SERVICE LIFE PREDICTION AND RISK ANALYSIS OF REINFORCED CONCRETE GRAVITY FLOW PIPES USING RELIABILITY THEORY

By

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Abstract

Reinforced concrete pipes are susceptible to different types of deteriorations that threaten their structural capacity and serviceability. Failure of these structures or losing parts of their operational capabilities may cause undesirable consequences that affect the surrounding environment, public health and the economy. The main objectives of this research are to estimate the service life, and to evaluate the level of risk of reinforced concrete sewer pipes (RCP) that are under persistent chemical deterioration caused by the sulfide attack that leads to excessive erosion along the pipe's interior wall. In order to estimate the service life, reliability theory is used by implementing concrete cover limit state function, and the probability of exceedance is calculated as a time-dependent parameter. Herein, the predicted service life is defined as the time at which the probability of exceedance is equal to 10%, choosing this probability is based on engineering judgment. Regarding risk level, a simple product of the probability of exceedance and the consequences of failure is used; risk is considered in a qualitative context in this work.

The proposed methodology has been applied to a sample of 30 RC pipes located in Arlington, Texas, USA. Pipes are in different conditions; some of these pipes have insignificant erosion and have expected service life greater than 120 years, however, other pipes are in severe condition and with a predicted service life of 60 years or less.

Chapter1

1.1 Introduction

Pipes are one of the most crucial structures that serve populations. These structures can be buried underground, installed on the surface, or may be placed beneath the water level. Typically, they are built for the purpose of transporting a substance (e.g., wastewater) to and from certain sources and throughout a distribution system. Generally, pipes are installed in order to make the flow of material easier and faster. For instance, reinforced concrete is a composite nonhomogeneous material that is composed of steel reinforcement and concrete. Commonly, these reinforcements take the shape of a rounded cage that is covered by concrete. This type of the pipe has proven to be one of the most durable pipes due to its resistance against rusting, burning, tearing, buckling and defects. Moreover, these pipes are highly durable in most environmental elements, and in general, are more reliable in strength than other alternatives, especially flexible pipes (AmeriTex pipes & products).

As concrete is one of the most common constituent base material in construction, it is expected to be implemented at a high rate in comparison with other materials; since it can accommodate any shape, it requires less energy for production, and it can be formed at any location. According to American Concrete Pipe Association (ACPA), preferences of concrete pipes over other pipes depend on the demanded properties that are available in concrete and missed in other material; RC pipes have a high compressive strength, and manufacture compliance which is the value, the durability, the efficiency and performance of the structure.

Plain concrete, in general, has a compressive strength ranging from 4000 psi up to 8000 psi and steel cage reinforcements in one or two layers carry tensile stresses. American Association of State Highway and Transportation Officials (AASHTO) and American Society for Testing and

Materials (ASTM) standards classify concrete pipes into different classes according to its capacity against D-load test (i.e., dead bearing loads on the three edges expressed as a pound per linear foot per foot of the inside pipe diameter) (ASTM C76. 2015; AASHTO M170. 2015). The strength of concrete pipe is controlled by wall thickness, compressive strength, shape, and amount of reinforcements according to the American Concrete Pipe Association (ACPA).

Durability, as defined by the ACPA, is the capability of a structure to sustain the surrounding environmental effects for an acceptable period. Physical and chemical factors, including freezing and thawing, abrasion, exposure to acid sulfate, and chloride attack affect the service life or the durability of RCPs significantly throughout their life-cycles. RCPs are expected to resist any source of deterioration. One common degradation mechanism involves sulfide attack; this is the main contributor in the erosion of the inner wall of RCP (Wells et al, 2009); therefore, the selection of concrete type and curing process is essential in pipe manufacturing; (ASTM C76. 2015) provides the design standards for these pipes. According to the design specifications i.e. (AASHTO, ACI, etc.…) RC pipes should have enough capacity to resist the surrounding stresses; for example, hoop stresses act circumferentially on the pipe, bending stresses develop due to weight, impact loads and concentrated masses may be applied (e.g. weight of the soil column above the pipe), axial stresses caused by thermal expansion or applied force may develop, and fatigue stresses result from cyclic loading on the pipe.

