitor and predict the performance of the water distribution systems and support asset management decisions. However, the mathematical models developed in the past suffer from low reliability due to limited data used to create models. Also, any effort to build sophisticated mathematical models should be supported with a comprehensive review of the existing recommendations from research and current practices. This study presents a framework to support repair and rehabilitation decisions for water utilities using water pipeline field performance data.

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my advisor, Dr. Sunil K. Sinha, for his assistance and guidance throughout this research. I appreciate his patience and energy with which he directed me. I would also like to extend my thanks to Dr. Jason Deane, Dr. John Little and Mr. James Carolan for serving on my committee and their valuable suggestions during this process.

I would like to acknowledge the United States Bureau of Reclamation who provided funding for this research. Along with this, I would like to recognize Virginia Tech, Sustainable Water Infrastructure Management (SWIM) center, and ICTAS II for providing infrastructure for conducting this research.

I am deeply grateful to my sisters Mrs. Sakriti Vishwakarma and Mrs. Smriti Vishwakarma who always believed in me and encouraged me throughout this process.

I am thankful to all my colleagues at Virginia Tech especially Mr. Pururaj Singh Shekhawat, Mr. Pruthvi Patel, Ms. Aprajita Lavania, Mr. Hao Xu and Mr. Jayraj Patel who worked closely with me in supporting my research and providing insightful comments. I would also like to thank my friends Ms. Binita Saha, Mr. Jayesh Charthal, Mr. Suraj Gupta, Mr. Saurabh Pant and Mr. Unmukt Deswal for helping me stay focused throughout the process.

I would like to dedicate this thesis to my parents Mr. Arun Kumar Vishwakarma and Ms. Veena Vishwakarma for the unconditional love and support.

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1. Introduction

Aging water infrastructure is a major economic and development issue for the United States. The US has a massive network of one million miles of drinking water pipelines lying underneath the surface (Grigg 2005). Unfortunately, drinking water pipelines receive less care than they deserve due to their subsurface nature. The American Society of Civil Engineers (ASCE) Infrastructure report of 2017 graded the drinking water infrastructure of USA a “D”. It also reported that around two trillion gallons of treated drinking water are wasted through 240,000 water main breaks per year in the United States (ASCE 2017). The study also mentioned that an estimated $1 trillion is required to maintain and expand service to meet demands over the next 25 years. This infrastructure crisis requires a comprehensive study of the factors causing premature failures and affecting the different material of pipelines during its lifecycle. Also, the absence of any data collection, critical parameter identification, and standardization protocols underline the need to bring the data to a standard platform. The standardized data needs to be fed into a framework of analysis to understand the performance, failure, economic, operation and maintenance and the lifecycle cost characteristics for the pipeline network.

The focus of the research is to build a performance analysis framework to guide water pipeline asset management decisions. This framework will be different from other analytical techniques used in the past because it will collate the past studies to determine the modeling factors, how to group them into homogeneous groups and what the break points between the data values should be. In most previous studies, the mathematical models developed from data obtained from utilities have proved unreliable when used in real-world situations due to the limited sample size and parameters used to develop the model. The framework can be utilized to understand the critical parameters to consider in developing performance analysis models for water pipeline infrastructure using data collected from multiple water utilities to answer the most important overarching questions for water pipeline asset managers:

1. What is the current condition of the water pipeline?
2. What is the predicted life of the pipe segment in the current utility environment?
3. What is the cost to the utility for proactive vs reactive operation and maintenance (O&M) strategy?

This step-by-step framework will aim to build a foundation to answer these questions separately for metallic, plastic and concrete pipeline materials. The overall outline of this study is shown in Figure 1.

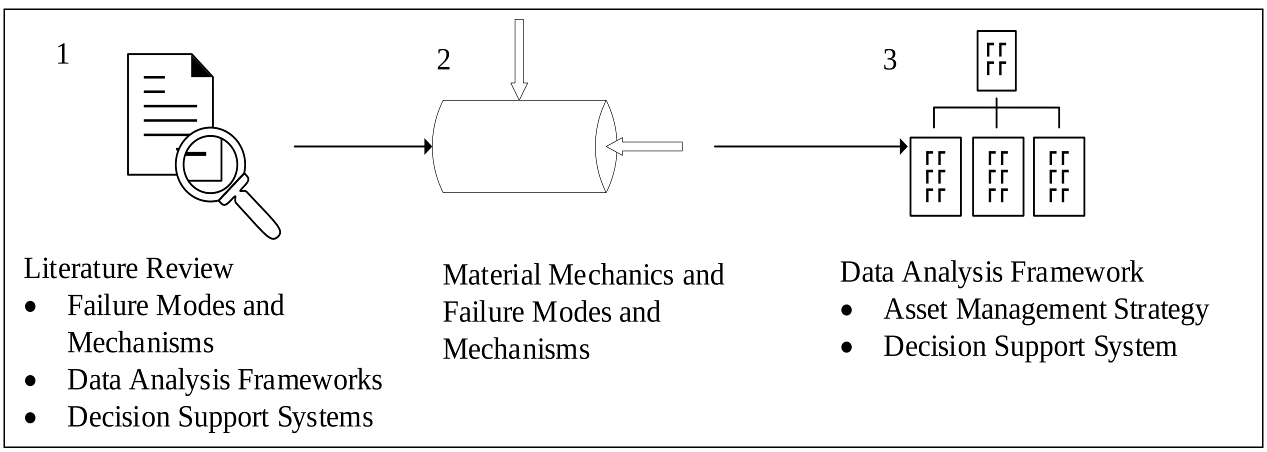

Figure 1: Outline of thesis

The proposed framework in this study can be used as a part of a risk-based decision support system. Estimating risk involves calculating the product of Likelihood of Failure (LoF) and

Consequence of Failure (CoF). Predicting failure requires identifying the critical factors and the covariates using a systems understanding and historical failure data. The influencing factors discussed in this study have been explained to form cohorts in the dataset. Modeling based on these cohorts will improve the reliability of the model as the analyses will be separate for each homogeneous group. Eventually the results of the data analysis from the cohorts can be compiled to understand the difference in performance for different materials subject to various environments.

2. Literature Review

2.1. Background

Water utilities in the US take important asset management decisions to provide water at the optimum level of service utilizing their already limited budget. Decisions to replace water pipes will be critical over the next 25 years, with estimated replacement costs exceeding $1 trillion (American Water Works Association 2012). Such complex issues have been researched in other fields. Past studies have advocated the need for managing and utilizing multidisciplinary knowledge bases to solve decision-making problems in the fields of transportation and logistics (Petrović et al. 2018), environmental policy (Huang et al. 2011)and medical (Sittig et al. 2008).

2.2. Need for Systems Understanding

Similar studies in civil infrastructure systems call for system understanding and life cycle risk-based decision making (Gui et al. 2017; Lee et al. 2018). However, it is essential to determine the performance of the water pipeline system before determining the risk. Various studies have been conducted to understand the water pipeline performance, studying the effect of the soil, bedding, weather, lining, coating, pipe appurtenances (valves and hydrants) on the lifecycle of the pipeline material. Previous studies have proposed a standard data structure with over 100 parameters to guide water utilities in pipe performance analysis (St. Clair et al. 2014). This research-based its approach to identifying the failure modes and mechanisms for different pipeline materials to identify critical parameters for building a data analysis framework. However, the failure modes and mechanisms need to provide the extent and severity to which the causes affect the pipelines to be able to guide the performance analysis. This underlines the need to develop a systems understanding of the deterioration modes. This is helpful to identify the covariates for performance and risk models and to provide parameters for standardized data collection to guide water utilities.

2.3. Material Mechanics and Failure Modes and Mechanisms

Previous studies have also explained the pipe performance characteristics presenting a detailed view of the changes in ANSI/AWWA standards and technological advancements in ductile iron pipe manufacturing along with failure and forensic analysis of corrosion pit development and calculating the time taken for the pit to fully penetrate the pipe wall (Rajani et al. 2011). Studies have also discussed the major issues affecting the adoption of Poly Vinyl Chloride (PVC) pipes by water utilities, namely the leaching lead and organotin stabilizers used in the manufacture of PVC pipes (Davis et al. 2007). The study also discusses the ANSI/AWWA and ASTM standards to define PVC performance (mainly hydrostatic and thermal integrity). Other, more mathematical modeling based, studies focused on the failure modes and mechanisms observed in Polyethylene (PE) pipes along with deterministic methods to predict long-term performance (Davis et al. 2008). Performance standards studied in this research are similar to PVC pipes, namely resistance to thermal, hydrostatic loads and resistance to slow and rapid crack growths. The study also mentions that there is not enough documentation of PE failure modes and mechanisms, due to the relatively new installations, and most premature failures have taken place due to third party interferences and poor installation practices. Studies have also been conducted on other materials like Asbestos Cement (AC) which explained the changes in manufacturing processes and installation trends of Asbestos Cement pipes in the US along with their failure mechanisms, non-destructive tests and the remaining useful life prediction (Ghirmay 2016). Some studies linked the performance characteristics very well with changes in standards and variations in wall thickness in different variants of the pipe along with condition assessment techniques (Hu et al. 2013). (Hu et al. 2013) also explained the modeling techniques to evaluate the current condition of AC pipes using deterministic methods along with predicting remaining service life and guidelines for rehabilitation and replacement methods. The study also explained in detail modeling techniques to evaluate the current condition of AC pipes using deterministic methods along with predicting remaining service life and guidelines for rehabilitation and replacement methods.

2.4. Need for data standardization and database management

The literature review of different pipe materials showed that all materials have different failure modes and mechanisms and there have been improvements in their manufacturing and installation processes which reflects in their standards. This knowledge is essential to understand the essential and non-essential parameters and help determine a standard data collection protocol which can provide adequate data for mathematical modeling and lower costs for water utilities. Also, this can help in the data analysis and help explain the sudden change of trends in pipe failure rates and O&M practices.

Incorporating a systems approach to a big data problem involves having a robust and flexible data management program. Preprocessing and preparation of data are essential to any data analysis effort. Hence it is imperative to make the data management phase more efficient in order to save time and costs. There is an absence of a standard data collection and compilation protocol in the water industry in the US resulting in a lot of effort in processing the data and preparing it for analysis. However, the challenge in data collection begins with the definition of a failure. Most utilities record failures as maintenance calls or work orders but do not differentiate according to the type or severity of the failure.

Previous studies have addressed the problem of identifying the important data attributes imperative to a data-driven asset management program and underlined the need to provide an effective guide for water utilities to aid the data collection and analysis process for advanced asset management (Park et al. 2015). The data collection strategy for a water utility should be based on how the data will be used (Grigg 2017). Grigg presented a methodology to investigate water pipeline failures and develop an effective data collection strategy to improve the performance of distribution systems. Parms-Priority, which is a decision support tool for water pipe replacement stresses on the collection of good quality data and requires at least three years of failure history data to be able to perform underlying statistical analysis (Moglia et al. 2005). The pipeline data collection should begin when the asset and records should be maintained throughout the lifecycle (Cox, 2003). Cox also explained that collecting incorrect or inadequate data will compromise all future data collection programs and there should be more focus on identifying the critical parameters to understand the pipeline network.

Some studies have also discussed the problem of unknown material and installation dates and incorrect pipe lengths in the collected data (Jenkins et al. 2015). The system understanding developed by the extensive literature and practice review can be utilized at this stage to make educated assumptions for the missing values by correlating urbanization and pipe material (Pelletier et al. 2003). This will introduce some bias based on the confidence in the assumption made which can be accounted for by including a categorical parameter. UKWIR’s national mains failure database resulted due to the co-operation of all the UK water companies and can be used successfully to guide asset renewal plans (MacKellar and Bodycote 2006). This study also mentioned that the largest challenge was to collect accurate information from the field during repairs and suggested using “Expert Systems” on a hand-held device to facilitate the same. However, the study only explained the database as a flat-file database and didn’t explain how the database could be improved to a relational database with the capability to perform spatial analyses. These studies helped build an understanding of database management systems used for analysis of water pipeline data and underlined the need to develop standardization protocols in the water industry.

