

Analyzing Corrosion and Modeling of Damage Phenomena for Drinking Water Pipelines



Dessalegn Ahmed Yeshanew

A dissertation submitted to the

Department of Mechanical Engineering

School of Mechanical, Chemical, and Material Engineering

Presents in Fulfillment of the Requirement for the Degree of Doctor of
Philosophy in Manufacturing Engineering

Office of Graduate Studies

Adama Science and Technology University

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Adama, Ethiopia

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Declaration

I hereby declare that this Dissertation entitled “**Analyzing Corrosion and Modeling of Damage Phenomena for Drinking Water pipelines**” is my original work. That is, it has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials used for this dissertation have been duly acknowledged through appropriate citations.

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We, the supervisors of this dissertation, hereby certify that we have read and revised the dissertation entitled “**Analyzing Corrosion and Modeling of Damage Phenomena for Drinking Water pipelines**” prepared under our guidance by Dessalegn Ahmed and submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Manufacturing Engineering. Therefore, we recommend the submission of the dissertation to the department for further review and defense.

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We hereby certify that the recommendations and suggestions made by the board of examiners are appropriately incorporated into the final version of the dissertation entitled “**Analyzing Corrosion and Modeling of Damage Phenomena for Drinking Water pipelines**” by Dessalegn Ahmed.

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LIST OF ACRONYMS

AWWA	American water works association
DCI	Ductile cast iron
DCM	Deterministic corrosion model
DIP	Ductile iron pipe
DO	Dissolved oxygen
DWDS	Drinking water distribution systems
DM	Deterministic modeling
EDS	Energy Dispersive X-ray Spectroscopy
EIS	Electrochemical impedance Spectroscopy
ER	Electrical resistance
ERW	Electrical resistance welding
FOS	Factor of Safety
GS	Galvanized steel
HDG	Hot-dip galvanizing
MIC	Microbially influenced corrosion
NACE	National Association of Corrosion Engineers
pH	Acidity and alkalinity of the soil
PL	Passive layer
PPM	probabilistic physical modeling
PVC	Polyvinyl chloride
SCC	Stress corrosion cracking
SEM	Scanning Electron Microscope
SRB	Sulfate-reducing bacteria
TDS	Total dissolved solids
VHN	Vickers hardness number
WDS	Water distribution system
XRD	X-ray Diffraction

ABSTRACT

Material corrosion is a challenging problem that causes deterioration of the device under services such as water pipes and other buried structures. Through pipe wall thinning, corrosion causes a loss of thickness and functional integrity due to a variety of corrosion mechanisms. The primary difficult issues of buried water pipelines are galvanic, uniform, and pitting corruptions, in increasing order, among a range of corrosion types. This dissertation aimed to analyze corrosion damage mechanisms, characterize corrosion morphology, and modeling of damage phenomena for ferrous water pipelines. To achieve the objective, different research works were carried out including water physicochemical testing, soil corrosivity test, microstructural analysis, modeling of corrosion failure phenomena, weight loss evaluation, and corrosion characterization methods used. Characterization of corrosion morphology and analysis of pipes corrosion failure mechanisms were studied from failed in-situ conditions of buried ferrous pipes which were served for 20-40 years in the Addis Ababa water distribution system. To study the main internal corrosion mechanisms, different laboratory tests of water physicochemical investigation were employed utilizing DR 900, inoLab pH 7310P, Palintest Photometer 7100, and Miero 800. Similarly, soil laboratory tests were used to investigate exterior corrosion causes. The long-run rate of corrosion was predicted by modeling corrosion damage phenomena. The corrosion morphology and microstructures were studied using a scanning electron microscope JEOL, Japan and an optical microscope, respectively. Corrosion characteristics such as maximum pit depth, area, volume, and pit opening form were determined utilizing Mountains image analyzing and surface metrology software. The results of corrosion characterization using the software were validated using a 3D optical surface profilometer microscope. Water physicochemical test indicates: CaCO_3 is 77 - 215 ppm, pH is 7.05 – 7.86, total dissolved solids were 84.10 -262.8 ppm, ClO_2 is 0 – 0.5 ppm, Fe^{3+} is 0.0 – 0.55 ppm, and dissolved oxygen (80-81 ppb). From water test, the results show that the main causes of internal pipe corrosion damage mechanisms were identified as dissolved oxygen, CaCO_3 , TDS, and ClO_2 . The amount of released iron concentration (Fe^{3+}) and weight-loss method was used to assess the rate of pipe corrosion damage. Operating pressures, water velocity, service load, deposits, and water resistivity all create differential cells that promote metallic pipe corrosion. The soil moisture content of 23 to 37.5 percent, pH of 7.04, and electrical conductivity of 0.105 to 313 ds/m^2 were recorded in the soil laboratory. The soil types had total nitrogen levels as low as 0.06-0.10. The major contributing factors to external corrosion damage were found as soil resistivity, moisture content, soil load, and long-term soil corrosive rate. The results present that the corrosive behavior of soil on the buried iron pipes was moderately corrosive. Cracks were discovered at the subsurface of the pipes after SEM corrosion analysis. A real-life water pipeline distribution system was utilized as a case study to show the application of the proposed corrosion model for validating the results against the current state of corrosion-damaged pipes. The plan for replacing or repairing buried iron pipes requires knowledge about environmental corrosivity, pipe performance, and long-term corrosion rate. To prevent the risk of corrosion, water pipelines require regular inspections, maintenance, and applying corrosion protection such as coating. Water suppliers and industry will use the findings of this study to investigate corrosion occurrences at any stage of damage.

Keywords: Materials corrosion; corrosion mechanisms; corrosion modeling, iron pipes; external corrosion; internal corrosion, manufacturing products

CHAPTER 1. INTRODUCTION

1.1 Background

Buried water pipes are affected by complex phenomena of corrosion damage mechanisms such as environmental, stresses induced and operational conditions. To understand the corrosion behavior of water pipe failure sources, analyzing corrosion and modeling phenomena is crucial to determine the rate of corrosion which leads to making the right decision of pipeline replacement. Corrosion of buried water pipes is an unavoidable phenomenon that loses the pipe's mechanical, physical, and chemical properties due to the effects of soil and water environment in addition to operational conditions such as water flow rate and pressure.

Underground water pipes inevitably corrode due to the influences of the water and soil environment, as well as operational factors like water flow rate and pressure. As a result, the pipe loses its mechanical, physical, and chemical qualities. Around the third millennium (3000–2001 BC), the water supply distribution system was established (Mala-Jetmarova et al., 2015). When a variety of materials, including iron and copper, were discovered, the water distribution system became advanced. Iron ore is found mixed with hydroxide and oxide. Using a blast furnace, the ores are then processed to produce pig iron (>90% iron). When iron is attacked by corrosion, it converts into stable oxides. This indicates that the formation of the iron-making process and corrosion deterioration are inverse relations. Cast iron pipes had been utilized in water distribution systems for over 500 years (Li et al., 2014). With the advancement of human civilization, the water pump was discovered to lift out water from a well and distribute it in any direction.

Cast iron was the first ferrous pipe used for transporting water in large quantities beginning in the 1600s, and it became the dominant water pipe material in the 1800s and 1900s, with significant coverage of buried water pipes until recent years. The literature discussed that cast iron was gradually replaced by ductile iron pipe (Kodikara, 2018). Due to this, in the mid-19th century, the service pipelines have grown in size, type, and number (Miettinen, 2018). The exiting of corrosion has been known to mankind since man manufactured metallic products like spears and simple hand tools. At the time when the understanding of man increased and observed the failure of materials' appearance and stopped the service function, the definition of

corrosion has been given as the degradation of materials when reacting with the environment through time function. Numerous corrosion forms affect pipes including microbiologically induced corrosion, uniform corrosion, galvanic corrosion, erosion corrosion, crevice corrosion, and pitting corrosion.

The study of corrosion damage phenomena on buried water pipelines has a long and substantial history. However, mechanical and electrochemical corrosion in the soil and water has multiscale processes on the buried metal surface and entire structures. Furthermore, the process of corrosion, environmental corrosivity difference, and operational condition variations are the main variables that do not match typical corrosion research with the study of a specific environment. In the modern water pipeline system, ductile iron pipe is replacing cast iron pipes due to its ductile property which able to resist water pressure. The main challenge of ductile iron and galvanized pipes is localized pitting corrosion.

1.2 Corrosion of Metal Pipes

Ferrous materials are utilized for different applications such as water pipes due to their mechanical and cost advantages. To get iron products, there have been several steps starting from the ore up to the final products which consumes much amount of energy during each step of the conversion process. Whereas corrosion needs lower energy to form rust from the combined reaction of oxygen, iron, and water. Corrosion weakens engineering products caused by the interaction of materials with their surroundings over time. Corrosion growth is a slow process failure caused by the electrochemical reactions, stresses induced, and operating service conditions. Despite being susceptible to corrosion, pipelines are vital infrastructure that contributes to a country's economic, social, and overall quality of life. Corrosion is an unwanted occurrence that harms metallic objects such as pipes and industrial equipment (Jianfeng et al., 2022). Corrosion is the main damaging mechanism of water pipelines which leads to the loss of physical and mechanical behaviors of buried pipes with time function (Wasim & Djukic, 2021). Corrosion occurs on the material's surfaces that are exposed to harsh conditions, and it gradually wears away the materials, causing the structures to fail (Javaherdashti, 2000).

The effect of iron pipe corrosion scales creates a change in water taste and color in the drinking water pipe in addition to damaging the pipe wall (Yang et al., 2012). Erosion corrosion develops by the reaction of liquid with the wall of a pipe made of metallic material, either on a

visible or microscopic level surface damage that is invisible to the naked eye. Corrosion causes the damage of buried water pipelines and leads to the deterioration of water quality and pipe structure (Pietrucha, 2015; Yongjun, 2019). The majority of water pipe distributions are composed of metal pipes such as cast-iron, ductile cast iron, and galvanized steel, and are buried in the earth. Old and deteriorating metal pipes have resulted in an unexpectedly high rate of failures due to their long-term service and exposure to harsh conditions in the soil. Corrosion is still a major issue all over the world (Wasim et al., 2016). In water pipelines, the failure condition of corrosion is double due to pipes being subjected to soil load, operating conditions (water velocity and internal pressure), and soil corrosivity, all of which cause pipeline damage. Pipeline failure has extensive effects on public health, customer acceptance, water treatment costs, and the economy such as pipe maintenance and replacement. In this regard, water supply companies are increasingly under pressure to implement preventative maintenance and appropriate pipeline renewal methods to decrease risks.

Underground water pipes have been attacked by overlying soil whereas internal corrosion is caused by aggressive water. Internal pipe corrosion failure results in leakage caused by corrosion products and microbiologically influenced corrosion which leads to unwanted changes in water quality (Dao et al., 2021). Even though pipe failure due to corrosion of soil and water is an old problem, corrosion is still uncontrollable even using the application of advanced corrosion protection technology. Different methods have been applied to determine the evolution of pitting corrosion. For instance, the mathematical model was used considering soil physicochemical variables such as pH, resistivity, redox potential, and electric potential to predict the growth of localized corrosion (Alamilla & Sosa, 2009).

The occurrence of corrosion on metallic products is categorized into two conditions: (1) when the metal is exposed to a liquid electrolyte (water, aqueous solution) and (2) when the metal is exposed to a gaseous atmosphere (oxidation, high temperature, and so on). Similarly, salts, microorganisms, soil type, concrete, and pH levels increase chemical reactions on the pipes' surface which are the primary causes of corrosion (Zhang et al., 2018). Corrosion also differs depending on the position of the installed drinking water pipe; the horizontal pipe has a higher corrosion rate than the vertical pipe due to deposits. The situation of corrosion scale is different in physical and chemical characteristics and hence it is amorphous (Li et al., 2016). The corrosion phenomena process consequences several influences as indicated in Figure 1.1.

Before attempting to manufacture a product from alloy, manufacturers need to study the effect of each element in the compositions over another in the microstructures. This helps to reduce failure due to de-alloying and the nature of corrosion production when dissimilar materials come into contact. The formation of galvanic corrosion at the contact surface and in the intergranular structure corresponds to this kind of corrosion (Zhang et al., 2018). The properties of elements are critical in the fabrication of metallic alloys, such as manganese, which can improve grain refinement, microstructural stability, and tensile strength when added to 1% Mg wt.

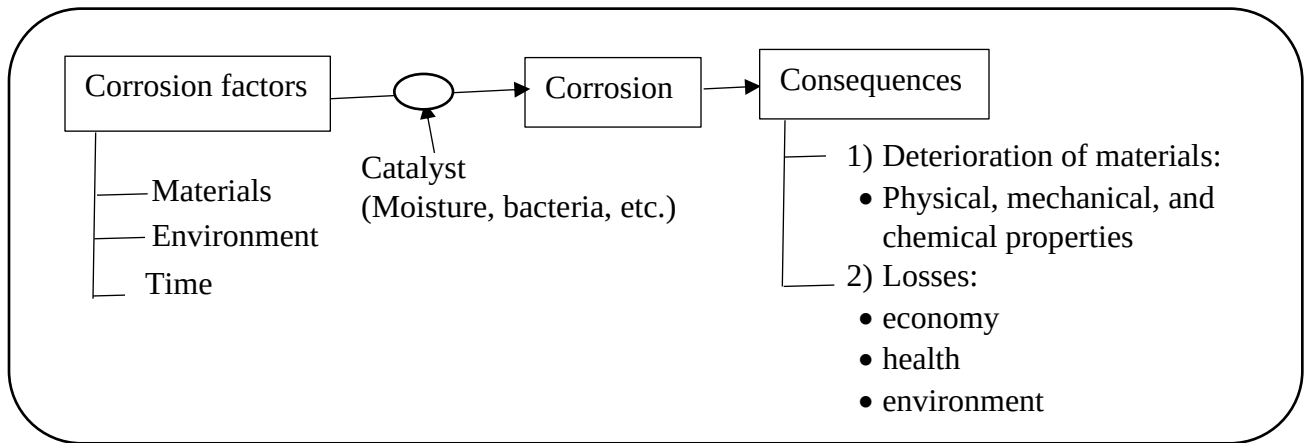


Figure 1.1 Corrosion damage phenomena and their impacts

One of the influences of corrosion is creating localized leakage in the pipes (Qiu et al., 2018) due to the growth of corrosion in the two situations; viz., from the water inside of the pipe and the soil which covered the pipe. Both forms of internal and external environments accelerate the corrosion of a pipe which shows pipe corrosion is unique from other buried materials. The flow of liquid that creates pipe wall wear caused by erosion-corrosion is common problem for industrial piping, especially for pneumatic, aerospace, transportation, and chemical industries (Ishibashi et al., 2018). External corrosion environments such as bacteria cause dense corrosion scales on the cast iron pipes which affects the quality of water (Ameral et al., 2018). Pipe corrosion is resulted from an electrochemical process that affects water quality and hence the electrochemical test is important to determine the corrosion behavior (Haibo et al., 2014). Corrosion has a multi-scale model on the ferrous metals in the soils such as anode/cathode activity, oxide effect, a triple-phase boundary (soil/water/metal) interface, soil dynamics, and macro-environment (Colombo et al., 2018). The symptoms of pipeline damage are pipe wall

fracture caused by pressure, temperature variation, and the type of soil environment (Asadi & Melchers, 2018; Cole & Marney, 2012).

In the case of internal corrosion, calcium carbonate (CaCO_3) and other minerals scale deposits at the metal-water interface in the pipe induce corrosion on the steel pipe (Zakowski et al., 2016). Temperature promotes the minerals to inhibit interfacial scaling of carbon and stainless-steel corrosion. When metal corrosion exists on the water pipe, dissolved oxygen reduces into hydroxide ions at cathode sites and this leads to increase water pH values consequently CaCO_3 deposit occurs on the metal-water surface. When CO_2 and O_2 dissolve in the water, it carries these gases (impurities) potentially increasing the corrosion of carbon steel at the metal-water interface (Tian et al., 2018). In addition, stray current causes corrosion damage when it flows from metallic pipe to the surrounding soil, metal oxidation occurs, and when the current flow towards buried pipes from rails and other electrical groundings (Rovere et al., 2013).

1.3 Forms of Corrosions on Ferrous Materials

Ferrous materials are widely used by industries and service sectors due to their cost and mechanical advantages. Although using metal products has many benefits for humans, pipe corrosion challenge the biggest threat to lifespan and service quality. Buried water pipes corrode over time due to an electrochemical reaction between the environment and ferrous pipes. During the chemical interaction, metal is oxidized and dissolution happens at the anode and the ions are discharged into the bulk water from the pipe wall which influences water quality.

Metallic ion release into the bulk water is the function of an oxidation reaction in the electrochemical interaction, which influences the chemical, and physical characteristics of water and pipe walls (Science & Gas, 2015). Different types of corrosion can exist on the water pipe but the most influential pipe corrosion damages are: (1) pitting corrosion which affects localized pipe surface damage; (2) galvanic corrosion which arises from the contact of dissimilar metallic alloys; and (3) uniform corrosion which creates uniform pipe thickness loss (Cui et al., 2018; Hou et al., 2016; Science & Gas, 2015b). Pitting corrosion is a challenging issue of buried water pipes which deteriorates localized pipe surfaces. It has continuous progressive damaging processes of pitting initiation, propagation, and termination that go through until leakage formation.

During the initiation stage, the film cracks at first condition due to a variety of causes such as pipe and environment interaction, non-homogeneity in the corrosion scale, and the existences of chloride and fluoride make the rate of corrosion more faster. Furthermore, oxygen and water moisture combine to generate electrochemical reactions at the cathode, forming hydroxide ions, and at the anode, causing metal dissolution in the electrochemical reaction. There are also various forms of corrosion including, intergranular, stress corrosion cracking (SCC), and de-alloying corrosions which are caused by mechanical loads and microstructures.

Various types of corrosion, including intergranular, dealloying corrosion of microstructure failure, and stress corrosion cracking caused by mechanical actions of soil load and water pressure. Corrosion influences water quality by creating heavy metals such as Pb, Cu, Ni, Cr, Mn, and others in the pipe wall (Sun et al., 2017). The wall deteriorates when the deposition of these materials increases in the pipe, especially when there is no water flow condition (Vanaei et al., 2016). Corrosion of the pipe wall was observed due to the presence of water hardness containing calcium and calcite compounds (Zakowski, et al., 2016). Internal corrosion scales are made up of several crystalline phases, including goethite (α -FeOOH), magnetite (Fe_3O_4), and lepidocrocite (γ -FeOOH) tend to be dominant, while siderite (FeCO_3), and hematite (Fe_2O_3) are frequently found as scales (García et al., 2015; Sanjuan et al., 2014; Shuai et al., 2017). Additionally, pipeline deterioration and collapse are influenced by a variety of elements, including the environment, pipe material, and operational service, all of which contribute to pipeline damage (M. Li et al., 2016).

Several sorts of studies have been done in numerous countries throughout the world, including the National Science Foundation (USA), the Australian Research Council (Australia), the Engineering and Physical Sciences Research Council (UK), and the National Research Council (Canada) (Noble et al., 2019). This demonstrates that the effect of corrosion on buried metallic structures remains an active research topic, as managing corrosion risk is challenging due to the interaction of environmental and material types. The mechanisms of internal corrosion damage become dominant over the pipelines as the service years increase with the combined effects of environmental, material, and corrosion attacks. Water pipeline failure conditions are mainly grouped into two processes: (1) structural degradation that is incapable to resist stresses acting on it, and (2) the slow reduction of pipe wall caused by corrosion and water pressure degrades structural capacity and water quality. Water pipe corrosion failure

mechanisms are related to soil conditions (Wasim et al., 2016, 2018), microorganisms (D. Liu et al., 2019), and water quality parameters (Hu et al., 2017).

1.4 Cost of Corrosion

The expense of water pipes is covered with a minimum amount including the cost of manufacturing the pipe, transportation to the site, installation costs including labor and equipment, backfill materials and compaction, and corrosion control. The cost of water pipe corrosion damage also includes water loss, excavation, maintenance, pipe replacement, and failure of other assets. Furthermore, according to a study conducted by (B. Hou et al., 2017), the cost of corrosion in the world including pipelines and other manufacturing products is predicted to be USD 2.5 trillion, or 3.4 percent of the global national product (GNP).

Corrosion costs for water pipes can be broken down into two cost type expenses: (1) direct costs, which cover pipe materials and labor, and (2) indirect costs, which include maintenance and corrosion inhibitors. Overdesign, production interruption due to plant shutdown, product contamination, transportation asset damage, maintenance, and health are all examples of corrosion's impact. This suggests that corrosion-related concerns should be thoroughly investigated to better understand failure processes and adopt safety policies for a long-term economy and good health. The economic loss includes: replacement of corroded equipment, overdesign to control corrosion, maintenance, for instance, painting; shutdown of factory due to corrosion failure; contamination of a product; damage of equipment adjacent to that in which corrosion failure occurs, etc. (Coelho et al., 2020).

1.5 Iron Pipe Materials Coverage

With the grows of towns and cities, the need for iron-based pipe materials has increased. Cast iron pipes had been used for transporting water and sewerage effectively around the world. As can be evidenced in the kinds of literature, two-thirds of water pipes are iron pipes about 48% cast iron, and 19% ductile iron (Cole & Marney, 2012; C. Zhang et al., 2017). In the late 1880s to 1930s grey cast iron pipes were manufactured in upright sand molds placed in a pit known as pit cast iron (Kleiner & Rajani, 2001). Later, at the beginning of the 1930s, spun cast iron pipe was manufactured from horizontal sand or metal mold spun and water-cooled externally. It has better properties than grey cast iron pipe. The continuous development of improved cast iron pipe material leads to attaining of ductile cast iron in 1948. Cast iron pipes have been used for

water conveying for more than 500 years (Pipe, 2001). The material compositions of cast iron water pipe were changed to get ductile properties due to the reduction of graphitization (graphite flakes) (Kleiner & Rajani, 2001). Iron-based pipes are more utilized in several countries such as Beijing and Australia, and the coverage of ferrous pipes reaches more than 70 % (Xu et al., 2011).

1.6 Manufacturing Process of Water Pipes

The manufacturing process can cause pipe failure due to defects. The likelihood of common defects includes micro-cracks, non-uniform wall thickness, porosity, and inclusions. Galvanized steel pipe is made from steel sheet metal and welded by using seamless electrical resistance welding. The zinc coating is achieved by pickling/cleaning steel pipes to remove the scales and oxides from the steel surface using ammonium chloride solution before applying hot-dip galvanizing in a tank. This method has helped to get a uniform coating, strong adhesion, and long service time due to the zinc coating thickness (55 μm to 0.6 mm) and heat treatment. The mechanical properties of pipe products are influenced by their microstructure arrangement, chemical composition, and morphology of grains.

Ductile cast iron pipes are commonly used as water mains in distribution systems because of their good mechanical and corrosion-resistance properties. The alloying compositions of this pipe contain 3.2–4.2 percent carbon by weight. During manufacturing, defects including porosity, irregular wall thickness, inclusions, cold shunts, and shrinkage are all reasons that contribute to failure mechanisms of spun or pit cast-iron pipes. Ductile iron pipe is made from grey cast iron pipe compositions by altering the graphite microstructures from flake to spherical form and adding inoculants like magnesium to the molten iron to improve the pipe's mechanical properties. The centrifugal casting procedure is used to produce ductile cast iron. Graphite reach cast iron has been given many names, including ductile iron, nodular cast iron, and spheroidal graphite iron. The incorporation of spheroidal or nodular graphite inside the alloying components provides the ductility feature (Fragassa et al., 2016). To prevent corrosion, cement mortars as protective inside liners and an external coating. Different types of coatings, such as zinc, bituminous, and epoxy, are used to protect corrosion of ductile iron. Minimum zinc usage is 200 g/m^2 at 99.99 percent purity with a thickness of 50-70 μm (Petrova et al., 2019).

1.7 Corrosion Damage Mechanisms of Water Pipelines

Pipelines deteriorate due to the influences of corrosion damage mechanisms such as microbiologically induced corrosion, stress corrosion cracking, corrosion fatigue, and electrochemical corrosion. The investigated sample pipes are currently in a physically and mechanically degraded state due to the pipelines being susceptible to any specific damage mechanism and influenced by a variety of factors, for example pipe manufacturing process, water physicochemical composition, soil environment, etc. Pipe corrosion damage mechanisms are also categorized as internal and external environments including operational conditions (flow velocity and pressure), external loads (soil and traffic), temperature, and corrosion pit geometry. Corrosion-induced failures are common to all pipe diameters. Pitting corrosion is frequently associated with these failures, having produced the weakening of material compositions of the pipe and causes failure (Islam & Farhat, 2017). Even though zinc has good corrosion resistance properties, the coating can easily be attacked by the soil during the time process. For this reason, failure of the pipeline due to corrosion caused by the low-value soil pH of water less than 4 damages the pipelines before their expected service of a lifetime (Colombo et al., 2018). It is difficult to forecast the rate of corrosion because there are many factors such as water pH value, temperature, soil environment, fluid velocity, salt, acid, pipe materials, etc.

1.8 Failure Modes of Pipelines

Corrosive substances in the soil react electrochemically with the pipe material, causing pipe corrosion. To assess the state of pipes, mechanical and physical evaluations are important to identify the severity of the corrosion status of buried pipes. The major factors influencing water pipe failure are related to environmental, operational, and pipe intrinsic (Andrew et al., 2019). Pipe strength deteriorates when wall thickness decreases, resulting in pipe mechanical failure. Pipe damage can occur for a multitude of reasons; for example, temperature changes caused by environmental and seasonal variables induce pipe cracking. The failure modes vary depending on the variety of environmental and operational conditions. For example, damage mechanisms of cast iron are environmental factors; other causes of failures such as manufacturing defects, human error, and unexpected levels of pipe loading all play a role in the large number of pipe failures that occur each year.

Localized holes and longitudinal cracking are the two most common failure types in ductile pipes. Corrosion pitting causes wall thinning, which leads to blowout holes. Consequently, the pressurized water weakens the thin pipe wall, causing it to break, resulting in a hole. Moreover, the transient pressure of water while changing pressure which creates cyclic pressure and water hammer which enhances the breakage of the pipe. Steel pipes are manufactured using seamless welds. These pipes are well-known for their durability and capacity to transport water under high pressure. Steel is easily corroded due to the creation of ferrous oxide deposits on pipe walls, which can cause deposits and cause turbulent and slow water flow, resulting in erosion-corrosion.

Other failures arise from soil aggressiveness and which initiates corrosion and leads to pipe surface damage. There are various mechanisms of pipe corrosion but the main is a natural phenomenon, water corrosively, flow velocity, burst pressure, soil environment, and soil load. Mostly observed pipes corrosion are pitting, uniform, and erosion corrosions which lead to pipe gradual deterioration.

1.9 Modeling of Pipe Remaining Service Lifetime

Prediction of the remaining life of corroded water pipes is an important issue for the water supply company to manage corrosion status. For this reason, identifying the existing corrosion parameters in a certain environment are helpful to develop a mathematical model to estimate corrosion behaviors. Many years of statistical data recording about pipe maintenance, failure history, and soil and water corrosivity properties have been required to create a corrosion model. The reoccurrence of pipe failure over a long time needs recorded data to develop a model based on the failure history. The probabilities of corrosion mechanisms of pipeline failure probabilistic are also caused by unknown factors, according to a study done on probabilistic physical modeling of small cast-iron pipelines (300 mm exterior diameter) (Ji et al., 2020). Pipe performance must be examined using statistical data based on a lifetime of observational data to investigate pipeline failure mechanisms. The probability of pipe damage is due to internal factors like dissolved oxygen and chlorine, as well as external factors such as soil characteristics, with long-run service time.

Various models have been used in previous work to represent the processes of stress corrosion cracking (SCC) formation with time-dependent and metallurgical compositions effect

(Sun et al., 2014). Some of the corrosion models focus only on the pit depth impact that influences water pipe lifetime while others addressed the problem of SCC comprehensively. Depending on the available data, most pipe failure models are probabilistic or deterministic. When there are known correlations between numerous variables, deterministic models are frequently used. Deterministic models can be either mechanical or empirical. The mechanistic approach predicts the service lifetimes of the pipes whereas the empirical approach focused on the failure rates of pipes (Urquhart, (2010).

1.10 Motivation

Corrosion from the inside and outside of subsurface water pipelines causes sudden collapse, which has an impact on the economy and public health. To understand how corrosion damages water pipelines, it is essential to know the characteristics of pitting corrosion and the morphology of corrosion of buried pipe at both the surface and subsurface. Regarding the buried pipelines, investigating external and internal corrosion mechanisms is particularly significant for controlling corrosion and decision-making on pipe maintenance and replacement. The gradual deterioration of water pipelines caused by corrosion needs serious attention because drinking water pipe has the risk exposed to corrosion scales. When pipelines are damaged by corrosion, it leads to several consequences including resulting in poor water quality, health risks, and an increase in the cost of pipe maintenance and replacement.

Water pipes, in particular, are exposed to soil and water environments, resulting in additional corrosion-related indirect costs. In this case, corrosion is costly issue that results in a loss of property functionality and shorten service life. In addition, corrosion is a severe issue that damages ferrous materials and industrial products that affects a country's economy directly. Overall, the motivation of this dissertation work is to investigate why corrosion occurs on buried water pipelines by identifying corrosion damage mechanisms, and characterization of corrosion morphologies. and modeling of long-term time-dependent deterministic pipe corrosion damage phenomena.

1.11 Statement of the Problem

Buried water pipelines are basic infrastructures that have a significant influence on the economic, environmental, and social aspects. Metal dissolution is the main fundamental damage mechanisms of buried metal structures due to corrosion. Corrosion of underground

infrastructures such as oil, gas, and water pipelines is the main problem of economic and other losses. There is also difficult situation to understand how buried pipes have deteriorated. This indicates that pipe damage being environmental and operational dependent and hence the failure is neither uniform nor identical.

Corrosion-induced water pipe damage is a challenging problem for water suppliers of aging pipelines around the world. Despite numerous studies that have been conducted on water pipe damage mechanisms, pipe failure conditions are not well understood and corrosion behavior nor characterize by environmental corrosiveness. ~~Corrosion is a natural occurrence that has a direct and indirect impact on our lives.~~ In water pipelines and other manufacturing items, metallic corrosion is an active issue. Water pipe damage causes treated water to be wasted and pipe material to be lost, which is a widespread and costly problem in the water distribution system. The deterioration of water quality is another societal health danger posed by the pipeline before it reaches the extreme failure level. The reoccurring condition of water pipes damage deteriorates water quality and damages pipes and the loss of treated water. Despite the water has treated as per the required standard, the quality of water can be affected by the corrosion of pipelines. The damaging mechanisms of water pipes are so complicated due to a variety of factors arising from water and soil environments creating inside and outside corrosion damage respectively.

Common damages have a negative social impact which is feeling of hesitation to corrosion, loss of lives, and environmental pollution resulting from corrosion damage to different structures. Pipeline failures are unexpected and often produce losses. Understanding the nature and causes of pipe failures is important in making decisions about pipeline rehabilitation and replacement. Corrosion is an unavoidable problem that can be existed almost in all industries and water pipelines, and hence it is assumed one of the worst technical disasters of metallic pipes. Corrosion also dangerous issue in the industries causing deterioration and breakdown of parts, frequent downtime, and potential treat to personnel and the environment. In addition to the loss of direct monetary costs, corrosion is a serious issue because it leads to the depletion of metallic resources. The effect of corrosion is not only limited to the water pipelines but also the consequences of scale released contaminated meals, resulting in health threats. Corrosion causes loss of mechanical strength and disintegration occurs as the thickness

of the material is gradually reduced, creating downtime in the workplace, deterioration of the material's appearance, and loss of materials' properties.

The concern of water pipeline corrosion damage still exists even though different alternatives to alloying metal pipes are available on the market. It is an extremely complicated problem to manage corrosion risk due to a variety of causes. Corrosion of underground pipes causes a gradual deterioration of water pipes with time which leads to the damage of pipes and consequently creates economic and health effects. The impact of corrosion is not only limited to engineering products but also the deterioration of minerals and ores in their respective environments. The existing condition of the pipes is damaged for many reasons, such as the effects of soil and water physicochemical processes and long-term water flow service loads also contribute to pipe wall damage Figure 1.2. Due to soil corrosivity and bacterial attack, the pipe surface is more severely affected. The internal pipe wall also fails to owe to operational conditions, corrosion, erosion, and operating conditions in addition to water factors.



Figure 1.2 Photograph of pipe corrosion patterns

In Ethiopia, product designers, and government, are not focused on the estimated effect of corrosion, and as a result, material deterioration occurs under favorable conditions, resulting in unexpectedly high annual costs for water pipeline replacement, maintenance, and the purchase of coating materials and spare parts. Internal corrosion of water pipes can cause a variety of issues, including decreased thickness, loss of water quality, corrosion scales and color changes, and pipe leaks. External corrosion also generates uniform and localized corrosion, lowering the mechanical and physical properties of the pipe. Corrosion attacks all types of

materials, but its impact on buried ferrous water pipelines is double due to internal and external corrosion caused by water and soil parameters.

Corrosion weakens the physical and mechanical properties of materials, resulting in a variety of consequences, as indicated in Figure 1.3. Even though corrosion damage to water

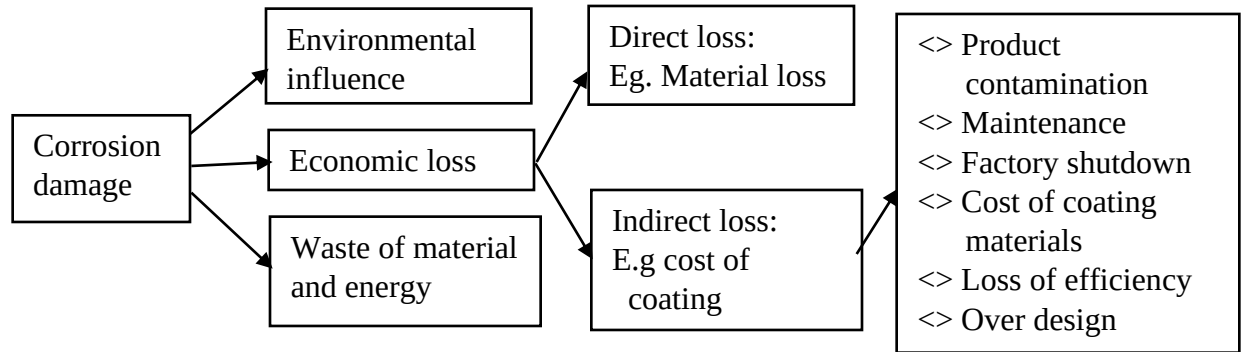


Figure 1.3 Classification of corrosion influence

pipes have a long history, such corrosion failure is still widespread on water pipelines and other industrial items, even with contemporary corrosion management systems. The problem of corrosion is a great topic among fields including material science engineers, water pipe distribution owners, product designers, health care, industries, hospitals, economists, researchers, etc. Moreover, buried pipes always create doubt for the owners of the distribution system due to sudden and frequent corrosion damage of the pipes.