Overall, this study tries to estimate the service life of the RCPs that have been in operation for different years, and are susceptible to loss of wall thickness due to erosion. Moreover, this study incorporates risk assessment that can ultimately help the city and the decision makers to schedule and prioritize maintenance or replacement of the pipe systems.

1.2 History

Pipes were the solution for the old population when wastewater accumulate in the city and cause fatal serious diseases and make life intolerant. These people thought carefully to get rid of wastewater and at the same time import pure water for drink and agriculture use.. According to (Walshauser. 2012), The first implementation for pipe was performed by Egyptian 3000. B.C.; they used copper pipe, Chinese in the 2500 B.C. used bamboo pipes to transfer gases from a gas well, also in the commence of 2000 B.C. Greeks developed pipe industry using bronze, fired clay and hollowed pipes.

The 19th century witness the pioneering of metal pipes; in 1815, William Murdock fitted the entire city of London with a coal-burning lamp system using discarded muskets, also, in the mid of this century, steel industry commenced due to the invention of the Bessemer process, and during the second end of this century, at least two million feet of steel pipe was installed and spreaded everywhere with competitive prices and better installment.

According to (Walshauser. 2012), concrete pipes have a well-known reputation throughout the years starting in the Roman empire when they built the Cloacae maxima back in 1800 B.C which composed of masonry and cement paste. In 1842 at Mohawk NY, the first concrete pipe is installed and sustain for 100 years followed by installation in New England cities in the mid of the 19 century. The first reinforcement incorporation in concrete pipes was done by the French back in the late of the 19th century and then brought to the united states and Australia in 1910.

Development of pipe never stops, it keeps growing from the first reinforced concrete pipe in 1905 through the prestressed pipe back into the 1930s and first steel cylinder pipe in 1942. Also, the pioneering of in the pipe industry allow the use of larger diameter from 4 in up to 17 ft.

1.3 Literature Review

The durability of reinforced concrete structures and RCPs specifically, is one of the most interesting and challenging topics that researchers have investigated. This study presents a literature review that explains the mechanism of RCP deterioration and the main factors contributing to this deterioration.

1.3.1 Sewer Pipeline Deterioration

The social and economic costs of pipe failure has motivated the development of advanced management techniques for pipe replacement and maintenance (Berardi. et al. 2008). In order to prioritize pipe maintenance, it is necessary to understand the deterioration mechanisms of different pipes. This section discusses briefly the deterioration forms that happen to different pipes materials. According to (Engelhardt. et al. 2002), bursting in any structure occurs when the residual capacity is inadequate to resist the applied force. The capacity of the structure must resist surrounding stresses and any large debris that accompanies the flow that goes throughout the system.

As defined by (Kleiner. et al. 2001), deterioration or defects can be divided into two main categories; first, structural deteriorations decrease the structural capability to resist stresses and lead to failure range from hairlines cracks up to total collapse depending on the material type of the system as shown in (Figure 1), Second, operational and maintenance defects happen in the inner surface of the pipe like deposit, debris, and roots, etc.…, they reduce the hydraulic capacity and degrade the water quality. Hydraulic capacity failure may result from increasing the amount of water because of infiltrations that take place generally at the joint and along the pipe wall altering the catchment characteristics. (Figure 2) presents roots that intervene the pipe at the joint.

Figure 1: Total pipe collapse.

Failure types differ from one pipe to another, a brief summary of pipe types with their historical background and common failure types are presented in the following table by (Reed et al. 2004).

Figure 2 : Roots intrusion.

Table 1 : Common properties and failure types (adapted from Reed et al. 2004).

<table>
<tr><th>Pipe Material</th><th>Typical Date of Install</th><th>Notes</th><th>Common Failure Mechanisms</th></tr>
<tr><td>Pre-stressed concrete.</td><td>1942</td><td>Composed of a steel cylinder and a concrete core. After attaching the concrete to the cylinder, the pipe is cured and wrapped with high tensile steel wire. The steel wire and cylinder are coated with cement to protect the steel components.</td><td>For instance, corrosion of the steel will cause it to swell, which can crack additional cement and expose additional steel.</td></tr>
<tr><td>Polyethylene</td><td>The 1980s</td><td>Includes low density, medium density, and high-density polyethylene. Higher performance polyethylene pipe became available in the 1990s</td><td rowspan="2">Plastic pipes are typically resistant to chemical deterioration. Sunlight can degrade pipes over time. Some types of plastic pipes become brittle due to high temperatures or age</td></tr>
<tr><td>Polyvinyl Chloride (PVC)</td><td>The 1950s</td><td>Includes Unplasticised PVC (PVC-U), Molecular Orientated PVC (PVC-O), and Modified PVC (PVC-A). Long-term material-related problems uncommon and have decreased as manufactures and installers gained experience. Improvement in tapping procedures has resulted in fewer problems with the taps. (Smith et al. 2000)</td></tr>
</table>