2.5. Summary

A review of the literature and current practices presented a need to use the studied failure modes and mechanisms in a framework which could define the factors affecting the performance of water pipelines more accurately and comprehensively. It was also understood that the discrepancy in the data and the lack of standardization in the definitions of failure and performance need to be addressed as a critical part for any water pipeline asset management program for the water utility.

3. Material Mechanics and Failure Modes and Mechanisms

3.1. Introduction

Water distribution system infrastructure includes all the components utilized for distributing treated water such as pumps, valves, hydrants, joints and pipelines. These systems provide water for residential, commercial and fire-fighting purposes. Water pipelines form a majority part of the distribution systems and hence maintaining pipelines in a cost-effective way is always a challenge for water utilities.

3.2. Components of Water Distribution System

Distribution system infrastructure consists of pipes, pumps, valves, storage tanks, reservoirs, meters, fittings, and other hydraulic appurtenances that connect treatment plants or well supplies to the consumers. It is imperative to study the system interdependencies and how they affect the water pipelines during the lifecycle. This section is organized by pipe material types, discussing the changes in their manufacturing technologies and industry standards, common failure modes and mechanisms (of pipe and its appurtenances) and the lifecycle data parameters.

3.2.1. Valves and Hydrants

Pipe performance is also affected by other system elements like joints, valves, hydrants, fittings, and other appurtenances. Hence it becomes equally important to understand the performance of these elements and their effects on the pipe performance. For example, water hammer is the major cause of concern which is caused due to abruptly opening or closing valves or hydrants. A closing or opening of a valves or hydrants at the end of a pipeline system can cause a pressure surge due to a sudden change in the momentum of the fluid (water) enclosed. Surges take the form of pressure waves that beat against the walls of the pipelines and can speed of the deterioration of weaker pipe sections.

3.2.2. Pipelines

Water pipes can be classified as transmission mains, distribution mains, service lines, and plumbing systems. Transmission mains are large diameter pipelines used to transport water over from a treatment facility to a storage tank. Distribution mains are smaller in diameter than the transmission mains. Service lines carry water from the distribution main to the building being served. Premise plumbing refers to the piping within a building or home that distributes water to the point of use. Although service lines and premise plumbing are part of the distribution system, they fall outside the jurisdiction of the water utilities and are not studied in this research.

3.2.1.1. Material Mechanics and Failure causing factors during pipeline lifecycle

Pipe material forms one of the most important elements of the pipeline system as it forms the fundamental parameter of every modeling or analytical approach. Of the many types of pipe in use today, no one type fits all conditions of service. Knowledge of the different types of pipe will allow the operator to select the one that best fits the installation.

Different pipe manufacturing associations suggest optimistic design life for their respective pipe materials. However, as pipes of the same material will have different ages at failure in different pipe networks, the indicator for pipe performance should not be design life but performance life i.e., the predicted life of pipe in the utility network when influenced by real-world conditions. This requires knowledge of the pipe material and its lifetime performance in the real-world conditions.

There are various factors contributing to the failure of water pipelines during their lifecycle. Poor design and poor project planning can affect the pipeline performance during the design phase. Poor storage and manufacturing defects like inclusions, voids introduced during casting affect the pipeline performance during the manufacturing phase. Some factors that affect during the construction phase of the pipeline lifecycle are the quality of backfill, bedding thickness, type of backfill soil, damage during the transportation of the pipe and damage from any other third party. During O&M, there are many factors which vary with time and can accelerate deterioration cumulatively with other factors like corrosion, hydraulic pressure surges, stray currents. All these factors have been grouped into 4 factors namely Design, Manufacturing, Construction and O&M as shown in Figure 2.

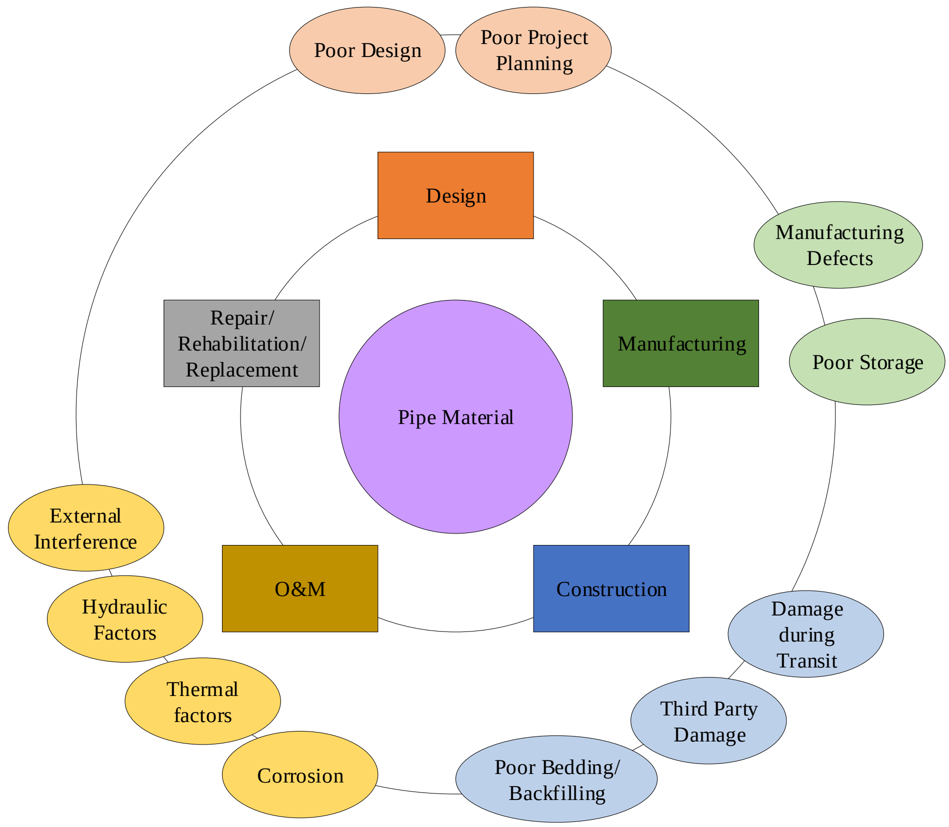

Figure 2: Causes of failure during pipeline lifecycle

Design and manufacturing of water pipelines have been standardized for the industry and can be studied from standards published by various pipe manufacturing associations. The factors contributing during the operational phase of the pipeline lifecycle are diverse owing to the soil environment, weather, topography, and practices of the specific water utility. These factors must be identified and their effects on the pipe material lifecycle must be known to have a reliable and robust analysis and deliver accurate results. Some of these factors have been illustrated in Figure 3.

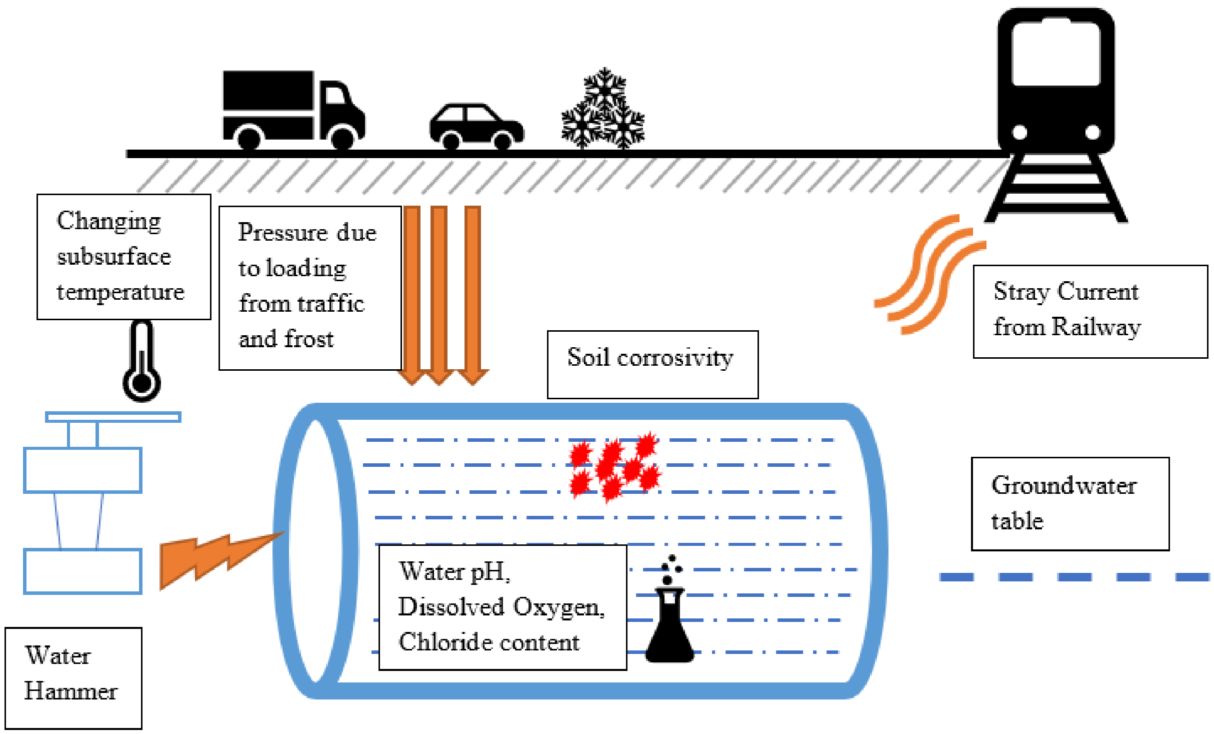

Figure 3: Common factors influencing water pipeline systems while in operation

Factors affecting the operation and maintenance phase of the pipeline lifecycle can be divided into the following factors:

1. Mechanical factors: Physical stresses which affect the integrity of the pipeline system which includes material properties that govern the variation in the design strength over time and hydraulic factors like internal pressure, water hammer and negative pressure.

2. Thermal factors: Temperature difference between the soil and the potable water and freeze-thaw cycles in the soil during extreme winter can cause structural deterioration.

3. Chemical factors: Chemical characteristics of soil like high concentrations of sulfides, chlorides, nitrates, low pH and of water like dissolved oxygen concentration, hardness, alkalinity can contribute to pitting corrosion and tuberculation. Presence of dissimilar metals can cause a potential difference and cause galvanic corrosion of the less noble metal. Water with varying chloride levels can also cause selective leaching of graphite from ferrous pipes and lead to graphitic corrosion (Council 2009).

4. Biological factors: Poorly drained, wet soils with little or no oxygen that contain sulfate ions, organic compounds, and minerals contain sulfate-reducing bacteria which produce sulfides causing microbiologically induced corrosion (Council 2009).

5. External Interference: Presence of stray currents from railway tracks and underground electrical lines can cause corrosion. Ground settlement due to washed up bedding and earthquakes can also cause loss of support and failures. Third party damage to the pipeline during installation or repair is also one of the major causes of pipeline failure.

3.2.1.2. Failure Modes and Mechanisms

The failure mode of water pipes can be defined as each type of failure which occurs within the pipe and failure mechanism is an event which causes the pipe to reach one or combined strength and serviceability limit states (Pelletier et al. 2003). The study also mentioned that limit states are of two types: ultimate limit state (burst or loss of stiffness) and serviceability limit state (deformations, clogging, buckling).

Selection of pipe material during installation or replacement of water pipes is one of the most important decisions in asset management of water pipes. It is important to track the changes in the standards, manufacturing processes and other technological advancements for the pipe materials to develop a robust framework for analysis which can explain and capture trend changes and outliers in the pipe performance during data analysis.