(i) Justification of Working on the Current Research

Manufacturing engineering studies about manufacturing process and properties of materials. Without identifying specific properties of the material, manufacturing is nothing. Thus, before trying to manufacture the material into the required design, it is crucial to understand the physical and chemical properties of a material. Corrosion is one of the main chemical properties of a material that affects the service time of a pipet due to the deterioration of the internal structure and outside surfaces of the material. Intergranular and intragranular corrosions are the main challenges of a material internal structure that means the material's compositions damaging the other elements in the microstructure which affects the internal strength of the material and forms cavities and cracks. Therefore, in one or another way, corrosion is having direct relation to manufacturing engineering, especially for the application of powder metallurgy, and a foundry. Hence, understanding corrosion properties is the main one to develop new materials. In conclusion, to design and manufacture a product understanding

the corrosion property of each composition is very necessary to solve the effect of one material over another.

(ii) Research Novelty Statement

The novelty of working on the current research states about water pipe corrosion damage is the challenge problem due to both external and internal corrosion attacks simultaneously which leads to the sudden failure of pipes. In addition, the combined influence of corrosion and stresses such as water pressure and soil load induced on the pipe accelerate the rate of pipe failure. In this regard, pipe corrosion damage influences societal well-being by affecting water quality and incurring costs to the owner of the water supply.

In general, the works of literature show that the research on the corrosion failure of underground installed water pipes mostly deals with the pipe wall thickness and maximum pit depth determination. The current research addresses the gap and presents comprehensive results showing the summative effect of corrosion and loads induced on the pipe, investigating corrosion phenomena, corrosion characterization, modeling long-term corrosion rate, and analyzing corrosion mechanisms. Thus, studying analyzing corrosion, and modeling damage phenomena for drinking water pipeline research is relevant for identifying corrosion damage mechanisms which makes it a novelty beyond the previous works. Moreover, in Ethiopia, there was no research previously done in such scope on the corrosion failure of water pipelines.

1.12 Research Questions

To analyze corrosion mechanisms and develop model hypotheses, pipe material, water quality, soil corrosivity, and pipe age were important variables. The research questions focused in this dissertation are:

- How to determine the rate of maximum pitting corrosion of buried water pipes?
- Why does soil corrosivity condition attack buried pipes?
- How can the in-situ condition of corrosion-damaged water pipes be used to characterize corrosion morphology on the pipe surface and subsurface?
- How to develop corrosion damage phenomena to determine the long-term corrosion rate and the remaining service life of buried water pipelines?

1.13 Objectives

1.13.1 General Objective

Determining the rate of ferrous pipe corrosion and investigating behaviors of damage mechanisms for a given pipeline system is very crucial to understand corrosion characteristics and manage the influences of corrosion failure. The core objective of this dissertation is to analyze corrosion and modeling of damage phenomena for drinking water pipelines under in-situ conditions.

1.13.2 Specific Objectives

Specific aims are detailed objectives that were researched to attain the dissertation's overall goal. These include:

- a) To investigate internal pipe wall corrosion failure mechanisms and study the main factors of pipe damage parameters from the interaction of pipe materials, water physicochemical, and operational conditions.
- b) To analyze the corrosivity of soil physicochemical characteristics on buried pipes to determine the state of soil corrosion.
- c) To characterize corrosion damage morphologies on the pipe surface and subsurface that have developed over many years of exposure time.
- d) To develop a corrosion damage model for predicting the remaining lifetime of pipes and determining the rate of long-term corrosion deterioration.

1.14 Significance of the Dissertation

This research focuses on analyzing water pipeline damage mechanisms, which will help the pipe manufacturing companies, water supply stakeholders, industry, and society as a whole to give attention on the influence of corrosion. The outputs of this research will create awareness of pipe corrosion prevention, improve keeping water quality, and deciding the right time for pipe maintenance and replacement will be improved. This study will provide a remedy to the short pipe product service life and the degrading water quality. It can also offer information to the product manufacturers so that they can create long-lasting pipes that are environmentally corrosion resistant. Modeling of pipe corrosion damage phenomena also gives information on long-term corrosion rate which will help to understand environmental corrosivity and decision making for pipe maintenance and replacement.

This dissertation is more significant in terms of identifying and modeling the mechanisms of corrosion damage, as well as recommending control mechanisms to maintain water quality and extend pipe service life for long-term public health and economic benefit. Characterizing water pipe corrosion damage status under in-situ conditions provides vital information for water suppliers to maintain water quality and asset management and others including the direct and indirect expenses of pipelines are among the economic considerations, water quality assurance, and conservation of resources.

The results obtained in turn will help to evaluate economic and health loss due to corrosion and determine the future budgetary allocation for maintenance and replacement. The assessment of corrosion situations and prediction of long-run corrosion rate will serve as a comprehensive water pipeline management. The results of this research will help to create awareness of corrosion among pipe producers, industries, product designers, metal alloying processes, the government, and society at large.

In summary, a properly managed distribution system can potentially reduce impacts such as avoiding treated water loss, health risks, and economic aspects. Furthermore, the findings will be useful to industries and water distribution system owners in determining product corrosion damage, predicting pipeline lifetime, controlling corrosion, and determining the best time to maintain and replace pipelines.

1.15 Delimitation of the Study

The scope of this dissertation covers analyzing the corrosion damage phenomena of buried water pipelines, modeling and identifying corrosion damage mechanisms, and analyzing why corrosion is happening on the pipes. The main sources of corrosion factors such as soil and water environments were evaluated to analyze the corrosivity status of damaged pipes with time function. To investigate the rate of corrosion, the weight-loss method, soil laboratory analysis, and water laboratory tests were used. In addition, to determine the long-term rate of corrosion damage phenomena, a model was employed. Characterization of corrosion morphology and metallographic of the new pipes were examined by using a scanning electron microscope (SEM) and optical microscope (OM) respectively. Furthermore, analysis of pipe corrosion failure was studied using Mountains® surface analysis software to characterize the features of pitting and uniform corrosion at different surface layers of buried pipelines. The result of pitting corrosion

depth that was obtained from Mountains software was validated using a 3D optical surface profilometer microscope and they have a positive response on the measurement of pitting depth.

1.16 Limitation of Study

Although the dissertation was viable and met the objectives, there were some problems/limitations that hindered the study's timely progress due to a lack of primary data sources, shortage of funding, lack of laboratory equipment, and COVID-19.

1.17 Organization of the Dissertation

This dissertation is divided into five chapters. Chapter one consists of an introduction to the dissertation including, the background, problem statement, objectives, significance, delimitation of the study, limitation, motivation, and organization of the study. The second chapter contains a detailed assessment of the literature on the corrosion phenomenon, corrosion control, and preventative measures of underground water pipelines. Internal corrosion, external corrosion, stress corrosion cracking, microbially influenced corrosion, water pipeline corrosion damage modeling, corrosion inhibitors, cathodic protection, and research gaps are all discussed.

The third chapter discusses materials and methods. It discusses materials and methods. The sample materials selection and utilization of different methods to investigate corrosion and modeling of corrosion damage phenomena. Chapter four emphasizes results and discussion. The result part describes the findings obtained from the lab investigations. The findings were related to the literature review, aim, and research questions. The discussions section also interprets with detail analysis of the experimental results. The target of the discussion was to explain the findings and evaluate their coherence to address the research problem.

The conclusions and recommendations part of the dissertation states comprehensive ideas of the research and recommends some points to the scholars. The conclusion summarizes the study's findings, whilst the recommendation outlines some recommendations for stakeholders and future research that can be used by other researchers. This dissertation concludes with appropriate references and appendices. Overall, the dissertation was organized through detailed studies of:

- Analyzing corrosion phenomena, investigating corrosion damage mechanisms, and modeling pipe corrosion damage to determine corrosion rate and the remaining service

lifetime. DCI and GS specimens extracted with corrosion products were used for corrosion characterization under in-situ circumstances in the investigation.

- Investigating internal corrosion mechanisms and characterizing their effects on the pipe wall. The results obtained from this study have various useful applicable information for the industries and water distribution system owners to keep water quality, predict the lifetime of buried materials, apply planned pipe maintenance and replacement activities, and corrosion control.
- Examining the effect of soil parameters' corrosivity on the buried metallic pipes and specifying the corrosive nature of soils with time function. Corrosion is a complicated problem due to a variety of other than soil factors including pipe design, materials used, weather conditions, and water quality. This dissertation provides the outcomes of soil physicochemical carried out on water pipelines corrosion damage mechanisms to forecast the life of buried water pipelines.
- Characterizing corrosion behaviors at different surface layers of the pipes including environmental and metallographic factors to analyze corrosion morphology of underground galvanized steel (GS) and ductile cast iron pipe (DIP) in situ conditions. The results of the study have many advantages for the owners of industries to assess corrosion failure at an early stage.
- Developing a long-term deterministic model of corrosion damage phenomena that can determine the remaining service lifetime of water pipes.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

Corrosion of water pipes is a challenging problem that creates material deterioration and loss of economy to the water distribution system. Even though several studies have been conducted on the corrosion phenomena and prevention mechanisms, corrosion is still an unsolved problem. This is owing to the existence of various corrosion mechanisms relating to pipe material, inherent environmental differences, stresses induced, and service conditions. Understanding corrosion damage phenomena and prevention mechanisms are crucial to elongate the service time of buried structures. Corrosion of pipe walls is an unavoidable problem and degradation of water quality which becomes a health threat.

This literature chapter discusses the works of related works of literature on water pipe corrosion and covers several sections relating to pipe manufacturing methods and material compositions, corrosion phenomena, corrosion mechanisms of buried pipes, internal pipe corrosion failure mechanisms, water physicochemical, stress corrosion cracking, crack growth, external pipe corrosion damage, pipe corrosion process in the soil, microbially influenced corrosion (MIC), modeling of corrosion damage phenomena, power function of corrosion modeling, modeling of pitting corrosion, corrosion attacking process and prevention mechanisms, and research gaps identification.

Over time, buried pipelines' consistency is uncertain due to corrosion and other factors including operational, material, and environmental conditions. The manufacturing of pipelines after World War II increased which led to more pipeline installations within cities around the world and even connected different countries to supply liquid and gas (Ramírez et al., 2016). Corrosion is the mechanism that changes properties of underground materials and leads to gradual structural failure in infrastructures that have serious impacts on the health and environment threats (Norsworthy, 2014). In addition, underground pipe corrosion is extremely complex due to the variability of local soil corrosivity and operation conditions which incur many losses such as pipe maintenance and replacement (Amaya et al., 2021; Shekari et al., 2017).

Corrosion influences different aspects such as safety-related to the explosion and the release of toxic products, depletion of resources, appearance, economic (Chauhan et al., 2021;

Najmi et al., 2016), and product service life. Buried metal structures need special attention while designing a product such as the relation of material-soil environment corrosion characteristics. Corrosion converts materials into their original state of oxides or ores (Samimi, 2012). Several researchers have tried to determine the optimum service lifetime of buried metallic pipe structures (Mahmoodian & Aryai, 2017).

2.2 Objectives of the Literature Review

This dissertation used various related works of literature to investigate existing knowledge on the corrosion failure of buried water pipelines, which are given in the references section. The objectives of the literature survey are given below.

- 1) To survey an extensive literature review focused on the pipe internal corrosion, external pipe corrosion, modeling of buried water pipelines corrosion damage phenomena, and characterization techniques of corrosion.
- 2) To get comprehensive knowledge related to buried water pipelines' corrosion process, corrosion damage mechanisms, stress corrosion cracking, and corrosion preventive methods.
- 3) To identify the existing gaps in the area of water pipeline corrosion damage. In addition to this, to assess the consequences of corrosion in the works of literature including loss of materials threats to health, and socio-economic well-being.

2.3 Pipe Manufacturing Methods and Material Compositions

Iron-based water pipes are giving wide water transportation service due to their mechanical properties to control the hydraulic effect. Pipelines are essential infrastructure that plays a significant role in the social well-being, economic development, and quality of life of a country (Hou et al., 2016; Noble et al., 2019). Pipe material composition and manufacturing method contribute to intergranular and corrosion. For instance, DIP contains low content of phosphorus and sulfur but magnesium is higher content in the DIP which is added in the melt of grey cast iron before casting. The addition of magnesium (Mg) causes the carbon within the molten iron leads to precipitate upon solidification to create nodules in the structure. The study of DIP has been conducted since 1928 (Bonds et al., 2015). The strength and ductility of functional requirement mechanical properties were obtained by applying heat treatment to

eliminate brittle microstructures. In such a process, the final microstructure of DIP consists of a uniform distribution of graphite nodules within the ferritic iron matrix.

2.4 Corrosion Phenomena

Corrosion phenomenon is a process that happens on the surfaces of buried pipelines with the interaction of the material and the environment. A variety of corrosion forms are obtained from corrosion phenomena with the function of material, environmental, and service lifetime (Ayodeji et al., 2021). The process of buried pipe corrosion is achieved by a variety of factors and mechanisms in the corrosion phenomena resulting in different corrosion forms such as uniform and pitting corrosions. The process of corrosion begins on the external surfaces of metallic structures forming galvanic cells when the top of the pit contacts with oxygen (cathodic site) and the lower part of the pit release oxygen (anodic site). The growth of the pit increases with the accumulation of deposits such as chloride, soil, and other particles. Deposits on the iron pipes lead to intense corrosion cells that impact the water quality and lifetime of the pipeline network (Chawla et al., 2012; Gerke et al., 2016; Li et al., 2018). The rapid pipe surface dissolution at the anode which converts the iron into ions due to corrosion leads to premature damage of pipelines at localized sites.



Iron-based corrosion is often reduced into their oxidation to form several oxides. For instance, the impact of dissolved oxygen and water on the metallic surface enhances the formation of corrosion products including iron-hydrated oxide (Sarin et al., 2001).



Iron pipe materials relatively resistant to corrosion are because of the formation of a passive layer (PL) on the surfaces of the pipes. The PL can be broken by different mechanisms such as erosion-corrosion and water velocity which lowers the critical value and shear stress on the PL becomes higher to form erosion-corrosion leading to thinning of the surface. Several kinds of research have used image processing to characterize corrosion morphologies and to interpret the damage situations such as pit depth and volume (Bondada et al., 2018; Khayatazad et al., 2020). The formation of external corrosion scales outer surface of buried water pipes is caused by electrochemical reactions between pipe and soil materials (Deo et al., 2019).

2.5 Corrosion Mechanisms of Buried Pipes

The causes of corrosion damage on the buried metal surface are broadly categorized as material compositions, environment, operational, and different manufacturing process phases which lead to deteriorating aesthetic and mechanical properties (Alamineh, 2018; Hou et al., 2016). Corrosion is a complex and costly problem that challenges iron water pipes and degrades water quality (Ji et al., 2020) and it is a natural process (Wei, 2022). The mechanisms of corrosion damage become dominant over the pipelines as the service years increase because of the influence of combined effects of soil load, water pressure, and corrosion attack.

Some of the factors are related to pipe material (Li & Liu, 2019), while others are associated with soil conditions (Wasim et al., 2016, 2018), microorganisms (Liu et al., 2019), and water quality parameters (Hu et al., 2017), in addition to operating conditions (Islam & Farhat, 2017; Ji et al., 2017). Pipeline breakage is caused by the total influences of environmental and operational conditions which leads to the growth of pitting corrosion, and damage can also arise from the sources of defect during manufacturing. A water pipe can be broken for several reasons stresses including longitudinal which is caused by hoop stress, circumferential breaks beginning by longitudinal stress, bending stress due to soil backfill load, and pipe split traverse loads on the pipe joints.

The probable pipe failure can be observed either the pipes suddenly failed from giving up service or leaking water (Shin et al., 2018). These effects come from the gradual degradation of materials' surfaces leading to thin pipe thickness and weight loss before the structure completely stops its function. One of the distinct behaviors of corrosion is being highly complicated in the water and soil due to the variability of environmental contexts that can form corrosion scales. In this case, buried pipeline safety management is important to identify the risks at the early stage (Sun et al., 2017). The outside pipe surfaces are primarily affected by electrochemical corrosion due to the presence of minerals and soil moisture acting as an electrolyte (Li & Mahmoodian, 2013).

2.6 Mechanisms of Internal Pipe Corrosion Damage

According to the estimate of researchers, iron-based water pipes have been utilized extensively in several countries (Swietlik et al., 2011; Veschetti et al., 2017). In some cities, the percentage utilization of iron tubes reached 91%, such as in Warsaw. Water quality parameters are major causes of pipe surface damage forming a variety of corruptions such as pitting, erosion-

corrosion, and uniform corrosion. Furthermore, corrosion product deposits and operational conditions are the main responsible damaging factors of water pipelines. The main influential stress in the water pipeline is commonly the hoop stress resulted from the inner strain of the water pressure in the pipeline (Liu et al., 2017). Fluctuation of pressure in the pipe causes pipelines to perform within variable amplitude cyclic loading and/or fatigue loading (Chemicals, 2016). Cracks are developed in many reasons including corrosion fatigue, intergranular corrosion, and SCC in addition to water pressure.

The accumulation of trace elements on the pipe wall is the main cause of corrosion scales. According to a study conducted by M. Li and Liu (2019), Fe, C, Zn, Si, Ca, Al, S, Al, Ca, Si, Zn, C, and Fe are the main constituents of corrosion scales that were studied using energy-dispersive X-ray spectroscopy (EDS). The authors discussed the sources of corrosion scale are pipe material imposed deposits of Zn, Ca, and Fe and water compositions cause scale are Si, Al, and S. Typically, common corrosion products that are formed on the pipe wall consists oxyhydroxides including goethite (α -FeOOH), lepidocrocite (γ -FeOOH)), iron (II, III) oxides (e.g., magnetite (Fe_3O_4) and iron oxide carbonates (e.g., siderite (FeCO_3)) (Yang et al., 2012).

2.6.1 Corrosion of Water Physicochemical

In drinking water, bacterial communities have a great effect on the formation of dense corrosion scales, especially during stagnant flow conditions. (Beimeng et al., 2015; Haibo Wang et al., 2014) compared the effect of bacterial corrosion on the cast iron pipe between drinking water and sterile water in the laboratory using electrochemical and physicochemical measurements. The result shows that corrosion was more inhibited in the drinking water than in distilled water. As the concentrations of these ions increase, the protective layer of corrosion scales can easily break and causes further growth of pitting. In aging water pipes, chlorine is consumed due to internal corrosion (Yamini et al., 2006). Similarly, water quality influences the rate of iron release, corrosion scale evolution, dissolved oxygen consumption, and bacterial community (Hu et al., 2018).

The presence of dissolved chloride-containing salts such as sodium chloride (NaCl), magnesium chloride (MgCl_2), and calcium chloride (CaCl_2) cause localized corrosion at rest condition of water flow (Ling et al., 2018; Lytle & Schock, 2016). These dissolved salts cause the formation of pitting, SCC, and crevice corrosions by breaking passive or protective

corrosion films (Chauvin, 2017). The presence of dissolved oxygen and chloride is the main mechanism of pitting corrosion formation. In addition, the increased amount of Ca, S, and Cl influences water quality and form corrosion scales (Hu et al., 2017). Similarly, the release of metallic ions formed on the pipe wall is a great issue for water quality in the water distribution system (M. Li et al., 2020). As the increase in the concentration of sulfate, calcium, and chloride in the water, water quality is also impacted by the bacterial community in the pipelines (Lytle et al., 2015; Sarin et al., 2004; Sun et al., 2014).

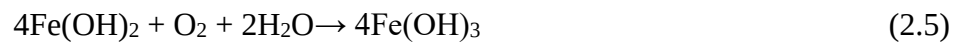
In the water distribution, several types of corrosion scales are formed including akageneite (β -FeOOH), ferric hydroxide ($\text{Fe}(\text{OH})_3$), and ferrous hydroxide ($\text{Fe}(\text{OH})_2$) (Hao, 2016; Peng et al., 2010) which are dominantly affecting water quality. Previous research has shown that increasing alkalinity from 80-150 mg/L can reduce red water occurrences on the pipe surface (Hu et al., 2017; Taylor et al., 2019). The presence of dissolved oxygen in the water increases as the pressure and pipe diameter increase. Oxygen reacts at the cathode which promotes pitting and corrosion scales (tubercles). It works as an electron acceptor produces by the corrosion of metallic ions and converts into hydroxyl ions Eqn. 2.3.



Water quality deterioration depends on the iron concentration and dissolution of corrosion scales in bulk water. The iron ions release indicates that the corrosion rate is higher in the water. The OH^- ion reacts with Fe^{2+} ions to produce ferrous hydroxide at the anode as shown in Eqn. 2.4.



With more dissolved oxygen, $\text{Fe}(\text{OH})_2$ reacts with oxygen to form oxidizes of $\text{Fe}(\text{OH})_3$ as indicated in Eqn. 2.5.



Green rust has resulted from corrosion scales of water pipe in the steady water condition. The study worked by (Swietlik et al., 2011) revealed that stable green rust was found on the corrosion scales of pipe walls which can deteriorate water quality. Chloride and sulfate content plays a great role in the formation of internal corrosion (Pipes et al., 2018).

2.6.2 Stress Corrosion Cracking

SCC is electrochemical and mechanical dependency (Griggs et al., 2016). Susceptibility to SCC of steel pipelines under cathodic protection in near-neutral pH and high pH of soil environment was evaluated in the SCC process (Z. Y. Liu et al., 2016). The newly initiated cracks are semi-elliptical wherein the crack length at the normal surface (D) is greater than two times the crack depth (a) crack presented in Figure 2.1. From the fracture-mechanics factor of view, strain is intensified at the location of the metallurgical discontinuities in the intergranular features.

SCC formation on buried pipelines relies upon numerous parameters including coating characteristics (Wenhe et al., 2016), temperature (Tik, 2018), soil chemistry (Wasim et al., 2018), electrochemical reactions (Liu et al., 2018; Pipelines, 2020). In addition, the process of SCC on the X52 pipeline steel is influenced by mechanical and environmental factors (Contreras et al., 2016). As the yield and ultimate stresses increase susceptibility to SCC also increases. The crack tip can be anticipated by the stress concentration factor (SCF). The SCF characterizes the amount of water pressure to create hoop stress-causing propagation of cracks.

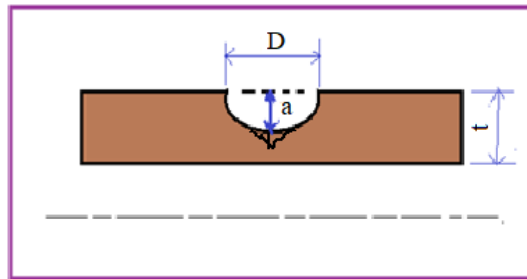


Figure 2.1 Schematics of pipe pitting-crack features (Wasim et al., 2018)

2.6.3 Crack Growth

Crack growth depends on the growth of corrosion film fracture and the rate of metallic dissolution at the crack tip. In this stage, the cyclic water hammer is assisting crack growth in addition to water bursts during no-service times. As mentioned, and proven in Figure 2.2, intergranular corrosion can stop passive cracks at the penetrating tip of intergranular corrosion. The mechanism for each crack initiation and increase is predicated upon on fracture of the brittle passive crack alongside the grain limitations which ends from localized plastic deformation

generated by the stress. For crack initiation, further progress in intergranular corrosion on the outer pipe surface and additionally with the inside pipe wall takes place intergranular cracking. Crack initiation increases the operating conditions, pipe surroundings, and mechanical loading conditions.

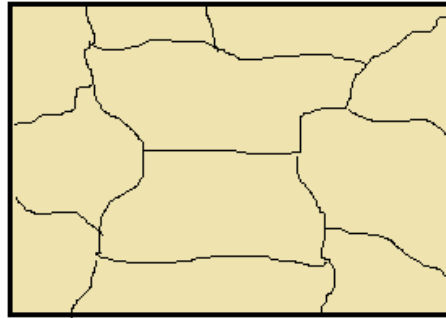


Figure 2.2 Schematic of typical intergranular corrosion (Contreras et al., 2016)

2.7 External Pipe Corrosion Damage

Soil corrosivity is the main challenge of pipelines forming external pipe surface corrosion damage. Most of the kinds of literature used soil solution to test the corrosivity of soil by burying it in a pipe in a box containing soil samples; due to a long time (years) taking corrosion to happen (Liu et al., 2009; Yan et al., 2008). Corrosion damage of underground water pipe results from electrochemical reaction with a function of time process at the soil/pipe interface (Deo et al., 2019). The corrosivity of soil also depends on the soil type and grain size (Valor, et al., 2019). The authors also categorized soil corrosivity in an increasing order based on the grain size as sandy clay < loam < clay loam < clay. Redox potential (RP) is essential to measure the degree of aeration in the soil. it depends on the DO in the soil and provides information about the presence of microbes such as sulfate-reducing bacteria (Maru, 2019).

Water pipelines' overall performance is influenced by the water content and embedded soil environments and weather conditions (Shi et al., 2020). Analyzing the quantity of bicarbonate (HCO_3) inside the soil that surrounded the pipe could be very critical as it complements pipeline corrosion by forming Fe_2O_3 and water pressure corrosion cracking (PCC) (Gadala & Alfantazi, 2014). Soil surroundings that consist of chloride, bicarbonate, dissolved CO_2 , bacteria, soil type, sulfate, and temperature are elements influencing the ferrous pipe corrosion rate. Soil residences which include resistivity, pH, moisture content material, chloride,

bulk density, bicarbonate, redox potential, and sulfate content material have been said as primary soil parameters (El et al., 2020).

Corrosion of buried ferrous metals in the soil is usual problem for the owners of different distribution systems including water, gas, oil, and sewerage around the world. The corrosion failure mechanism of water pipes is a localized corrosion attack forming leakage (Cole & Marney, 2016). External corrosion occurs from the direct contact of the soil environment with the pipe surface. This is due to soil having several parameters including pH, moisture content, sulfides, chloride, mineral salt content, sulfate, etc are the major factors that assist pipe degradation in the soil (Maru, 2019). The failure modes are categorized as fracture which is caused by stress concentration of crack tip and rupture due to loss of pipe wall thickness (Li & Yang, 2012).

The process of pipe corrosion is enhanced by the porosity property of soil which relates to aeration in the soil for the passage of oxygen and water moisture (Kode et al., 2009). Soil corrosivity is enhanced by its resistivity and conductivity due to electrolyte reactions in the soil (Alberto et al., 2007; Khaled & Hackerman, 2003). Moreover, bulk soil conductivity is directly proportional to the contact of the pipe surface which assists in the formation of preferential corrosion cells. The main soil corrosion products found by X-ray diffraction (XRD) characterization are goethite (α -FeOOH), magnetite (Fe_3O_4), maghemite (γ - Fe_2O_3), and lepidocrocite (γ -FeOOH) (Arce et al., 2011).

A variety of iron oxides and oxy-hydroxides generated at the cathode and anode are the end products of the electrochemical process. Iron-hydroxide is created when the Fe^{2+} ions combine with OH^- , and as the reaction progresses, the hydroxide turns into magnetite. Corrosion is exacerbated when the soil's concentrations of the ions chloride (Cl^-) and sulfate (SO_4^{2-}), which can result in additional electrochemical attacks. Surface corrosion of underground water pipes is caused by chemical and/or electrochemical interaction at the soil/pipe interface (Deo et al., 2019). Water distribution providers, sewerage, and asset managers for oil and fuel line distribution cannot avoid the corrosivity of soil on ferrous materials as the time-of-service grows (Britton, 2016). In addition to mechanical damage, longitudinal cracks, SCC, operation conditions, and environmental considerations, there are many other ways that water pipes can

be damaged including, microbes, minerals, and stray current all contribute to soil corrosivity, which damages pipes' surface (Daku et al., 2019).

Corrosion of iron pipes with the internal soil is a complex phenomenon due to several variables including pH, aeration, redox potential, moisture, soluble ionic species, resistivity, and microbiological activity (Freitas et al., 2012). A typical pipe damage mechanisms causes loss of money which covers pipeline replacement and maintenance costs. The electrical conductivity (EC), soil pH, moisture, and soil type can attack the surface of buried water pipes. Other soil parameters including soil mineral content, chloride, and sulfide can attack buried pipe surfaces (Hajj et al., 2013). A similar study conducted by (Suganya et al., 2018) shows the impact of soil corrosivity factors including chloride and moisture content in the laboratory on time function. Soil moisture having <20% shows high resistivity amount; in turn, it indicates low electrical conductivity (EC) (Pavel et al., 2018). The soil moisture was analyzed based on the investigation of corroded galvanized steel pipe with different contents of soil moisture (Li et al., 2016).

The study of (Hao, 2016; Ji et al., 2012; Soriano & Alfantazi, 2016) used a method of watershed segmentation to characterize corrosion defects and to describe the morphology of pipe surface corrosion in any stage of corrosion attack. Detection of corrosion early is important to ensure the integrity of water pipelines and avoid water contamination as well as save the loss of treated water (Hoang, 2019). Figure 2.3 depicts the XRD pattern of corroded surfaces of iron pipe including common and different corrosion products (Zhao et al., 2018; Hao, 2016). One of the reasons for the formation of different types of corrosion products is the surrounding environmental and localized material variability.

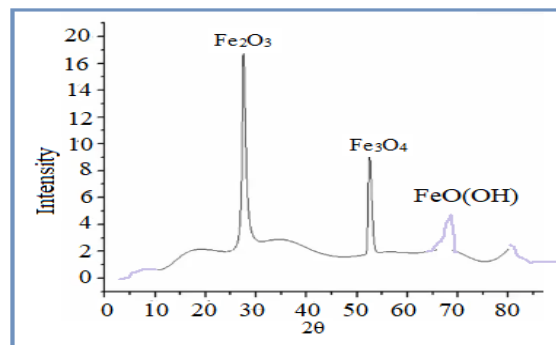


Figure 2.3 Schematics of XRD patterns of corrosion products of pipe (Zhao et al., 2018)

2.7.1 Pipe Corrosion Process in the Soil

Soil corrosion is the root cause of buried pipeline damage which damages pipe surface (Mahmoodian & Aryai, 2017). Even with the use of modern corrosion prevention techniques, soil corrosion of buried pipelines is an issue with a long history. In-Line Inspections (ILI) offer information concerning the internal and outer pipeline circumstances to determine the remaining wall thickness (Amaya et al., 2019). The ILI provided data to develop a model of pipe degradation to the extent of corrosion defects even though uncertainties and degradation processes are challenging for assessing entire pipelines. The phenomena of corrosion needs preconditions including anodic, cathodic, and electrolyte. The anodic site can be developed by microstructure and product local defects.

Soil resistivity is a useful measure of the concentration of dissolved salts that determines soil corrosivity. Various soil corrosion models discussed in the review (Cole & Marney, 2012) reveal water movement and oxygen transport in the soil are the main iron oxide formation in the electrochemical reaction. Furthermore, external corrosion is affected by several soil parameters as presented in Figure 2.4. In addition, the manufacturing process has significant impacts on understanding the corrosion mechanisms of pipelines (Li et al., 2016).

In the corrosion of metals, resistivity is the main soil variable that determined the degree of coil corrosion. (Mohebbi & Li, 2011) conducted an experimental investigation to study the corrosion behavior of cast iron buried in different soil corrosion environments for one year.

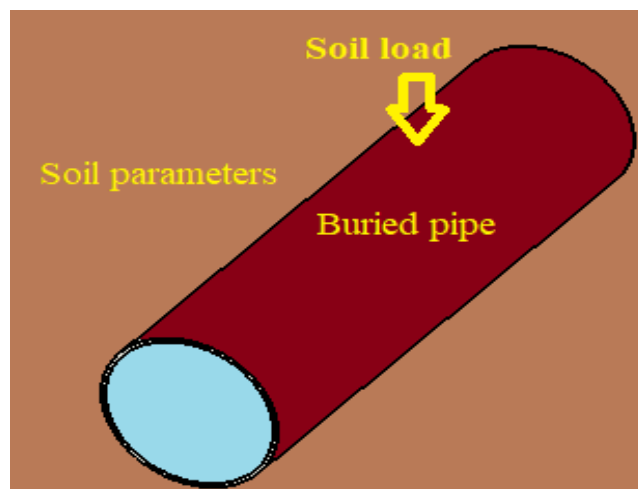


Figure 2.4 Factors affecting soil corrosion buried pipe

2.7.2 Microbially Influenced Corrosion (MIC)

External corrosion also depends on the activity of microbiology, soil characteristics, and the corrosion process. Microbially influenced corrosion (MIC) is developed by soil bacteria that secrete enzymes and compounds on the pipe surface to form a biofilm (Usher et al., 2014). Microbial growth of corrosion rate on the buried pipes increases in the soil where fertilizer is added due to the existence of higher concentrations of nutrients such as ammonium (NH_4), and nitrate (NO_3) from fertilizer (Melchers, 2007).

Neutral soil pH contributes to the creation of a diverse microbial community and the least diversity exists in acidic soil (Fierer et al., 2016). Particle size has an impact on the growth of corrosion on the buried pipes which relates to oxygen diffusion, water holding capacity, and transportation of mineral species (Cole & Marney, 2012). Soil particle size affects the conditions of microbiology in terms of microbial number, diversity, and distribution of bacteria. For instance, clay soil has fine particle which restricts oxygen and water diffusion which lowers microbial condition but the progress of corrosion is higher in the clay soil. MIC is a form of corrosion caused by soil microorganisms such as bacterial activities. The main mechanisms of MIC are the formation of differential aeration or chemical concentration cell, cathodic depolarization, and acidic attack (Marsili et al., 2018).

In general, water pipe is influenced by water and soil environments in addition to the operation conditions and soil load Figure 2.5. According to the scholars, internal pipe wall corrosion is initiated by trace elements such as lead, copper, and others while deposited on the soil-pipe interface (Li et al., 2018). Similarly, external pipe surface is mainly damaged by soil resistivity, low value of pH, moisture content, and chloride (Colombo et al., 2018; Song et al., 2017). The presence of soil electrical resistivity is the main indicator of soil corrosivity attacking pipes' surface due to chemical content, and temperature (Wang et al., 2018).

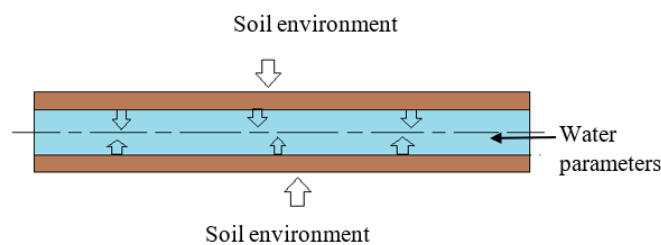


Figure 2.5 Schematic of water pipe corrosion environments

2.8 Modeling of Corrosion Damage Phenomena

Modeling is a method of employing mathematical language to describe anything from its physical state. It expresses a large amount of data with a simple formula, either to solve a current problem or to forecast the occurrence of scientific understanding in the future. The process was time-dependent with several pitting formation stages including nucleation, propagation, and steady-state or passivation phases before termination or leakage formation. For example, a stochastic corrosion growth mathematical model was utilized to evaluate the growth of localized pitting corrosion damage (Wang et al., 2019). The stochastic corrosion damage rate model for buried pipelines helps to estimate the rate of pitting corrosion in three phases including nucleation, growth, and termination or leakage formation. Similarly, long years back; corrosion damage was estimated by using a deterministic model of corrosion rate using Eqn. 2.6 (Engelhardt & Macdonald, 2019).

$$V(t) = \frac{dh}{dt} = v_0 \left(1 + \frac{t-t_0}{\tau}\right)^{\exp(a-1)} \quad (2.6)$$

Where t_0 is starting time, v_0 is initial corrosion rate, and n , τ are positive constant values. As the service time increases, the oxide films formed as a defect on the pipes surface which serves as protecting passive layer.