Glass fiber reinforced polymer pipes	The 1960s	Combines the corrosion resistant properties of glass fibers and the physical properties of polymers. A most common application is in large diameter water transmission mains.	
Ductile iron	The 1960s	Another improvement in manufacturing cast iron pipes. Stronger than spun grey iron pipes and pit grey cast iron pipes. Often lined or coated to reduce corrosion.	Corrosion to steel is a common cause of failure, and protective coatings can be damaged by flexing or bending of the pipe.
Asbestos Cement	The 1950-1960	Fairly resistant to corrosion (except acid)	Corrosion due to acid, leakages at taps, hair cracks at ends of pipes.

1.3.2 Structural Type Defects in RC Pipes

As a structure ages, the probability of failure increases; therefore, it is mandatory to deeply understand the mechanism of failure possessed by each pipe. As explained previously, pipes can have two categories of defects: structural and the operational defects. Many kinds of literature discuss the effects of the defects on the pipe performance and try to produce models to estimate or quantify the defects and relate them to the service life of the pipe; see Table 1.

(Zhang. et al. 2013) states that cracking is a common structural defect in RCPs; these cracks might be longitudinal, spiral or circumferential. In a study of 303 reinforced concrete culverts, it was found that 63.7% of the pipes failed due to cracks and 70% of these pipes failed by longitudinal crack and the rest is due to deformation and extension (Zhang. et al. 2013). Cracks are not the only reason RC pipes deteriorate; these cracks provide direct contact between water and air with steel reinforcement, which can lead to excessive corrosion and ultimately reduce the structural capacity of a pipe. Loads on a pipe is both vertical (self-weight, soil loads, traffic loads, reaction load) and horizontal pressure (soil pressure as hoop stress), these loads cause inner tensile stress on the inner and outer face of the pipe. Another influence is the type of supports beneath the pipe; if they are curved, the reaction will be smaller and dispersed. The construction procedure and material selection are critical and influencing failure (Zhang. et al. 2013); for instance, using cold draw reinforcement instead low carbon reinforcement is unfavorable because the first is brittle which is undesirable when the pipe is under impact bear load and periodic loads like the construction of roadbed, centrifugal casting result in cracking in the inner and outer protection surfaces, also in regards of curing process, even though steam curing is the desired method, concrete will be under shrinkage cracks, crazing, evaporation of moisture on the surface and large Temperature stresses if it is not implemented properly. Pipe's shape plays an important role in failure regards; the round shape of pipes produces difficulties in handling and transportations which leads to cracks and destruction.

Since RC pipes are classified as rigid pipes, they are prone to structural defects mentioned in Table 2.

Table 2: Common structural defects for rigid pipes.

Defect	Description	References
Longitudinal cracks and fractures	Happens at the springing level and at crown level due to excessive ring stress.	(WSA/FWR. 1993).
Tension cracks	Diagonal cracks from the point of overload.	(White. 1974).
Circumferential cracks.	Due to excessive bending and shear stress resulted from relative movement of pipes.	(WRC. 2001).
Broken	Representing an advance stage of fracture at which fracture propagate from its origin	(Jones. 1984).
Socket bursting	Excessive pressure at the joint due to expansion.	(White. 1974).