Studying influencing factors helps understand and target the critical parameters to analyze during data analysis. These have been summarized in the following sections from the literature and can be observed during a repair event or forensic analysis of exhumed pipeline. The following section explains the advancements in manufacturing technology and failure modes and mechanisms of different material types which is critical the development of the material cohort-based analysis framework.

3.2.1.3. Metallic Pipeline Materials

Metallic pipes can be classified as cast iron (CI), ductile iron (DI), galvanized iron (GI) and steel as shown in Figure 4.

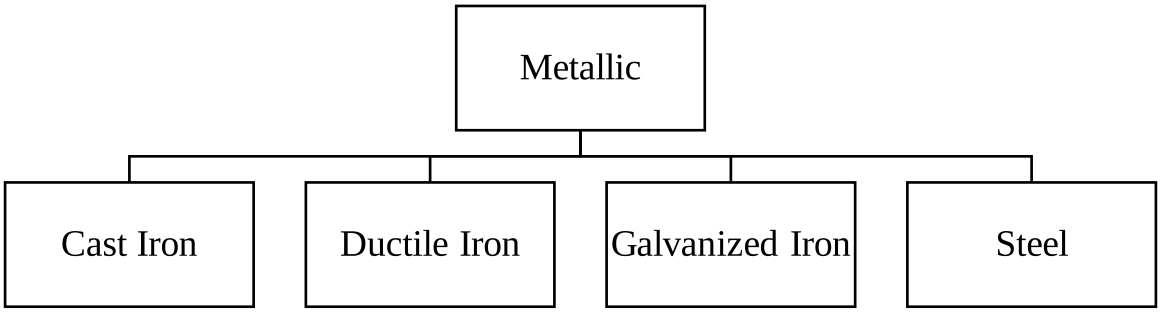

Figure 4: Metallic pipe types

3.2.1.3.1. Cast Iron pipe

Grey CI pipes were introduced around 1900 into the market and were produced by casting molten iron in vertical sand molds. Due to misalignment of the central core mold, many of these pipe walls did not have a uniform thickness. Spun grey iron pipes were then introduced into the market around 1930 and were widespread till 1960. This process included having molten cast iron poured into cylindrical molds made from metal or sand lined, which were rotating at high speeds, so the pipe walls were formed by centrifugal force. Due to the lack of knowledge and casting inconsistencies during the manufacture of cast iron pipes, they were usually manufactured as pit cast iron pipes with a thickness much greater than required. As an unintentional consequence, the pipeline survived longer in highly corrosive environments due to the presence of extra material. As a result, many of the CI pipes installed before the 1930s can still be found to deliver the level of service despite being in service for more than hundred years (American Water Works Service Co. 2002). Higher strength coupled with lack of casting inconsistencies introduced in spun cast iron pipes led to thinned wall sections leading to higher failures due to corrosion than the pre-1930 CI pipes.

Figure 5 shows the advancements in the manufacturing technology and standards for Cast Iron pipe material in the US.

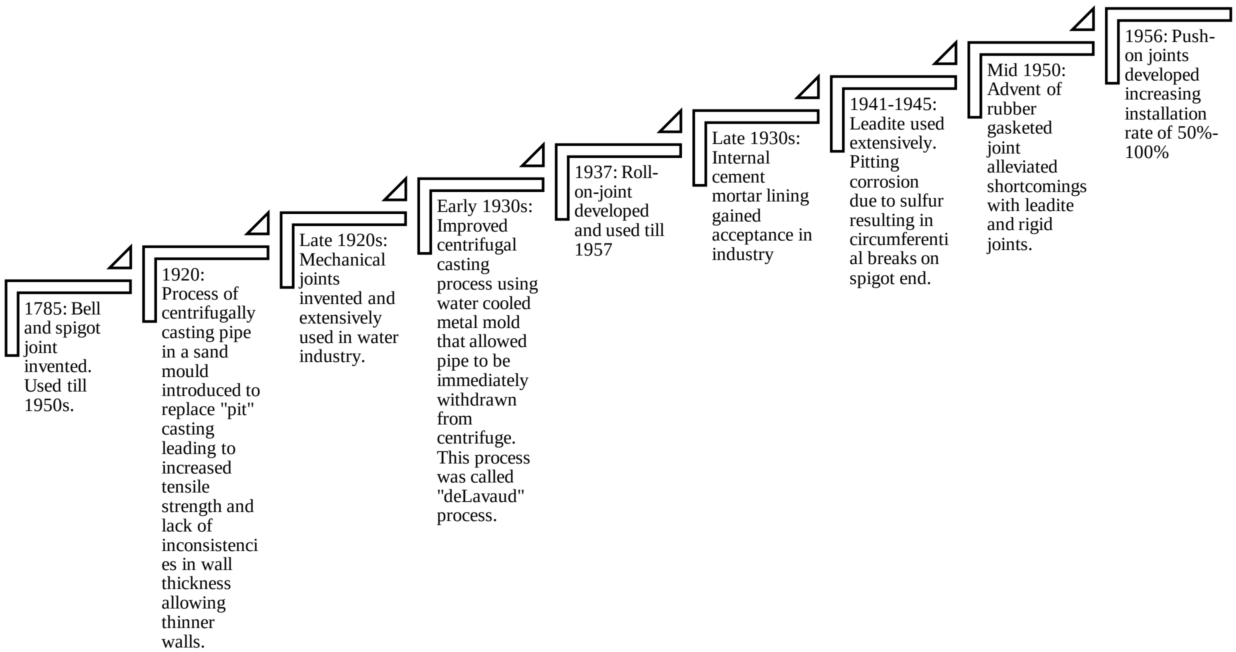

Figure 5: Timeline for changes in standards and technological advancements for CI pipes

3.2.1.3.1.1. Failure Modes and Mechanisms of CI pipe appurtenances

Pipelines are also affected by other elements of the water distribution system like joints, valves, coatings, linings, and hydrants. Water utilities often record failure events as work orders tagged to pipe segments, even if it is due to an appurtenance. Therefore, it is essential to identify failures due to the poor condition of joints, valves, linings, and coatings and analyze these separately. The common failure modes and mechanisms can be joint failures, caused due to the displacement of joint or improper sealing or corrosion of bolts and backing ring; lining failures like blistering and wrinkling due to evaporation of surface-lining interface solvent or poor adhesion and high temperature, respectively; or other failures due to inclusion, which are unintentional objects created in metals during manufacturing creating crack initiators (Figure 6), or due to third party damage due to improper excavations near pipes.

Until around 1950, lead joints were commonly used on cast iron pipe. The use of lead joints is now prohibited because of the potential threat of lead contamination, leakage due to differential thermal expansion leading to longitudinal splits and pitting corrosion on spigot due to sulfur leading to circumferential breaks. Mechanical joints replaced the bell and spigot joints as the most popular method of joining cast iron pipe.

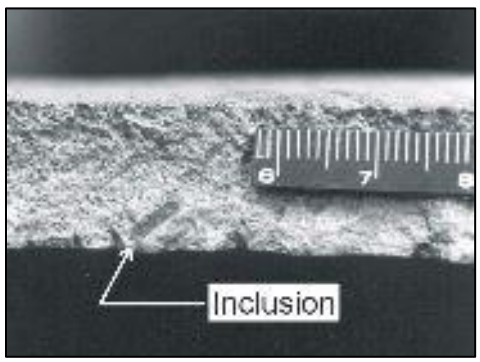

Figure 6: Inclusion failure (Makar et al. 2001)

3.2.1.3.1.2. Failure Modes and Mechanisms of CI pipes

The commonly observed failure modes reported for CI pipes are circumferential cracks, which are mostly observed due to restrained thermal contraction, inadequate bedding and soil swelling (Rajani et al. 1996) for diameters less than 16 inches; longitudinal splitting due to internal water pressure surges, live and dead loads; bell splitting, caused due to thermal differential between the CI material and leadite joints in cold temperatures (Figure 7 (a)); bell shearing, caused due to axial forces pushing spigot into bell of adjacent pipe (Figure 7(b)); spiral cracks, caused by a combination of bending forces and internal pressure (Figure 7(d)) and corrosion in the form of pitting (Figure 7(c)), graphitization, blow out holes and tuberculation (Figure 7(e)). In terms of service life, smaller diameter pipes are more prone to these failure modes. Larger diameter pipes fail due to a combination of corrosion and internal pressure surges (Kodikara et al. 2017) due to the extra margin of safety during manufacturing. However, the study failed to provide information on whether the pipes were coated/encased or the design standard of the pipe.

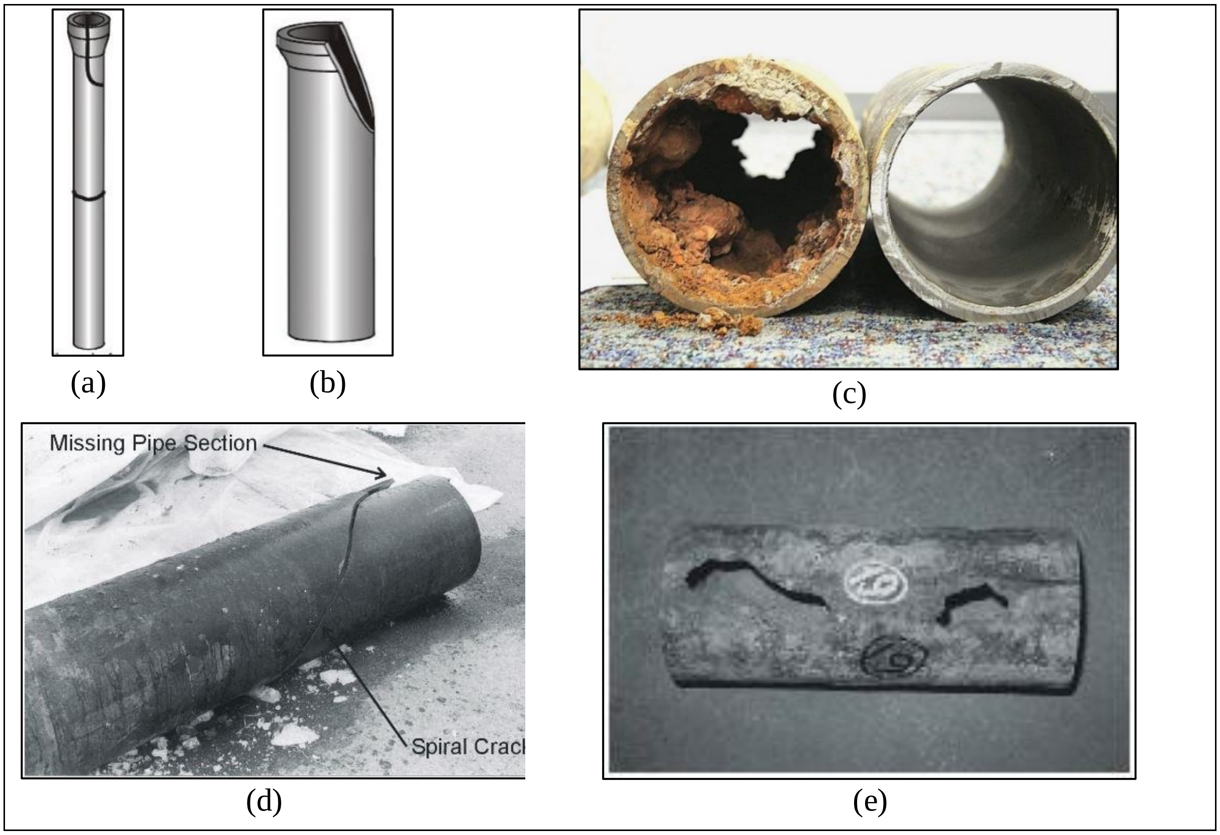

Figure 7: Failure Modes and Mechanisms of CI pipes (a) Bell Splitting at the top portion of the pipe. (Makar et al. 2001); (b) Bell Shearing in Cast Iron Pipe (Makar et al. 2001); (c) Tuberculation in CI Pipe; (d) Spiral Crack(Makar et al. 2001); (e) Heavily corroded CI pipe (Makar et al. 2001)

3.2.1.3.2. Ductile Iron pipe

Ductile Iron pipes were introduced in 1955 as a replacement for Cast Iron pipes due to easy machineability and corrosion resistance while providing additional strength, toughness, and ductility. As a result, there have been fewer records of DI pipes breaking and their modes and mechanisms documented as compared to CI pipes. Figure 8 shows the changes in ductile iron standards and manufacturing technologies.