Corrosion is the product of electrochemical reactions with time processes (Wang et al., 2017). In the process of corrosion, there is a change of mass related to current density as stated by Faraday's law in the electrolysis (Scheiner & Hellmich, 2007). The formation of passivation films trying to stop corrosion has resulted from the interreaction of iron hydroxide and molar mass with the density of iron pipe (Graedel et al., 1990). The current density of the cathodic site leads to the deposition of corrosion product whereas the current at the anodic site results in the dissolution of iron pipe materials (He et al., 2017). The deposits act as shielding effects of corrosion products and form passivation on the pipe surfaces (Ezuber et al., 2020; Petersen & Melchers, 2012).

2.8.1 Power Function of Corrosion Modeling

Soil corrosivity attacks pipelines forming preferential corrosion cells on the external pipe surface. Corrosive conditions can exist in every soil environment to some degree. The most types of corrosion that cause pipeline damage are pitting corrosion (Asadi & Melchers, 2017; Weigang Wang et al., 2019), SCC (Liu et al., 2017), and uniform corrosion caused by soil and

microorganisms (Wu et al., 2014). Other types of corrosion such as crevice corrosion and galvanic corrosion also contribute the damage of pipelines.

A statistical model was developed from the analysis of discrete soil samples on the buried coated pipe after several years of collecting data (Valor, et al., 2009). The authors focused on the target variables including exposure time, maximum pit depth, pipe-to-soil potential, soil properties redox potential, coating type, water content, pH, resistivity, chloride, bulk density, sulfate, and bicarbonate content. This approach is modified from (Rossum, 1968) as shown in Eqn. (2.7):

$$P = k(t - t_0)^n \quad (2.7)$$

Where k and n were taken from regression, analysis within the range of soil and pipe dimensions, and t_0 is the pit initiation time, the value of K depends on the redox potential, pH, dissolved ions concentration, and resistivity. Similarly, n is found from pipe to soil potential, pipe coating, soil bulk density, and water content. The authors also found values of k to 0.144 (sand-clay-loam), 0.163 (clay-loam), and 0.178 (clay) while the value of n was 0.734, 0.793, and 0.829 for the sample soils. The researchers then concluded that the corrosiveness of soil level as clay > clay loam > sandy clay loam. Similarly, other scholars utilized to determine the rate of pitting corrosion at any time to determine maximum pit penetration model was used with a time function to determine the behavior of corrosion in different soil environments. In the equation, $d_{\max}$ is dependent variable whereas independent variables are time, soil, water, and pipe dimensions.

The modified probability-based model of a Monte Carlo simulation based on the environmental conditions was utilized to estimate the pitting and crack growth rate ($n < 1$) with the time change. Furthermore, (Caleyo, et al., 2009) utilized the Markov chain methodology to estimate pit growth at the transition probability between pit states with the function of environmental parameters derived from (Velázquez et al., 2017). Where v and k are constants given based on the parameters of soil environmental corrosivity. The authors used the values of 0.33-0.70 and 1-3 for v and k respectively.

2.8.2 Modeling of Pitting Corrosion

Pitting corrosion damage is a highly complex phenomenon involving a series of degradation of the physical and electrochemical properties of pipelines. Pitting is the main destructive type of corrosion damage on the pipelines forming localized dissolution in the electrochemical reaction. When the pit depth grows, mass transfer increases from the pipe surface to the surroundings. Several scholars have developed various models to forecast the maximum pitting corrosion depth in water pipelines, recognizing its significance in safety assessments and structural reliability analyses (Aryai et al., 2022). Various theoretical foundation methods have been applied analytically or by combining real field data with statistical methodologies, resulting in the development of various empirical to fully stochastic models. Several scholars have evolved diverse models to predict maximum pitting growth in water pipelines (Larin et al., 2016).

The power-law model is effective to evaluate time-dependence corrosion growth. It is widely applicable for modeling several environments including soil, water, and atmosphere with the pipe variables. M. Romanoff developed a model of pitting corrosion with time dependence to determine maximum pit depth from the exposure time of buried ferrous pipes for (17-year) of corrosion data recording in the range of various soils. Various theoretical frames had been carried out analytically or by combining actual subject statistics with statistical data, ensuring the development of diverse empirical to completely stochastic methods. The power-law model is used for the majority of known empirical mathematical models to predict the pitting corrosion depths of the pipelines. The model was extended based on the findings of (Caleyo, Valor, et al., 2009), and it can be described by the using Eqn. (2.8), in which k and n are constants, $d(T)$ shows maximum pit depth, and T denotes time in years. The authors have attempted to improve and extend the power-law model by creating more exact techniques to express the values of k and n for a given soil environment.

$$d(T) = kT^n \quad (2.8)$$

The pitting corrosion damage (PCD) rate was modeled by (Alamilla & Sosa, 2008) with the function of buried steel pipes. This model has its limitation regarding enough access to data and later the model developed by (Caleyo, Valor, et al., 2009) described pitting rates as initial and long-run impacts depending on the time and soil corrosivity. Such a model requires data

recording for several years and in-line inspections. The growth of pitting defects was modeled by the Markovian approach using the stochastic model for water pipelines. This model is used for predicting pit development with time function. Using environmental factors as a function, transition probabilities between pit states were developed by several authors (Teixeira et al., 2008; Valor et al., 2013; Valor & Caleyó, 2007). Previous works of literature utilized simple and analytical methods to predict maximum pit depth. Previous studies focused on external corrosion modeling without including the impact of internal corrosion which creates pipe leakages.

2.9 Corrosion Attacking Process and Prevention Mechanisms

Corrosion damage to water pipelines is a known problem faced by water suppliers around the world. Underground pipeline corrosion control and prevention depend on environmental concerns such as water, soil resistivity, water quality, and many other factors. The most frequent corrosion controlling and preventing methods are applying the coating, designing corrosion-resistant alloys, corrosion inhibitors, and cathodic protection. Despite several corrosion-controlling mechanisms being available, environmental and cost-associated analyses are very important to select effective and economic protective methods.

Pipe rehabilitation is useful to remove deposits from pipe walls by using cable-pulled scrapers and hydraulically driven materials that can clean the pipe wall with the help of water pressure (Raspati et al., 2022). The decision of pipe rehabilitation involves comparing the cost of rehabilitation and replacing pipelines with the new installation. The maintenance information system (MIS) of pipeline management is useful to control all the distribution lines using a database system.

2.9.1 Inhibitors

The function of inhibitors is vital to water pipe distribution system to delay further corrosion attacks of pipe walls even though they are the cause of bacterial growth potential to create a biofilm (Fang et al., 2010). Common corrosion inhibitors that are applied in the drinking water system include zinc orthophosphate, polyphosphates, and sodium silicates with doses from 0.7-2 mg/L (American Water Works Association, 2016; Edwards et al., 2002). Inhibitors are made from synthetic materials which have been used to reduce the attacking of corrosion effect (Aljamali et al., 2019; Soudani et al., 2018). A similar study conducted by (Yu et al.,

2010) reveals that the function of inhibitors has great importance to water pipelines distribution system for delaying further corrosion attacks of pipe surfaces even though they are the cause of bacterial growth potential to create biofilms. Inhibitors should be environmentally friendly and effective for the intended corrosion protection (Zeng et al., 2021). Common corrosion inhibitors that are applied in the drinking water system are zinc orthophosphate, polyphosphates, and sodium silicates with doses from 0.7-2 mg/L (Edwards & McNeill, 2002; Harmon & Harmon, 2015; Nour et al., 2012). The authors discussed that polyphosphates and zinc orthophosphate are two corrosion inhibitors often used in drinking water systems. The inhibitors can correct lower pH water into near-neutral conditions.

Internal corrosion controlling strategy in drinking water is useful to reduce red water complaints by adding some inhibitors such as orthophosphate. A study conducted on the galvanized steel pipe shows that adding 1 mg/L of orthophosphate with pH controlling being 7.5 reduced the problems of iron released, turbidity, and zinc release from 36-87% in the transportation of ground water (Tang et al., 2018).

2.9.2 Coating

Coatings create electrical insulation to the material of the pipes from their surroundings which can stop the flow of current and prevent the formation of corrosion cells. The process of corrosion on the pipelines under disbonded coating is assisted by the concentration of oxygen and moisture. In addition to this, environmental corrosivity is more influential in the breaking of coating bonds such as high pH and carbonate concentrations (Fu et al., 2009). The authors utilized three parameters including immersion time, oxygen concentration, and wet-dry cycle on the scanning Kelvin probe (SKP) to investigate the corrosion process of the X65 pipeline undercoating and the result shows localized corrosion was developed under damaged coating. There are a variety of coating materials such as organic polymer matrix, hot deep galvanized, epoxy, paints, etc. (Luo et al., 2021) which are used for prolonging of service life of buried structures (Alos et al., 2022).

Pipe SCC occurs in soil and water due to the early decay of coatings (Ayello et al., 2014; Protection et al., 2018; Yan et al., 2008). The dismantling of the coating can be the result of several reasons. Water could seep through the coating and reach the interface of the metal surface, which would contribute to local damage to the coating. The technique of

electrochemical impedance instrument has been widely used to study the performance of the coating and corrosion of metal surface under the coating (Mcintyre & Pham, 2016; Hang et al., 2019; Zhong et al., 2008). As a result, a local electrochemical process that occurs at the micro-defect such as small crack or hole in the coating enhances the corrosion pit. Pitting corrosion is also caused by several reasons including inclusions during manufacturing (Wang et al., 2018), electrochemical reactions (Song et al., 2017), Non-uniform stress, and non-uniform protective coatings.

2.10 Research Gaps Identification

The issue of corrosion impact is not only limited to health and economy but also degrades minerals and ores in the earth (Bastidas, 2020; Singh, 2018). Corrosion of ores and manufacturing products indicate the future worry of materials shortage in the world (Gardiner & Melchers, 2002; Korniloff et al., 2015). Long-term corrosion damage of old pipes is the main health risk to human life due to the existence of heavy metals and changes in water test and color (Dinelli et al., 2012; Khan & Saleem, 2018). Water pipes require ongoing active maintenance and follow-up due to their service character. The combined impacts of pitting corrosion, SCC, and the influence of particular environmental corrosivity remain unresolved issues even though corrosion has been studied for more than seven decades.

Numerous studies have been undertaken on underground pipelines using a variety of approaches, such as corrosion modeling, laboratory immersion tests, and characterization of exhumed pipes from the field (in-situ condition) of the real environment, to examine corrosion damage morphologies, corrosion controlling, and prevention methods. Yet, gaps are existing in the characteristics of pitting corrosion damage due to inherent variability of material, operational condition, and environmental factors. Although researchers have been conducted in the last decades, more of them focused on the effect of corrosion on underground pipes than on detailed characterization of corrosion morphology at the surface and subsurface of buried pipes under in-situ conditions. This research focused on the investigation of corrosion damage mechanisms and model corrosion rates of the buried iron pipelines. The total effect of pitting corrosion and corrosion cracking is noted in this study as one of the main causes of water pipeline deterioration. From the survey of extensive works of literature, the following gaps can be drawn:

- The problem facing the water supply owners is the decision-making of the appropriate time to replace pipelines.
- External pipe corrosion is yet needed an in-depth study of corrosion damage mechanisms due to the variability of soil factors (Azoor et al., 2019). In this phenomenon, soil corrosively is a major cause of water pipelines damage and its severity varies from place to place depending on soil parameters and corrosivity conditions. This is because of the nature of the soil being inherently variable in its corrosivity behavior. In this regard, this research focused on identifying major soil corrosivity attacks on the ferrous underground pipelines.
- External pipe corrosion is not only limited by soil aggressive properties but also there are main factors including microorganisms and soil backfill load induces bending stress.
- Internal pipe corrosion is an active problem due to the effect of water quality parameters reacting with pipe wall. The rate of pipe corrosion is more with the presence of water pressure and flow rate.
- Corrosion damage modeling has been conducted to represent corrosion rates by different scholars. Despite, researchers have contributed their efforts to analyze the corrosion process, pipeline corrosion damage mechanisms, and proposed corrosion controlling methods, still there is a gap to describe the evolutions of corrosion using a mathematical model due to limited data access.
- Corrosion controlling mechanisms are very crucial to extend the service years of water pipelines. Despite several researchers proposing controlling mechanisms such as applying coating, inhibitors, and others, still other alternative corrosion-controlling mechanisms are needed due to inherent environmental parameters variability.
- The problem of pitting corrosion and the inherent difference of environmental factors are more complex and cause failure. According to different scholars, pitting is the predominant cause of damaging pipelines due to environmental variability factors (soil & water).
- Limited works of literature are available focusing on either one or two corrosion damage mechanisms (CDM) of drinking water pipelines. But this dissertation incorporates several corrosion damage mechanisms including the pipe manufacturing process,

operating conditions, electrochemical corrosion, water, and soil physicochemical corrosivity, stresses induced on the water pipelines, and the effects of these mechanisms.

- Designers have not included the effect of corrosion as a design criterion.
- The Ethiopian government has not yet focused on the loss of materials and industrial equipment due to corrosion. The direct materials deterioration and the cost of indirect materials (coating) incur higher costs annually due to corrosion.
- In Ethiopia, despite the economic and social influence that exists when a water main breaks and underground metallic products fail, no work has been done to analyze corrosion damage and understood the mechanisms that cause pipes damage and failure-controlling methods.

Even though, it is possible to mention more previous works, herein below are the selected articles listed chronologically showing a summary of related works of literature Table 2.1. The table presents the assumption taken by the authors and possible gaps that can be identified from their studies.

Table 2. 1 A summary of selected previous works

No.	Article	Author/s	Limitation/assumption taken by the authors	The possible gap can be identified
1	Probability failure analysis due to internal corrosion in cast iron pipes	Yamini et al., (2006)	Chlorine is considered as the cause of internal corrosion	There are other internal corrosion factors such as deposits and dissolved oxygen
2	Stochastic modeling of pitting corrosion : A new model for initiation and growth of multiple corrosion pits	Valor et al., (2007)	Stochastic model simulating pitting corrosion	Investigating environmental corrosion factors and characterization is very important.
3	Modeling steel corrosion damage in the soil environment	Alamilla et al., (2009)	Corrosion damage proses is an irreversible	The impact of water variables and operational conditions are missed.
4	Long-term corrosion of cast iron cement-lined pipes.	Petersenet et al., (2012)	External pipe corrosion is the main concern	Investigation of microstructure, water pressure, and soil load is missed.
5	Corrosion behavior of galvanized steel due to typical soil organics	Soriano et al., (2016)	Soil organics are the cause of corrosion on the galvanized steel pipe	The soil load stress exerted, pressure and bacterial corrosion on the pipes are missed.

No.	Article	Author/s	Limitation/assumption taken by the authors	The possible gap can be identified
6	Pitting corrosion of older underground cast iron pipes. Corrosion Engineering, Science and Technology	Asadi et al., (2017)	Analysis and interpretation of pit depth data from a sample of severely corroded pipe.	Visual observation has limitations to get pit depth data at the micro level and below.
7	Impacts of water quality on the corrosion of cast iron pipes for water distribution and proposed source water switching strategy	Hu et al., (2018)	The impact of water parameters on the pipe corrosion	The influences of pressure and bacteria were not included.
8	Characterization of corrosion morphologies from deteriorated underground cast iron water pipes	Deo et al., (2019)	Pipe structure failure with corrosion patches	Needs to incorporate corrosion behavior.
9	An image processing method for morphology characterization and pitting corrosion evaluation	Codaro et al., (2019)	Image analysis is an alternative method of corrosion characterization.	Needs to include investigating corrosion mechanisms.
10	Image Processing-Based Detection of Pipe Corrosion Using Texture Analysis and Metaheuristic-Optimized Machine Learning Approach	Hoang and Tan et al., (2019)	Image processing is the timely and accurate detection of corrosion on the pipe.	Requires to include corrosion phenomena and corrosion causes.

No.	Article	Author/s	Limitation/assumption taken by the authors	The possible gap can be identified
11	Effect of dissolved oxygen concentration on stress corrosion cracking behavior of pre-corroded X100 steel base metal and the welded joint in wet–dry cycle conditions	Gong et al., (2020)	• Influence of dissolved oxygen (DO) on the stress corrosion cracking.	• The influence of operational conditions is not considered.
12	Statistical soil characterization of an underground corroded pipeline using in-line inspections.	Amaya et al., (2021)	• Measurements of defect depth and soil properties using inline inspection.	• The impact of internal corrosion was not included.
13	Corrosion-induced failure of the ductile iron pipes at micro- and nano-levels.	Wasim et al., (2021)	• Corrosion failure at micro and nano levels	• Including corrosion failure mechanisms are important.
14	Failure assessment of corrosion-affected pipeline networks with limited failure data availability	Aryai et al., (2022)	• Development of corrosion model based on the statistical analysis of the parameters.	• Characterization corrosion behavior was missed.

CHAPTER 3. MATERIALS AND METHODS

3.1 Introduction

Analyzing corrosion and modeling of damage phenomena for drinking water pipelines is the main issue which helps to identify corrosion failure mechanisms of buried pipes. The phenomena of corrosion are inherent and need careful attention to prevent sudden breakage of the pipes and require frequent checking of water quality. this chapter discusses on the purposively selected materials including old and new pipes of galvanized and ductile cast iron for microstructural analysis. similarly, old pipes which were actively damaged were collected from different sites of Addis Ababa city. To study environmental corrosion factors, soil which was surrounded the pipes was collected to analyze the in-situ condition of corrosion behavior. in addition, to investigate the effect of water parameters on the pipe wall, samples of water were gathered from the same sites where old pipes were collected.

A variety of appropriate methods were utilized to characterize corrosion and modeling damage phenomena for water pipes including, image processing, experimental testing of soil corrosivity, microstructure and corrosion morphology analyses, determining corrosion rate, modeling of corrosion damage phenomena, model theoretical frame, modeling of external corrosion damage phenomena and modeling of stress corrosion cracking.

3.2 Materials

3.2.1 Sample Collection and Preparation

Corrosion-damaged samples can be prepared from two possibilities of in-situ and ex-situ conditions. The ex-situ method utilized an artificially prepared mixture of chemical forming electrolytes (artificial corrosion environment) whereas the in-situ technique of sample preparation utilizes natural environmental conditions. This study preferred to analyze the samples obtained naturally damaged by the soil and water environments. Corroded pipe samples from real-world pipe distribution systems, where environmental conditions are complex were studied with the in-situ condition to get reliable results as compared with laboratory tests (Pepes et al., 2018). In-situ condition corrosion damage (CD) of 100 mm diameter galvanized steel (GS) samples that had been in service for more than 15-20 years and 350 mm diameter ductile cast iron (DCI) water mains samples served more than 30 years were collected from Addis Ababa

water pipelines distribution systems for corrosion behavior analysis. In addition, new pipe samples were prepared for microstructural study from each type of pipe. The coating thicknesses of DCI and GS pipes were 25 and 55 μm respectively.

The field survey was utilized to obtain actual detailed information such as pipeline compositions, installation history, pipes age, original thickness, and diameter, buried depth and width, soil types, coatings, thickness loss, pitting profiles, samples of water and soil, pressure, and location of pipes corrosion attacks are very important to analyze water pipeline corrosion mechanisms. The samples were then quickly taken to the laboratory to protect against further atmospheric corrosion and to remove soil particles mechanically using a plastic brush and cotton cloth before analyses. After photographing, the samples were cut into sections to evaluate corrosion morphology. The surface damage thickness was compared with the original pipe thickness to determine thickness loss. The pipe's elemental compositions of the pipes were determined using a spark spectrometer. The samples were dust-free after being cleaned with a cotton cloth and ground with silicon carbide abrasive paper. Then the spectrometer of Oxford Instruments PMI-Master Smart, Germany was calibrated. To reduce the possibility of compositional testing error, each sample was tested (burned) three times by spark spectroscopy at different points to get average reading values, as shown in Tables 3.1 and 3.2. Meanwhile, five water samples were gathered from the same locations for the analysis of internal corrosion factors from water physicochemical Figure 3.1. In this research, mechanical characteristics of new ferrous pipes are taken from the manufacturing data shown in Table 3.3.

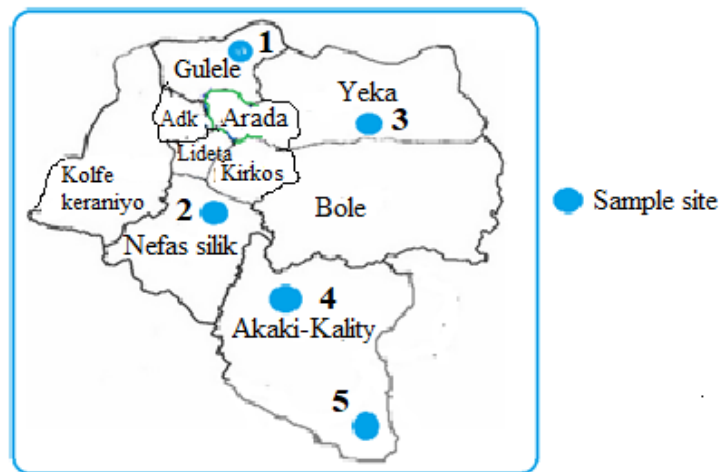


Figure 3.1 Sites of samples collected in the municipal

Table 3.1 Elemental compositions in the galvanized steel pipe

Elements by wt.%										
C	Mn	Si	Ni	P	Mo	Cr	S	V	Al	Fe
0.087	0.41	0.117	0.06	0.01	0.01	0.10	0.01	0.09	0.05	Bal.

Table 3.2 The material composition in the ductile iron pipe in Wt.%

Elements												
Pipe	C	S	P	N	Si	Cr.	Ni	Mo	Cu	Ti	Mg	Fe
DIP	3.600	0.032	0.090	0.340	2.250	0.070	0.060	0.001	0.080	0.14	0.008	Balance

Table 3.3 Mechanical properties of tested water pipes

Pipe type	Yield strength (Mpa)	Tensile strength (Mpa)	Elongation (%)
Galvanized steel (BS 1387: 1895)	276	342-450	10-14
Ductile iron pipe (ISO 2531:2009), Class E	289	330-412	10

3.2.2 Soil Samples Preparation

The corrosivity of soil conditions determine the service lifetime of underground water pipes. The purpose of conducting the soil test was to investigate external pipeline corrosion damage mechanisms. Soil compositions and types inherently vary from one location to another due to the variability of soil mineral composition (Singh & Agrawal, 2012). To investigate soil corrosivity on galvanized and ductile iron pipes, eight soil samples were obtained from different sites in the city that were contacting the pipes. Samples of soil were collected from the surrounding buried pipe at the depth of 40, 80, and 120 cm. The collected bulk soil samples were screened by removing foreign materials, drying the soil samples in the air, and sizing the grains into smaller particles considering the procedures (Deo et al., 2014). Later, the samples were selected visually based on their physical properties, grain size, color (red, black, and brown), and moisture content (Perko et al., 2006). The soil samples had been put in plastic bags and direct separation of foreign materials (sublimation), was employed. The soil (in situ) was weighed using a digital balance having an accuracy of 10^{-3} grams and the soil bulk weight was reported as 1268, 2525, and 3590 grams. The soil samples were dried in the open air for seven days at room temperature and measured their weight to determine moisture content. The samples were then coded to identify the results easily.

3.3 Methods

In this experimental research, both quantitative and qualitative approaches were used in this study. The qualitative research approach was conducted by using visual observation of a field survey and description of corrosion-damaged pipes to evaluate the status of corrosion on the pipe surfaces. The quantitative approach utilized experimental data analyses to investigate corrosion damage mechanisms. Experimental design is a very important method for analyzing the impact of corrosion parameters on the underground pipes using the scientific approach. The study focuses on experimental investigations of corrosion patterns and mechanisms of water pipe corrosion damage using various approaches and methods based on the general framework research flow as presented in Figure 3.2. The methodologies that were employed to address each of the dissertation's aims are listed below:

- To get experience, a thorough review of the literature on corrosion phenomena was surveyed to gain knowledge of what was already known.
- To achieve objective number 1, a water laboratory test was conducted to investigate internal water pipe corrosion damage mechanisms.
- To test objective number 2, a soil physicochemical laboratory test was conducted to study the soil corrosivity status on the buried pipelines. To avoid error, the soil samples were taken from the depth of the pipeline which has contacted the pipe surface.
- To address objective number 3, an optical microscope and scanning electron instrument were used to analyze the microstructure of new pipes and the morphology of the corrosion pattern of corrosion damaged pipe respectively. Corrosion characterization at the subsurface and surface was studied by using Mountains surface morphology analysis software and SEM analysis and then the results of corrosion morphology were validated by using a 3D optical surface profilometer.
- To meet objective number 5, a deterministic long term pitting corrosion growth model was developed to evaluate the rate of long-term corrosion and the remaining lifetime of buried water pipelines. The model was validated with a case study and sensitivity analysis.

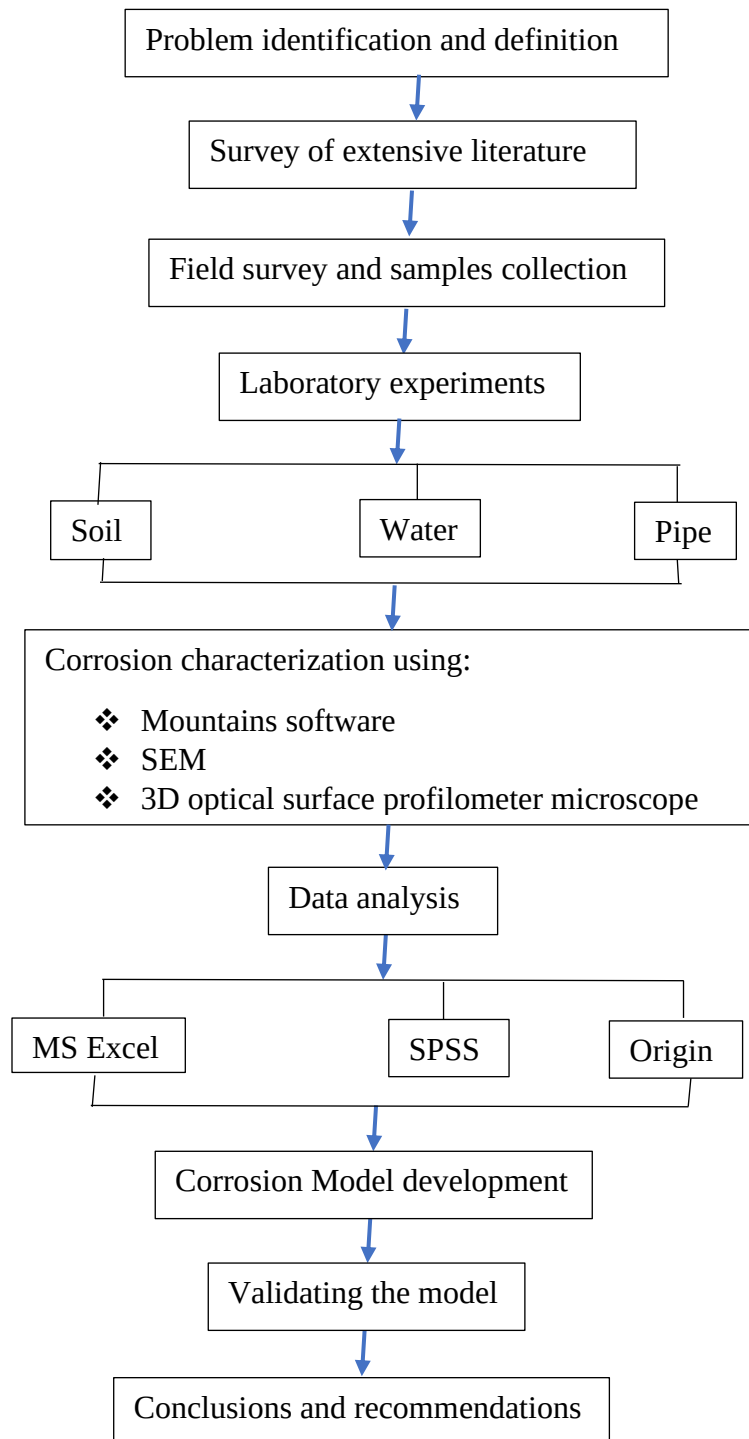


Figure 3.2 The conceptual frame of research methodology

3.3.1 Image Processing

To characterize corrosion morphology, digital image processing analysis software followed the procedures shown in Figure 3.3. Mountains digital surface analysis software; Digital Surf, France was used to characterize corrosion morphology and pit features. The software detects the image situation based on the method of threshold segmentation of ISO 25178-2 watershed standard to determine corrosion characteristics from the sources of SEM images. It is important to characterize the degree of corrosion patterns of old pipe surfaces. The image processing (IP) algorithm converts the SEM image of the corrosion failed surface and characterizes it by applying watershed segmentation method to display the results using graphs and tables.

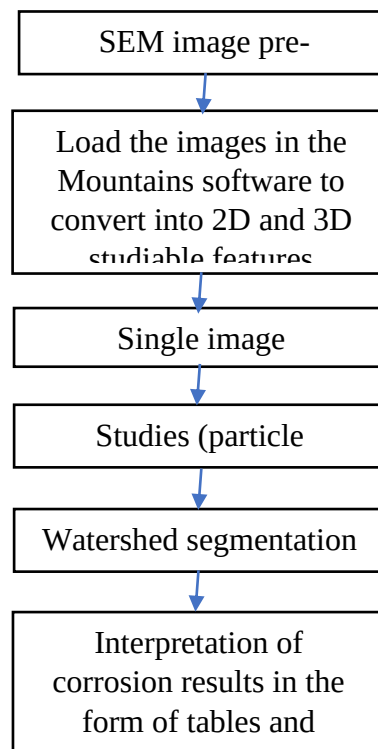


Figure 3.3 Procedures for image processing

3.3.2 Water Physicochemical Laboratory Testing

Water parameters were tested using laboratory equipment such as the Miero 800, Burette Lab pH 7310p, DR 900, and Palin test Photometer 7100 (Germany 2018) for detecting conductivity, total hardness, water pH, chlorine dioxide, and released iron test were used to

investigate major pipe wall corrosion damage mechanisms. Details of water laboratory test procedures are shown in Table 3.4.

Table 3.4 Water physicochemical laboratory procedures (WHO, 2011)

Water parameters	Amount of sample	Laboratory equipment	Procedure
1. Chlorine dioxide	10 ml	RD 900	- Take a 100 ml sample of water 1 diethyl phenylene diamine (DPD1) - Mix the reagent DPD1 completely - Put the water sample with reagent into the photometer to get the result in mg/l.
2. Iron Fe^{3+}	10 ml	Palintest Photometer 7100	- Take 100 ml sample water in to test tube - Add Fe^{3+} reagent into the test tube and dissolve it well - Insert the sample into the photometer and waited for 1 min. and take reading as ppm
3. Water pH	100 to 400 ml	Inolab pH 7310P	- Put water sample 100 – 400 ml into the beaker tube - Insert the pH probe into the tube - Take a reading from the display
4. Total hardness – CaCO_3	100 ml	Burete	- Put a water sample of 100 ml into the tube - Add a small amount of Erichrome Black T ethylene diamine (EBT) indicator and shake - Adding 2 ml buffer solution - Titrate with 0.01N EDTA solution until the color changes from pink to blue - Take the volume consumed and multiply with constant values of 0.056 and 17.857 - Take the result as ppm or mg/l.
5. Conductivity	100 to 400 ml	Miero 800	- Put water sample 100 – 400 ml into the tube - Insert the conductivity probe into the sample and take the reading Temperature of the water sample: 21–25 °C.
6. Total dissolved solids	100 ml	Burete	- Put water sample 100 – 400 ml into the tube - Insert the TDS probe into the sample and take the reading from the display

3.3.3 Experimental Testing of Soil Corrosivity

Corrosion of buried water pipes has environmental and economic consequences due to soil corrosion. Investigating soil corrosivity is useful for risk assessment and designing

environmentally compatible pipes. The deterioration rate of the buried pipe surface is influenced by the soil's physicochemical characteristics and the pipe materials. The nature of the soil is complex and is variable in its type, texture, and elemental compositions from area to area in distinct soil layers. Detailed soil laboratory experimental procedures are described in Table 3.5.

Table 3.5 Soil laboratory test procedures (ASTM D4959-07)

Parameters	Laboratory Equipment	Sample wt.	Testing procedures
Soil pH	Benchtop HI2210 PH meter	10 g.	• Preparing soil sample. • Calibrate the pH meter. • Mix and stir the soil-distilled water solution for 30 min. • Temperature, 21.9 OC • Take the reading
Electrical conductivity	Benchtop electrical conductivity meter 4310 JANEWAY)	50 g	• Preparing sol sample • Calibrate the device • Mix and stir the soil- • distilled water solution for 30 min. • Temperature 22.10 °C & take the reading
Total nitrogen (%TN)	Digestion unit and distillation unit -Titration, burette	10 g	• Preparing soil sample • Calibrate the device • Chemicals used H₂SO₄, Na₂SO₄, H₃BO₃ • Allow staying for 2 days.
Soil texture	Soil hydrometer	50 g	• Preparing sol sample • Mix the soil with water and stir it with a glass rod • Add Sodium hexametaphosphate to disperse the soil coagulated • Allowed to stay for 3 hours

(i) Measuring Soil Bulk Density

The soil bulk density (BD) designates how the compactness of the soil grains in a given soil type. It determines the porosity or aeration of the soil. The BD of soil was measured by weighing the mass of dried soil powder on a beam balance of accuracy of 0.001g and dividing it by the volume of soil. The soil having more porosity lets oxygen move inside the soil which can create pipe corrosion reacting with soil moisture. Air-dried soil with uniform grain size (<2 mm) was put in the cylinder and calculated its volume using and weight Eqn. (3.1). The bulk density (ρ) is then computed by using Eqn. (3.2) and taking the average density of three samples

to minimize error. For this experiment, the average mass of soil was 1370 g, and volume (v) equals 1092 cm³.

$$v = \frac{1}{4}\pi d^2 h \quad (3.1)$$

$$\rho = \frac{m}{v} \quad (3.2)$$

(ii) Evaluating Soil Moisture Content

The weight-loss method was used to determine soil moisture content based on the standard of the American Society for Testing and Materials ASTM D4959-07. The soil samples were obtained from the embedded buried pipes at depths of 40, 80, and 120 cm. The samples (in situ) were then weighted using a digital balance having an accuracy of 10⁻³ g with a known weight of the container. The dried soil weighed with the container to know the weight discrepancy and multiply by a hundred to get the value in terms of percentage Eqn. 3.3.

$$\text{Soil moisture } (S_m) = \frac{(W_s) - (D_s)}{(D_s)} \times 100 \quad (3.3)$$

Where w_s is wet soil in (g) and D_s is dry soil in (g).