1.3.3. Operational and Maintenance Defects

The other types of defect are operational and maintenance defects. Concrete pipes have a distinct and common defect that is categorized into the operational and maintenance defect. This defect is known as corrosion or erosion of the inner surface of the pipe. Erosion may happen due to different factors like the flow rate of the stream, chemical compounds developed in the pipes, emitted to the atmosphere and threatening the expected life of the pipe. Sulfide compound is the main agent responsible for the deterioration of RC pipes and its role has been discussed in different literature. Before discussing how it works, understanding the sulfides development mechanisms is a crucial step. Sulfide in wastewater has the following forms (Pomeroy and Richard. 1974):

1. Insoluble metallic sulfide: presented in the form of several iron sulfides like FeS, Fe_4S_5, and FeS_2 with a limited presence of some other metallic ions like copper, zinc, and lead, etc.…..
2. Dissolved sulfide expressed in term of H_2S and HS^-.
3. Secondary sulfide S^{-2} which has an insignificant presence in the wastewater.
4. From organic compound sulfur like; thiols (CH3-SH), thioethers (CH_3-S-CH_3) and disulfide (CH_3-S-S-CH_3)

From all the anticipated forms of sulfide in wastewater, there must be sources where these compounds grow in sewer pipelines:

1. Industrial waste diffuses into the main sewer lines or leakage of groundwater has high sulfide concentrations; however, these resources are not the main contributor to the sulfide growth in the pipe (Pomeroy and Richard. 1974).

2. Sulfide mainly result from the reduction of inorganic sulfate compound in an anaerobic environment (with the absence of oxygen) by Sporovibrio Desulphuricans anaerobic organism. At the first instant sulfur inorganic compounds appears in the form of sulfate SO_4^{-2} (Parker.1951). Now this sulfate is reduced (loss of bond with oxygen) to sulfide and the organic matter is oxidized by that oxygen, where C a representative of the organic matter thiols (CH3-SH), thioethers (CH3-S-CH3) and disulfide (CH3-S-S-CH3).

$$SO_4^{-2}+2C+2H_2O \longrightarrow 2HCO_3^{-}+H_2S \text{……Eq 1}$$

3. sulfide generation form compounds containing organic sulfur formed due hydrolysis of proteins by the loss of the sulfhydryl group (Parker. 1951):

$$\begin{array}{l} NH_2 \qquad\quad NH_2 \\ CH\text{-}CH_2\ CH_2\text{-}CH+H_2+4H_2O \longrightarrow 2H_2S+2NH_3+2CH_3COOH+2H.COOH..\text{Eq 2} \\ COOH\ \text{-}S\text{-}S\ COOH \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad \downarrow \\ \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad 2H_2+2CO_2 \end{array}$$

An anaerobic environment is essential for reducing sulfate (SO_4^{-2}) because it is based on losing bond of oxygen; therefore, any existence of oxygen will alter this process and reduce the rate of reduction. Because wastewater sewer lines are most of the time is partially filled; it is highly aerobic environments, and this means that the reduction process will take place beneath the water level along a slim layer that provides the proper condition for this process. Normally the slim layer is 0.04 in thick and its thickness is dependable on the flow velocity within the pipe itself. If any oxygen exists in the stream it will be consumed by the aerobic bacteria.

Oxygen in the stream is one of the main constraints regarding sulfide production. The slim film consists of two aerobic and anaerobic layers. Respectively, if the concentration of the oxygen in the first layer is high, it will oxidize any sulfide that is generated by the other layer, but a lower oxygen presence will be demolished by the aerobic bacteria and this will give the sulfide the chance to escape from the film into the stream. The sulfide is susceptible to depletion by oxygen and it depends on the concentration of both sulfide and oxygen to be more than one-tenth mg/l. oxidation can be biologically or chemically, but the biological reaction is more rapid. The overall product is thiosulfate:

$$2O_2+2HS^- \longrightarrow S_2O_3^{-2}+H_2O \text{....... } Eq\ 3$$

The rate of consumption of sulfide ranges from 1-2 mg/l-hr. in fresh water up to 10-15 mg/l-hr., also while the flow exhibit more turbulence, the more the aeration and hence the more oxygen concentration in the water. (Figure 3) shows the slim film in its two layers.