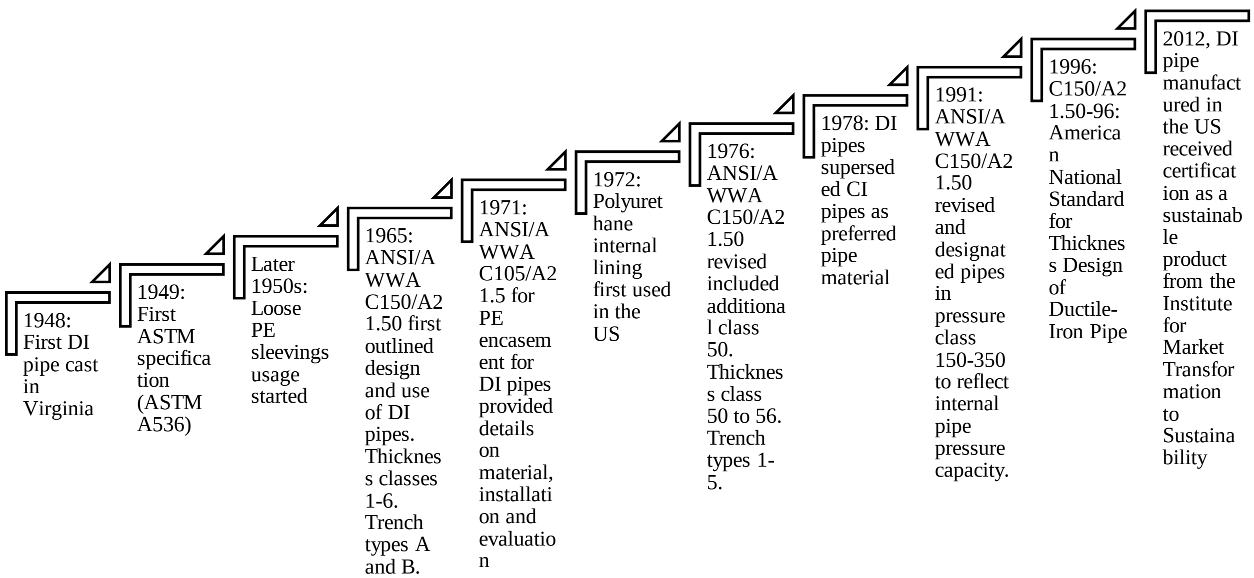

Figure 8: Timeline for technological advancements and changes in standards for DI pipes

The design of DI pipes has been focused on reducing the thickness while maintaining structural strength. This reduced thickness in DI pipes make them susceptible to failure due to corrosion mechanism.

3.2.1.3.2.1. Failure Modes and Mechanisms of DI pipe appurtenances

Failure modes and mechanisms of DI pipe appurtenances are similar to CI pipes and can be referred from section 3.2.1.3.1.1.

3.2.1.3.2.2. Failure Modes and Mechanisms of DI pipes

There have been fewer incidences of DI pipe failures due to external stresses and more due to corrosion and third party damage (Rajani et al. 2011). It has been observed that failure modes for smaller DI pipes are not similar to CI as small diameter (4”-12”) DI pipes are less susceptible to circumferential and longitudinal splits as are observed for small diameter CI pipes (Rajani et al. 2011).

3.2.1.3.3. Plastic Pipe

Plastic Pipes can be classified into three main types, Polyethylene (PE), Acrylonitrile Butadiene Styrene (ABS) and Polyvinyl Chloride (PVC) pipes as shown in Figure 9.

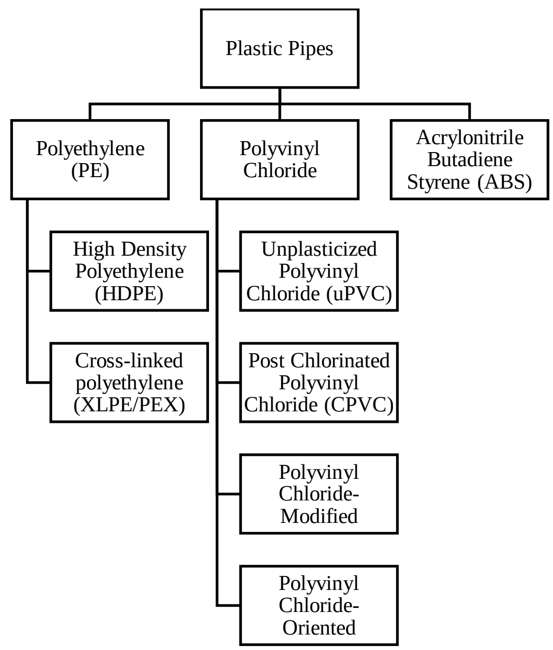

Figure 9: Types of plastic pipes

The use of plastic has increased dramatically as a water-supply pipe because of advantages like resistance to corrosion, ease of installing, handling and connection and good flow characteristics. The disadvantages are that being non-metallic, it cannot be thawed by electric resistance methods if frozen nor can it be located underground with electronic pipe locators unless a copper tracer wire is provided with the pipe installation.

The joints on plastic pipes are generally of the slip joint construction and the fittings generally made of cast iron or plastic. Services may be tapped directly into the pipe, but most utilities use service saddles to make service connections.

3.2.1.3.3.1. Polyethylene pipe

In North America, Polyethylene (PE) pipes have been used for water supply since the 1980s. Main advantages of PE pipes include a high strength-to-weight ratio and higher flexibility as compared to other materials. Continuous improvement of the material has enhanced its performance through increased resistance to creep rupture strength, stress cracking and rapid crack propagation (Davis et al. 2007). These pipes are also used in the lining and trench-less technologies, where the pipes are installed without digging trenches without any disruption above ground. Figure 10 shows the technological developments and changes in standards of PE pipes.

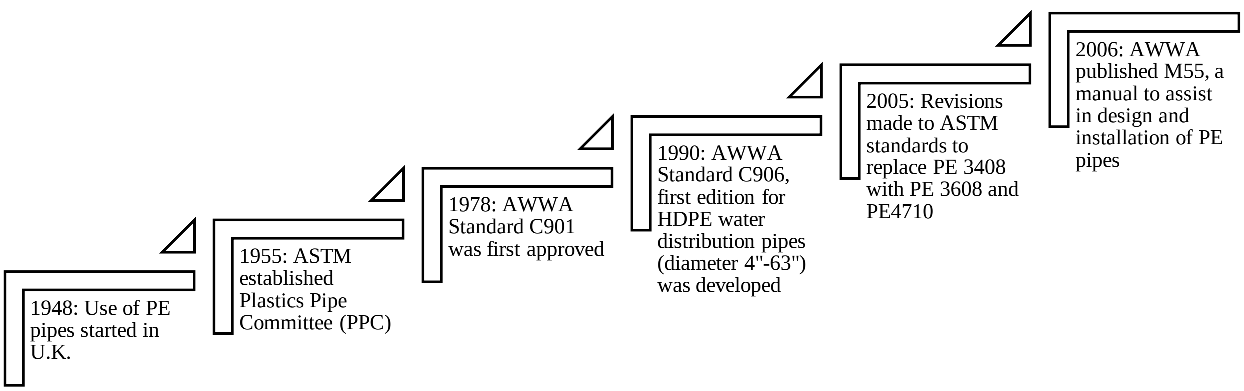

Figure 10: Development of Standards over the years for PE pipes (Rubeiz 2004)

3.2.1.3.3.1.1. Failure Modes and Mechanisms of PE pipe appurtenances

PE pipes are affected by the failures of its appurtenances like the cracking of socket, displacement of the gasket of the push fit and slip on collar; poor adhesion and embrittlement of the solvent weld; joint displacement leading to infiltration of embedment material and external contaminants (Figure 11).

Figure 11: Joint Displacements. Source: Abolmali, A., Motahari, A. and Hutcheson J.(2010)

3.2.1.3.3.1.2. Failure Modes and Mechanisms of PE pipes

Commonly observed failure modes and mechanisms in PE pipes are stress cracks which are predominant for HDPE pipes and occur due to brittleness because of manufacturing flaws and inclusions (Figure 12 (a)), and longitudinal cracks due to hydraulic pressure surge and water hammer; blisters due to manufacturing flaws and UV radiation exposure; excessive deformation (Figure 12 (b)) or inverse curvature (Figure 12 (c)) in extreme cases of the surface due to heavy loading on top of the pipe or insufficient bedding support; corrugation growth in the pipe’s interior liner due to the transfer of stress from the outer corrugated wall to the inner liner affecting flow characteristics (Figure 12 (d)).

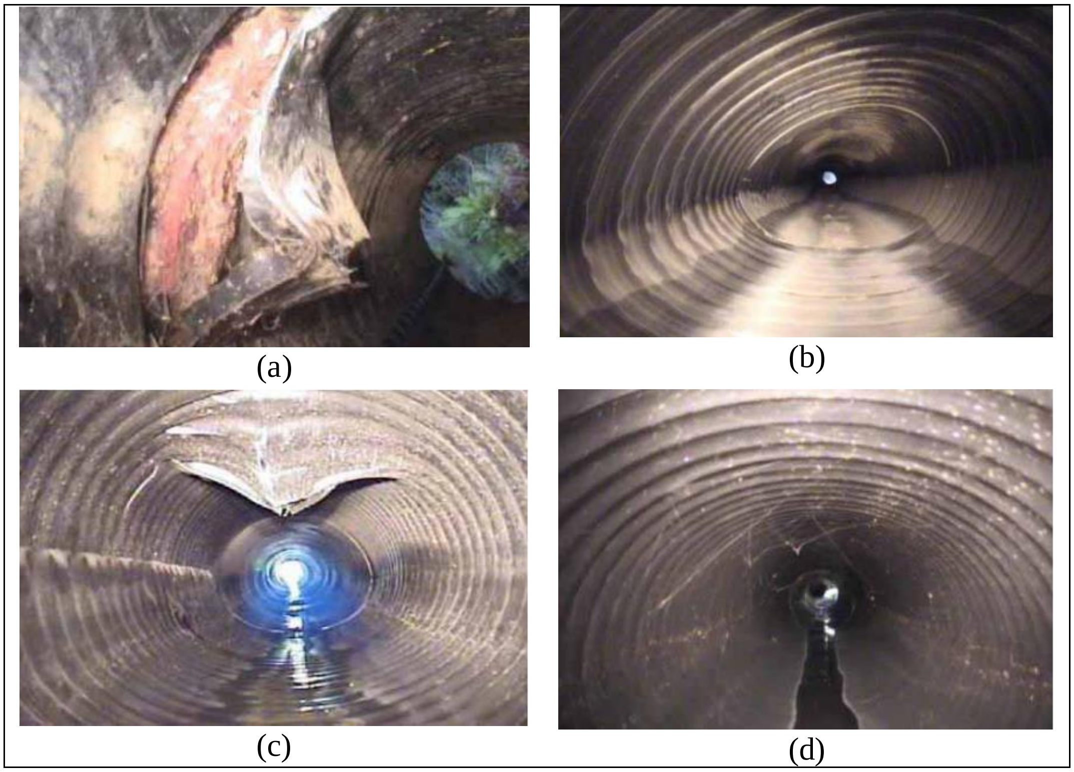

Figure 12: Failure Modes and Mechanisms of PE pipes. (a) Cracks observed in PE pipes (Abolmali, A., Motahari, A. and Hutcheson J.(2010)), (b) Deformation in PE pipes (Abolmali, A., Motahari, A. and Hutcheson J.(2010)), (c) Inverse Curvature in PE pipes (Abolmali, A., Motahari, A. and Hutcheson J.(2010)), (d) Corrugation growth observed in PE pipes(Abolmali, A., Motahari, A. and Hutcheson J.(2010))

3.2.1.3.3.2. PVC pipes

PVC pipes have been increasingly used in the water distribution systems since the late 1970s. Most water utilities were accepting of PVC pipes due to the low cost at installation, ease of installation and corrosion resistance. Most of the standards developed for PVC have focused on providing the adequate thickness to handle the pressure surge events. The changes in the PVC pipe standards and milestones are shown in Figure 13.