(iii) Measuring Soil pH

The pH and conductivity of the soil were evaluated using a Benchtop HI2210 pH meter and conductivity meter, Figure 3.4(a, b) respectively after calibrating in the standard buffer solution. The soil test was performed in the ratio of 1:1.25 soil-water suspension and following ASTM standards (Valley, 2012).

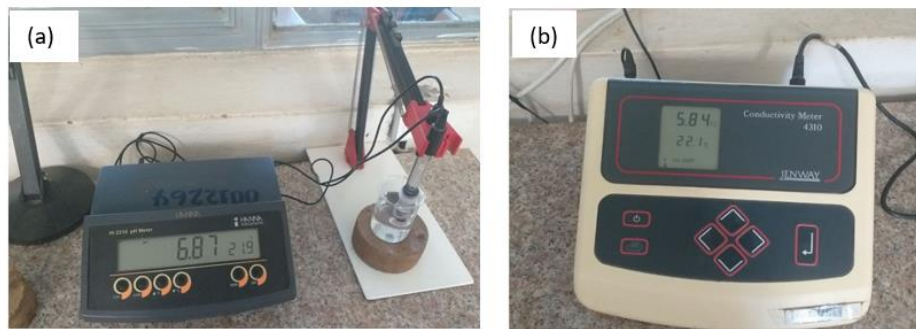


Figure 3.4 Soil laboratory equipment: (a) Benchtop pH meter; (b) Conductivity meter

(iv) Determining Soil Electrical Conductivity

The electrical conductivity was measured in the prepared mixture ratio of 1:1.25 soil-to-water suspension using a conductivity meter. The calibration was done utilizing the usual conductivity reference solution considering the ASTM standard (Campus, 2018). Such an experiment is effective for two things: at first; it helps to determine the amount of salinity (salt content) of soil in deci-Siemens per meter (ds/m). The stray current can pass through to the surrounding soil as current flows from the pipe to the soil. Air-dried 50g soil having a grain size of less than 2mm was put into a glass beaker and 100 ml of water was added to the graduated cylinder. The soil solution was stirred very well using a glass rod and allowed to stay for 30 minutes. During this time, stirred suspension every 15 minutes to homogenize the soil and water mixture as well as to dissolve salt materials. Soil electrical conductivity depends on texture, moisture content, dissolved electrolyte, and porosity (Rhoades et al., 2015).

(v) Determining Soil Resistivity

Soil electrical conductivity (σ) and resistivity (ρ) have inverse correlation and hence computed the value of resistivity from the report of σ . Resistivity was calculated from the values of electrical conductivity Eqn. 3.4.

$$\rho = \frac{1}{\sigma} \quad (3.4)$$

(vi) Evaluating Soil Texture

It is one of the issues which affect soil corrosivity to the buried structures. Soil corrosivity level is categorized based on the soil type and grain size that allows the moisture-holding capacity in the soil described in increasing order as sand < loam < clay. Similar work shows the grain sizes soil of soil is categorized as sand (4.76-0.074), silt (0.074-0.002), and clay < 0.002) mm diameter (Terzaghi & Peck, 2016.). Various studies focused on soil corrosivity and categorized the order of corrosiveness as sand-cay-loam < clay-loam < clay in increasing order of corrosivity (Valor, et al., 2009). Soil texture (S_t) describes the compositions of soil and grain size distribution. It was evaluated based son the ratio of the weight of the sample (w_s) and total weight (w_t) and described in percentage as shown in Eqn. 3.5.

$$S_t = \frac{w_s}{w_t} \times 100 \quad (3.5)$$

3.3.4 Microstructure and Corrosion Morphology Analyses

Optical microscope and scanning electron microscope (SEM) were utilized to characterize microstructures of new pipe materials and corrosion morphology respectively. Sample preparation procedures of OM (Huvitz HR-300 series) were done following standard procedures including cutting, mounting, and grinding using emery paper grit numbers (400-2000). The samples were washed with running tap water during grinding to remove fine chips from the grounded surface before continuing to the next finer grit paper. The pipe samples were polished with a grit of a 6-micrometer disc before being etched into the solution of ethanol 50 ml and 1% of HNO_3 for 3-4 seconds to produce a mirrored surface before analysis. Additionally, six corroded samples were cut from DIP and GS pipes having 18 x 20 mm size to study corrosion morphology by using SEM-JEOL Japan). The SEM images were taken several times to characterize external and internal surfaces in micro-level with different magnifications starting from 1mm including (500, 200, 100, 50, and 20) μm . Below 20 μm , the image was blurred which was unable to differentiate details.

3.3.5 Determining Corrosion Rate

The mass loss of corroded pipes was studied based on the corrosion rate calculation model considering buried exposure time (in-situ condition) from the period of pipe installation up to the failure was determined in terms of mass loss per unit area Eqn. 3.6.

$$C_{\text{rate}} = \frac{K \Delta W}{A \rho t} \quad (3.6)$$

Where ΔW is mass change and C_{rate} is corrosion rate in g and mm/y, respectively; A is the corroded surface area in cm^2 ; t is buried time in hours; $K = 8.76 \times 10^4$ is a constant value of error minimization and $\rho = 7.86 \text{ g/cm}^3$ is the density of steel pipe.

3.3.6 Modeling of Corrosion Damage Phenomena

Deterministic and stochastic models are well-known for predicting the status of pitting and corrosion behavior from a given soil and water environment to analyze corrosion rate. Pitting corrosion accounts for a greater percentage of underground pipe corrosion than other forms. Its process can be evaluated using a mathematical model to predict the long-term rate of pitting corrosion based on parameters including pipe material, operating conditions, and environmental variables. Moreover, a localized corrosion patch on the outer pipe surface is formed based on the variables of time function (t) and environmental factors Figure 3.5. The

current study proposed a new mathematical corrosion model based on physical characteristics such as external and internal corrosion maximum pit depth, pipe age, and wall thickness to determine the remaining service lifetime.

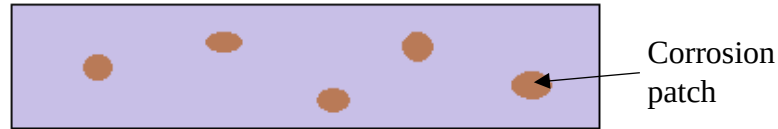
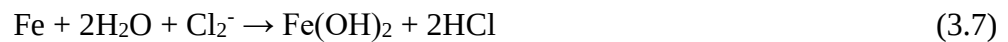


Figure 3.5 Corrosion patch

The rate of corrosion becomes faster as chloride concentration increases on the iron materials which converts FeOOH film to form a ferric ion. At the anodic site, ferrous oxide (Fe^{2+}) attracts chloride ions from the anion site towards the corroded surface which increases localized corrosion attack Eqn. (3.7).



3.3.7. Model Theoretical Frame

In this study, the model considered the assumptions related to the pipe material's physical conditions, environmental, and stresses induced on the buried pipes. The assumption covers:

- Corrosion damaged pipe thickness
- Narrow pits cause crack formation.
- Axial or longitudinal stress and hoop (circumferential) stress.
- Electrochemical corrosion parameters (soil and water corrosivity)
- Stress concentration factor.
- Internal and external maximum pits determine the remaining pipe's thickness

Developing a new approach to pipeline corrosion damage modeling that considers deterministic corrosion rates based on statistical data, pipe material specifications stresses induced on buried pipes, and environmental corrosiveness factors such as water and soil parameters. A systematic procedure approach was followed to develop a corrosion damage model to be confident in the results data validation was conducted using a case study. Primarily, the theory of uniform corrosion and pitting formation with the contribution of crack and leakage formation was clearly defined. Secondly, parameters were measured and some of them are

collected from the Addis Ababa water distribution system as a case study to get valid data. And thirdly, calculations were conducted and then compared with other scientific works of literature.

previously several corrosion models have been proposed to determine the corrosion damage rate on buried pipelines, still, the combined influence of corrosion damage mechanisms needs further scientific analysis. Corrosion fatigue cracks are caused by the combined effects of pitting corrosion and cyclic water hammer pressure. The correlation of factors contributing to model formation was based on the environmental, operational, and pipe material inspection data mining. A mathematical model considering soil physicochemical variables such as pH, resistivity, redox potential, and electric potential is used to predict the growth of localized corrosion failure of underground ferrous structures (Alamilla & Sosa, 2009). The statistical model is important to evaluate pitting corrosion including pit depth, perforation, and the number of leakage and breakage.

When input variables are difficult to access, the model becomes more complicated. It also requires validation using literature works and a case study of the physical water distribution system. In this study, the model is developed from the existing environmental factors, and operational conditions. The physical/statistical model tries to predict water pipe damage by analyzing the electrochemical reaction and the loads exerted and the capacity of the pipe to resist both environmental and stress situations. The remaining pipe wall thickness is reacting with water pressure, material loss due to corrosion, and subject to soil backfill load.

The soil and water pressure acting on the buried pipes cause stress in both longitudinal and circumferential directions. Circumferential (hoop stress) results from vertical loads such as soil backfill and internal pressure whereas longitudinal stress results from the exertion of loads along the axial direction which causes the formation of cracks. Crack propagates when there is water hammer forming cyclic pressure which affects the pipeline's service life. A variety of probable failure types of buried pipelines are developed from the assumptions of pipe material design specifications, environmental corrosivity, electrochemical corrosion, and operational conditions. Buried ferrous pipes are mainly affected by electrochemical corrosion of soil moisture serving as an electrolyte which damages the pipes forming uniform and pitting corrosion (Askari et al., 2019).

3.3.8 Modeling of External Corrosion Damage Phenomena

In the presence of dissolved oxygen, chlorine (Cl_2) reacts with oxygen (O_2) to form chlorine dioxide (ClO_2) which attacks the surface of pipelines. The size of the pit is directly proportional to buried time. Assuming the pit is conical in shape with maximum pit diameter D_{max} , maximum pit depth h , and dissolution rate V as indicated in Figure 3.6. The volume of the pit is calculated by using Eqn. 3.8.

$$V = \frac{1}{12} \pi D^2 h \quad (3.8)$$

With a given time T , in any year of exposure, maximum pit depth is evaluated with a known constant corrosion dissolution rate, d_r Eqn. 3.9.

$$h_{\text{max}} = \frac{12 \cdot d_r \cdot T^{1/3}}{\pi D^2} \quad (3.9)$$

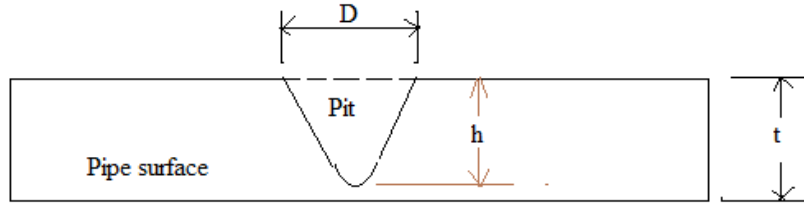


Figure 3.6 Schematics of pit depth

Figure 3.7 shows the newly proposed model of a time-dependent deterministic model of pipeline corrosion phenomena to predict the risk of pipe buried water pipe under the adverse combination effect of narrow pitting corrosion and stress cracking corrosion. The remaining pipe thickness is determined by adding uniform thickness loss with maximum pit depths of internal and external pipe surfaces and subtracting from the original thickness is modeled as shown in Eqn. 3.10.

$$T_r = T_o - (T_u + I_d + E_d) \quad (3.10)$$

Where T_r is the remaining thickness, T_u is loss of uniform thickness, I_d is the internal pit depth and E_d is external pipe surface pit depth and h_{max} is the corrosion depth rate. The pipe data and soil characteristics were used for the model development. The growth of pitting corrosion at any year (Y_i) in the long run is modeled as shown in Eqn. 3.11.

$$h_{\text{max}} = \frac{T_o - (T_u + I_d + E_d)}{Y_i} \quad (3.11)$$

As pitting expands at a higher pace in isolated locations, resulting in stress concentration areas due to the action of water pressure, which causes cracks to form due to mechanical and electrochemical factors. The faster the corrosion rate increases, the worse the pipe leakage and the loss of money for maintenance and replacement due to pitting corrosion. Pitting can also be aided by localized differential soil conditions at the pipe's surface. As the pitting grows, longitudinal and circumferential stress becomes greater. The rate of external pitting corrosion was modeled using soil factors with the function of buried time. Velazquez et al. (Caleyo, Valor, et al., 2009) suggested a predictive model of pitting corrosion for underground pipelines. The authors obtained results but the model has a shortcoming in that it does not account for both maximum pit depths of interior and external pipe surfaces.

$$C_r = K(t_o - t_i)^n \quad (3.12)$$

Where C_r is corrosion rate, K is constant to minimize error, t_o is original thickness, t_i is the thickness at inspection year and n is an exponent. In this research, the condition of pitting growth at any year is predicted using the following mathematical modeling Eqn. 3.13. The model considered soil and pipe parameters with the function of installation time. Maximum pit depth, p_{max} is resulted from the combined effects of water and soil parameters with the function of time.

$$p_{max} = (k + 1) \left[\frac{(t_o - (t_r + p_i + p_e))^n}{Y_i} \right] \quad (3.13)$$

Where P_{max} is corrosion rate, k is the regression sum of more corrosive soil parameters, t_o and t_r are original and actual remaining thickness respectively, p_i and p_e are internal and external max pit depths, Y_i is any inspection year and n is the exponent obtained from the regression sum of soil environmental corrosion factors, ($n = 1.83$). The growth of corrosion is a dependent parameter whereas pipe material type with its dimensions such as pipe age, water, and soil parameters are independent variable which is contributing to the development of the model. Each parameter has its contribution to the acceleration of pitting corrosion and hence maximum pitting depth is the result of the collective effect of these variables on the buried pipelines. Multi-regression analysis was utilized using Statistical Package for the Social Sciences (SPSS V25) to determine k and n for the proposed model.

$$T_k = k_0 + k_1rp + k_2mc + k_3cl + k_4Tn + \dots k_i(v) \quad (3.14)$$

Where T_k is the total values of k , rp is redox potential, cc is chloride content, re is soil resistivity, $k_i(v)$ is the i^{th} any variable, and T_n is total nitrogen.

$$T_n = n_0 + n_1ps + n_2Ec + n_3bd + n_4pH + \dots n_i(v) \quad (3.15)$$

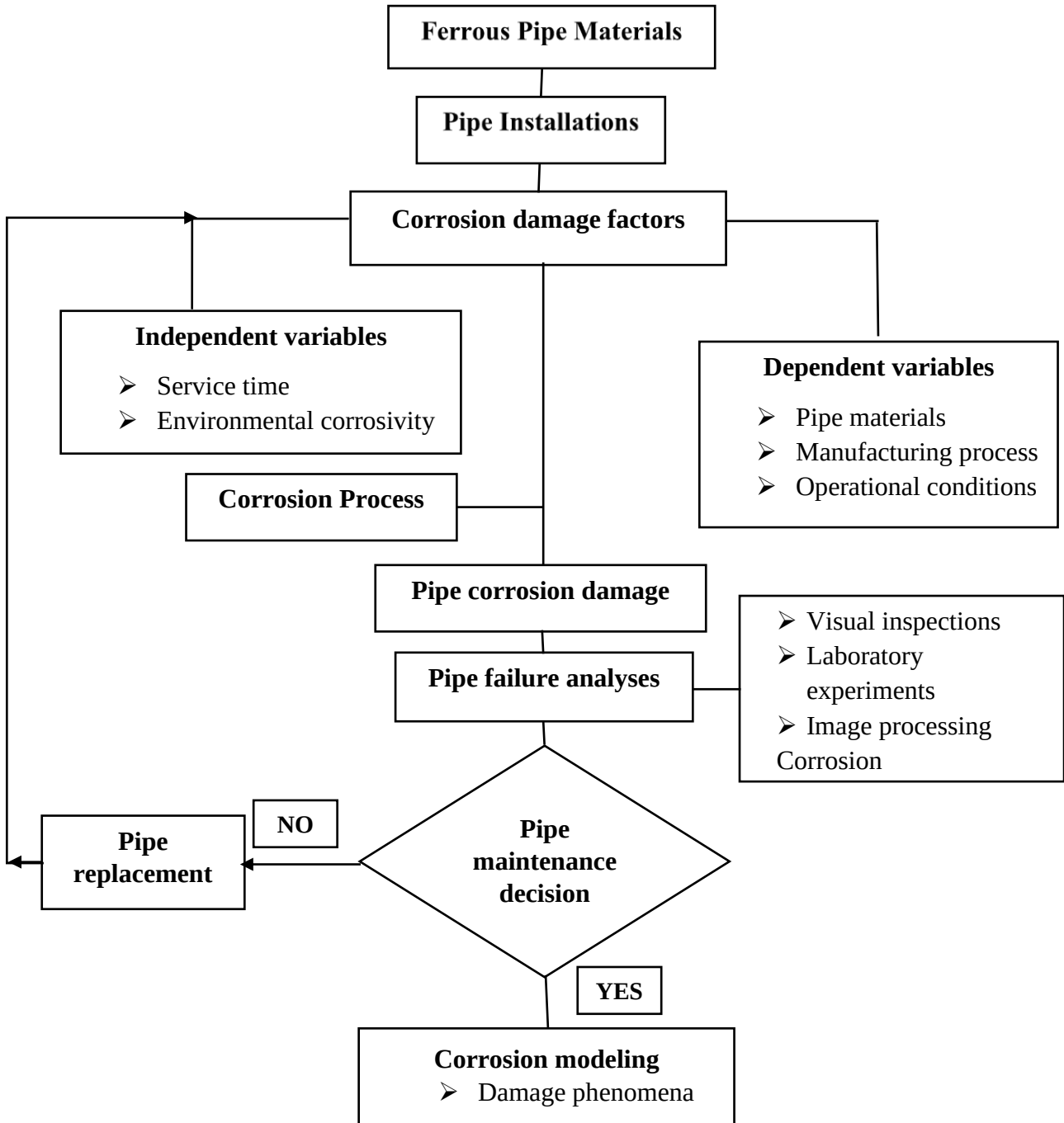


Figure 3.7 Deterministic corrosion damage model

Where T_n is the total values of n , pp is the pipe to soil potential, mc is moisture content, and bd is soil bulk density. The functional proportionality of k is the function of pH , redox potential resistivity, and $n_i(v)$ is the i^{th} n parameter. Similarly, the exponent value n is the function of moisture content, coating type, bulk density, and pipe-to-soil potential (Valor, et al., 2009). The model utilized basic parameters shown in Table 3.6 for the development of pit depth and the remaining service time. The values of K and n are the function of independent variables.

Table 3. 6 Table Observed soil and pipe parameters

Soil parameters	Symbol	Unit	Measuring/testing method
Soil pH	SP	pH	pH meter
Maximum pit depth	D_{max}	mm	Mountain software
Exposure time	t	Year	Operating records
Electrical conductivity	EC	dS/m	Conductivity meter
Moisture content	Mc	%	Weight loss calculation
Total nitrogen	T_n	%	Calculation
Chloride content	Cl	gm/Kg	Titration
Bulk density	Bd	g/cm^3	Calculation
Redox potential	RP	mv	Oxidation-reduction potential meter
Coating	C	---	Direct observation
Ductile iron pipe	Dip	pc	Measuring the diameter (350 mm)

3.3.9 Modeling of Stress Corrosion Cracking

Figure 3.8 shows axial (σ_a) and circumferential or hoop stresses (σ_c) exerted on the pipe with localized pitting. The cracks can be formed by one of the stresses having greater magnitude. Cracks begin at the pipe's surface, where the most stress is induced and the deepest pit is formed. With time function, the SCC frequently initiates pit formation during exposure to the service environment. SCC is accelerated by fluctuating water pressure and cyclic water hammering. When the axial stress (σ_a) exceeds than (σ_c) the crack direction developed along circumferential (σ_c) direction and vice-versa with the effect of SCC.

Buried pipelines are exposed to tension due to water pressure and compression caused by soil load. Corrosion pits are responsible for the initiation of SCC due to non-homogeneities of compositions, inclusions, and grain boundaries. Localized metallic dissolution occurs from the breaking of oxide films on the pipe surface. Forms of corrosion such as de-alloying, crevice corrosion, and intergranular can assist to the evolution of localized corrosion in the pipe material

structure and SCC begins at such localized corrosion damage with the aid of tensile egress. On the other hand, crystallographic orientation and internal microstructure highly influence the pitting propagation and morphology of the pit.

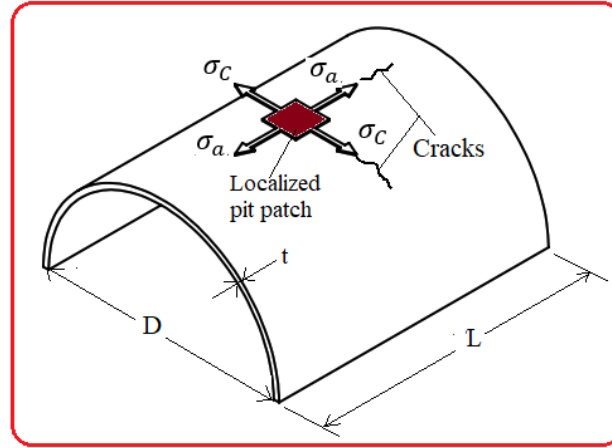


Figure 3.8 Schematic of stress concentrations

Pitting corrosion and stress corrosion cracking are caused by water pressure and time-dependent electrochemical corrosion respectively. The contribution of pitting growth leads pipe cracks with time-dependent under normal working water pressure. The pit growth was evaluated by an exponential pit growth model of power-law. The process of perforation caused by the deepest pits extended until termination and leakage formation. Corrosions of the water pipe are a slow reduction in wall thickness through service years. Because various theoretical frames and assumptions are utilized to build the models, when either of the models is applied to identical instances, a variety of conclusions can be obtained. The effect of soil load and the reaction of water pressure acting perpendicularly with pipe surface which loads to expand and/or contract the pipe is described by Poisson's ratio (ν). The uniform circumferential water pressure exerted on the pipe's inner wall is expressed using Barlow's equation of pipe hoop stress Eqn. 3.16. The most frequent cause of pipe failure is pitting corrosion, which is more common than other types of corrosion. Even though various proposed models for determining pit depth exist, little effort has been made to construct a model to represent the effect of SCC and pitting propagation on buried water mains.

$$\sigma_c = \frac{pr}{t} \quad (3.16)$$

Where σ_c is circumferential stress, p denotes water pressure, r is pipe radius and t is pipe thickness. The combined effect of corrosion and internal pressure creates longitudinal pipe failure on large water mains (Jiang et al., 2019). A water pipe is considered a thin-walled cylindrical tube susceptible to internal and external electrochemical corrosion, as well as strains induced on the underground pipes from water pressure and soil load Figure 3.9.

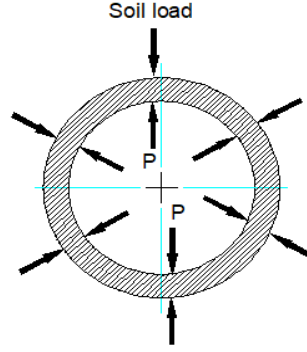


Figure 3.9 Schematics of buried pipe stresses

Predicting long-term corrosion rate is depending on the data recording including installation time, pipe initial thickness, thickness loss at any service year, and age of the pipe during evaluation Eqn. 3.17 (Velázquez et al., 2017). The model focuses primarily on the identification of the physical conditions of buried pipes such as age, soil type, pipe material, operating conditions, soil load, and environmental corrosiveness.

$$C_r = \frac{T_o - T_1}{y_i} \quad (3.17)$$

Where C_r is the rate pitting corrosion in millimeters per year, T_o is the original thickness, T_1 thickness loss during evaluation and y_i is the year of assessment. The opening of pitting has hemispherical shape having pit depth (h), as it enlarges both in diameter and depth.

CHAPTER 4. RESULTS AND DISCUSSION

4.1 Introduction

Water pipeline corrosion damage is an inevitable phenomenon that needs identifying failure mechanisms of the buried pipes and corrosion characterization to determine the rate of corrosion. The results and discussion on the investigations of corrosion morphology and mechanisms are presented in detail including investigations of the physics of pipe failure conditions, types of corrosion on the buried pipelines, investigation external pipe corrosion process and damage mechanisms, internal pipe wall corrosion analysis, characterization of corrosion features, studying of microstructures, analysis of stress corrosion cracking, characterization of corrosion using image processing, analysis of long term corrosion rate, modeling of pipe corrosion damage phenomena, validation of corrosion model, sensitivity analysis, pipe corrosion prevention and contributions of the dissertation.

4.2 Water pipe Design and Manufacturing

Improper pipe manufacturing leads to developing defects such as nonuniform thickness, inclusions, microcracks, and porosity that increases the likelihood of pipe damage. A pipe having defects can easily be affected by corrosion. There are a variety of water pipe design considerations to resist the effects of operational conditions (pressure and flow rate) stress induces and corrosion. After the product design analysis, considering the manufacturing aspect is very important to fabricate good pipe product.

(i) Ductile Cast Iron Pipe Manufacturing Technique

Ductile iron pipe (DIP) was manufactured to have certain performance requirements such as corrosion resistance and good strength as compared with grey cast iron. It has nodular shape graphite in the microstructure which gives good mechanical property. The manufacturing process of DIP is centrifugal spinning by allowing molten metal poured into a rotating steel mold. Materials used for melting are grey cast iron and steel scraps. The required ductility property is achieved by adding manganese element during melting. Small amounts of magnesium in the iron cause the carbon to change from a lamellar to a spheroidal shape, boosting tensile strength and ductility. It has several manufacturing processes including

selecting materials to be melted, melting, pouring in the rotating mold, allowing them to cool, making cement mortar line, and utilizing epoxy coating.

(ii) Galvanized Steel Water Pipe Manufacturing Method

The manufacturing process of galvanized pipe is cold rolling of steel sheet metal, annealing to relieve strain hardening, hot deep galvanizing, and inspection. To ensure the bond between the steel and zinc coating, the steel surface must be thoroughly cleaned before galvanizing. The steel will then be dipped into molten zinc and allowed to cool by being removed from the molten bath. Zinc coating protects the pipe from corrosion for the time being and enhances the strength and durability of the steel.

The main causes of buried water pipeline damage mechanisms is simultaneous corrosion of the external and internal surfaces of the pipes. In addition to significant financial losses due to damaged structures, rust also results in several consequences such as . In this chapter, detailed discussions of the results of the experiments study were presented on the failure of water pipes due to corrosion problems on the galvanized steel (BS 1387:1895) and DIP (ISO 2531: 2009, Class-E) pipe materials. In this section, corrosion of external pipe surface and internal pipe, and wall corrosion was investigated by taking five sites of water supply system in Addis Ababa (Finfinnee) capital city Figure 3.1. The results presented in the chapter were major causes of corrosion damages, mechanisms of corrosion, causes of soil corrosion such as soil pH, soil acidity, soil resistivity, type of corrosion formed, water parameters testing, and corrosion product microanalyses were conducted to study the corrosion process and investigate corrosion mechanisms. In addition, the characterization of corroded pipe samples was analyzed using Mountains surface morphology analysis software to characterize corrosion according to ISO 25178-2 watershed segmentation standard to characterize corrosion morphology and pitting characteristics. In the end; corrosion modeling was developed for pitting corrosion evolution to predict lifetime of the buried pipes.

4.2 How does corrosion of water pipe occur?

Corrosion is a usual phenomenon that develops due to materials reacting with their surroundings over time. In nature, metals are typically discovered in their stable, oxidized (corroded) state. In the process of refining, the oxides of iron are chemically reduced to produce usable metal, with the iron atoms remaining in their elemental (unoxidized) state. Refined iron

then tends to return to its more stable form, iron oxide reacting with oxygen and water, as well as under soil. Materials are susceptible to corrosion's tendency to deteriorate, and buried pipelines are particularly exposed to internal and external environments due to their damaging conditions attacking the pipes at the same time.

The susceptibility to water pipe damage is influenced by several parameters, including pipe manufacturing, water quality, operation circumstances, and soil environment. Continuous metallic ions can release into the water once a corrosion cell had formed on the pipe's surface. This is caused by the interaction of many factors, such as the pipe material, the soil corrosivity status, and the physicochemical characteristics of the water, with the help of stresses induced on the pipelines. The most common type of pipe corrosion damage is electrochemical corrosion. Stress corrosion cracking and pitting corrosion are the two basic damaging mechanisms of pipe failure. The failure rate is faster when the combined influences of sharp pitting corrosion with cracks are developed by the fluctuating water pressure which reduces pipe service life pipes.

4.3 Investigations of Physics of Pipe failure Conditions

Internal corrosion results from chemical reactions taking place on the surfaces of pipes which causes material deterioration brought on by microbiological reactions, and electrochemical. The pressure and velocity of water, among other parameters, have an impact on the internal corrosion of pipelines by forming erosion-corrosion. Based on the investigations that have been done on the geometric morphology of corrosion, the bottom parts of both internal and external pipe surfaces are damaged by pitting corrosion Figure 4.1. This is caused by erosion corrosion and the deposits from the inside wall that accelerate the rate of pitting corrosion during the night time or at stagnant water conditions. External pipe corrosion damage is affected by pitting and uniform corrosion. This happens due to the accumulation of moisture content being higher at the bottom of external pipe surface which develops electrochemical reactions with the help of oxygen. The soil's corrosivity assists corrosion cell formations at different locations on the pipe surface. The soil load causes the pipe to be bent and forms crack initiation.

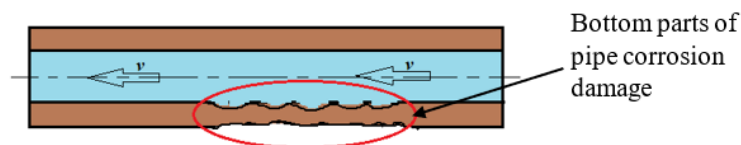


Figure 4.1 Schematic locations of internal and external pipe corrosion damage

The form of corrosion affecting the pipe surfaces is pitting corrosion caused by electrochemical reactions. Other types of corrosion such as stress corrosion cracking and uniform corrosion identified as secondary corrosion damage mechanisms. Internal corrosion deposits form a layer of tuberculation which is an inevitable phenomenon on the pipe wall. The corrosion cell formed in the areas where high tuberculation exists. The deposits assists formation of deep pitting corrosion formation. The condition of deposits varies among the position of pipeline installation. In the horizontal position installed pipes are more exposed to the settlement of deposits which can accelerate the rate of corrosion. Tuberculation is caused by an electrochemical reaction in metallic pipes. The reaction of bacteria with pipe wall buildup tuberculation. In the long term, as the deposits grow, it disturbs pipe water flow and develops erosion-corrosion.

4.4 Types of corrosion on the buried pipelines

The long-term water pipe service condition causes pipe wall thinning due to erosion corrosion. At no water flow condition, the deposits such as calcium carbonate lie on the surface of the pipe and are stuck on the wall. As the thickness increases, water turbulence creates which accelerates the rate of erosion and corrosion. The process is cyclic which creates a mass loss to the pipelines. Erosion-corrosion is the effect of electrochemical corrosion and operating conditions. Changes in water pressure and flow rates produce a turbulent flow that causes erosion on the pipe wall. These actions are ongoing. As the service load increases, its severity rises. Erosion is caused by water flow and long time service load. It forms a rough surface on the pipe wall due to the different degrees of corrosion damaged surface. The corrosion product of erosion-corrosion depends on the compound found in the pipe and the condition of corrosion variables.

Metals have multiscale grains and microstructures that are separated with certain grain boundaries. The type of localized corrosion formed by the preferential corrosion at the grain boundaries is intergranular corrosion. The main causes of intergranular corrosion are alloying element segregation and defects in the microstructure. Corrosion then occurs along the boundaries which form a dark line acting as an anodic site where elements segregate. Ductile iron pipe affected by graphitic corrosion. The distributed discrete nodules in the microstructure contacting with the other grain boundaries form graphitic corrosion due to dissimilar in nature. On the other hand, the addition of magnesium creates nodules which led the pipe to have good tensile strength and ductile properties.

Dealloying is a form of localized corrosion formed under an electrochemical reaction in which an element in the alloyed metal selectively segregates in the microstructure and is removed from it which causes the weakening of mechanical properties. When the iron in the pipe is leached away by corrosion, graphitization happens. Pitting corrosion forms a small hole or cavity in the pipe surface. The corrosion product of pitting results from the interaction of iron, oxygen, and moisture or water. Pitting corrosion occurs when localized corrosion creates a pit in the pipe surface. When corrosion pits get larger, it causes deterioration of pipes and contributes to the concentration of stress. The pipe structure gradually fails where corrosion pit growth is maximum when it is supported by internal pressure, and soil load which forms bending moments. Pitting formation has certain processes such as pitting initiation, propagation, and termination or leakage formation.

Uniform corrosion that formed when the pipe thickness is reduced uniformly around the buried pipe. Such type of corrosion damage belongs to magnetite; Fe_3O_4 and hydroxyl groups (OH^-) and other ferrous oxides on the surfaces of pipe to form corrosion products. Galvanic corrosion is formed between the coating material and the outer metallic surface. It can also occur in dissimilar metallic alloying elements due to the difference in electrode potentials between the two materials. Galvanic corrosion is formed between the contact of dissimilar materials while anode and cathode sites are developed. The galvanic corrosion cell is created when pipelines contact the soil.

Pipe corrosion also caused by a low water pH value which contributes to the formation of SCC with the effect of water pressure. A higher pH value, results in anodic dissolution at the crack tip, which encourages the crack evolution and propagation in the SCC process. The type of SCC forms on the external surface of the buried pipe is either high pH (>9) SCC which produces intergranular cracking or neutral pH SCC, which forms transgranular corrosion with a soil pH of 6 to 8. Transgranular corrosion is localized corrosion that formed along the cracks due to the stresses acting on the pipes.

Stress corrosion cracking (SCC) is the effect of tensile stress and corrosion on the water pipes. The SCC initiates at the corrosion area and tensile stress propagates major and tributary cracks which leads to structural failure due to the growth of localized corrosion rate. Under tensile stress, the SCC develops due to the grain boundaries exposed to the aggressive

environment and the pipe damage accelerated by the effect of corrosion. Crack formation and propagation caused by a pipe burst, water hammer, working pressure, and soil load accelerate pipe failure with the aid of corrosion. Once a single main crack is created, other several branches propagate easily and the pipe is damaged at an early stage, and consequently, the pipe itself failed. The SCC causes the pipe to fail before the intended service time by forming initial micro-cracks in the pipe structures. The SCC is assisted by the burst of pipes which develops stress inside the pipes and the corrosion formed on both inside and outside surfaces leads to form leakage and pipe break.

4.5 Analysis of Soil and Water Microbiologically Influenced Corrosion

Microbiological corrosion is the most damage mechanisms of buried pipelines that exist on the external and internal pipe surfaces. The pipe surface is affected by microbiological corrosion, which forms a biofilm on the buried pipe's surface, and has the potential to cause external corrosion. Over time, bacterial colonies in the soil also deteriorate pipes' surface. Different kinds of bacteria exist in the soil create biofilms which weakens pipes with time. Corrosion of pipe surface by sulfate-reducing bacteria is typically associated with the formation of iron sulfides (FeS). In an anaerobic environment, sulfate-reducing bacteria oxidize organic materials, convert sulfate into sulfide which plays a key role in the corrosion of buried structures.

Microbiologically corrosion occurred from the presence of microorganisms within the water which creates biofilms. In the process of microbiologically influenced corrosion, microbes can grow actively in biofilms develop certain chemical, microbiological, and physical factors, that cause corrosion to develop. During nighttime when water flow at rest, this condition facilitates the formation of bacteria in the pipe wall. Bacteria also develop with the existence of dissolved solid particles which form biofilms on the pipe's internal surface. The electrochemical forming pitting corrosion holds deposits. The accumulation of such deposits on the bottom pipe wall assists the growth of bacteria. The bacteria accelerate the process of electrochemical corrosion and the deterioration of pipe surfaces which leads to the growth of the corrosion rate. As a whole, internal corrosion which results in iron dissolving into the water and forming iron oxide produces iron compounds as particle matter in the water and results in "red water," which degrades the water's quality.

Due to both microbiologically driven corrosion and electrochemical corrosion, the pipe wall gradually degrades or disintegrates the pipe all. Oxides and other compounds that have been transformed into a stable condition similar to the ore are found in corrosion products. When the passive films are breaking by any means, corrosion cells developed at the specific surface. For instance, the corrosion film can easily break with the help of water pressure and dissolved oxygen. During water flow conditions, the velocity of water washed away the deposits and erosion-corrosion develop. At no flow condition, again deposits and bacteria damage the pipes wall. In such a manner, the cycle of microbiological corrosion continues until pipe leakage.

4.6 Analysis of External pipe Corrosion Process

Corrosion of the outer pipe surface reduces the integrity, appearance, and service lifetime of the pipes. The deterioration of pipelines is influenced by the continuous electrochemical reaction which forms a variety of oxides on the water pipe surface as indicated in Figure 4.2. Corrosion damage starts from the exposed surface of metallic products and progresses to structural failure when rust forms during the electrochemical process. Buried pipelines are attacked by the mechanisms of the electrochemical processes consisting of anodes and cathodes on the outer surface of the pipes. The process begins at a random location forming corrosion cells on the surface of the pipe. Pitting initiation formed for several reasons including grain boundaries interface, non-uniformity of an alloying element, and rough surface all contributed to the formation of the anode. Anodes and cathodes on the buried pipes resulted from variances in the moisture content. The soil moisture is serving as an electrolyte in the chemical reaction process of soil and pipe surface. The distribution of anodes and cathodes is depending on the microstructure of the pipes and environmental corrosion conditions. Corrosion growth takes place at the anode due to the migration of electrons towards the cathode to meet with the ions for the formation of oxidation (rust) which results from migration of electrons.

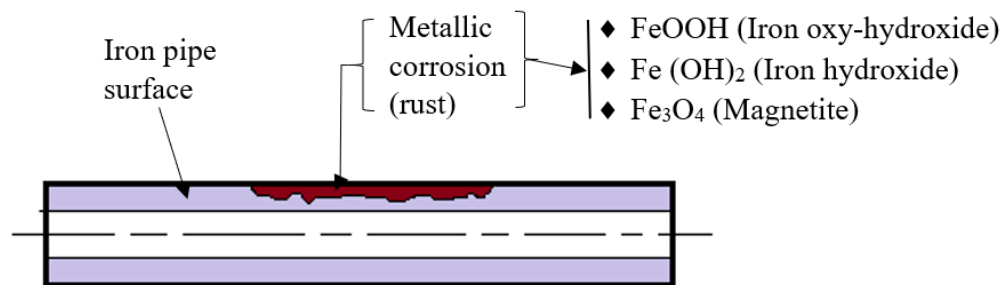


Figure 4.2 Process of external pipe surface corrosion damage

Visual inspection was conducted to get qualitative information on the extent of damaged pipes and the growth of corrosion status. The reddish and dark brown colors of corrosion products and the surface irregularity of the pipes were evaluated by visual observation. Photographs of corroded pipes sample were taken on the most corroded part to get insights into conditions of corrosion behavior Figure 4.3. The visual inspection observed from the field survey of real case pipe assessment indicates, that the range of corrosion damage observed from uniform corrosion to the extreme failure condition up to hole formation from inherent variability of corrosion parameters reacting with pipe surfaces in the long time.

The factors that create deterioration of the mechanical properties and aesthetic of buried metal surfaces include material compositions, the environment, operational conditions, and various manufacturing process stages. Because of the influence of these failure mechanisms, corrosion is a complicated and costly issue that puts a strain on iron water pipes and lowers water quality. The combined impacts of soil load, water pressure, and corrosion attack cause the processes of corrosion damage to become more prevalent over the pipes as the service years grow. Two major categories can be used to classify the failure processes of water pipelines: Due to structural deterioration that cannot resist stresses, and the gradual loss of pipe walls brought on by corrosion and water pressure, the structural capacity and water quality that belong to the system are diminished. Operational conditions and other factors including pipe material structure, soil environment, soil microorganisms, and water quality parameters contribute to pipeline failure. Pipeline breakage is produced by the combined impacts of environmental and operational situations, which accelerates the rate of pitting corrosion. A water pipe can break for a variety of stresses induced including longitudinal stress from hoop loads, circumferential breaks starting from longitudinal loads, bending stress from soil backfill loads, and pipe split traverse loads on the pipe joints.

4.6.1 Investigation of External Corrosion Damage Mechanisms

External pipe corrosion is the main factor contributing to the weakening of water pipe surfaces which increases the risk of failure. External corrosion is a result of interaction between the pipeline and the soil found around it. Due to the constant and gradual soil environmental attack on the pipelines, the occurrence of corrosion is expected. The types and compositions of soil are naturally specific to each site since the soil minerals vary from place to place. The nature of soil also varies from the same location to different depths. The soil environment comes into

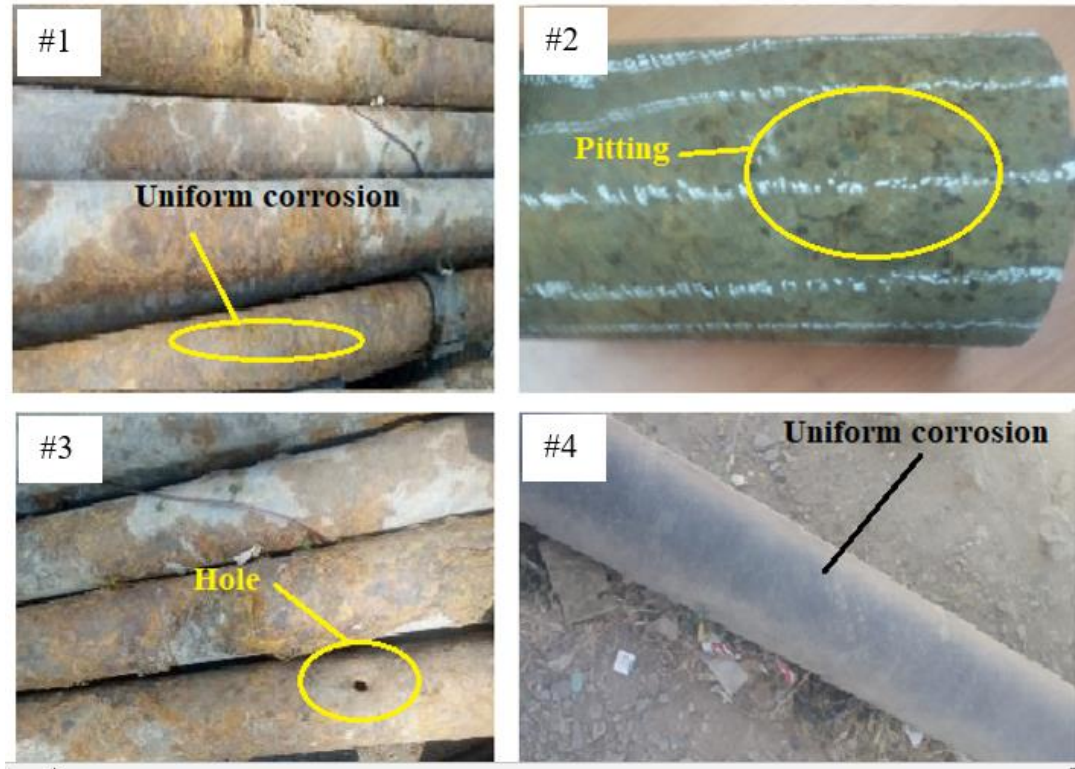


Figure 4.3 Photograph of corrosion damaged pipes (site #1, #2, #3 & #4 respectively).

direct contact with the pipe surface, causing external corrosion through the process of electrochemical reactions. This is due to soil having several parameters including pH, moisture content, sulfides, chloride, mineral salt content, sulfate, etc are the main variables that contribute to pipe degradation in the soil and forming cracks. The failure modes are categorized as fracture which is caused by stress concentration at the crack end and rupture due to loss of pipe wall thickness caused by soil corrosion. Corrosion of buried pipes is the usual engineering problem that deteriorates the structures and creates a loss of cost. Electrochemical interactions between the materials of the pipe and the soil parameters result in the formation of external corrosion containing oxides and scales the buried water pipelines.

Electron migration to the cathode is speeding up when the rate of metallic dissolution at the anode increases. Pitting formation, pitting propagation, and pitting termination are all steps of the process that continue until the pipe is damaged. The pits can be left open (uncovered) or covered with a semi-permeable membrane that is cup-like or hemispherical. As corrosion pits grow and later terminate, several consequences occur including pipe leakage, breakage, brittle failure, fatigue failure, SCC, and corrosion fatigue due to the creation of stress concentration

locations. A variety of iron oxides and oxy-hydroxides form at the cathode and anode during the electrochemical reaction, as shown below.



An electrochemical reaction at the soil/pipe interface causes corrosion damage to underground water pipe surfaces during service time. Due to moisture, microbes, minerals, and stray current, soil corrosivity damages the pipes. Iron-hydroxide is created when the Fe^{2+} ions combine with OH^- , and magnetite is created as the reaction progresses. The following examples demonstrate how corrosion is accelerated by rising soil chloride (Cl^-) and sulfate (SO_4^{2-}) ion concentrations, which can result in additional electrochemical attacks:



In addition to the electrochemical corrosion, the soil environment contributes a variety of external pipe failure mechanisms including stress corrosion cracking, corrosion fatigue, pitting, uniform attack, galvanic corrosion, crevice corrosion, and intergranular corrosion. and microbiologically influenced corrosion on the buried pipes.

4.6.2 Soil Texture and Compositions Analysis

The proportional quantity of clay, sand, and other mineral particles of varying sizes in the soil is referred to as soil texture. Determining the percentages of sand, clay, and silt in the soil are investigated using hydrometer method of evaluating soil texture using quantitative measurement. Soil texture has a direct relation to corrosivity behavior. For instance, fine soil particles such as clay have the capacity of holding moisture content which causes corrosion to the buried pipes. Figure 4.4 depicts lab results of soil grain sizes having three categories: silt, sand, and clay are mixed in nature and textural class (TC) is identified as loam (L) soil. The result indicates that the corrosivity degree of loam soil is mildly corrosive that's a lower impact on the pipelines than clay soil does. Soil texture refers back to the size fineness and uniformity

of soil. The type of soil and grain size are the reasons for gradual pipe surface damage with time function. The amounts of soil texture ranged from 16-26%, 30-34%, and 44-50% for clay, silt, and sand correspondingly.

The percentage compositions of soil from the three sites contain the average values of 47% sand, 31% silt, and 22% clay. Based on the laboratory of soil type analysis, it belongs to loam soil and its corrosivity condition was identified as moderate corrosive to the iron pipes. Soil composition contains mineral particles and organic matter which are the remains of animals, plants, air, moisture, and living organisms.

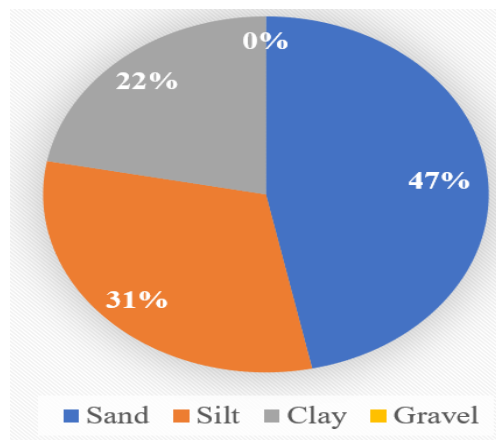


Figure 4.4 Average soil compositions of the selected sites

The soil composition determines soil texture based on the constitute of particle size among soil compositions containing sand, clay, and silt and the combination of these particles. The corrosivity of soil depends on the percentage of clay contents. Figure 4.5 presents the soil texture of the selected samples containing sand, clay, and silt. Soil corrosion is higher where clay content is more in the compositions. For example, soil sample #3 taken from site three contains 26% of clay which shows more corrosion to the buried water pipes whereas soil sample #1 taken from site one holds 16% of clay which indicates less corroding status to the ferrous pipes. When the amount of clay increases, its moisture content is larger, and the soil's corrosivity becomes aggressive. In other way, even though the percentage of sand content is higher, its corrosivity status is less than that of silt particle content due to its water content being less than silt particles.

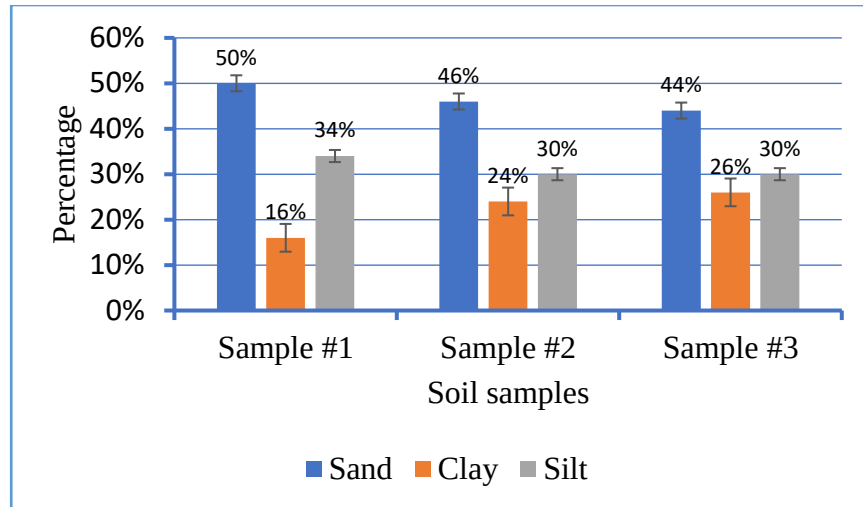


Figure 4.5 Soil samples texture

4.6.3 Analysis of Soil Physicochemical

Corrosion is the result of electrochemical reaction that damages the mechanical and physical properties of pipes due to the migration of electrons from anodic to cathodic sites. Numerous soil physicochemical factors contribute to soil corrosion, which is an unavoidable and serious problem for underground water pipes and other structures. This is the reason soil containing a variety of parameters including soil pH, resistivity, sulfide, chloride, and moisture content are the soil parameters that have the greatest impact on buried materials.

4.6.4 Soil moisture content

Because of soil moisture concentration variations, the effect of soil isn't necessarily consistent across pipe surfaces. Moisture content depends on the annual rain fall conditions. For instance, the annual rainfall reaches up to 1200 mm in the case area, which significantly increases the soil's moisture content (MC). The combined effects of soil variables, such as moisture content, pH level, aeration, temperature, microbes, soil texture, and minerals with salt compounds, determine soil corrosivity behavior. The MC of soil is analyzed as one of the foremost soil corrosion causes to underground iron pipes. The corrosion characteristics of the soil on the buried water pipes were studied based on the moisture contents of the samples. Soil moisture acts as an electrolyte underground to form metallic corrosion.

When the MC increases, soil corrosivity becomes more aggressive. Soil corrosivity condition is based on the MC which is categorized as less, mildly, and moderately corrosive in

increasing order of corrosivity. Seasonal weather conditions have a great role in the recording of a high amount of moisture variations. From the soil laboratory test, the results of soil MC indicate that the corrosivity values (23.7%, 30.8%, and 37.5%) are evaluated for, less corrosive, mildly corrosive, and moderately corrosive correspondingly Figure. 4.6.

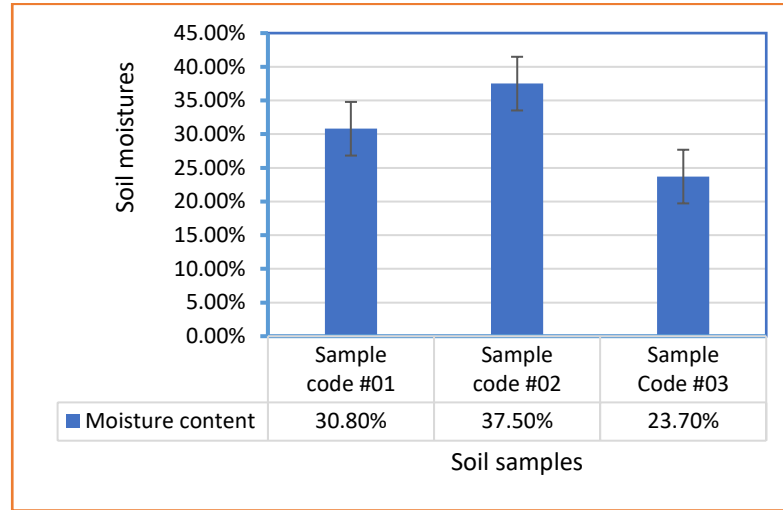


Figure 4.6 Soil moisture content

up to 1200 mm which led to moist the soil for several months in a year. A soil having an EC of more than 4ds/m is corrosive to the ferrous pipes due to consisting of soluble salts such as Mg, Ca, Na, SO₄, and Cl (Campus, 2018). The process of corrosion requires a lower energy state to release electrons to create corrosion (oxidation) of metal at the anode. The study investigated by (Galai et al., 2018) indicates soil water content from 25-30% is aggressively corrosion failure of buried iron pipes. A similar study conducted on soil corrosivity based on moisture content was categorized as less corrosive (0-20%), mildly corrosive (20-40%), and moderately corrosive 40 to 60% (Gupta, 2009). Based on the soil moisture content analysis, soil moisture is more corrosive to the buried pipes.

4.6.5 The Effect of Soil pH on Pipe Corrosion

The purpose of soil pH testing was to determine the basicity or acidity of a soil solution to investigate the conditions of soil corrosivity. The amount of pH relates to the deterioration of buried pipes and assists in the formation of microorganisms at a higher level of pH > 8 (Estefan et al., 2013). In this study, the results of soil pH ranged from 6.98-7.04 which is near a neutral soil pH value. The results of soil pH are categorized as “non-corrosive” to the buried water

pipes. Soil pH identification is helpful to determine the corrosivity behavior of the soil where pipes are installed. A soil environment having a near-neutral pH value (7) is needed to prolong the life of iron pipes. According to several researchers' findings, soil pH value ranges from 5-8.5 is a good condition which is a negligible impact on ferrous underground pipes but contributes to the development of intragranular corrosion. Near-neutral soil pH also permits a favorable environment for sulfate-reducing bacteria formation. Table 4.1 shows the summary of tested soil samples which was focused on the purposively selected soil corrosivity parameters.

Table 4.1 Laboratory results of soil physicochemical analyses.

Soil parameter	Soil sample code			Soil corrosivity condition
	#1	#2	#3	
Amount of resistivity (Ω .Cm)	4274	3195	9524	High corrosive
PH	6.98	7.04	7.04	Normal
Electrical Conductivity (dS/m)	0.234	0.313	0.105	Corrosive
%Sand (wt/Wt)	50	46	46	Moderately corrosive
%Clay (Wt/Wt)	16	24	26	
% Silt (Wt/Wt)	34	30	30	
Soil textural class	Loam	Loam	Loam	Moderately corrosive
Total nitrogen (%TN)	0.06	0.10	0.16	Less corrosive
Dry soil bulk density (ρ)	1.25	1.22	1.23	Corrosive

The soil properties are not the same in different areas. It has also different corrosion characteristics as the depth of soil increases. This shows the property of soil is complex due to a variety of soil layers and compositions in its nature. Based on the evaluation of pH, the corrosivity behavior of soil belongs to the range of “non-corrosive to less corrosive” level.

4.6.7 Soil Electrical Conductivity

The extent of dissolved salt was evaluated in the soil-water solution determined by the value of electrical conductivity (EC) which was measured by the conductivity meter. It is an indirect investigation method of salt content (Campus, 2018). A soil having an EC of more than 4 ds/m at 25 °C is said to be saline means the salt content of the soil is higher due to the soil

containing soluble salts such as Mg, Ca, Na, SO₄, and Cl indicating the presence of salt within the soil (Ulery et al., 2008).

4.6.8 Studying Soil Resistivity

Soil corrosivity and resistivity have an inverse relationship which means higher resistivity has a low corrosivity condition Table 4.2. The condition of soil corrosivity was studied in the laboratory by determining the amount of resistivity.

Table 4.2 Soil corrosivity status

Soil parameter	Value	Soil corrosivity condition	Source of reference
Resistivity	0-500 ohm. cm	Extremely corrosive	ASTM soil corrosivity rates
	501-1000 ohm. cm	Extremely corrosive	
	1001-2000 ohm. cm	Severely corrosive	
	2001-5000 ohm. cm	Moderately corrosive	
	5001-10000 ohm. cm	Mildly corrosive	
	>10000 ohms.cm	Very Mildly corrosive	
Moisture	0-20%	Less corrosive	
	20-40%	Mildly corrosive	
	40-60%	Moderately corrosive	

The soil that contains relatively lower resistivity is more corrosive properties than the buried metallic structures (Zhou et al., 2015). For instance, dry soil contains low moisture levels that retain high resistivity and such type of soil property was categorized as low corrosivity to the underground pipes (Bhattarai et al., 2013). Soil conductivity has an inverse correlation to its resistivity. Conversely, soil conductivity has a direct relation to moisture content and has a higher corrosion contribution factor. The presence of electrical conductivity and resistivity indicates soil corrosivity situations are aggressive to the buried pipes. As soil moisture content is higher, resistivity lowers, and the evolution of corrosion to the buried structures increases. A higher resistivity value has a lower corrosivity potential whereas a lower resistivity value causes more pipe corrosion damage.

The growth of corrosion in the soil is higher due to the presence of moisture that can create resistivity which increases the rate of pipe corrosion failure in the soil. The lower amount of resistivity indicates higher corrosive properties. Soil that contains much amount of moisture has low resistivity whereas dry soil contains higher resistivity but low corrode. Investigation of the electrical resistivity of soil helps to determine soil corrosivity and the suitability for the pipes to be installed. Soil resistivity is the technique of determining soil electric resistance capacity which will help to study the condition of current flow from buried pipes to the soil.

The migration or loss of electrons from the pipe indicates the corrosion process. It varies in line with the soil mineral compositions, temperature, moisture content, and depth of soil where the samples are taken. The result of soil resistivity was evaluated from the reciprocal values of electrical conductivity (σ). Based on the soil resistivity investigation, the result was reported as 42.74, 31.95, and 95.24 $\Omega\cdot\text{m}$ respectively Table 4.1. In this case, the study of soil resistivity conditions on the buried iron pipes was identified as moderately to mildly corrosive potential. Soil resistivity and conductivity have an inverse relation. Soil that has high resistivity means low conductivity and belongs to less corrosive to the buried structures. Soil resistivity is affected by moisture content, soil type, and bulk density (Bhattarai et al., 2013; Maru, 2019).

4.6.9 Analyzing the Effect of Total Nitrogen on the Pipe Corrosion

Total nitrogen (TN %) describes the presence of microbial remains, decayed plants, and different amounts of composition in the soil. There are various contents of nitrogen compounds in the soil including ammonium (NH_4), nitrite (NO_2), and nitrate (NO_3). Table 4.1 depicts the laboratory report of soil total nitrogen (%TN) within the range of 0.06-0.10. The result shows the minimum amount of nitrogen content in the soil due to more depth of the pipe (80-120 cm). This shows the concentrations of nitrates decrease as the depth of soil increases and vice-versa. Top soil contains much amount of humus which holds more nitrate which can be corrosive to the buried iron pipes due to the presence of microorganisms in the soil, TN initiates microorganisms-influenced corrosion. As a whole, Soil corrosivity has a complicated phenomenon due to a variety of soil parameters including soil pH, sulfate-reducing bacteria (SRB), moisture content, resistivity, oxygen content (aeration), temperature, sulfate, chloride, texture, salt, microorganisms, minerals, electrical conductivity, soil type, etc.

4.6.10 Analyze External Corrosion Damage mechanisms

Soil corrosion is a complex problem that attacks buried pipelines in different ways including electrochemical, mechanical (soil load), and microorganisms. Other weakening mechanisms of water pipes are related to the type of liquids and gas conveying through the pipes that react with the inner wall of the pipes in addition to the working conditions such as pressure and flow rates. Evaluation of soil corrosion condition has several advantages including protecting against pipe corrosion damage and keeping water quality. The mechanisms of corrosion damage of buried structures are understood but the status of soil corrosivity is different from place to place due to the inherent environmental variations. The study focuses on the investigations of soil corrosivity parameters on the buried ferrous water pipes of the city water distribution system to identify major corrosion factors of buried pipes. Based on the study, moisture content, resistivity, total nitrogen (%TN), soil type, and texture were identified as the main corrosive factors to ductile iron and galvanized steel pipes.

The soil analysis result shows that soil moisture content was identified as the major corrosion potential of other mechanisms. This is due to the impact of fine grain sizes in the soil textures such as the percentages of clay and silt is more in the soil. Electrical conductivity was recognized as the main parameter of soil corrosivity due to conductivity behavior to the stray current whereas soil pH is categorized under negligible corrosive factor to the buried pipes but promotes bacterial activity. To minimize soil corrosion; studying the environmental context of soil corrosivity is a primary solution that can create the chance to correct during the design, manufacturing phases, and testing of corrosion resistance of the pipes to produce environmentally adaptable water pipes and control soil corrosion. To control soil corrosion, this study proposes two solutions: (1) water supply owners need to conduct a soil test before installation and (2) the use of less corrosive materials such as volcano red ash and gravel or sand around the pipes before buried is a good technique to control corrosion and prolong the service life of the pipes.

Eventually, the results obtained from the experimental analyses help to understand soil corrosivity status and others including predicting the remaining service life of buried water pipes, changing the path of the pipeline where necessary, and taking actions of corrosion controlling strategy. External corrosion characteristics of buried iron pipes are influenced by the soil parameters of corrosion formation through a chemical or electrochemical reaction. The rate of corrosion damage accelerates as the amount of moisture and oxygen increases in the soil. Soil

parameters like electrical conductivity and soil type have their effect on the pipe surface damage. Overall, site #2 is more corrosive to underground pipes than sites #1 and #3, according to soil physicochemical studies, with corrosivity statuses ranging from "moderately corrosive to mildly corrosive" in decreasing order.

4.7 Internal Pipe Wall Corrosion Analysis

Localized corrosion can occur when corrosive substances are combined with deposits on the pipe wall. The removal of scales during sample analysis aids in evaluating pitting aspects. Corrosion products have different colors such as white, red, and brown Figure 4.7. The corrosion product having white color is ZnO and the red color represents Fe_3O_4 while the brown color is identified as Fe_2O_3 . Based on the visual observation, at some random points on the surface of the pipes, the geometry of corrosion has different sizes, shapes, and depths of localized corrosion. The surface irregularities observed on both internal and external surfaces were a result of soil and water effect during long-run service years. After the protecting zinc coating has oxidized, the steel surface begins to form corrosion scales around the pipe and localized corrosion damage continued to the subsurface of the pipes even further attacking the whole pipe thickness.

Internal pipe corrosion is influenced by water physicochemical parameters such as alkalinity, protective film stability, and low pH, as well as the presence of heavy metals in the drinking water, which can induce corrosion and threats of health risks. Similarly, corrosion mechanisms such as dissolved oxygen concentration, erosion-corrosion, and corrosion behavior of the pipes were identified as the key internal pipe corrosion damage. The other corrosion mechanism of the pipe wall is the alloying process of pipe manufacturing due to the contact of dissimilar alloying elements which forms galvanic corrosion. To mention collectively, the main pipe failure mechanisms are corrosion, the presence of defects during manufacturing, the impact of

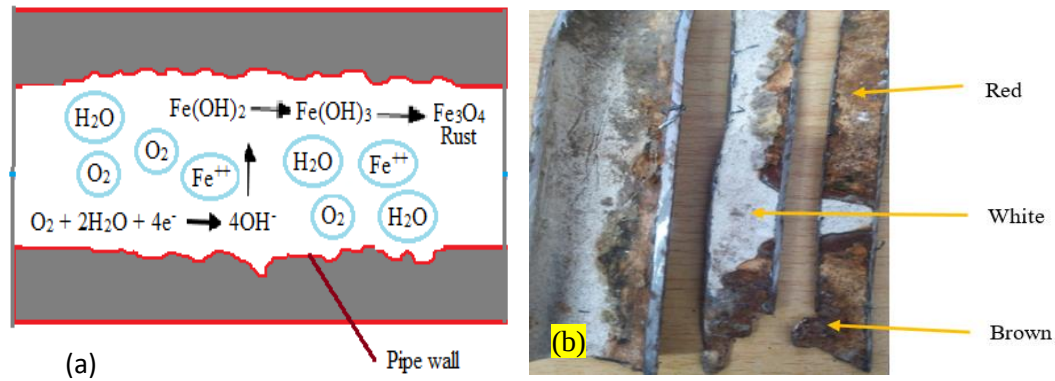


Figure 4.7 Corrosion formation process: (a) Schematics of pipe wall & (b) Internal pipe corrosion pattern

some water physicochemical, and water flow rate with high pressure. When ferrous oxide reacts with dissolved oxygen and water it forms a corrosion scale (magnetite, Fe_3O_4).

4.7.1 Corrosion Damage Mechanisms for Internal Pipe

Investigating corrosion damage mechanisms, water quality, and prediction of the remaining pipe age and corrosion control, are major concerns of water supply owners. The characteristics of corrosion damage depend on the condition of corrosion films or scale formation and growth. Uniform and pitting corrosion is the result of the pipe corrosion process. When the pipes interact with different types of damage mechanisms, the long-term continuous oxidation process causes the pit depth to grow and be covered in corrosive deposits which leads to the pipe surfaces forming holes. Many factors, including water pipe materials and manufacturing processes, bacteria, water treatment chemicals, dissolved oxygen, and a lack of planned inspection and maintenance, all contribute to the pipe wall corrosion damage. Additionally, dissolved gases such as oxygen and carbon dioxide in water transport are other causes of corrosion mechanisms (Vertova et al., 2017). Other internal causes of corrosion are water velocity and pressure erosion-corrosion and stress corrosion cracking over service time. Water flow is categorized as low velocity (0.07 m/s), medium velocity (0.4 - 0.6 m/s), and high velocity (approximately 1.5-2 m/s) (Treesa et al., 2019). Water pipes damage symptoms such as localized pitting size, pipe wall fracture, and surface deterioration are critical characteristics to consider while doing pipe maintenance (Journal et al., 2016; H. Zhang et al., 2018).

Corrosion is an unwanted result obtained from the reaction between the environment and materials with time function. The pipe structure deterioration is caused by the factors of soil corrosivity and water environment corrosion aggressivity conditions. The bond of the coating is damaged by different causes such as environmental, operational conditions, and mechanical factors. Water physicochemical that affect pipe walls are identified as dissolved oxygen (80-81 ppb), conductivity (171.4 – 493.4 $\mu\text{S}/\text{cm}$), CaCO_3 (77 - 215 ppm), total dissolved solids (TDS) (84.10 – 262.8 ppm), service load, and ClO_2 (0 – 0.5 ppm).

The results of the water physicochemical laboratory test are shown in Table 4.3. The pH of the water was found to be between 7.05 and 7.86, which is within the standard WHO range of 6.5 to 8.5 (4th edition, 2011) and does not influence pipe corrosion. The lower level of ClO_2 (0.0-0.5 ppm), on the other hand, implies that the amount is highly influenced by pipe wall corrosion. Chlorine dioxide is used in drinking water as a disinfectant; however, it has a degrading impact on pipe walls (Shams et al., 2019). Under the electrochemical process of cathodic and anodic reactions, the release of scales into the water results in a loss of water quality (Hu et al., 2017).

Table 4.3 Water physicochemical analysis results

Water parameter	Site codes					WHO (2011)
	#01	#02	#03	#04	#05	
pH	7.71	7.05	7.64	7.68	7.86	6.5-8.5
Chlorine dioxide (ppm)	0.5	0.05	0.0	0.12	0.0	0-0.2
Total hardness (CaCO_3) (ppm)	84	87	90	77	215	61-121
Fe^{+3} (ppm)	0.45	0.0	0.1	0.55	0.05	0-0.3
Conductivity of water ($\mu\text{S}/\text{Cm}$)	171	197	197.3	157.8	493.4	up to 400
Total dissolved solids (ppm)	91.6	105	105.4	84.10	262.8	up to 500
Dissolved Oxygen (ppb)	80	-	-	81	80	—

This is due to the dissolution of iron taking place at the anode (Eqn. 4.9) and creating a pit depth that can hold chloride and other ions which accelerates the rate of localized corrosion.



While the cathodic reaction is affected by oxygen:

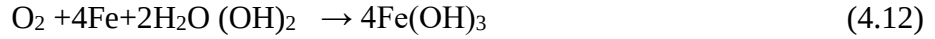


The presence of inorganic salts and organic matter in the water as microscopic particles are capable of forming deposits on the pipe wall at stagnant conditions of water flow indicates the presence of total dissolved solids. As presented in Table 4.3, the total dissolved solids (TDS) ranged from 84.10 to 262.8 ppm. The highest TDS value was found in sample code #5, which was 262.8 parts per million (ppm). This demonstrates that the number of solid particles in groundwater is higher than the number of solid particles in surface water due to the presence of dissolving substances while water moves in the soil (Alamineh, 2018). Though the TDS level was higher than in other samples, it did not affect health, but the solids were able to develop deposits on the pipe wall over time during water stagnant conditions and damage the pipe surface. The lab test result of water electrical conductivity (EC) ranged from (157.8 - 493.4 micro-Siemens per centimeter ($\mu\text{S}/\text{Cm}$)). The EC depends based on the amount of iron released and the total dissolved particles in the water. The presence of EC indicates the potential of water able to pass the flow of electric current from the pipe is higher which enhances the rate of internal corrosion.

As it is presented in Table 4.3, the lab result of ferric ion (Fe^{3+}) ranged from 0.05-0.55 ppm in the analyses. This indicates the rate of iron dissolution is higher in some of the samples. The results of water physicochemical obtained from different sites 02, 03, and 05 reported ferric oxide was at normal conditions whereas sites 01 and 04 were higher amounts of ferric ion release. This indicates, that the rate of internal pipe corrosion condition is enhanced by dissolved oxygen. As the attack of ferric oxide increases, it has great potential to form a magnetite (Fe_3O_4) compound of corrosion scale which affects water taste and color. The other factor of internal pipe corrosion is water hardness caused by dissolved calcium irons which form protective scales on the pipe wall. As the size of the scale increases during the stagnant condition of water flow, the scale layer creates turbulent and develops erosion-corrosion.