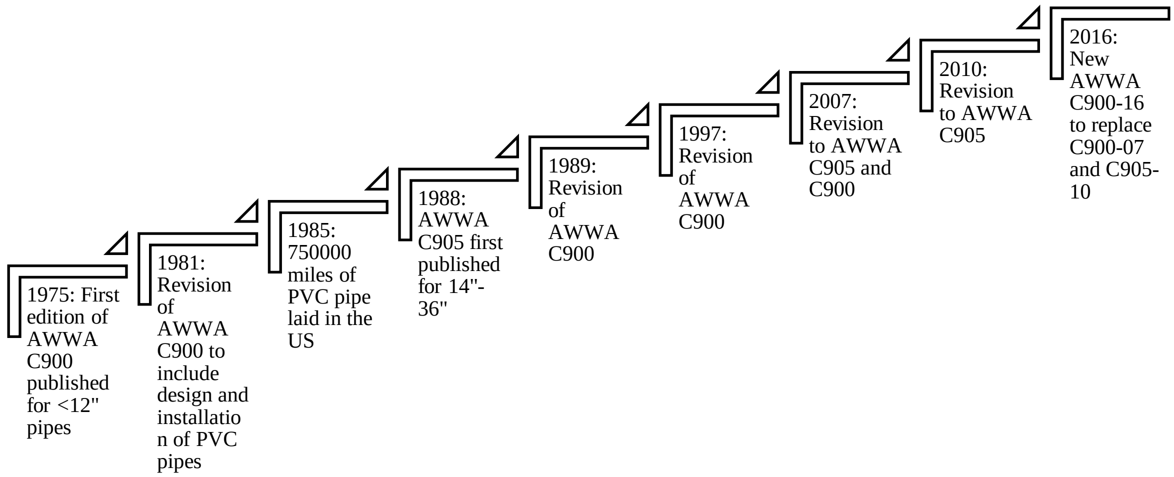

Figure 13: Changes in standards and technological advancements for PVC pipes

3.2.1.3.3.2.1. Failure Modes and Mechanisms of PVC pipe appurtenances

Failures on PVC pipe appurtenances occur mainly on PVC pipe joints. These failures occur in the form of broken joints which could be due to the ground settlement, differential thermal expansion of the joint and over insertion of the pipe into the joint causing cracking of bell. Poor installation practices can also lead to failure during tapping of PVC pipes.

3.2.1.3.3.2.2. Failure Modes and Mechanisms of PVC pipes

The typical failure modes of PVC pipe failure are failure due to brittleness, which can occur due to exposure to UV radiation during storage or other manufacturing issues like inclusion; environmental stress cracking (Figure 14 (a)), which can occur due to localized solvation of the polymer molecules in the presence of organic solvents in the soil; blistering due to manufacturing flaws, abrasions and frost; and longitudinal splitting due to ductile fracturing which occurs when material yields before failing indicating high hydraulic pressure. Figure 14 (b) shows a pipe showing indicators for 3 different failure modes.

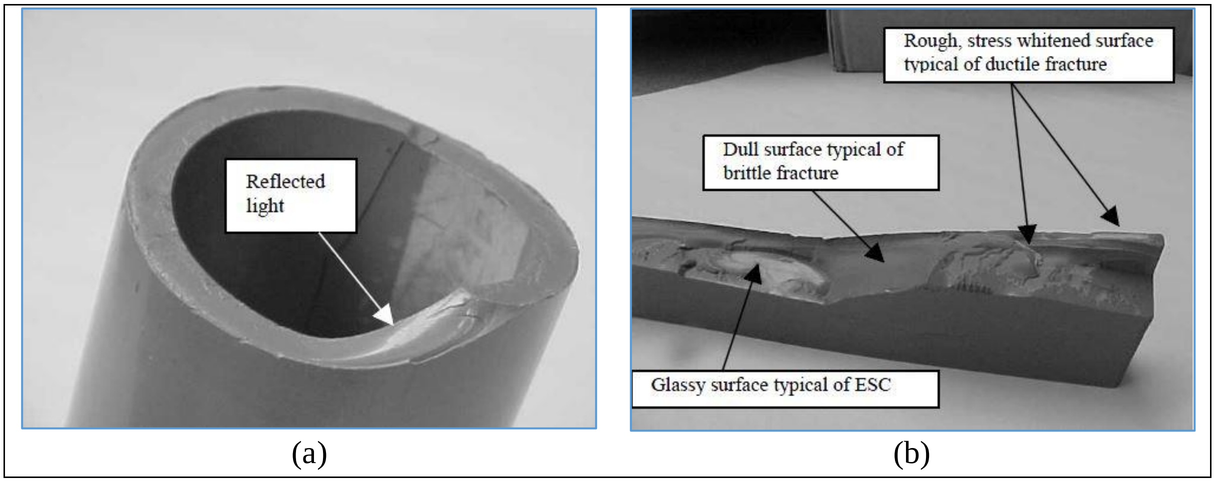

Figure 14: Failures in PVC pipes. (a) Environmental Stress Cracking (Knight 2003), (b) All 3 kinds of fracture in PVC Pipe (Knight 2003)

3.2.1.3.4. Concrete Pipes

Concrete pipes can be divided into Reinforced Concrete Pipe, Steel Cylinder type, Noncylinder type, Prestressed Concrete Cylinder Pipe (PCCP) and Bar Wrapped Concrete pipes as shown in Figure 15. However, this study will only focus on PCCP pipes owing to the relative presence in the water distribution systems

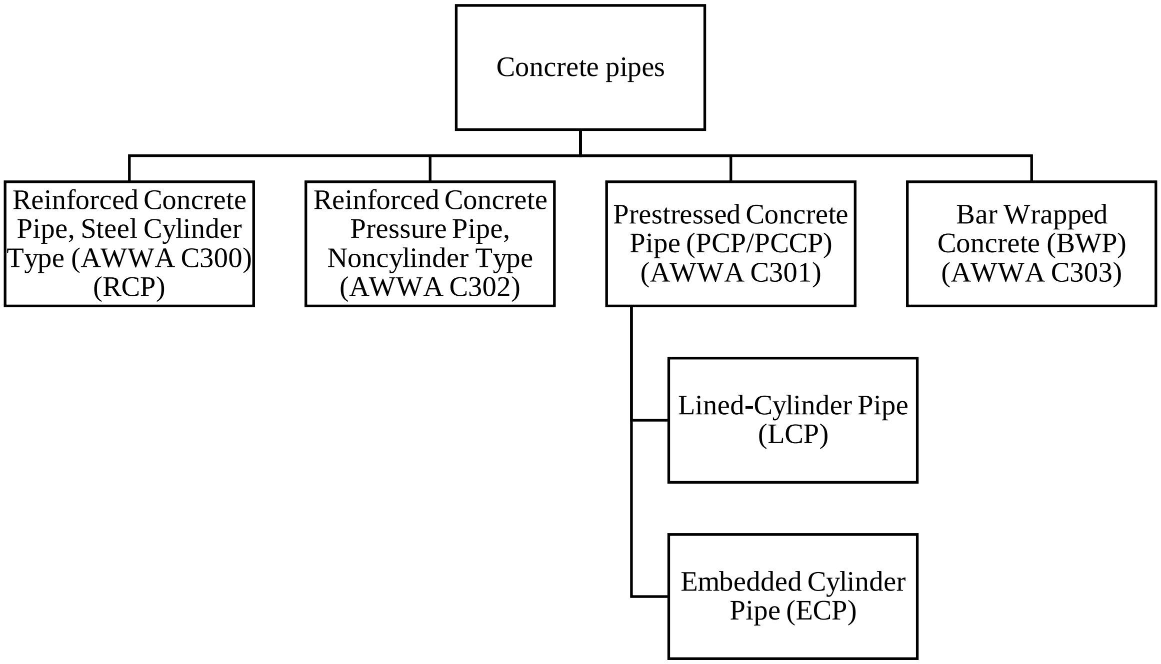

Figure 15: Types of Concrete pipes

3.2.1.3.4.1. Prestressed Concrete Cylinder Pipe, Steel Cylinder Type (AWWA C301)

Prestressed concrete pipes (PCCPs) were first developed in the United States (AWWA C301, 1999) in 1942 due to technology developed for prestressing concrete during World War II. However, those were lined pipes and the scarcity of steel led to the introduction of the embedded type in 1953. Lined PCCP pipes have the concrete core lined with a steel cylinder with diameter range 16”-60”, and embedded PCCP have the steel cylinder embedded within a concrete core with a diameter range 30-256”. They have been used successfully for large diameter operations under roads with heavy traffic and contaminated organic lands where ground movement is more common. in many utilities. However, PCCP pipes undergo failure due to many chemical degradation mechanisms which have been summarized in the following section.

Figure 16 shows the advancements in the manufacturing technology and standards for PCCP pipes in the US.

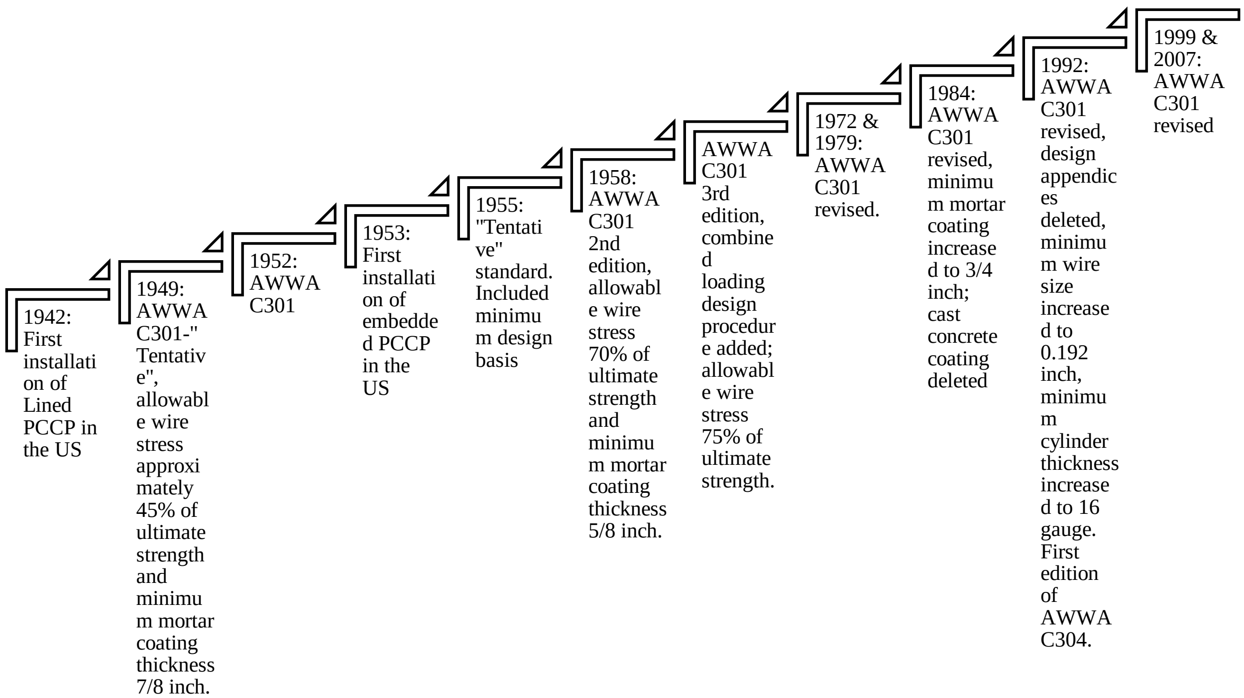

Figure 16: Changes in standards and technologies for PCCP pipes over the years

3.2.1.3.4.1.1. Failure Modes and Mechanisms of PCCP pipe appurtenances

Failure in PCCP appurtenances can occur in joints due to corrosive soils, cracks in joint welds or linings due to buckling of pipe, poor adhesion, high subsurface temperature and blistering due to evaporation of steel lining solvent.