During the chemical reaction of iron, oxygen, and water, dissolved oxygen (DO) induced the formation of iron oxides in the water. Internal pipe wall corrosion is accelerated by DO, which was deoxidized at the cathode during electrochemical processes. The DO's laboratory report indicated that the results were in the 80-81 ppb range, indicating that internal corrosion is accelerated and ferrous oxides are formed due to chemical reaction:





4.7.2 Characterization of Internal Corrosion Morphology

Surface corrosion of underground water pipes is caused by a chemical and electrochemical interaction of soil, water, and pipe interface. Internal pipe corrosion morphology caused by the water environment was characterized by the image processing method. The topography of the corroded surface filled with watershed segmentation was generated from the SEM image Figure 4.9. It displays that the image was divided automatically by the software into several particles and labeled by the numbers with grain boundaries. This is important to characterize corrosion features as per particle level. After the characterization of each particle and the results are summarized by the software itself in the form of tables and graphs. In general, even though, the concentrations of drinking water physicochemical are at standard levels and have no health effect, some parameters can be the mechanisms such as dissolved oxygen, total dissolved solids, erosion-corrosion, and water pressure are the main actors to the damaged pipe wall.

Figure 4.8(a) shows the graph of minimum and maximum pit depths are 40 and 120 μm respectively. Figure 4.8(b) also displays the result of maximum height (Z-max) which is above the mean line of surface features. The graph shows the roughness or irregularity of corrosion-damaged surface values ranging from (40-70) μm . Figure 4.8(c) also presents minimum and maximum pit areas ranging from (400-1600) μm^2 . Additionally, Figure 4.8(d) is indicating the volume of the pit varied from (10,000-40,000) μm^3 among the particles. Similarly, Figure 4.8(e) presents the evaluation of pit shapes (roundness) per particle. Corrosion morphology characteristics were further characterized using Mountains surface analysis software. The characterization was conducted at the particle level to get threshold corrosion characteristics and to determine other important morphologies including, grain boundaries, and pitting features such as pit area, depth, shape, cavities, and diameters from the 2D picture of SEM source using the watershed segmentation to get the results statistically in the form of Table and topography image as shown in Figure 4.9.

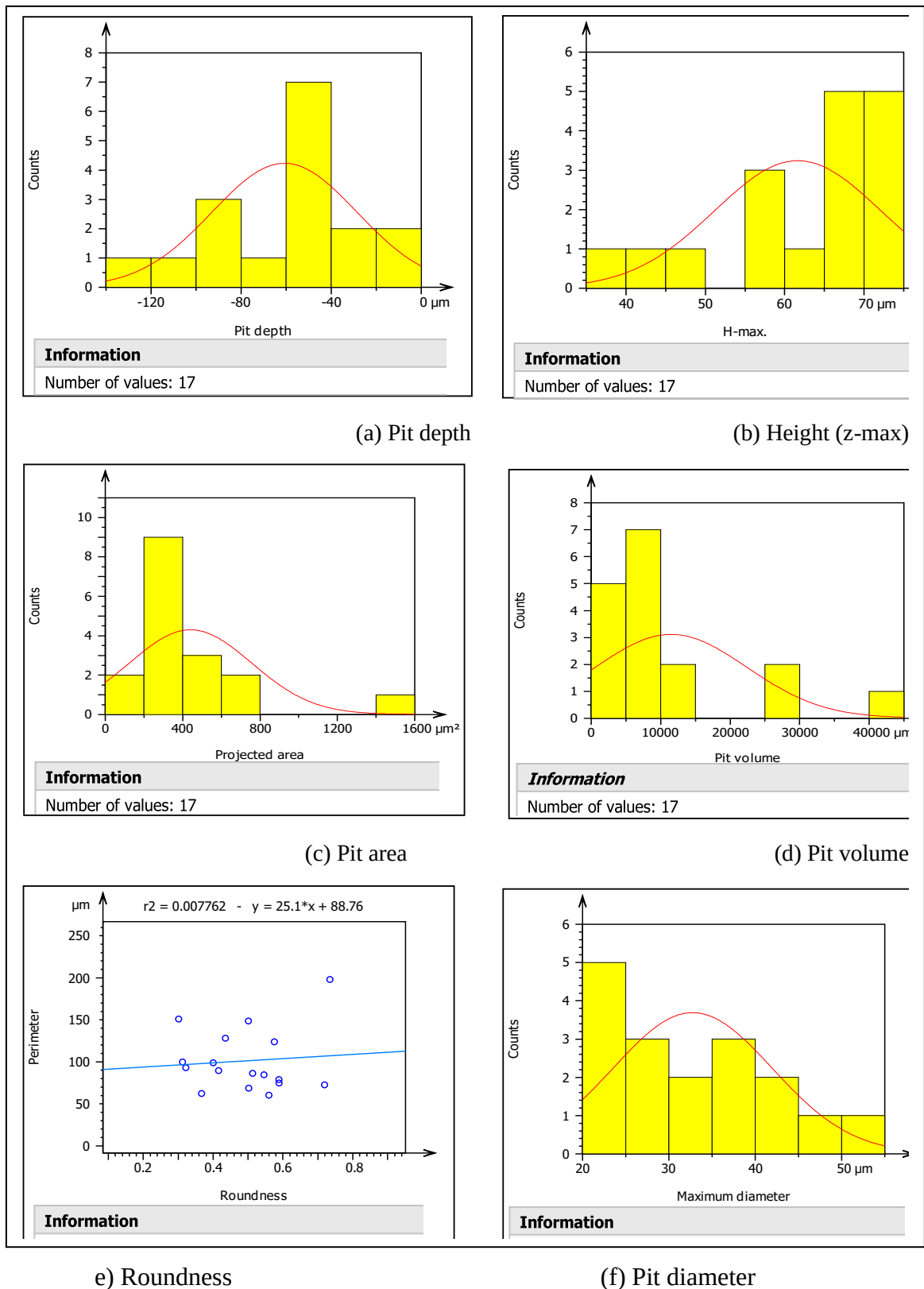


Figure 4.8 Characterization results of pitting corrosion

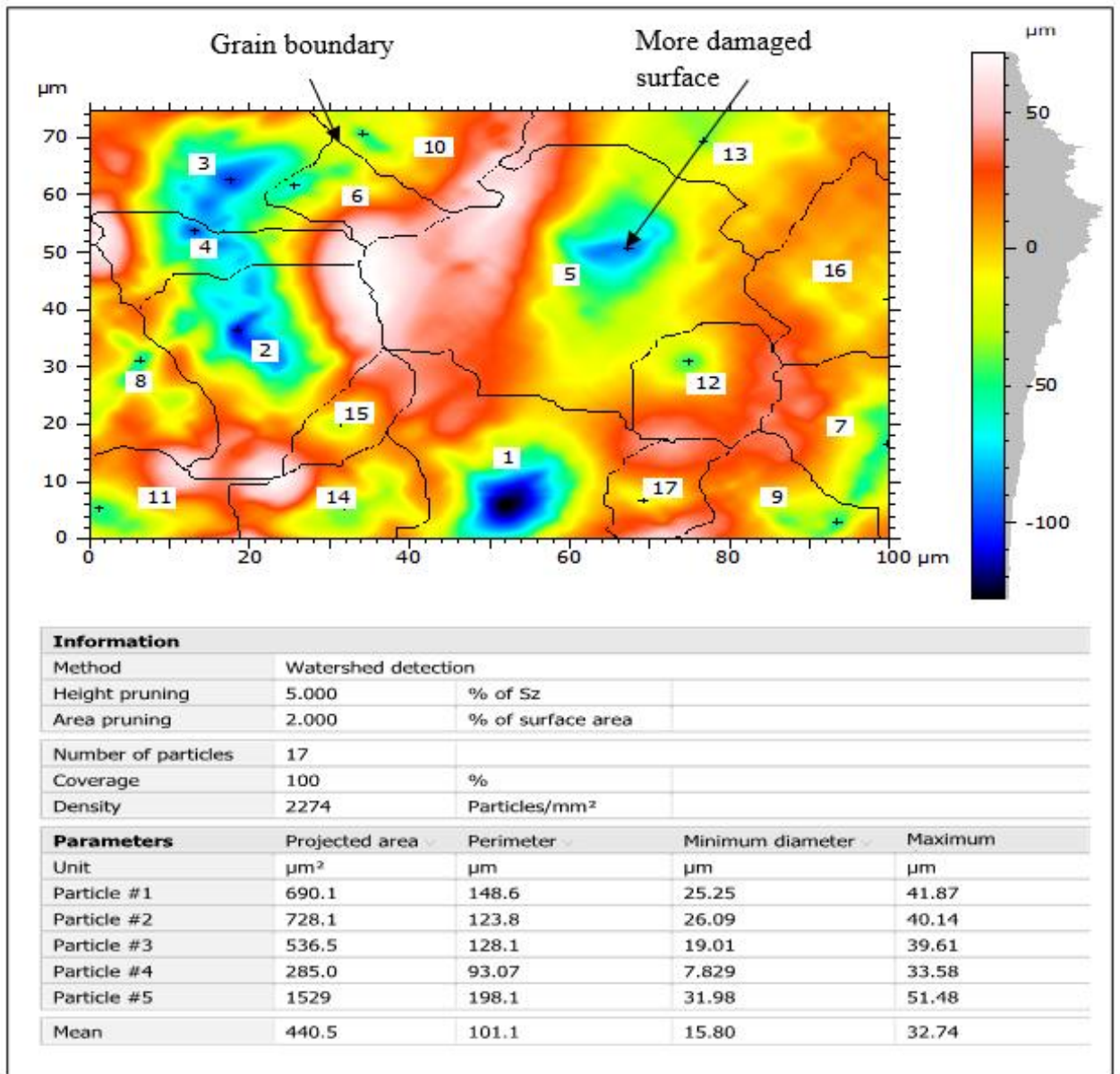


Figure 4.9 Corrosion morphology of watershed segmentation

Internal corrosion has a different morphology from external corrosion, owing to fundamental differences in environmental corrosion mechanisms Figure 4.10 and 4.11. On the internal pipe wall of DCI variety of corrosion forms were observed including perforation and erosion-corrosion. This is due to the service load, age, and operation conditions such as water pressure and velocity in addition to the water parameters. On the other hand, external corrosion is affected by soil factors including moisture content, soil bacteria, resistivity, and total nitrogen.

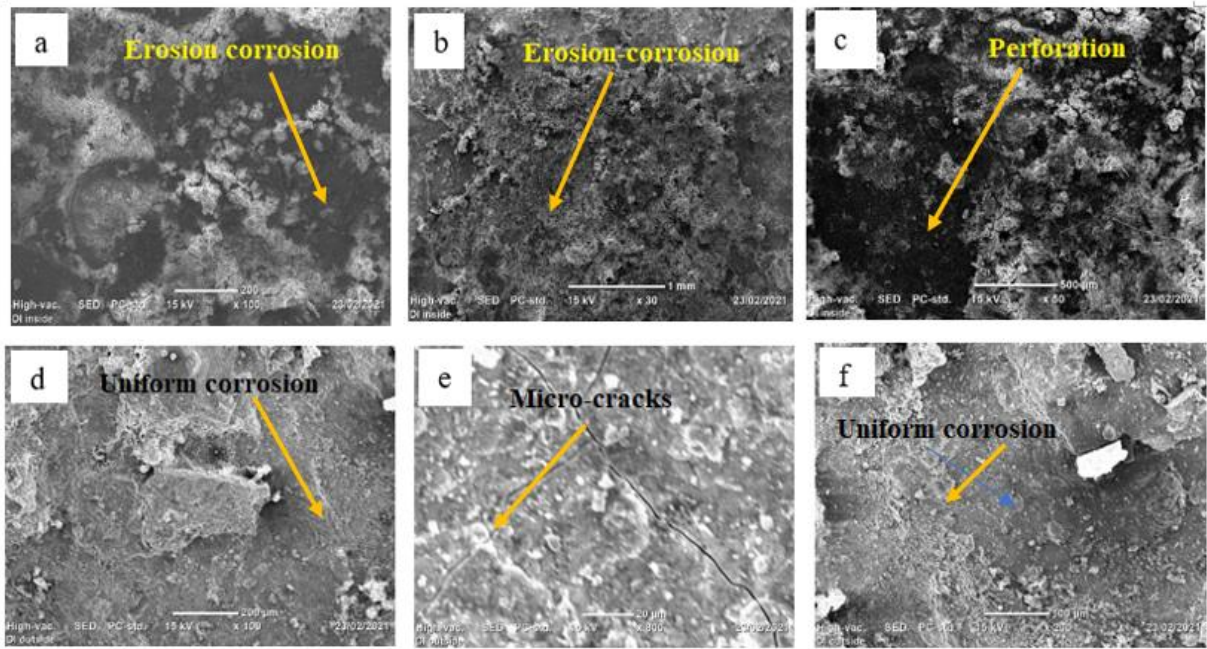


Figure 4.10 SEM image of corrosion morphologies patterns of DCI pipes: (a, b & c) internal surface; (d, e & f) external surface

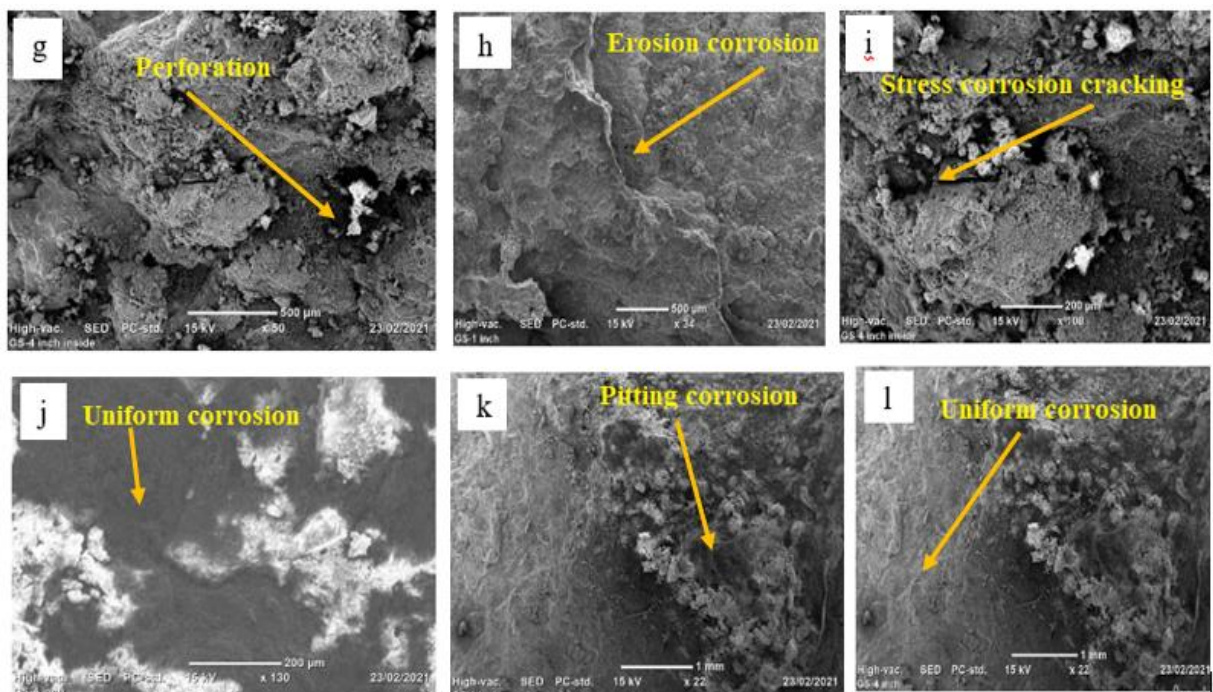


Figure 4.11 SEM image of corrosion morphologies patterns of GS pipes: (g, h & i) internal surfaces; (j, k & l) external surfaces

Internal pipe corrosion damage mechanisms (CDMs) were studied on the DCI and GS water pipes and corrosion characterization was performed to investigate corrosion behaviors. Internal pipe corrosion is also caused by dissolved oxygen, ClO_2 , and total dissolved solids, according to water laboratory test results. Another cause of iron pipe corrosion is soil corrosivity, which attacks external pipe surfaces and causes uniform and localized corrosion. Due to the dissolution of metallic ions during electrochemical reactions, a scanning electron microscope (SEM) corrosion morphology study reveals the deterioration of pipe walls with uneven surface profiles. The SEM image characterization also shows that a micro-crack has formed in the pipe subsurface wall, indicating that the pipe has failed due to the combined impacts of narrow pits and water pressure. The study concluded that the reduction in pipe thickness was due to the combined effects of water parameters, erosion-corrosion, and the rate of water flow.

Based on a variety of investigation techniques including SEM analysis, visual inspection, weight loss calculation, image processing, and water physicochemical analysis, internal pipe wall corrosion is a costly problem that needs more attention. To summarize, internal corrosion is a complicated process caused by a range of causes such as the interaction of water pipe materials with the environment. Internal pipe corrosion can also be caused by trace elements such as lead, copper, and others while deposited on the surface of pipes. On the other hand, the external pipe surface is mainly damaged by soil resistivity, low value of pH, moisture content, and chloride. The presence of soil electrical resistivity is the main indicator of soil corrosivity attacking the surface of pipes due to chemical content and varying temperatures. To manage corrosion mechanisms, water supply owners need to conduct frequent inspections, maintain historical pipe data, test water quality after treatment, wash pipelines regularly, and apply preventative maintenance.

4.8 Characterizations of Corrosion Morphology on the Pipe Surface

This study explored characterizations of corrosion morphologies for both external and internal pipe surfaces and the subsurface of corrosion-damaged galvanized steel and ductile iron water pipes. The characterization considered manufacturing process and environmental factors and how the buried pipe surfaces continuously reduced their aesthetic and mechanical properties with time function. The proposed method of corrosion characterizing using Mountains digital image surface analysis software is a fast, cost-effective, and favorable technique that analyses

corrosion failed surfaces at the particle level. The SEM and image processing analyses confirmed that micro-cracks are observed in the subsurface due to environmental and stress corrosion cracking (SCC). Internal pipe wall corrosion damage is caused by different parameters but the main pipe surface damage mechanisms are grouped into two categories; viz, deposits on the wall during the stagnant condition, and localized corrosion. The acceptability of corrosion defects was investigated using image processing based on the ISO 25178-2 standard, microstructure analysis, and corrosion morphology characteristics.

4.9 Visual Inspection

Figures 4.12(a, b) show the internal corrosion of galvanized pipes and ductile cast iron respectively. As visually compared with the two pipes, more corrosion damage was observed on the galvanized pipe wall. Such differences existed from a variety of corrosion parameters including type of pipe material, service age, soil environment, water environment, and operation conditions. In addition, corrosion scale and localized pitting corrosion were detected visually at the macro level. To determine the type of laboratory choices and corrosion characterizations as well as to gain insight into the severity of the corrosion status, visual inspection is essential.

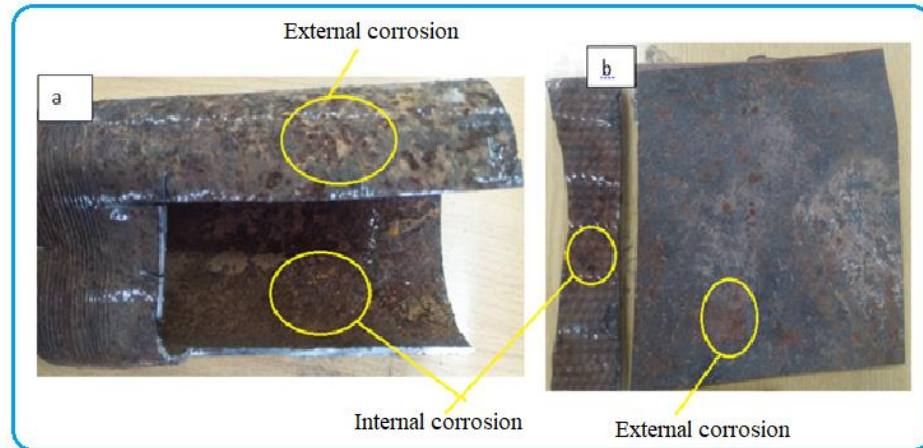


Figure 4.12 Photographs of typical pipes' internal and external corrosion patterns: (a) GS pipe and (b) DIP pipe

Based on the various characterization of corrosion morphology of buried pipes concerning environmental factors and pipe materials, the rate of corrosion deterioration process was categorized as: (1) pipe coating corrosion damage; (2) external pipe surface weakening, and (3) subsurface corrosion degradation and failure of pipe structures. This study provides

knowledge of water pipes' corrosion damage processes at the surface and subsurface of the pipes. The outcome of this study will be important for the water distribution system and infrastructure owners including industries and transportation sectors to understand the process of corrosion which leads to deciding on controlling mechanisms at an early stage. It is also very important for industries to evaluate corrosion behaviors on iron materials at any stage to investigate corrosion status. The study also gives input for the pipe manufacturers to design environmentally compatible water pipes for such types of environments to address the demand of customers that can get a longer service life of water pipes. The study recommends regular pipe inspection, maintenance, and water testing are very important to the water distribution system owners.

4.10 Microstructures study

The composition of alloying elements and the manufacturing process can create defects that contribute to corrosion formation especially when there are voids and micropores in the structure. Figure 4.13 displays optical microscopic (OM) cross-sections of galvanized steel metallographic structures. The microstructures reveal all of the grain size and boundary structural information, which is seen as a homogeneous distribution of alloying elements.

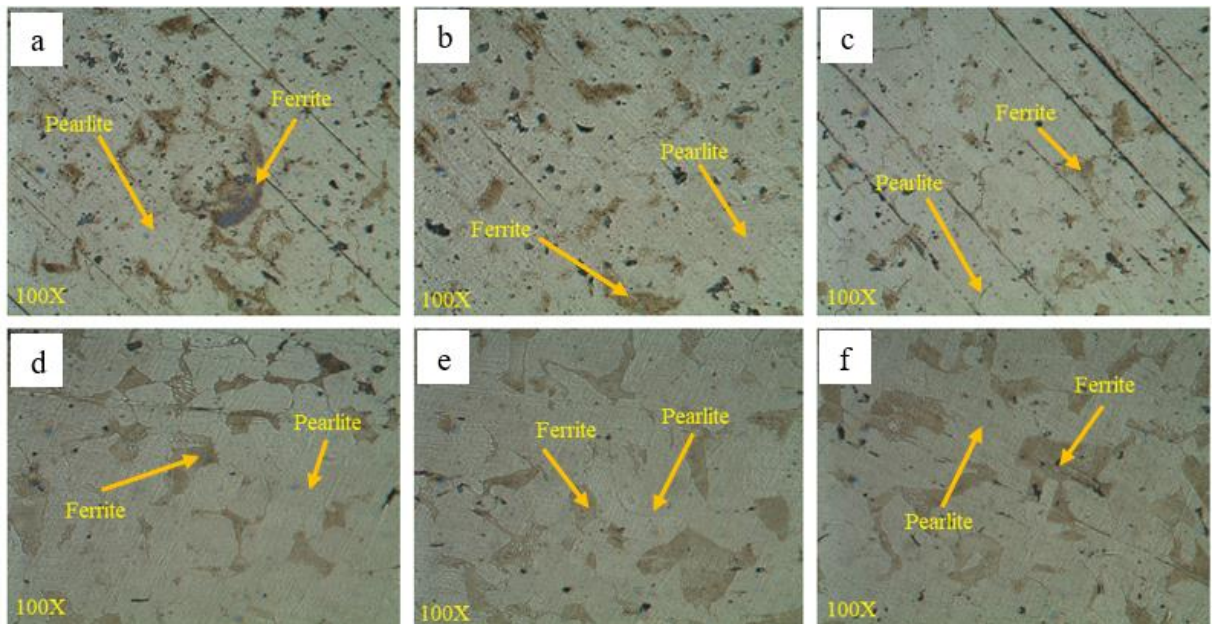


Figure 4.13 Microstructures of GS base metal for new pipe

The microstructures were analyzed at a magnification of 100X under optical metallurgical microscopy and the structures were observed as pearlite with white color and ferrite marked by gray color. The cross-sectional surface micromorphology shows the possibility of particle deterioration occurrence on the surface where at the interface between ferrite and pearlite due to the two dissimilar structures acting as galvanic corrosion. Corrosion can be occurred between the grain boundaries as the service age of pipes increases due to the internal stress corrosion cracking (SCC) developed by water pressure and soil load leading to cracking of the surfaces along the weak boundaries.

The uneven distributions of alloying elements lead to microcracks at the boundaries and develop low corrosion resistance to the products which forms intergranular corrosion along the contact lines. Directional grains can create intergranular corrosion that causes the formation of microcracks in the structure (Rumaisha et al., 2016). Nonuniform alloying elements and grain structures develop uneven morphologies in the internal microstructures which form intergranular corrosion. The microstructure analysis was conducted from the sample of the new galvanized steel pipe cross-section, not from the top or bottom surface. The reason was to evaluate the internal details easily from the cross-sectioned part.

The typical ductile iron pipe used for the characterization is shown in Figure 4.14. The distribution and number of alloying elements affect the microstructures and defect formation. The microstructures indicate a spheroidal graphite shape distributed in the DIP structure

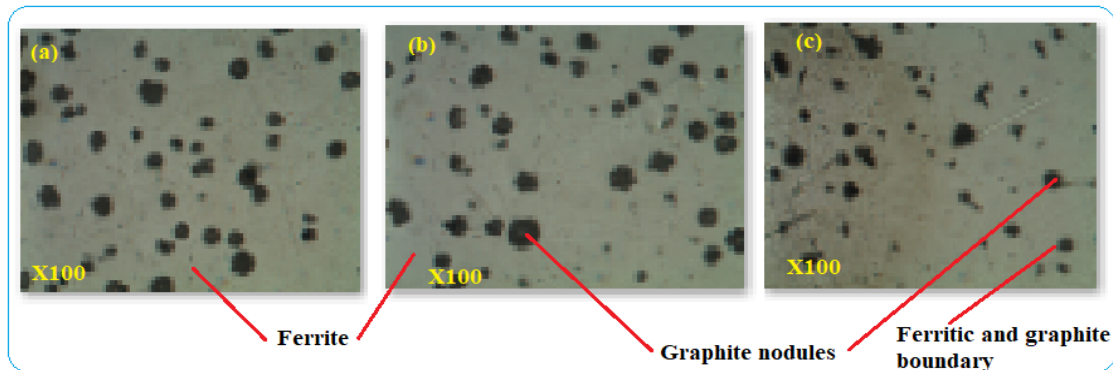


Figure 4.14 Microstructures of DIP pipe base metal for new pipe

surrounded by α -ferrite. Graphite makes the pipe have better tensile properties than other types of cast-iron pipes. The size and shape of graphite depend on the manufacturing process of the pipe.

4.11 Analysis of Stress Corrosion Cracking

The combined effect of corrosion and tensile stress generates stress corrosion cracking (SCC), which is formed with the aid of environmental-assisted cracking caused by water and soil stresses induced on the pipelines. The lifetime of the pipe reduces due to the external load constantly stressing the pipe and the fluctuating water pressure exerted on the internal pipe wall. Water pressure opens the crack and corrosion of the pit increases its depth whereas the external pipe surface is influenced by soil load to bend the pipe. To overcome such failure, considering yield strength which is one of the design criteria of mechanical properties helps to get good ductility for the pipes. The other mechanical property of the water pipe is the hardness of the pipe material, which has a relation to crack formation. A pipe that has a greater hardness value has a better property of crack resistance.

Table 4.4 shows the results of average Vickers hardness (VH) values of water pipes from the three trial tests. The hardness of the 100 mm diameter GS pipe sample registered as 166.03 VH number which indicates more resistance to crack than the ductile iron pipe. The hardness value of galvanized steel pipe (GSP) is more than ductile iron pipe (DIP) which indicates GSP has more resistance to crack than DCI. This mechanical property was attained during the heat treatment of pipe manufacturing.

$$VH = \frac{\text{constant} \times \text{test force}}{\text{The surface area of indentation}} = 0.102 \times \frac{2F \left(\sin\left(\frac{136}{2} \text{deg}\right) \right)}{d^2} \quad (4.13)$$

Where F is the load in Kg.f and d is the average length of the diagonals formed in the indented area in mm².

Table 4.4 Vickers hardness test values of water pipes

Load (kg. f)	Dwelling time (sec.)	Specimen	Number of tests			Average Vickers Hardness
			1	2	3	
10	10	φ100 mm GS pipe	166.8	164.5	166.8	166.03
		φ350 mm DCI pipe	163.4	162.3	161.2	162.30

The SCC is not uniform due to the mechanical effect at a certain location where anodic sites developed on the surface of the pipe due to corrosion. The SCC is mostly occurred by the stresses induced on the pipe. There are also several causes susceptible to SCC including grain size, texture, grain boundaries, and intergranular defect in the microstructure which leads to pipe cracks or localized fracture. The direction of stress corrosion cracking is perpendicular to the stress acting. Hence, circumferential stress is responsible for the initiation and propagation of cracks combined with corrosion attacks. The cracks of SCC were observed from the in-situ condition of old ductile cast iron and galvanized water pipes. Localized corrosion patches also contribute to the corrosion damage of ductile cast iron pipe. The patches lead to the growing pit depth and then a crack develops due to the combined effect of water pressure and soil corrosion Figure 4.15.

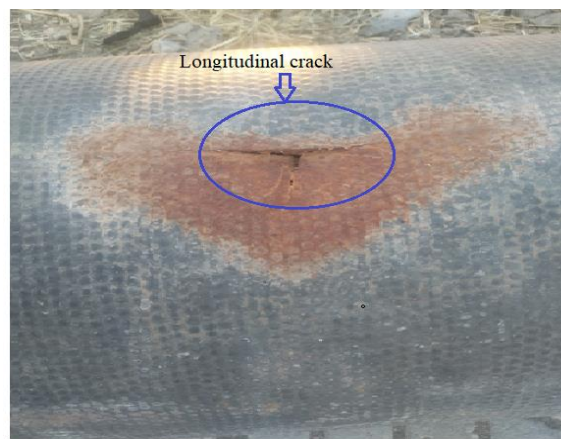


Figure 4.15 Typical localized corrosion patterns and longitudinal crack failure

The relative softness of the pipe material inhibits the crack formation and propagation in the ferrite microstructure. The yield strength is important to describe the failure of ductile materials like ductile cast iron pipe. Figure 4.16 shows comparative sizes of impressions between galvanized steel pipe and ductile iron pipe. similarly, Figure 4.16b has more impression size than GSP which means DIP is softer than GSP and becomes lesser to resist cracks. The actual crack conditions of the pipe were evaluated using SEM analysis, the micro-cracks started at the subsurface of both pipes. The shape of the cracks is in the case of ductile iron pipe non-directional cracks due to the contents of graphite distribution forming intergranular corrosion along the grain boundaries.

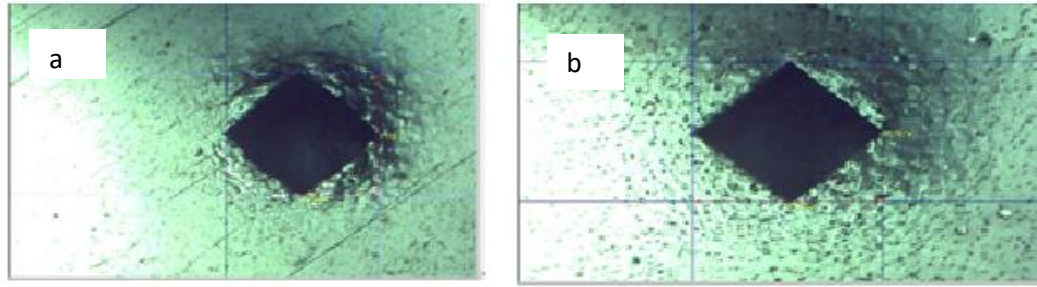


Figure 4.16 The impression sizes of Vickers hardness indenter: (a) galvanized pipe and (b) ductile iron pipe

4.12 Corrosion Crack formation processes analysis

A crack investigation was conducted using SEM analysis to understand the status of stress corrosion cracking and its mechanisms. Main cracks were observed along a circumferential direction but fine tributaries were visible along the longitudinal cracks. The SCC occurred at the near-neutral pH value of water (6.9-7.04) due to the transgranular effect which makes branched sharp micro-cracks show that the SCC is actively propagating on the surface of the pipe. Micro-cracks are generated from inside ferrite grain boundaries due to intergranular corrosion. Micro-crack is the mode of pipeline fracture on the DIP due to graphite nodules and pearlite structures trying to make a crack with the help of a cyclic water hammer and constant pressure (burst) which forms intergranular fracture (Jiang et al., 2017, 2019). Many environmental corrosion factors such as pH, Cl concentration. Temperature, hydrogen sulfide, amount of stress, and moisture are susceptible to SCC.

Dissolved oxygen concentration enhances stress corrosion cracking (SCC). As the concentration of DO increases, susceptibility to SCC initially increased and later decreases due to the formation of corrosion protective layers (Gong et al., 2020). The formation of cracks is caused by tensile stress caused by water pressure, narrow pit growth, and soil weight. Intergranular corrosion stops when a passive coating forms on the penetrating tip of intergranular corrosion. Both crack initiation and growth are caused by fracture of the brittle passive layer along grain boundaries, which is caused by localized plastic deformation caused by load application and/or other stress sources. The occurrence of SCC on water pipes is mainly caused by water burst pressure and metallurgical effect among alloying elements. The cracks of SCC were observed from the in-situ condition of old ductile cast iron and galvanized water pipes Figure 4.17.

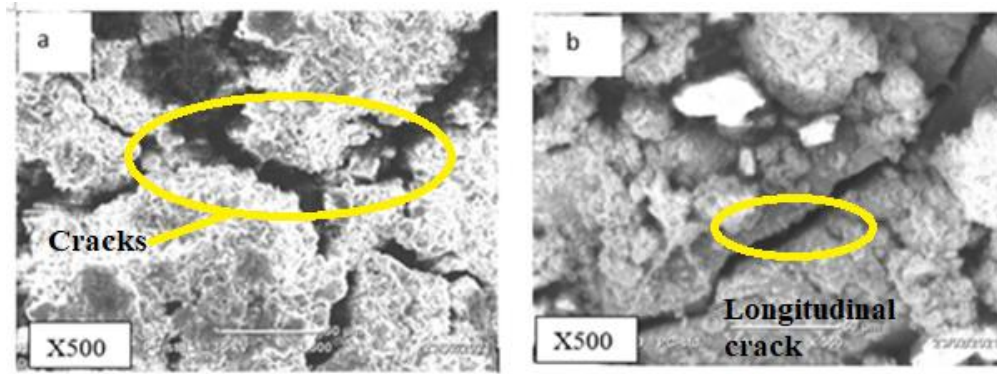


Figure 4.17 Stress corrosion cracking: (a) ductile iron pipe and (b) galvanized steel pipe

Intergranular cracking accelerates corrosion (along the outer surface as well as in the depth direction) and thus fracture initiation. The synergistic combination of material, environment and mechanical loading conditions causes crack initiation and growth. The corrosion rate, passivation/re-passivation kinetics, and qualities of the passive film are all determined by the material-environment combination. Any environmental or metallurgical factors that promote the passive film's stability (either an increase in thickness or a decrease in thickness).

4.13 Analysis of Internal Pipes Surface Deterioration

Several SEM imaged sizes were taken including (50, 100, 200, 500) μm & 1mm. For this study, 500 μm is used with a magnification of X50 as shown in Fig. 4.18. Figure 4.18a-c depicts the morphologies of internal corrosion in SEM images. Fig. 4.18a shows the SEM image of the DCI pipe wall which was damaged by the uniform and localized corrosions during the service years with operating water pressure of 150 to 350 KPa. Similarly, Fig. 4.18b presents corrosion damaged surfaces of galvanized pipes. Perforation and tubercles of iron pipes' surface depend on the pipe material, and the variety of corrosion products that affect service lifetime. Similarly, Figure 4.18c shows the corrosion crystals of GS pipe having irregular shapes and porous textures due to the formation of pitting at random locations which breaks corrosion films to have irregular shapes. The crystalline structure of iron-hydroxide corrosion products, which frequently contain alpha-, beta-, and gamma- FeOOH , is created during the pipe surface deterioration process. Through careful analysis of crystallographic structures, it is possible to get additional oxides such as Fe_3O_4 and Fe_2O_3 , which aids in the identification of corrosion mechanisms. Due to many factors, including pressure, corrosion phenomena are complicated and might result in unanticipated pipeline failure in the water distribution system.

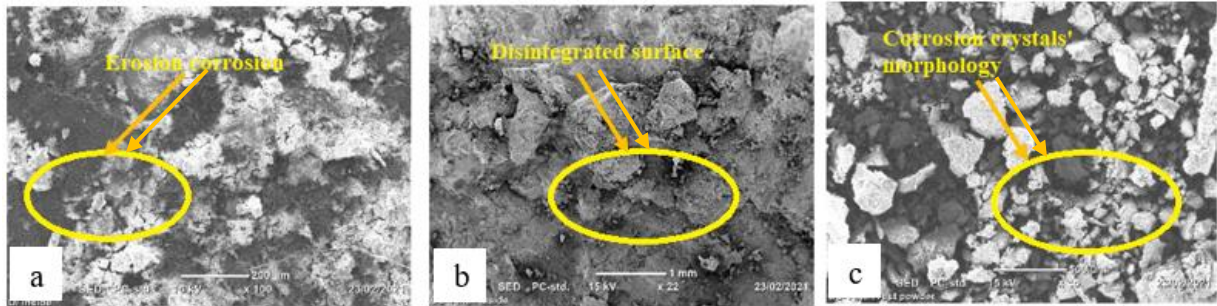


Figure 4.18 Micrographs of SEM internal pipe corrosions (50X): (a) DCI; (b) GS pipe and (c) Corrosion crystals of GS pipe

Corrosion is a form of defect on the surface of water pipes that needs early detection to evaluate the corrosion damage status of the pipes, control water contaminants, and apply maintenance activities. Analyzing the rate of pipe surface removal due to electrochemical reaction is useful to determine the corrosion characteristics on the pipes in a given area with a time function. The forms of corrosion formed on the water pipes during the service times are shown in Figure 4.19 with different irregular surfaces having pitting and uniform corruptions. The entire surfaces of the pipes were damaged with non-uniformly corrosion products. The features of corrosion-damaged surface morphology including pit shape, size, and depth depend on the behaviors of corrosion damage mechanisms.

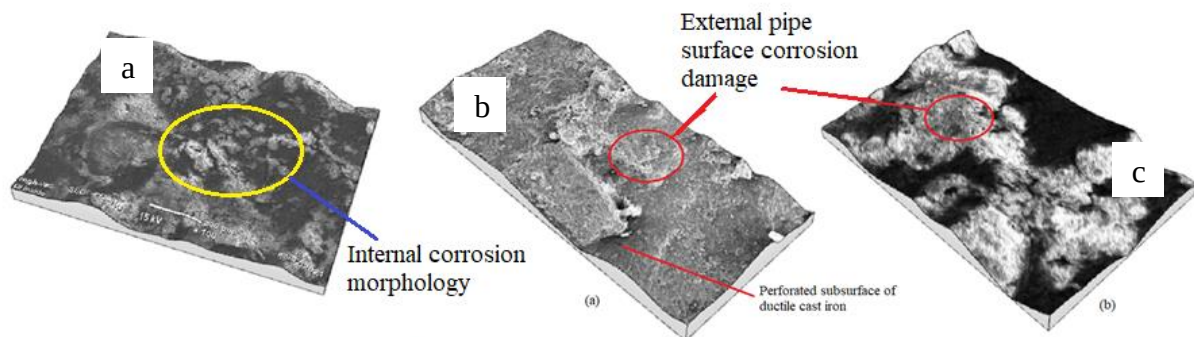
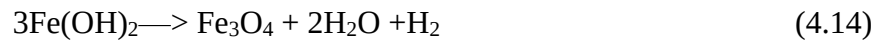


Figure 4.19 3D images of corrosion morphology: (a) Internal ductile iron pipe corrosion; (b) external Galvanized steel corrosion

Pitting is formed when the passive layer locally breaks which can easily attack the pipe surface. The process of the passive layer breakage is assumed as a galvanic cell that develops an anodic site where the pipe corrodes and the undamaged area acts as cathodic protection. The

process of corrosion begins at the anode due to the loss of metallic ions and a reduction reaction is formed at the cathode which consumes electrons in the process of electrochemical reaction. As the pit depth increases, it acts as a pocket to hold moisture, chloride, and mineral ions able to form acidic or salty depending on the content soil parameters which accelerates the corrosion rate. Corrosion damage of underground ferrous pipes begins at the outer surface and then continues to the subsurface according to the soil's environmental context. Studying the chemical interaction of the soil-pipe surface is crucial to identifying soil behavior, applying maintenance and replacement, and predicting pipes' operational service time. Soil moisture attacks the pipe surface by forming Fe(OH)_2 thin layer corrosion product and through time process which decomposes into magnetite in the presence of dissolved oxygen (Li et al., 2018).



Ductile iron and galvanized steel pipes are mainly used for water distribution due to their mechanical advantages. But their service life is challenged by different corrosion mechanisms such as the formation of small cracks, non-uniform coating thickness, and environmental impacts during the exposure time. Through the time process, buried pipes are interacting with soil and water environments in addition to operating conditions such as water flow rate and pressure conditions. From the detailed analysis, internal and external pipe corrosion mechanisms are grouped as (1) mechanical effects such as soil load and stress corrosion cracking (SCC) and (2) electrochemical reactions or environmental impacts with time function. The electrochemical reaction creates different stable corrosion products such as iron oxides and iron hydroxides which are indicators of surface deterioration. The process of pipe surface damage begins when the passive film breaks on different occasions which leads to pitting formation. Due to this, the pits continuously propagate and penetrate the surface of the pipe at random points, and later develop uniform corrosion when colonies of pits are joined to each other and the process continues till pitting termination or leakage formation.

The rate of pipe surface deterioration accelerates with the presence of chlorine ion which dissolves iron particles at the anodic site. Others such as galvanic, uniform, and pitting corrosions are the failure mechanisms of water pipes. The formation of pitting passes three stages; namely, pitting initiation, pitting growth, and pitting termination or leakage. At the initiation phase, the external surface including the coating has direct contact with moisture and

oxygen which can form films. The films then easily break due to an electrochemical reaction and create initial pitting which damages the coating and then the external surface.

The pits growth occurs at the second stage and damages the external pipe surface then it proceeds to the subsurface of the pipes due to the formation of depth. At this stage, stress corrosion cracking contributes to the rate of pit corrosion faster and the size of pits grows easily. Depending on the variations in pit depth and width, a local colony of pits meets each other and the surface of the pipes deteriorates layer-by-layer as shown in Figure 4.20(a, b). Further dissolution occurs at the anodic site and consequently, the growth of pits forms pipe breakage and leakage. The cycle continues to damage the external and subsurface are easily attacked by electrochemical reactions. When the pit depth increases, it can hold more amount of moisture and oxygen which accelerated the rate of corrosion till leakage formation. This indicates the combined effect of pitting and uniform corrosions leads to surface deterioration with time function. Figure 4.20(b) presents the result (topography features) of image processing obtained from external corrosion morphology of the DIP deteriorated surface which identified peaks and dale of the surface textures. The topography of the damaged surface is filled with watershed detection to process it for further analysis at the particle level categorizing by grain boundaries.

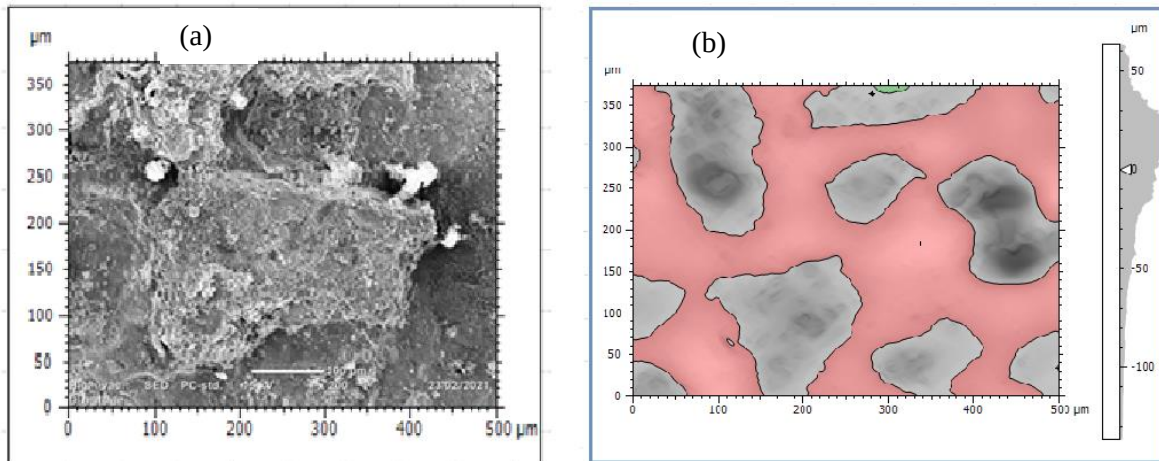


Figure 4.20 External corrosion damaged surface of DIP: (a) true color of SEM image and (b) corrosion scale morphologies

From the image analysis, it is concluded that the Mountains surface analysis software identified the topography of the corrosion failed pipe surface that the structure is deteriorated layer-by-layer creating the peaks and dale of corrosion damaged surface. In corrosion

characterization, pitting features such as diameter are very important parameters to describe the pitting situation in the relation to pit depth. The ISO 25178-2 watershed segmentation method is effective to detect the morphology of corrosion-damaged surfaces to determine the features of corrosion behaviors under in-situ conditions. The investigation determined that the maximum pit diameter is 50 μm . In addition, from corrosion characterization, the values of pit depth, area, and volume are 390 μm , 4000 μm^2 , and 1600 μm^3 respectively obtained from 20 years old corrosion failed GS pipe. Similarly, from the image processing; the pit depth of DIP is 380 μm , whereas the maximum pitting area and volume are 4000 μm^2 and 200,000 μm^3 respectively Table 4.5.

Table 4.5 A comparison of pitting features between GS and DIP pipes

Pipe type	Pit depth (μm)	Diameter (μm)	Area (μm^2)	Volume (μm^3)	Roundness
GS	310-390	20-50	4000	16000	0.7
DIP	290-380	28-60	4000	200000	0.8

4.14 Analysis of Image Processing

Image processing is an alternative method of analyzing pitting corrosion and surface morphology characteristics. Digital image processing characterization of corrosion has been developed to evaluate features of corrosion at any stage (Codaro et al., 2002). The method is also effective to investigate corroded surface morphology from low to peak ranges. A similar study conducted by (Hoang, 2019) confirms that corrosion detection using image processing based is a fast and effective method that replaces the time taken by human inspection. The statistical corrosion measurement was obtained from different image colors to extract the morphology of the pipe surface. According to their study, image processing corrosion characterization has an accuracy of 92.81% compared with the results of laboratory experiments.

Mountain's software was applied for analyzing corroded pipe surfaces to evaluate pit characteristics such as Pit depth, area, volume, diameters, density, and roundness. The investigation shows that the analysis of 2D SEM images and the reconstructed 3D images possible to characterize the geometric features of the pit. The software analyzes the data using mathematical regressions based on statistical input parameters relating to surface morphology

and pitting conditions that are obtained from SEM images. The behavior of pits on the buried pipes can be deep, shallow, and wide forming rough surfaces. Maximum pit depth was evaluated by adding minimum depth (Z-min) and height (Z-max) in-situ conditions after uniform corrosion attacked the thickness of the pipe during service time. The morphology shows that pitting corrosion shares a large contribution to the failure of pipe structures during long exposure of service time. Mountains surface analysis software is effective to detect the morphology of corroded surfaces at the micro-level and can measure pit depth, diameter, area, roundness, and volume with a small micrometer precision from the source of the SEM image.

The watershed topography of a corrosion-degraded pipe surface filled watershed segmentation with particle boundary in pseudo-color of the surface, which is ready for image processing analysis at the particle level. The blue color, in Figure 4.21b represents a more damaged localized surface whereas the red color depicts the top layer of the pipe surface which is going to be damaged layer by layer. During the study of corrosion characterization at the surface and subsurface of iron pipes, micro-cracks were identified. This scenario has happened as the depth of the pit increases, water pressure and stresses are responsible for the occurrence of cracks. Micro-cracks begin at the subsurface of the pipe due to narrow pits penetrating the pipe surface and leading to crack formation, propagation, and growth.

The characteristics and features of external corrosion-damaged surfaces indicate the morphology of pit depth, cracks, cavities, and peaks Figure 4.21a. The depth of the pit is increasing due to the release of metallic ions at the anode during the electrochemical reaction which creates pipe surface damage. Other pit characterization topographies including maximum and minimum diameters, pitting density, and the shape of pitting such as roundness are extracted from 2D pseudo-color images shown in Figure 4.21b. The image is fully segmented and filled with watershed to detect pit depth, area, volume, roundness, and diameters from the 3D image which was generated from 2D. The 3D and cross-sectional morphologies are shown in Fig. 4.22. Figure 4.22b indicates a variety of pit depths and deterioration conditions. The process of corrosion is enhanced by the accumulation of deposits in the pit pockets which accelerates the rate of corrosion.

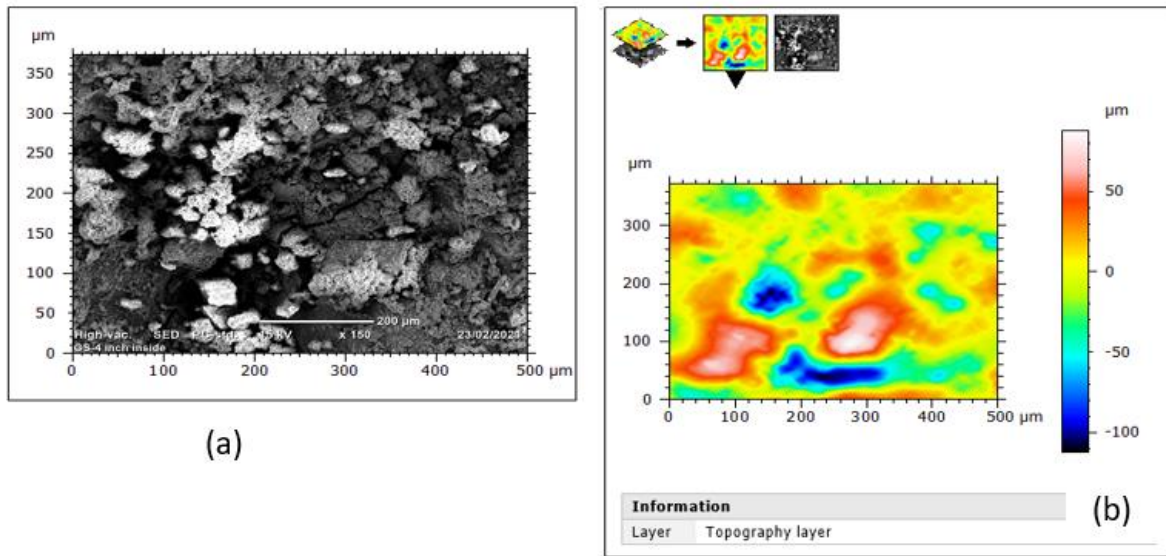


Figure 4.21 Image processing: (a) SEM view, (b) Topography layers

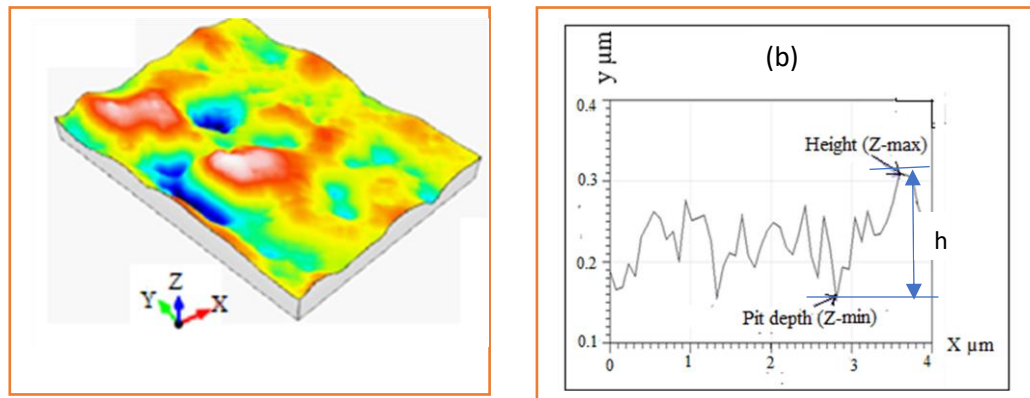


Figure 4.22 Corrosion morphology patterns of GS pipe site? (a) 3D image and (b) Cross-section of corrosion-damaged surface

The statistical results show that maximum pit depth equals the sum of the maximum peak (Z-max) and valley (Z-min) values, which is 200 μm after a 30% loss of the original pipe thickness of 5 mm. The average pit depth that existed on both internal and external surfaces was evaluated using Eqn. 4.15 to determine the remaining pipe thickness.

$$T_l = T_o - T_r \quad (4.15)$$

Where T_l is pipe thickness loss, T_o and t_r are the original and remaining thicknesses of the pipe sample.

Figure 4.23 shows watershed segmentation of internal pipe corrosion damage which was generated from the SEM image. The entire surface of the sample is filled with watersheds and divided into several particles with their boundaries. This is an important condition of image processing to characterize corrosion-damaged surfaces at the particle level. The figure shows a corrosion-damaged surface that was filled with watershed and studied at the particle level. The particles are colored automatically and divided by grain boundaries. The surface colored with blue, red, and yellow represents the decreasing order of corrosion damage. This method of corrosion characterization is used for determining the state of corrosion on metallic materials at any given time and aids to make decisions to apply corrosion-prevention strategies.

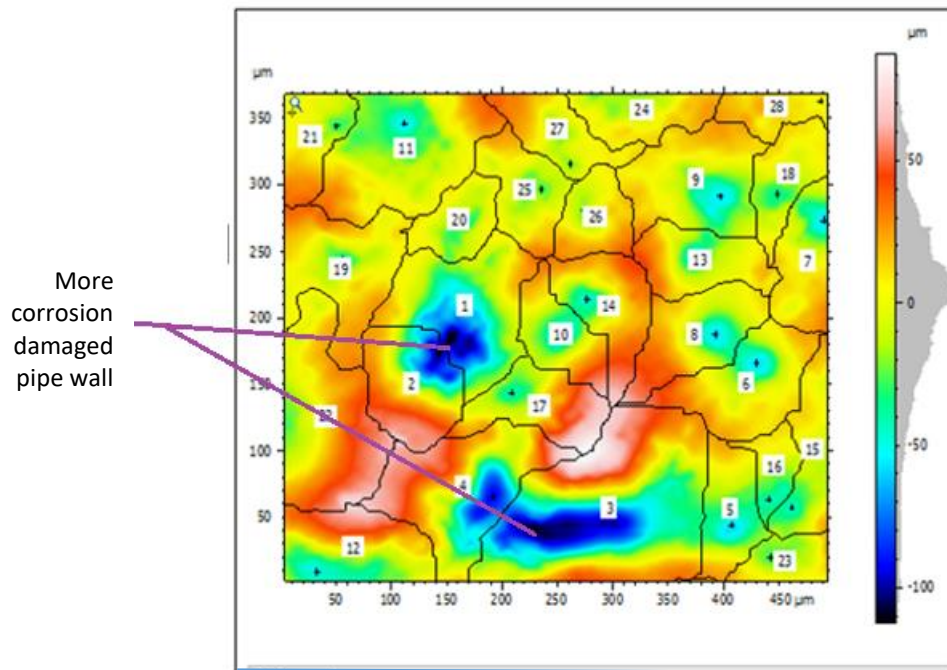


Figure 4.23 Topography of corrosion-damaged GS pipe

The SEM image was automatically divided by the software into several particles for detailed analyses of corrosion at the particle level. Based on the image processing result, the maximum pitting corrosion area and volume are (43164 μm^2) and (182845 μm^3) respectively reported as the rate of corrosion as shown in Figure 4.24 at particle #1.

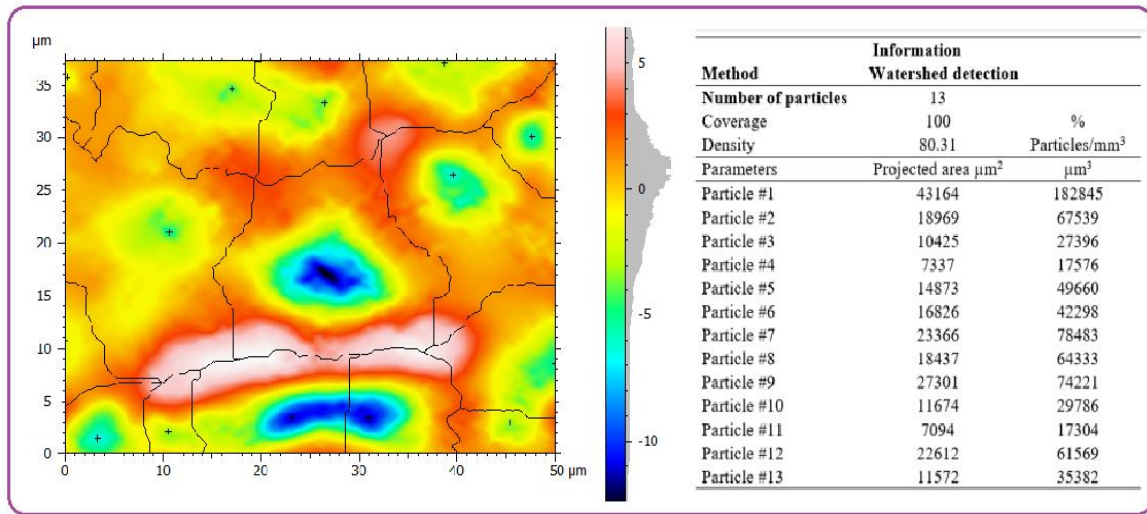


Figure 4.24 Corrosion pit area and volume per particle (GS) pipe

Figures 4.25 and 4.26 present corrosion characterizations of ductile cast iron using image processing to investigate corrosion morphology and pitting characteristics. Figure 4.25a is the SEM image source of the sample with its true color and Figure 4.25b depicts the topography of the corrosion-damaged surface filled by the watershed and the status of corrosion damaged surface is isolated by different colors showing that the sample is ready for corrosion characterization. Similarly, Figure 4.26a shows the 3D form of the watershed surface which describes the loss of pipe thickness while Figure 4.26b presents the cross-sectional details of the sample to demonstrate the depth of the pit and maximum height remaining on the pipe surface and Figure 4.27 represents values of pitting features.

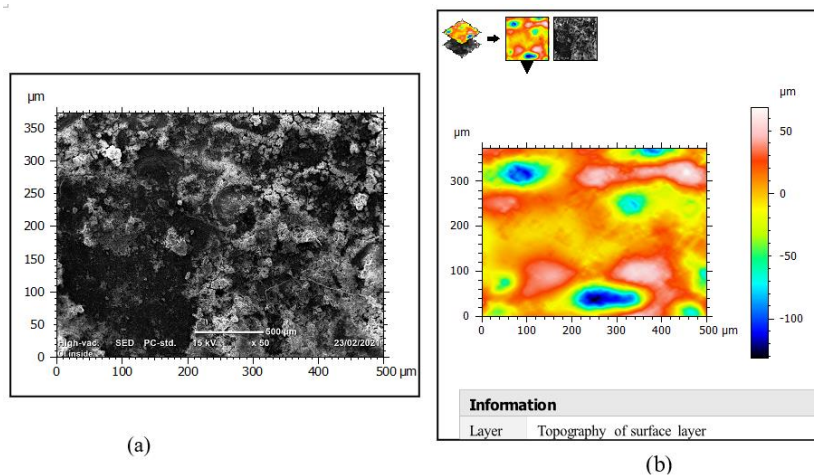


Figure 4.25 Corrosion characterization of DCI: (a) true color of SEM view, (b) Topography

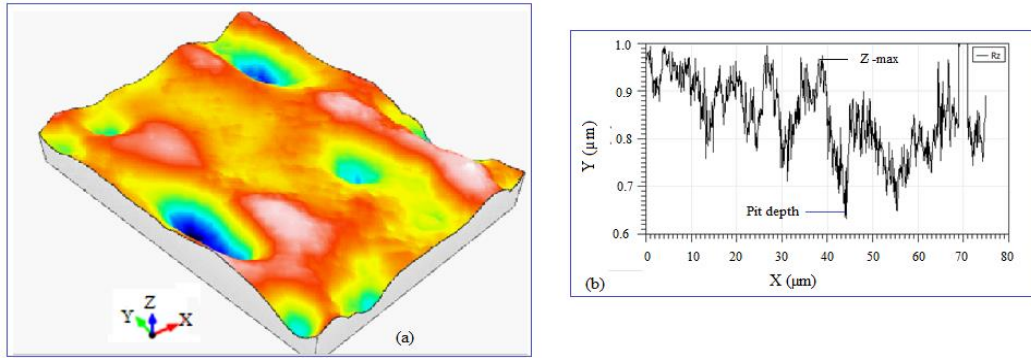


Figure 4.26 Corrosion morphology of DCI: (a) 3D image of topography and (b) Cross-section of corrosion-damaged surface

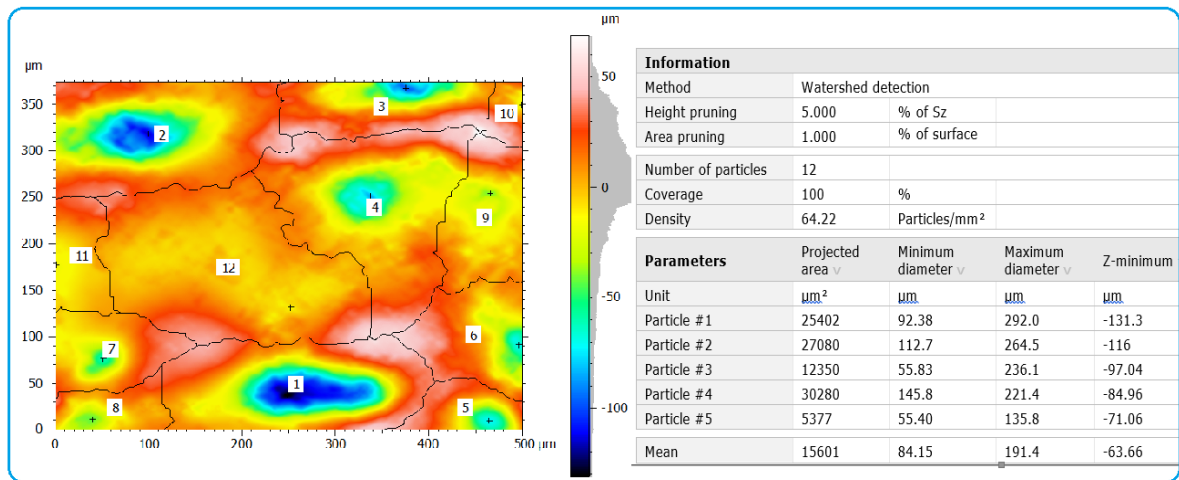


Figure 4.27 Watershed segmentation of DCI corrosion showing pit area and depth

Figure 4.28 also shows the results obtained from image processing on the internal corrosion-damaged surface obtained from the DCI pipe in the form of table and bar graphs respectively. The particle analysis of watershed segmentation describes the threshold condition of pitting features. The depth of corrosion is evaluated as the sum of peaks and valleys that equals 190 μm which is the threshold value after a 30% loss of 8 mm original thickness.

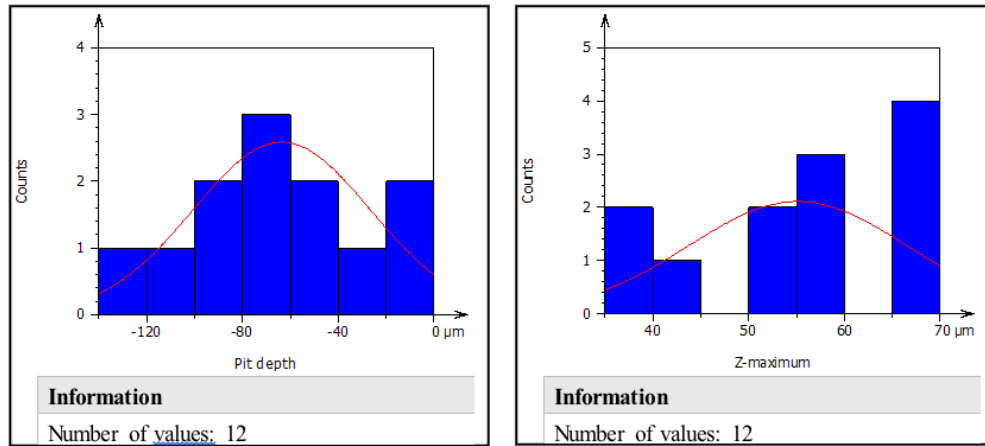


Figure 4.28 Result of image processing from DCI pipe: (a) Pit depth, (b) Height

4.15 Analysis of Corrosion Rate

The rate of corrosion was determined using the weight loss method from a typical 15-year-old GS pipe was determined based on the weight loss method. Using Eqn. 3.6, inserting the values of constant ($K = 8.76 \times 10^4$, ($\Delta W = 160$ g, $D = 2.54$ cm, $A = 2\pi Dh = 160$ cm², and $h = 10$ cm, $\rho = 7.86$ g/cm³ and $t = 131400$ hrs. estimated for 15 years) in the equation, the computation gives 0.084 mm per year. This corrosion rate value indicates the reduction of pipe weight and confirms the deterioration of pipe structure due to water physicochemical parameters, and soil corrosivity during the service year. Weight loss testing is a common method utilized for determining uniform corrosion rate. The specimen can be buried in the prepared wet soil or get from the real case pipe installation. This method utilizes variables such as time, corrosive environment, the density of a material, and the surface area of the sample (H. Liu et al., 2020).

As a whole, the rate of corrosion damage depends on a variety of mechanisms including water physicochemical forming oxidation and reduction process on the pipe wall, soil environment, erosion-corrosion, stress corrosion cracking, and the combined effect of these mechanisms. Once buried ferrous materials are corroded, characterizations are very important to understand corrosion behaviors from the viewpoints of water parameters and environmental impacts for the application of corrosion prevention methods. Chemical additions such as a little amount of sodium bicarbonate during water treatment, as per WHO standards, are highly helpful for controlling internal pipe corrosion (IPC). More corrosion-damaged locations were observed at the bottom of the pipe on both inside and outside surfaces. Based on the analysis of water

physicochemical, site #5 is more corrosive to the pipe wall. Similarly, the rate of metal dissolution in galvanized steel pipe is higher than in ductile cast iron pipe, according to pitting corrosion characterization using the software. For pipeline safety and water quality, periodic pipe washing and in-line inspection are important to control internal pipe corrosion.

4.16 Validation of Corrosion Pit Measurements

Exhumed pipes were subjected to laboratory examinations to determine pit depths, patch sizes, and wall thickness. The corrosion configuration profiles, which included pit depth and patch dimensions, were obtained by scanning the excavated pipe sections on the surfaces with a Zeta 3D optical surface profilometer microscope (OSPM), USA with a magnification of 20X. To obtain trustworthy results, random areas on the surface of samples were also evaluated. To valid previously characterized pitting features using Mountains surface analysis software (MSAS), a 3D optical surface profilometer microscope was used to measure pit depth value as shown in Figure 4.29. Both the results of the software and the OSPM have close responses to the pit depth measurement of corrosion-damaged pipes. The values of internal pit depth using MSAS and OSPM ranged from 190-200 and 212.85- 277.80 μm respectively. On the other hand, external pit depth values ranged from 310-390 and 283.54-353.36 μm respectively.

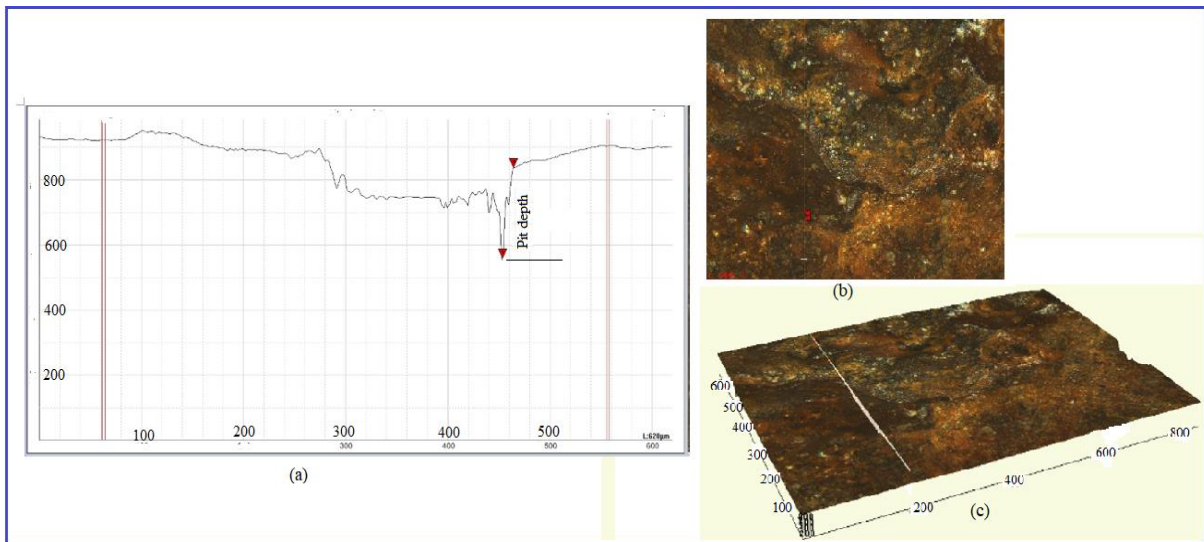


Figure 4.29 3D optical surface profilometer microscope: (a) graph of pit depth, (b) and (c) are 2D and 3D forms of corroded surfaces

Water flow with a long time of service load creates erosion corrosion which is typical corrosion morphology forming roughness on the pipe wall. A pit can be caused by scratches, localized surface defects, environmental corrosion, and variations of alloy compositions.