3.2.1.3.4.1.2. Failure Modes and Mechanisms of PCCP pipes

Failure modes in PCCP pipes can be categorized as cracks in mortar coating and concrete core, which occurs due to water reaching the cylinder. Indicators include high CO_2 content in the soil causing carbonation of mortar coating and groundwater activity. Cracks in coating or core can also lead to the delamination of the coating. Prestressing wire breaks is one of the more important factors affecting the long-term performance of PCCP pipes which can occur due to groundwater activity, spalling of mortar coating, settlement of soil, missing slurry application before wrapping, less distance between wrapped wires and hydrogen embrittlement of the wires due to excessive cathodic protection.

3.3. Summary

It is observed that failure modes and mechanisms vary for smaller and larger diameter pipes. Centrifugal CI is more common in the system although older pit cast and sand cast are still present.

Older CI pipes (Pre-1930), were usually manufactured as pit cast iron pipes with a thickness much greater than required. This ensured the pipes had enough material to corrode away before failing and performed better in corrosive environments as compared to newer variants. Lead joints were extensively used in the mid 1940s and are now prohibited due to the potential threat of lead contamination, leakage due to differential thermal expansion, and pitting corrosion on spigot due to sulfur leading to circumferential breaks. DI pipes are manufactured with greater strength for surge protection but have thinner walls as compared to CI pipes leading to corrosion threat.

Plastic pipes have good corrosion resistance, is easy to install, handle, and connect and has a good flow characteristic. However, slow crack growth mechanisms are predominant, and standards need to suggest more conservative thickness for pressure classes.

PCCP pipes have varied failure modes and mechanisms owing to a complex structure of cement mortar and metallic wires. Wire breaks are a great threat and need to be protected from the outside environment. PCCP pipes are installed as large diameter pipes and hence are critical because of the high consequence of failure.

4. Performance Analysis Framework

4.1. Introduction

Understanding most suitable environments for each pipe material is an integral part to guide installation practices and decisions on pipeline replacement. In the unpredictable, dynamic and complex underground environment of the pipeline system, there is a need to understand the mechanisms/process by which pipeline fails. All the parameters affecting the process vary temporally, affecting each other through linear and non-linear relationships. There have been various efforts to build mathematical performance models to study relationships between elements of the pipeline system and predict future performance, but most of the performance models are an over-simplification of the in-situ pipeline conditions, unreliable for real-world conditions and limited in including the cumulative effects of parameters affecting the internal and external pipeline environments leading to limited reliability for real-world use. In order to develop robust models, the mathematical and logical framework behind the analysis should be based on knowledge of the behavior of all the elements in the system and understanding of their relationships with each other. The most important part of this effort, as also observed in literature and practice, is the development of cohorts within the dataset studied. Cohorts or Management Strategy Groups (MSGs) classify the pipe materials into groups and show similar behavior in real-world situations (Park et al. 2015). Park also classified this based on Intrinsic factors, Operating Environment, and Operational factors. However, with each utility observing different performance life of pipe materials when compared with other utilities, it becomes critical to utilize expert opinion along with the use of statistical tools like k-means cluster analysis. Chapter 3 explained the typical failure modes for different pipe materials. These failure modes have been utilized to form the cohorts for different pipeline materials in this section.

The frameworks in Figures 17, 18, 19, 20 and 21 have been suggested by identifying the different failure modes and efforts have been made to delineate the cohorts using literature review. However, many of the causal factors for failure have not yet been quantified and need further experimental work to form cohorts. The factors which have been identified as the causes of failure but does not have explicit boundaries to form cohorts have also been suggested. The green boxes contain the cohorts which can help dissect the dataset and have separate boundaries while the qualitative factors which need do not have explicit boundaries have been shown in grey boxes. The blue boxes represent the failure modes and the orange boxes represent exclusions from the dataset which cannot be justified for the respective failure mode.

4.**2. Cast Iron pipes**

Figure 17 shows the performance analysis framework for CI pipes. The older pit cast iron pipes were manufactured with added thickness although the manufacturers lacked the knowledge and experimental techniques. As a result, the older CI pipes have survived longer in corrosive environments when compared to other CI variants and can be separated into a cohort. The CI pipes from 1930-1955 used leading joints extensively which might indicate more failure due to differential thermal expansion. Post-1955 pipes replaced leading with rubber gasketed joints, so they can be formed into a separate cohort as well. Also, failure modes in small diameter (<16”) CI pipes are different from the larger diameter pipes as observed from literature review so CI pipes can be divided into a smaller diameter and larger diameter pipes. Also, large diameter CI pipes fail due pressure surge events with pressure more than 10 MPa (~1400Psi) on corrosion pits (Kodikara et al.). The study also mentioned a loss of thickness greater than 85% presents a risk for the pipe and can even fail under normal operating pressures. There have been extensive studies to understand the effect of corrosive environments on CI pipes. Water pH below 4 and above 8.5 has been found to be highly corrosive to metallic water pipelines (Singley et al. 1984). A similar range was found for soil pH in another study for ductile iron pipes (ANSI/AWWA C105/A21.5-99, 1999). As ductile iron pipes have shown similar material characteristics, these ranges can be assumed to be a conservative estimate for cast iron pipes also. The study also explained that presence of positive or even trace amount of sulfides can create anaerobic conditions for sulfide bacteria to thrive and initiate corrosion pits. Also, the study mentioned that negative to 50mV of redox potential in the soil makes it highly corrosive. Soil resistivity is considered the most important factor considered while studying the effect of corrosive soils. Less than 2000 Ωcm is considered highly corrosive, 2000-2500 Ωcm as medium corrosive and greater than 3000 Ωcm as low corrosive (Council 2009). Studies on the effect of chloride on mortar coatings in PCCP pipes also suggest that trace levels of chloride in soil with pH between 9-10 can damage the mortar coating (Ge 2016). This can be used to suggest similar effects on the internal mortar lining in metallic pipes due to trace chloride levels in water.

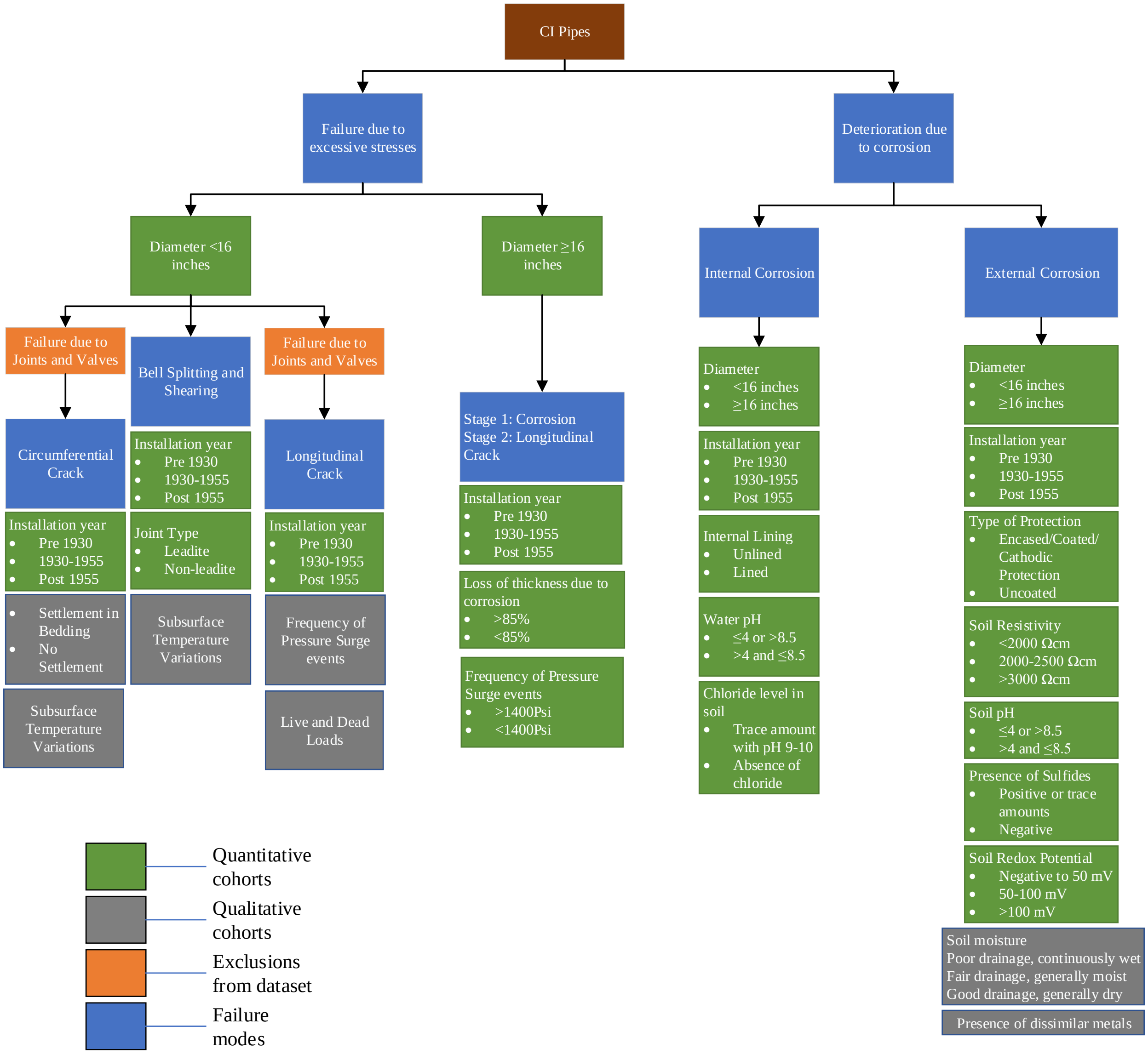

Figure 17: CI pipe performance analysis framework

4.3. Ductile Iron pipes

Literature and practice review has shown that DI pipes have failed more due to third-party damage and joint failure rather than other mechanical failure types like longitudinal or circumferential cracks due to higher resistance to stress cracking during manufacture. This shows that DI pipes have more strength to resist the internal pressure surges than CI pipes and fail more due to improper installation practices. However, due to lesser thickness as compared to CI pipes of the same pressure class, DI pipes have lesser material to protect against corrosion. The addition of pressure class to DI pipe standards in 1991 made available pipes with thinner walls for certain diameters (Rajani et al. 2011). This can be a point of inflection in DI pipe performance and should be investigated further by forming a separate cohort. The proposed framework for the analysis of DI pipes is shown in Figure 18.