To this end, the dissertation incorporates full structure; a metallographic examination was conducted to evaluate the microstructure of the pipe's patterns using a light optical microscope to check whether defects exist or not during the manufacturing process. To investigate the morphology of corrosion products, scanning electron microscope (SEM) analyses were performed on the exhumed pipes under in-situ conditions. Furthermore, corrosion characterization was carried out using Mountain software of surface analysis to determine pitting dimensions. To determine major corrosion mechanisms soil and water laboratory experiment test was carried out. The dissertation concludes that deterministic modeling of corrosion damage phenomena is useful to predict the risk of pipelined damage and to determine

Table 4.6 Factors of water pipelines corrosion damage mechanisms

Water parameters	Soil parameters	Manufacturing aspect	External factors
Resistivity, pH, chlorine content, salt, turbidity, total dissolved solids (TDS), temperature, trace elements, flow rate, pressure/burst, alkalinity, sulfate, dissolved oxygen, Conductivity of water, bacteria, deposits),	Soil resistivity, pH, moisture content, salt, soil dynamics, temperature, microorganisms, nitrate, sulfate, minerals, soil type, stray current, soil texture, bicarbonate content, chloride content, bulk density,	Material selection, material composition (alloying), design considerations, manufacturing process, residual stress, coating type, defects,	Earthquake, maintenance implementation, managing distribution system, pipe installation positions, environment, road construction, traffic, atmospheric condition, soil load, operating conditions (flow rate, pressure), soil load,

the remaining service life. The proposed method will help water distribution owners to apply maintenance and replacement strategies for existing and future management of pipelines. Overall, Water pipelines are exposed to various kinds of damage including electrochemical corrosion, stress-induced corrosion cracking, and operational conditions. Various factors and mechanisms contribute to the failure of buried water pipelines as shown in Table 4.6. These factors influence the pipes individually or in a combined way during the deterioration process.

4.17 Modeling of Pipe Corrosion Damage Phenomena

The process of corrosion depends on time and environmental conditions. Pipes are exposed to internal and external loads. The internal load is caused by water pressure and flow rate, whereas the external load contains soil backfill and traffic load where pipeline installation crossed roads. The reduction of pipe thickness caused by corrosion leads to relaxing the residual stress during the lifetime of the water pipe. This residual stress creates the probability of pipe mechanical failures such as bending due to corrosion and soil load. The strength of the pipe decreases as the loss of pipe thickness increases due to the effect of corrosion on the pipe structure. The type and variety of corrosion parameters cause reduced pipe service life and increase physical and mechanical failures of the pipe.

Prediction of long-term corrosion rate is crucial for the determination of corrosion rate and management of the remaining service life. The time-dependent long-term corrosion damage is a challenge to predict the exact period of pipe failure. It requires extensive data analyses related to pipe installation and the environment's corrosivity conditions. The deterministic time-dependent corrosion damage model is more effective to determine the rate of corrosion with time function. It requires much experimental data related to soil and water parameters of the independent variables to determine the dependent variable pitting corrosion growth. Pitting corrosion is considered a time-dependent deterministic damage process evaluated by an exponential pit growth model. Pitting corrosion occurs due to the presence of required conditions such as an anode, cathode, and electrolyte with pipe material in the electrochemical reaction. After having the required data, correlation, and regression analyses are important to investigate the relations of variables to identify less or more corrosive parameters.

4.17.1 Linear Correlation and Multi-Regression Model Variables

Correlation is the method used to measure the relationship between dependent and independent variables to describe the strength and direction of the linear association between the variables. Correlation does not indicate cause and effect but the relation of variables. Pearson relation r is designed to interpret the interval or ratio level of continuous variables. The values of the correlation coefficient (r) are decimal numbers ranging from -1 to +1. A positive sign indicates both variables increase and a negative sign represents when one variable increases, the other variable decreases. A perfect correlation of 1 or -1 indicates that the value of one variable can be determined by knowing the other variable whereas zero indicates no relationship between the two variables. The correlation matrix is used for analyzing the relationship between a group of variables.

The effects of soil measurement factors on corrosion rate and pit depth were evaluated using multiple linear correlations. Corrosion influence constant (k) and power (n) were identified via multiple regression analysis to minimize error and to increase the interpretability of the data set. The combination of soil parameters was considered as linear regression to find a relevant model. The Coefficient summarizes individual parameters to compare the R^2 value to the Sig. column. The R^2 value is always between 0 and 1. R^2 is a measure of variation in the model's dependent variables. It describes in the form of a table but is not able to describe all the individual correlation coefficients in the form of a graph. If significant (Sig.) $< R^2$, the result or dependent variable has a significant effect, and vice versa. The model of n and k were developed from values of measurement and laboratory investigations Table 4.7.

The operational, environmental, pipe material and time, and the dependence of maximum pit depth were modeled as a power function which was obtained from experimental soil test data using multi-regression analysis. The condition of the linear relationship between continuous variables is evaluated by Pearson correlation as shown in Table 4.8.

Table 4.7 Observed soil and pipe parameters

Soil parameters	Symbol	Unit	Measuring/testing method	Average value
Soil pH	Sp	pH	pH meter	7.02
Maximum external pit depth	Pe	mm	Mountain Software	1.92
Maximum internal pit depth	P _i	mm	Mountain Software	2.15
Exposure time	T	Year	Operating records	32+
Soil electrical conductivity	EC	dS/m	Conductivity meter	1.08
Moisture content	Mc	%	Weight loss calculation	31%
Total nitrogen	Tn	%	Calculation	0.05
Chloride content	Cl	gm/Kg	Titration	49
Bulk density	Bd	g/cm ³	Calculation	1.2
Redox potential	RP	mv	Oxidation-reduction potential meter	168
Pipe-soil potential	Ps	mv	Copper-copper sulfate electrode	0.2378
Soil bulk density	Bd	g/cm ³	Mass and volume measurement	
Coating type	C	---	Direct observation	Bituminous
Ductile iron pipe	Dip	pc	Measuring the diameter	

Table 4.8 Correlation of soil parameters for the value of n

		Correlations				
		hmax	Pipe-soil	EC	Bd	pH
Pearson Correlation	hmax	1.000	.425	.243	.610	.283
	Pipe-soil	.	1.000	.670	.587	.078
	EC			1.000	.417	.018
	Bd				1.000	-.162
	pH					1.000

The values of R^2 for k and n are determined using regression analyses as 0.886 and 0.907 respectively. The power function is suitable to describe the ongoing time change of the maximum pit depth greater than the values of significance (Table 4.9 & 4.11) indicating the choice of this model is a satisfactory condition.

Table 4.9 Coefficient of soil parameters for the value of n ($R^2 = 0.907$)

		Standardized	
Model		Beta (B)	Significant (Sig)
1	(Constant)	-315.437	.204
	Pipe-soil (Ps)	1.957	.827
	EC	-2.011	.770
	Bd	105.544	.199
	pH	26.544	.337

The model of the regression equation for n is, $B = 1.96(Ps) - 2.01(EC) + 105.54(Bd) + 26.54(pH) - 315.437$, and its value is calculated by multiplying with the mean values of the parameters.

$$n = 1.96(Ps) - 2.01(EC) + 105(Bd) + 26.54(pH)$$

$$= 1.96(0.2378) - 2.01(0.2357) + 105(1.2411) + 26.54(7.01)$$

$n = 1.825524 \approx 1.82$ is the value of the exponent in the mathematical model, Eqn. 3.13.

The presence of a relationship between variables is shown by a +ve sign, while a -ve sign shows that when one variable is decreased, the other increases. The focus of making this matrix was to see if there was a possible relation between the independent variables and to prevent the same data from repeating over and over again. The results presented in Table 4.10 show that weak-to-moderate relation exists between the variables.

Table 4.10 Coefficient correlation for the value of k (constant value)

Correlations						
		hmax	Redox potential	moisture	chloride	TN%
Pearson Correlation	hmax	1.000	.266	.119	.237	.304
	Redox potential		1.000	.096	.613	.710
	moisture			1.000	-.623	-.137
	chloride				1.000	.598
	TN%					1.000

Table 4.11 Coefficient correlation for value of k ($R^2 = 0.886$)

	Model	Standardized Beta (B)	Sig.
1	(Constant)	16.916	0.849
	Redox potential	.013	0.140
	moisture	-.147	0.529
	chloride	-0.07811	0.402
	Tn%	-138.741	0.049

The model of the regression equation for k is $B = 0.013(Rp) - .147(MC) - 0.078(Cl) - 138.74(Tn)$ which is calculated by multiplying with mean values of the parameters.

$$n = 0.013(62.2222) - 147(30.3222) - 0.078(509.5556) - 138.47(0.0822) + 16.92$$

$k = 1.85903 \approx 1.86$ is the constant value in the power function model, Eqn. 3.13.

In the present work, using multi-regression analysis the model values of n and k are determined as 1.83 and 1.86 respectively. The rate of pitting corrosion growth increases up to the subsurface of the pipe and then its depth continues at a constant damaging process until termination.

Figure 4.30 shows the long-term corrosion rate of buried pipes which is the result of the newly developed deterministic corrosion damage model of this dissertation. It also presents the remaining service life of the DCI pipe. The model is validated with the literature data of Velazquez et al. (Caleyo, Valor, et al., 2009) for the relevance of the proposed model. Both graphs show that the rate of corrosion increases as the service years increase with a variable corrosion rate depending on the inherent environmental variability of corrosion factors.. The deterministic power function model proposed in this dissertation is valid to describe the time evolution of maximum pit depth in water pipe surfaces. The rate of corrosion at the time of initiation ($t < 5$ years) was found to be negligible. Based on the model, the long-term corrosion rate ranges from 0.06-0.08 mmy⁻¹ on the buried ferrous pipes. This corresponds to an average wall loss is 5-8 mm for an exposure year of 15-25 and 30-80 years of GS and DCI pipes respectively depending on the environmental corrosivity and operational conditions.

. A similar study on the soil environment variables of resistivity pH, redox potential, and electric potential was used by Alamila et al. (2009) to construct a mathematical model for assessing localized corrosion failure propagation of buried pipes. The model effectively depicts the long-term corrosion progression of pitting damage using the power function.

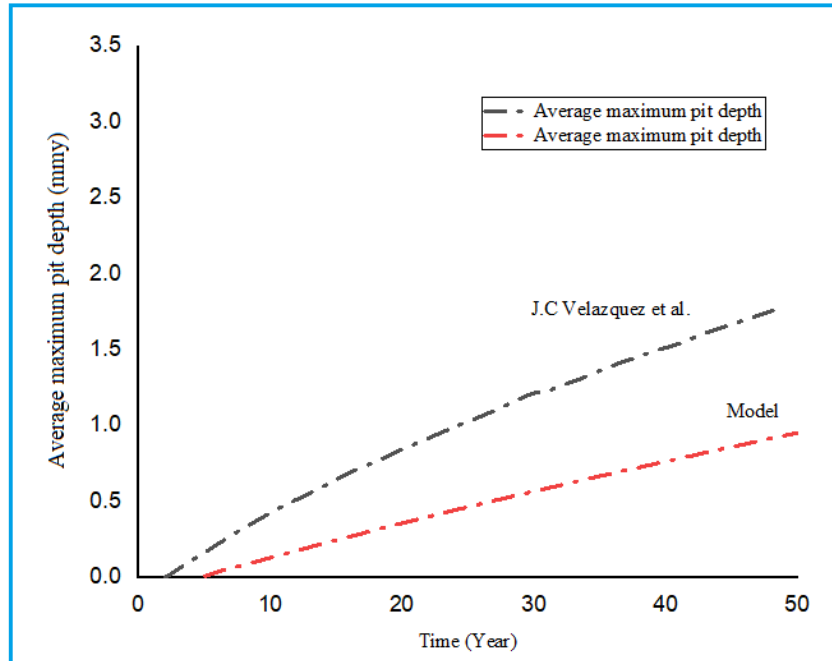


Figure 4.30 The long-term corrosion rate of pitting growth

The percentage errors of the literature and the newly developed model are 5% with a slight difference due to the inherent environmental variability of parameters. A similar study shows that a 5% error was tolerated in the design of predictive models to estimate corrosion in buried steel structures (Arriba-Rodríguez et al., 2020).

4.17.2 Validation of Corrosion Model

To validate, the model, the water distribution of Addis Ababa city was selected as the case study in this dissertation. The data were taken from soil and water psychophysical analyses, pipe physical dimensions, and corrosion characterizations. The model was developed based on the ductile cast iron main pipe's physical properties, internal pipe wall damage, and soil parameters. Corrosions of the water pipe are a slow reduction in wall thickness through service years. The gradual physical and chemical deterioration of the pipe leads to pipe leakage and breakage. According to (Asadi & Melchers, 2017; J. Ji et al., 2017; Weigang, 2019), the pitting corrosion depth relates to pipe age and the remaining pipe thickness. The evaluation of stochastic and deterministic models was employed based on the nature of the data to predict accurate models. The model takes into account pipeline coating as well as the impact of electrochemical corrosion of pipe material with water and soil factors on pipeline lifetime in the long term. Some of the works of the literature show that only pitting corrosion is leading to

pipe failure. While others tried to address SCC only as the main cause of the failure of the pipe. But, in this study, the combined effect of both corrosion types is given more emphasis and the model attempts to describe fully based on the physical parameters including environmental (water and soil corrosion behaviors), operational condition, pipe material, and soil load based on the stochastic and deterministic models.

Data of corrosion is measured by different methods such as surface analysis software (Mountain) and laser scanning device. Data on corrosion pit measurement can be taken from in-service pipelines using high-resolution laser scanning devices to generate 2D and 3D images of corroded surfaces (Al-Mubarak & Obot, 2021). The authors used these data for estimating the parameters of the proposed model. Deterministic time-dependent pipeline corrosion modeling is effective to predict the long rate of corrosion and determining the remaining service life.

4.17.3 Evaluation of Corrosion Modelling

A deterministic time-dependent model was proposed for the underground water pipelines considering pipe variables and the in-situ soil parameters that contact buried pipe surface including moisture content, electrical conductivity, chloride content, total nitrogen, bulk density, and redox potential. The results of soil factors were analyzed using statistical methods such as linear correlation analysis, and multiple linear regressions to determine the values of thickness' (k) loss and (n) corrosion growth conditions. The model revealed that k is influenced by moisture content and n is correlated with total nitrogen content. Model validation was carried out using a case study for practical application.

Modeling of corrosion damage analysis attempted to predict water pipe damage phenomena based on the physical data of environmental corrosion characteristics, loads and stresses to which pipe is subjected, and pipe material type. The residual pipe structure is easily deteriorated by internal and external corrosion in addition to the operational conditions and soil loads. This model shows how each corrosion parameter affects underground iron pipes and how they interact. More corrosion damage was observed at the bottom of the pipe both in the case of internal and external surfaces. This is due to the influences of direct contact water pressure, soil load, and corrosion damage mechanisms. The model also helps to estimate the

rate of corrosion with time variation that can describe the probability of pipeline failure in the long run.

Water pipe failure mechanisms include pipe material, the interaction of pipe-soil, pipe-water, internal and external loads, and material degradation due to electrochemical reactions. A real-life water pipeline distribution system (DS) was used as a case study to show the application of the proposed model for validating the results with the existing condition of corrosion-damaged pipes. On the bases of the deterministic time-dependent corrosion model and sensitivity analysis, a 30 to 80 years time frame is more relevant to the ductile cast iron pipe. The model is very close to the service age of the pipe. As an alternative solution, the safe condition of the pipe utilization is up to 50% loss of pipe thickness and this can be achieved based on regular inspection and an understanding of environmental corrosivity.

The suggested model will assist water distribution system owners in making the most informed decisions about pipe maintenance and replacement. This study can also help with the assessment of corrosion damage mechanisms, corrosion protection strategies, and utility asset management. The developed model's results are used not only to inspect pipes in the field but also to predict pipe failure based on corrosion rate. To maintain water pipelines safe, accurate corrosion damage forecasts and applying adequate corrosion control techniques are essential. Corrosion can be prevented and controlled by using appropriate pipe material that is compatible with the natural environment, an inspection of operating conditions, and the best pipe design. As a whole, the developed model can provide an immediate assessment of soil corrosivity and corrosion growth for the buried structures. Water pipelines are affected by a variety of corrosion types including pitting corrosion, uniform corrosion, microbiologically influenced corrosion, crevice corrosion, stress corrosion cracking, and galvanic corrosion. Although there are many distinct types of corrosion on buried pipelines, pitting corrosion is the most problematic. This study concludes that a time-dependent deterministic corrosion model was proposed to predict long-run pipe corrosion rate under the combined effects of narrow pitting and stress corrosion cracking.

4.17.4 Sensitivity Analysis

Sensitivity analysis was conducted to validate the model by investigating the major corrosion damage mechanisms. Sensitivity analysis is carried out to identify the most significant

variables contributing to pipe corrosion damage. The sensitivity analysis helps to understand how the variables of environmental, operational, and stresses are affecting water pipelines. Based on the analysis of water pressure, total dissolved solids and dissolved oxygen are observed to have the highest impact on internal corrosion. Similarly, the highest influential parameters of external corrosion are soil load, moisture, and electrical conductivity. Furthermore, electrochemical corrosion and pipe materials are major corrosion mechanisms. Based on the environmental corrosivity variables, pipe materials parameters, and service time, a corrosion model was proposed to predict the rate of pitting growth and the remaining service lifetime. The combined effect of environmental corrosivity and operational conditions on the pipe material is a major failure mechanism for buried iron pipes.

The process of model development considered water physicochemical, soil parameters, operational conditions, pipe data, and soil load as primary conditions. The sensitivity analysis shows that pitting corrosion of internal and external stresses is the main damage mechanism of water pipes that limits the service years. From the sensitivity analysis, the lifetime of the pipe is related to pipe thickness loss rate and stresses induced on the pipes. The safe operating water pressure is ranged from 150 to 1000 KPa for the water mains. According to the sensitivity analysis, the maximum corrosion pit depth and internal pressure have the biggest impacts on the probability of failure. The majority of a pipe's service life is influenced by corrosion defects and develops into a crack, increasing the likelihood of failure.

Generally, the model sensitivity has great importance for determining long-term pitting corrosion growth based on the parameters of pipe and soil variables which have greater influence. The experience obtained from this dissertation shows that the model will help in predicting external corrosion pitting growth depending on the soil's corrosivity status. The model will help to decide on repairing or replacing the existing old pipes based on the rate of corrosion and performance indicators such as loss of pipe thickness and water pressure resisting capacity. The model is also able to determine the expected remaining service (residual) life of the pipe and ensures that the necessary measuring actions can be taken before failure occurs.

4.18 Pipe Corrosion Prevention

Corrosion monitoring and pipe condition assessment are crucial for determining the state of circumstances for corrosion prevention. Corrosion mitigation techniques including paint

coating (tar or bitumen), epoxy coating, and polyethylene-encased coating for external corrosion protection should be utilized to increase pipe service lifespan. On the other hand, it is advised to add chemicals, like sodium bicarbonate, to the water in a quantity that complies with WHO standards to control the internal corrosion of pipes. Checking the impact of water quality parameters, maintaining cleanliness to minimize microbiological corrosion, applying routine inspection, and using sample testing are significant ways to mitigate internal corrosion. Additionally, cathodic protection and zinc coating, often known as galvanizing pipes, can be used to prevent internal corrosion. Implementing several strategies such as corrosion inhibitors, scarifying coatings, metal plating, protective coatings, improving pipe design, and altering environmental controls is essential to preventing corrosion overall.

In general, to prevent uniform and pitting corruptions on the buried pipes, investigating pipe materials properties in the compositions against each other is crucial to control intergranular corrosion which leads to cracks. In addition, environmental corrosivity can be minimized by studying according to the environmental context of soil corrosivity primarily which can create the chance to correct during pipe design and manufacturing phases. Utilizing corrosive materials such as volcano red ash and gravel or sand around the pipes before the pipe is buried is a good technique to control corrosion and prolong the service life of the pipes.

4.19 Contributions of the Dissertation

The motivation for this dissertation was the need to study societal well-being related to water pipeline corrosion damage which consequences pipe material deterioration, economic loss, and health threats. To achieve the goal, identifying corrosion damage mechanisms from water physicochemical, soil corrosivity, operation conditions, and pipe materials were analyzed. This was achieved by conducting different methodologies including, developing corrosion modeling using a deterministic corrosion model, corrosion morphology characterization using a scanning electron microscope (SEM), microstructural analysis utilizing an optical microscope (OM), and utilization of Mountains surface analysis software for determining pitting features to analyze corrosion morphology. The results presented in the dissertation can contribute to the body of knowledge of corrosion damage phenomena of water pipelines and the effect of corrosion on the physical and mechanical properties of buried pipes, which in turn enable keeping water quality and prediction of failure conditions and the remaining service life of pipes. The research also provides information for those who work in the area of corrosion prevention.

The contribution of this research can provide an assessment of pipe condition and water quality for practical corrosion monitoring and controlling. It can also assist pipe design engineers, metallic product designers, water pipe distribution owners, oil and gas pipeline suppliers, and asset managers in all industries. The research creates an understanding of the processes of pitting corrosion failure among all the underground installed pipe materials are similar unless the environmental and operational differences. Most pipe corrosion damage (approximately loss of thickness of more than 60%) is caused by pitting and uniform corrosion. This is due to the pit penetrating metallic material and the stress corrosion cracking develops with the help of tensile stress caused by water pressure and soil backfill.

The dissertation contains a comprehensive knowledge that covers the investigations of several corrosion-related phenomena including buried pipe condition, corrosion damage process and corrosion rates, pipe materials physical and microstructural analysis, threats of economic and health impacts, corrosion controlling mechanisms, prediction of pipelines failure model, corrosion mechanisms of environmental and operational conditions and characterizations of excavated and new iron pipe materials. As a whole, we need to save pipelines and at large material and energy from being damaged by corrosion through different corrosion control and prevention methods. Corrosion controlling can be achieved by using inhibitors, applying the coating, material selection, cathodic and anodic protection, and appropriate design for the specific environmental corrosion behaviors.

Corrosion research provides several benefits, including the development of materials that can adapt to environmental corrosiveness, loss minimization or economic benefit, creating health awareness, and reducing downtime in factories affected by corrosion. The study of corrosion protects socio-economic impacts relating to the effect of food, medicine, and beverages, which require immediate attention due to direct contact with materials surfaces, which results in the diffusion of released ions into food and drink items such as juice, beer, water, and soft drinks.

Different time inspections and determining corrosion rate help to predict the remaining service life of pipe thickness and it can serve as an initial data source. The next inspection can be evaluated based on the previous data information on the pipeline's failure conditions. Other data history related to pipe repair, leakage observation, and replacement is very important to the

experience of data recording and organizing to assess pipe status. In general, water pipe damage is a result of operational and environmental corrosiveness and stresses influenced by the time-dependent corrosion process. An inevitable effect resulting from corrosion is health and economic risks.

Replacement of aging pipes needs organized lifetime historical data recording of every single pipe. The lifetime cost of pipes covers water loss, maintenance, and replacement. Pipe corrosion is a complicated and costly problem that challenges water suppliers. A variety of parameters are responsible for the formation of corrosion including pipe material composition, manufacturing process, water quality, operation conditions such as flow rate and pressure, microorganisms, stresses, and inhibitors. This dissertation, in general, creates an understanding of the factors that influence water pipe corrosion, health threats, and economic aspect. Despite significant investments in pipeline corrosion prevention technologies such as cathodic protection, coatings, design improvements, inhibitors, and so on, have been applied corrosion is never totally avoided. As a result, pipeline corrosion must be controlled through a variety of methods, including pipeline monitoring, testing, maintenance, and inspection.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Aging and weakening of buried pipes are inevitable after several years of service due to corrosion being the most predominant failure mechanism of the pipes. From the experimental and sensitivity analyses, the physics of buried water pipe failure was understood that the combined effects of sharp pitting, corrosion fatigue, and stress corrosion cracking are the main factors that determine water pipeline service time. In this study, the experimental approach was utilized to characterize the morphology of corrosion and investigate internal and external corrosion damage mechanisms of buried water pipes. Based on the examination of the effect of each soil parameter including soil resistivity, moisture content, total nitrogen, and dissolved oxygen have the main effect on the investigated pipes' surfaces which accelerates continuously the rate of corrosion. Dissolved oxygen in the water and soil develops differential cells which accelerate the rate of corrosion on the ferrous pipes' surface.

The modes of pipe failures include brittle failure, crack, graphitization, pitting, blowout holes, circumferential and longitudinal fracture, pipe bending, etc. which are caused by different damage mechanisms. The mechanisms of water pipe damage are grouped under three categories, namely; (1) operational factors including water pressure, flow velocity, water quality, and maintenance practice; (2) environmental factors which cover climate, soil corrosivity, pipe bending, stray current, soil load, traffic; (3) physical factors such as pipe age, material, wall thickness, diameter, joint fitting, coating, defects from manufacturer side, temperature, etc.

From the water physicochemical analyses, the main mechanisms of internal pipe wall corrosion are dissolved oxygen, chlorine dioxide, total dissolved solids, and total hardness. Water pH has no significant effects on corrosion formation and water conductivity insists on corrosion cell formation. Internal water pipe corrosion was a complicated problem due to the interaction of water quality parameters with the pipe wall. From water test results, major causes of internal pipe corrosion damage mechanisms were identified as dissolved oxygen, CaCO_3 , TDS, ClO_2 , and resistivity of water which initiates a differential cell that accelerates pipe corrosion.

Based on the corrosion characterization using a scanning electron microscope, micro-cracks, and perforation are developed from the subsurface of the pipes. The microstructural analysis indicates the tendency of galvanic corrosion formation due to dissimilar structures (ferrite-pearlite) contacting each other in the case of galvanized steel which can form intergranular corrosion along the contact of grain boundaries and the structures between graphite of ductile cast iron and pearlite.

Soil corrosion was a complicated phenomenon due to the inherent environmental variations which affect buried structures in different ways such as mechanical (soil load), chemical, and biological (corrosion insisting on microorganisms). The influence of soil corrosiveness factors initiates pits formation and propagates its width and depth on the surface of pipes. Based on the lab results, a variety of soil corrosion damage mechanisms were identified including moisture content, resistivity, total nitrogen (%TN), soil type, and texture were understood as the main corrosive factors to ductile iron and galvanized steel pipes.

The soil analysis result shows that soil moisture content was identified as the major corrosion potential of other mechanisms. This was due to the presence of fine grain sizes in the soil components such as the percentages of clay and silt being more in the soil. The electrical conductivity of soil was recognized as the main parameter of soil corrosivity due to the conductivity behavior of the stray current. Another parameter of soil such as soil pH was categorized under slightly corrosive factors to the buried pipes. The soil analysis result also shows that the condition of soil corrosivity status is recognized as “less corrosive mildly and moderately corrosive” to the buried iron pipes of the municipal. Factors of external corrosion pipe corrosion were identified including oxygen, soil type, soil texture, chloride concentration, bacteria, and soil resistivity.

The most damaging mechanism of metal-based pipes is electrochemical corrosion creating pits on the surface of the pipes. Pitting corrosion with time function and the support of stresses leads to pipe leakage and breakage. Based on the Mountains surface analysis software ISO 25178-2 watershed segmentation method, corrosion features of damaged pipe surface containing maximum pit depth, area, and volume from the samples. Characterizations of SEM analysis indicate cracks were observed at the subsurface layer of the pipes. The rate of corrosion was more at the subsurface of the pipes than on the outer surface due to pit depth growth. The

results also show that uniform corrosion attacked the external pipe surface whereas pitting corrosion damaged the subsurface of pipes.

The microstructural evaluation using OM showed the grain size and boundaries of the structure were observed as uniform distribution of alloying elements. From the various characterization techniques, the rate of corrosion deterioration process was categorized as: (1) pipe coating corrosion damage; (2) external pipe surface weakening; and (3) subsurface corrosion degradation until failure of pipe structures. A deterministic time-dependent model was proposed for the underground water pipelines considering pipe variables and the in-situ soil parameters including moisture content, electrical conductivity, chloride content, total nitrogen, bulk density, and redox potential.

The deterministic was developed based on the power law to describe the growth of corrosion in the long term for predicting the remaining service life of underground water pipelines. The model focused to evaluate the growth of the corrosion process over time to estimate accurate prediction results. The proposed model can be applied for the data gathering of pitting corrosion, and estimation of pipeline service life and will be utilized to compare the results with laboratory immersion tests. The boundary conditions and assumptions of water pipe failure mechanisms were considered including pipe material, the interaction of pipe-soil, pipe-water, internal and external loads, and narrow pits. A real-life water pipeline distribution system was used as a case study to show the application of the proposed model for validating the results with the existing condition of corrosion-damaged pipes.

Generally, based on the study, the rate of corrosion damage depends on a variety of mechanisms including water physicochemical, operation conditions, soil corrosivity, soil load, manufacturing process, and the combined effect of these mechanisms. As a solution to control, external corrosion; soil corrosivity can be minimized by studying the environmental context of soil corrosivity primarily which can create the chance to correct during the design, manufacturing phases, and testing of corrosion resistance of the pipes to produce environmentally adaptable water pipes and control of soil corrosion. Additionally, the study proposes two solutions for corrosion control: (1) water supply owners need to conduct a soil test before installation, and (2) the use of less corrosive materials such as volcano red ash and gravel or sand around the pipes before buried is a good technique to control corrosion and prolong the service life of the pipes. Eventually, the results obtained from the experimental

analyses help to predict the remaining service life of buried water pipes, change the path of the pipeline, and to take action on the corrosion-controlling strategy of underground ferrous pipeline failure.

This dissertation is limited to analyzing corrosion and modeling damage phenomena for drinking water pipelines. It emphasizes the internal corrosion mechanisms, external corrosion mechanisms, characterization of corrosion at the surface and subsurface, and modeling of corrosion damage phenomena. Water physicochemical tests were limited to the investigations of corrosion failure factors including pH, chlorine dioxide, total hardness, the conductivity of water, total dissolved solids, and dissolved oxygen. On the other hand, soil physicochemical study was limited to the corrosion parameters of buried water pipelines including resistivity, soil pH, soil texture, total nitrogen, moisture, and soil density.

Pitting corrosion is the main failure mechanism of buried pipelines. However, the pit depths are not equal due to the water and soil environments having inherent differences during the electrochemical reaction. The pinhole creates when the values of external and internal pit depth are maximum at a point and equal to the pipe wall thickness. Corrosion mitigation methods such as applying coatings did not study due to the scope. Regarding the newly developed deterministic corrosion damage modeling, the limiting factor of the model was the unavailability of sufficient recorded data on corrosion management systems. This prompted the use of numerous water and soil laboratory experiments in this study to determine the key factors influencing pipe corrosion. Some of the detailed limitations of the model are:

- The time-dependent deterministic corrosion damage model can only predict the corrosion phenomena of ferrous buried pipelines.
- The model is considered the main factor of corrosion damage on the buried water pipelines, but it can accept additional parameters as required.

5.2 Recommendations

The influence of corrosion on the economy has been studied in developed countries and the loss of economy is expressed in terms of GDP (gross domestic product). Whereas in the case of Ethiopia, there is a significant gap in the field of studying the cost of corrosion at the country level in this regard. The water distribution system requires adequate historical data recording concentrating on basic information such as total installation length, pipe diameters, the proportion of pipe materials used, installation pattern, water quality impact on pipes,

operating conditions, and soil corrosivity features. Here are the lists of recommendations and outlooks for this dissertation:

- The process of corrosion is complex and hence, every influencing parameter needs to be studied in detail.
- The establishment of corrosion scientists and engineers at the national level who will volunteer their time to investigate corrosion's effect is important.
- The most efficient strategy to apply corrosion mitigation strategies is to understand the corrosion mechanisms and the processes of underground water pipeline deterioration to replace pipelines at the appropriate time.
- Water suppliers need to apply statistical models such as deterministic and stochastic pipe failure based on extensive historical pipeline data recordings to prevent corrosion damage, implement pipe rehabilitation, and increase service levels.
- In the water pipeline system, determining the remaining service life of each pipe segment and ensuring the safety of pipes before damage occurs is a favored way of making decisions on pipeline repair and replacement.
- Organizing a modern pipeline network management system and utilizing sensor-based failure data recording to assess the possible failure mechanisms of internal and external corrosion to control damage mechanisms.
- The design of environment-friendly with corrosion-resistant pipe materials and developing coatings is still a huge demand and can be a focus of future research areas.
- Increasing the percentage of corrosion-resistant materials such as chromium, aluminum, and copper in the existing compositions is advisable to manufacture a pipe that will serve for many years.
- Based on the predicted service lifetime, planning water pipe replacement is crucial to control the risk of corrosion. It is recommended that up to 50% of pipe thickness reduction is a safe condition to use the pipes.

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APPENDIX: List of Publications

This dissertation has led to the following publications:

- I. Yeshanew et al., 2021. Investigation of Soil Physicochemical Effects on the Corrosion of Buried Iron Pipes. *Journal of Basic & Applied Sciences*, 17, pp.95-106.

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This article is published in the Journal of Basic and Applied Sciences as © 2021 Yeshanew et. al. Investigation of Soil physicochemical Effects on the Corrosion of Buried Iron Pipes, SET Publisher. The journal is indexed in **PubMed** and the article is found in the NLM database.

- II. Yeshanew et al., 2021. Corrosion Characterization at Surface and Subsurface of Iron-Based Buried Water Pipelines. *Materials (MDPI)*, 14(19), p.5877.

<https://doi.org/10.3390/ma14195877>

This paper is published in the journal of Materials (MDPI) as Yeshanew et. al. 2021. Corrosion characterization at surface and subsurface of iron-based buried water pipelines. The journal is indexed in the SCOPUS, PubMed, Sci and others.

- III. Yeshanew et al., 2022. Internal Corrosion Damage Mechanisms of the Underground Ferrous Water Pipelines, *Advances in Science and Technology Research Journal*.

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This article is completed and published in the Advances in Science and Technology Research Journal (ASTRJ) as Yeshanew et. al. 2022. Internal Corrosion Damage Mechanisms of the Underground Ferrous Water Pipelines. The journal is indexed in the Web of Science.

- IV. Dessalegn et al., 2022. Modeling of Corrosion Damage Phenomena for Ferrous Materials: in the Case of Ductile Cast Iron Drinking Water Pipelines

The paper is presented for the national conference of the Recent Advances in Automotive and Manufacturing Technology/Engineering (RAAMT' 22) held on 11th July 2022 at FDRE Technical and Vocational Institute, Addis Ababa.