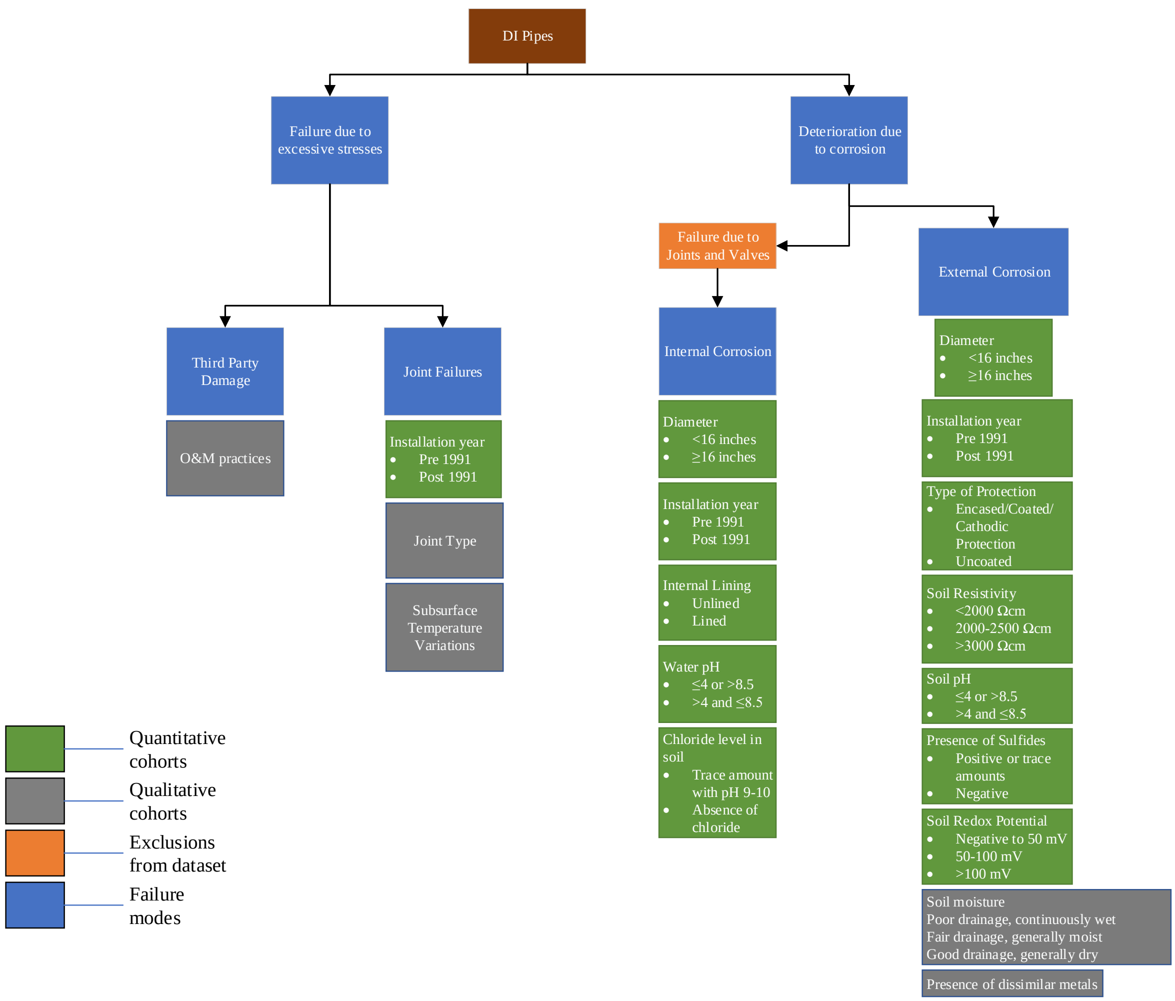

Figure 18: DI pipe performance analysis framework

4.4. Polyethylene Pipes

In 2005, revisions were made to ASTM standards to replace PE 3408 with PE 3608 and PE4710 for large diameter (>16”) HDPE pipes. It was explained that PE 3608 and PE 4710 had greater strength to handle internal pressure surges and hence required lesser thickness (Najafi 2015). The study also explained that the reduced thickness didn’t protect the pipes against the live loads (traffic load) and dead loads (soil lead) and can form a separate cohort for performance analysis. The study also mentioned that PE 3608 and PE 4710 could handle maximum short-term surge stress of 2000 psi. This can form a cohort to differentiate between PE 3608 (and PE 4710) and PE 3408. Figure 19 shows the proposed performance analysis framework for PE pipes.

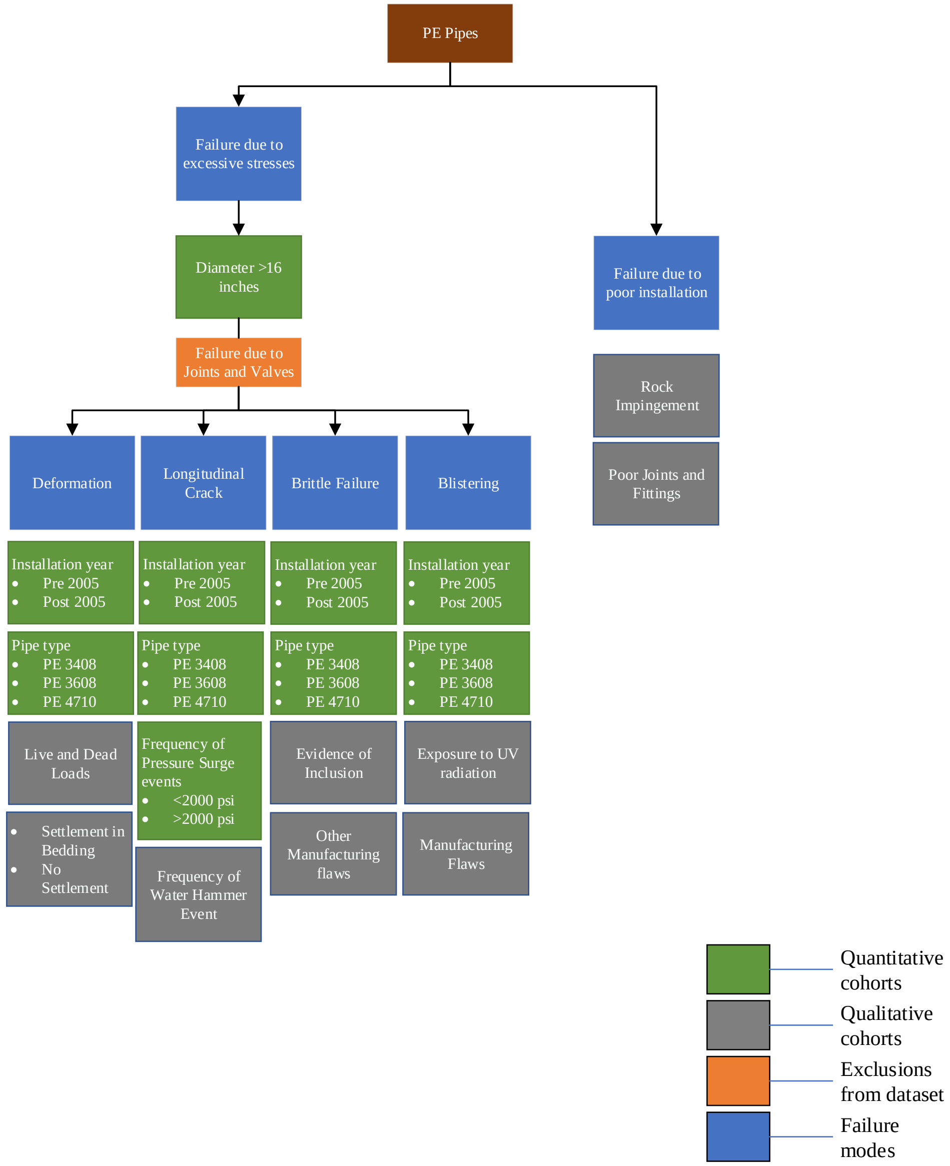

Figure 19: PE pipe performance analysis framework

4.5. Polyvinyl Chloride Pipes

PVC pipes standards have changed a lot of times over the years. The 2007 Revision to AWWA C905 and C900 can be used to form a cohort for performance analysis because in that year, the factor of safety was reduced from 2.5 to 2 and surge allowance was eliminated from C900 (AWWA, 2007). PVC-M (Modified) and PVC-O (Oriented) have better performance than PVC-

U (Unplasticized) pipes and can operate under higher hoop stress. Therefore PVC-M and PVC-O pipes have lesser thickness compared to PVC-U pipes for the same pressure class, but lesser thickness makes them more vulnerable to failure due to live and dead loads. The proposed framework for performance analysis of PVC pipes is shown in Figure 20.

Figure 20: PVC pipe performance analysis framework

4.6. Prestressed Concrete Cylinder Pipes

1964 was the point at which the change in standard became less conservative as it suggested a reduction in minimum wire size, increase in concrete core stress while wrapping wire, reduction in the minimum amount of Portland cement in core and reduction in minimum coating thickness (AwwaRF, 2008). The study also mentioned that this trend changed in 1984 in AWWA C301-84 with an increase in density of concrete core and increase in minimum coating thickness resulted in improved performance. As a result, Pre-1964, 1964-1984 and Post 1984 have been suggested as cohorts in this study. Also, studies have shown that Wire classes I and II have better resistance to hydrogen embrittlement when compared to Wire classes III and IV (Ge 2016). This study also mentioned that even trace amounts of chloride in soil with pH between 9-10 can affect the mortar coating and affect the concrete core. The proposed framework is illustrated in Figure 21.

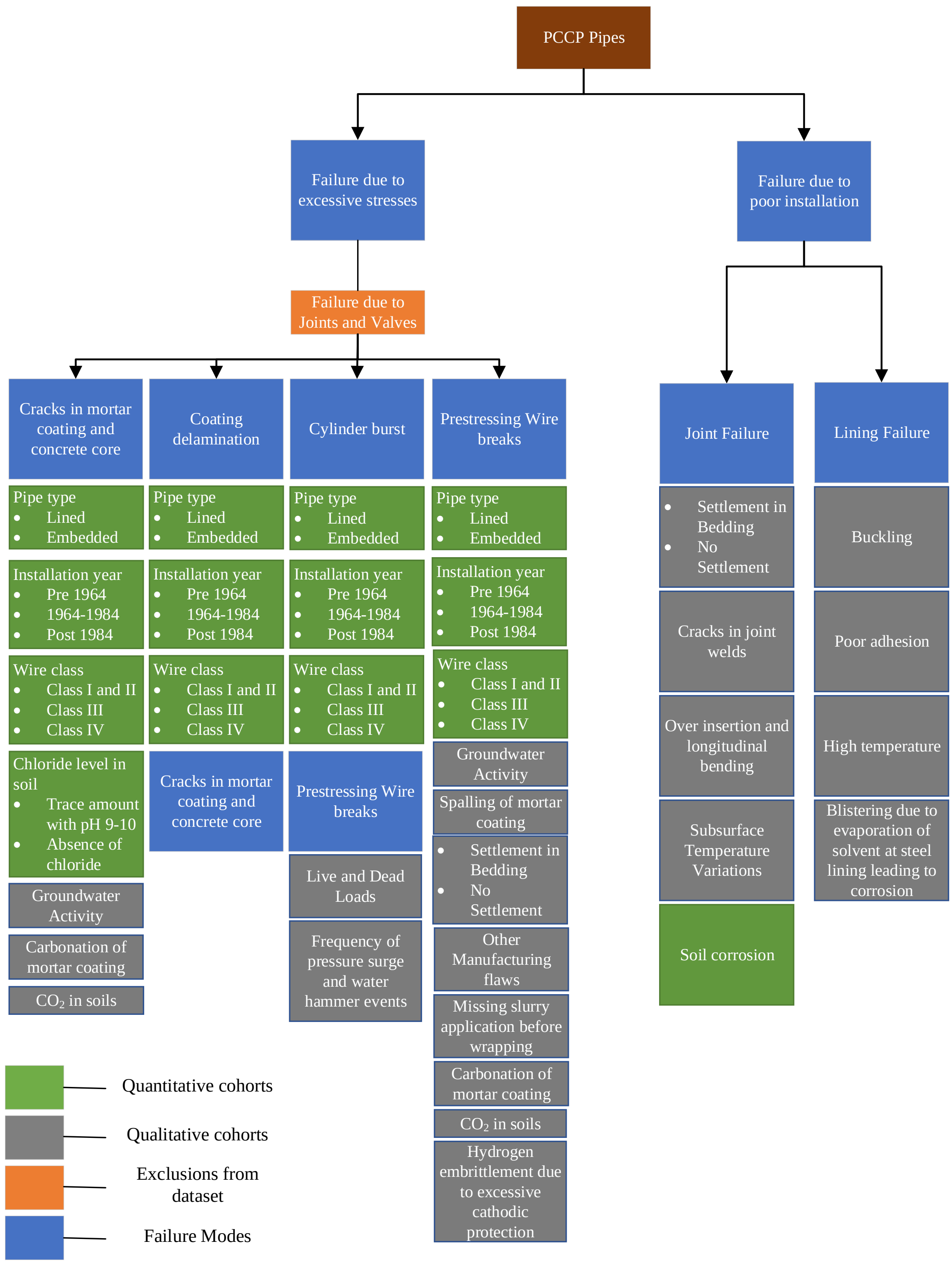

Figure 21:PCCP pipe performance analysis framework

5. Conclusions

In order to develop robust models, the mathematical and logical framework behind the model should be based on knowledge of the behavior of all the elements in the system and understanding of their relationships with each other. A model capable of mathematically replicating the real-world conditions to the maximum extent would be the best tool to utilize for supporting decisions. Thus, it is important to develop a data analysis methodology based on a comprehensive understanding of the pipeline system. The following list presents the conclusions from this study:

1. Studies have been conducted previously on the internal and external corrosion mechanisms of metallic pipelines.

2. Factors related to joint failure and third-party damage of water pipelines exist qualitatively and can be assessed after pipe exhumation for forensic analysis.

3. Loading factors like traffic loading and soil loading can be translated into safe pipe depths to form more cohorts in the dataset.

4. Manufacturing flaws like inclusions and voids in pipes and operational factors like frequency of surge events, improper installations, and bedding conditions are not accounted for during installation and manufacturing.

5. Subsurface characteristics like the presence of CO_2 in the soil and soil settlement can be estimated with inference based statistical studies or experimental studies.

6. More understanding needs to be developed on the deterioration mechanisms for all types of pipelines, joints, valves, and hydrants are required to develop better performance analysis frameworks.

6. Recommendations

The following recommendations can be made from the conclusions of this study to advance the state of performance analysis and improve the understanding of the water pipeline infrastructure:

1. The qualitative and quantitative nature of the different factors accounted for by utilizing approaches like mixed methods research to build more comprehensive analytical frameworks.

2. There is a need to standardize data collection, reporting of failure and condition assessment procedures in the US to reduce efforts and costs related to data quality assurance and quality control.

3. Water utility staff should understand the complexity of the water pipeline infrastructure system. Also, the personnel should know the critical data parameters and their importance.

4. There need to be uniform definitions of terms like a failure, break, and performance along with the development of indicators to assess pipeline performance.

5. All the factors affecting the pipeline performance mentioned in this research do not have the same influence. The next steps should be to weigh the relative importance the factors and how the influence can change over time.

7. References

1. Abolmaali, A. Motahari, J. Hutcheson, and T. Le. (2010). "Evaluation of HDPE Pipelines Structural Performance".

2. American Water Works Association, A., Denver, CO (2012). "Buried no longer: Confronting America's water infrastructure challenge."
3. American Water Works Service Co., I. (2002). "Deteriorating buried infrastructure management challenges and strategies." Environmental Protection Agency Washington, DC.
4. ASCE "2017 infrastructure report card." ASCE Reston, VA.
5. AWWA (American Water Works Association). 1965. American National Standard for the Thickness Design of Ductile-Iron Pipe. ANSI/AWWA C150/A21.50. Denver. Colo.: AWWA.

6. AWWA (American Water Works Association). 1976. American National Standard for the Thickness Design of Ductile-Iron Pipe. ANSI/AWWA C150/A21.50. Denver. Colo.: AWWA.

7. AWWA (American Water Works Association). 1991. American National Standard for the Thickness Design of Ductile-Iron Pipe. ANSI/AWWA C150/A21.50. Denver. Colo.: AWWA.

8. AWWA (American Water Works Association). 1999. American National Standard for Polyethylene Encasement for Ductile Iron Pipe Systems. ANSI/AWWA C105/A21.5-99. Denver, Colo.:AWWA.

9. AWWA (American Water Works Association). 2002. American National Standard for the Thickness Design of Ductile-Iron Pipe. ANSI/AWWA C150/A21.50. Denver. Colo.: AWWA.

10. AWWA (American Water Works Association) (1975). USA Standard for Thickness Design of Cast-Iron Pipe. USAS A21.1-1967/AWWA H1-67, Denver, Colorado.

11. AWWA C301-99, "AWWA Standard for Prestressed Concrete Pressure Pipe, Steel-Cylinder Type, AWWA, Denver CO, USA," 1999, American Water Works Association

12. AWWA C900, "Polyvinyl Chloride (PVC) Pressure Pipe and Fabricated Fittings, 4 In. Through 12 In. (100 mm Through 300 mm), for Water Transmission and Distribution," 2007, American Water Works Association.

13. AwwaRF. (2008). Failure of Prestressed Concrete Cylinder Pipe, C301-07. AWWA Research Foundation, Denver, CO.

14. AWWSC (American Water Works Service Company), 2002. Deteriorating Buried Infrastructure: Management Challenges and Strategies. Office of Ground Water and Drinking Water, US Environmental Protection Agency, Washington.

15. Committee on the Review of the Bureau of Reclamation's Corrosion Prevention Standards for Ductile Iron, P., National Materials Advisory, B., Division on, E., Physical, S., and National Research, C. (2009). Review of the Bureau of Reclamation's Corrosion prevention standards for ductile iron pipe, National Academies Press.

16. Council, N. R. (2009). *Review of the Bureau of Reclamation's Corrosion Prevention Standards for Ductile Iron Pipe*, National Academies Press.
17. Cox D (2003) Data Management Strategies for Pipeline Networks. In 'CSIRO/AWA 3rd Annual Seminar on Asset Planning & Operation: Use of Asset Management Data'. Melbourne, Australia. (CSIRO Urban Water)

18. Davis, P., Burn, S., Gould, S., Cardy, M., Tjandraatmadja, G., and Sadler, P. A. (2007). "Long term performance prediction for PE pipes."
19. Davis, P., Burn, S., Moglia, M., Gould, S. J. R. E., and Safety, S. (2007). "A physical probabilistic model to predict failure rates in buried PVC pipelines." 92(9), 1258-1266.
20. Ductile Iron Pipe Research Association (DIPRA), "Design of Ductile Iron Pipe," DIPRA/6-03/5M, AL, 2003.

21. Ge, S. (2016). "Development of a Numerical Model to Analyze the Condition of Prestressed Concrete Cylinder Pipe (PCCP)." Virginia Tech.
22. Ghirmay, A. M. (2016). "Asbestos Cement Pipe Condition Assessment and Remaining Service Life Prediction."
23. Grigg, N. S. J. J. A. W. W. A. (2005). "Assessment and renewal of water distribution systems." 97(2), 58-68.
24. Grigg, N. S. J. J. o. P. o. C. F. (2017). "Water Supply Pipeline Failures: Investigative Procedures and Data Management." 31(6), 06017004.
25. Gui, G., Pan, H., Lin, Z., Li, Y., and Yuan, Z. J. K. J. o. C. E. (2017). "Data-driven support vector machine with optimization techniques for structural health monitoring and damage detection." 21(2), 523-534.
26. Hu, Y., Wang, D., and Chowdhury, R. (2013). *Guidance Manual for Managing Long Term Performance of Asbestos Cement Pipe*, Water Research Foundation.
27. Huang, I. B., Keisler, J., and Linkov, I. J. S. o. t. t. e. (2011). "Multi-criteria decision analysis in environmental sciences: ten years of applications and trends." 409(19), 3578-3594.
28. Jenkins, L., Gokhale, S., and McDonald, M. (2015). "Comparison of Pipeline Failure Prediction Models for Water Distribution Networks with Uncertain and Limited Data." 6(2), 04014012.
29. Knight, M. L. (2003). "Failure Analysis of PVC and CPVC Piping Materials." *CORROSION 2003*, NACE International, San Diego, California, 7.
30. Kodikara, J., Rathnayaka, S., Zhang, J., Crawly, C., Zhang, D., and Blaha, F. "Lessons Learned from Large-Diameter Pipe Failure Case Studies." *Pipelines 2017*, 561-571.

31. Kodikara, J., Rathnayaka, S., Zhang, J., Crawly, C., Zhang, D., and Blaha, F. (2017). *Lessons Learned from Large-Diameter Pipe Failure Case Studies*.
32. Lee, J. Y., Burton, H. V., and Lallemant, D. J. S. S. (2018). "Adaptive decision-making for civil infrastructure systems and communities exposed to evolving risks." 75, 1-12.
33. MacKellar, S., and Bodycote, P. J. P. P. X., Washington (2006). "UKWIR national mains failure database."
34. Makar, J., Desnoyers, R., and McDonald, S. J. U. I. R. (2001). "Failure modes and mechanisms in gray cast iron pipe." 1-10.
35. Marlow, D., Beale, D., Gould, S., and Lane, B. (2013). Selecting Techniques for the Rehabilitation of Small Diameter Cast Iron Pipes.
36. Moglia, M., Burn, S., and Meddings, S. (2005). *Parms-Priority: a methodology for water pipe replacement*.
37. Najafi, M. (2015). "An Investigation Of Durability And Reliability Of HDPE Pipe For Large Diameter Water Transmission Applications."
38. Park, H., Ting, S. H., Jeong, H. D. J. J. o. P. S. E., and Practice (2015). "Procedural framework for modeling the likelihood of failure of underground pipeline assets." 7(2), 04015023.
39. Pelletier, G., Mailhot, A., Villeneuve, J.-P. J. J. o. W. R. P., and Management (2003). "Modeling water pipe breaks—Three case studies." 129(2), 115-123.
40. Petrović, G. S., Madić, M., and Antucheviciene, J. J. E. S. w. A. (2018). "An approach for robust decision making rule generation: Solving transport and logistics decision making problems." 106, 263-276.
41. Rajani, B., Kleiner, Y., and Krys, D. (2011). *Long-term performance of Ductile iron pipes*, Water Research Foundation.
42. Rajani, B., Kleiner, Y., Krys, D., Foundation, W. R., Construction, N. R. C. o. C. I. f. R. i., Scientific, C., Organization, I. R., and Research, U. K. W. I. (2011). *Long-term Performance of Ductile Iron Pipes*, Water Research Foundation.
43. Rajani, B., Zhan, C., and Kuraoka, S. J. C. G. J. (1996). "Pipe soil interaction analysis of jointed water mains." 33(3), 393-404.
44. Rubeiz, C. G. (2004). "Case studies on the use of HDPE pipe for municipal and industrial projects in North America." *Pipeline Engineering and Construction: What's on the Horizon?*, 1-10.
45. Singley, J. E., Beaudet, B. A., and Markey, P. H. (1984). *Internal Corrosion of Water Distribution Systems*.
46. Sittig, D. F., Wright, A., Osheroff, J. A., Middleton, B., Teich, J. M., Ash, J. S., Campbell, E., and Bates, D. W. J. J. o. b. i. (2008). "Grand challenges in clinical decision support." 41(2), 387-392.
47. St. Clair, A. M., Sinha, S. K. J. J. o. P. S. E., and Practice (2014). "Development of a Fuzzy Inference Performance Index for Ferrous Drinking Water Pipelines." 5(3), 04014003.