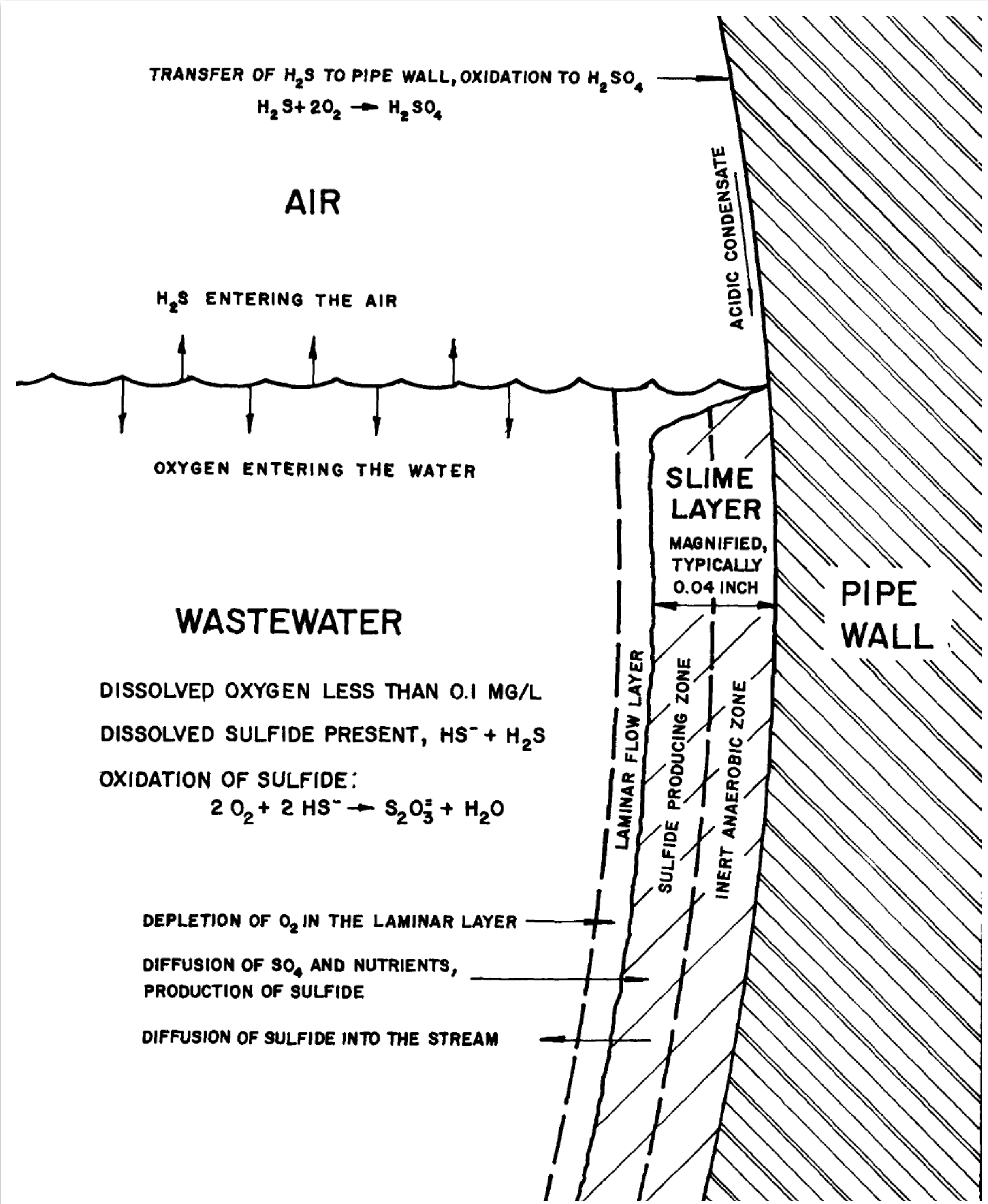


Figure 3: Slim layer with its corresponding reactions (Parker. 1951).

Not only the presence of aerobic environment in the water domain alter the concentration of sulfide in both of its forms (H_2S and HS^-), but also the velocity of the stream somehow is interrelated as the following (Pomeroy and Richard,1974):

1. As the velocity becomes higher the thickness of th e slim film become slightly smaller which means more chance of sulfide oxidation, however, this effect caused by the velocity has a negligible effect on sulfide growth.

2. As the stream flows, it carries different material that precipitates into the ground of the pipe, this precipitation requires small flow speed to allow settling of organic material, and because these accumulated sludges deplete oxygen, more sulfide growth is anticipated.

In conclusion, velocity increases the sulfide build-up indirectly as the velocity goes down. Following the sulfide build up below water level, emission of sulfide starts, however, the emission rate depends on different factors (Parker. 1951):

1. The Concentration of sulfide or hydrogen sulfide in the sewage.

2. The existence of any object on the surface that prevents H_2S from escape.

3. The thickness of the layer at the interference if O_2 and sewage surface.

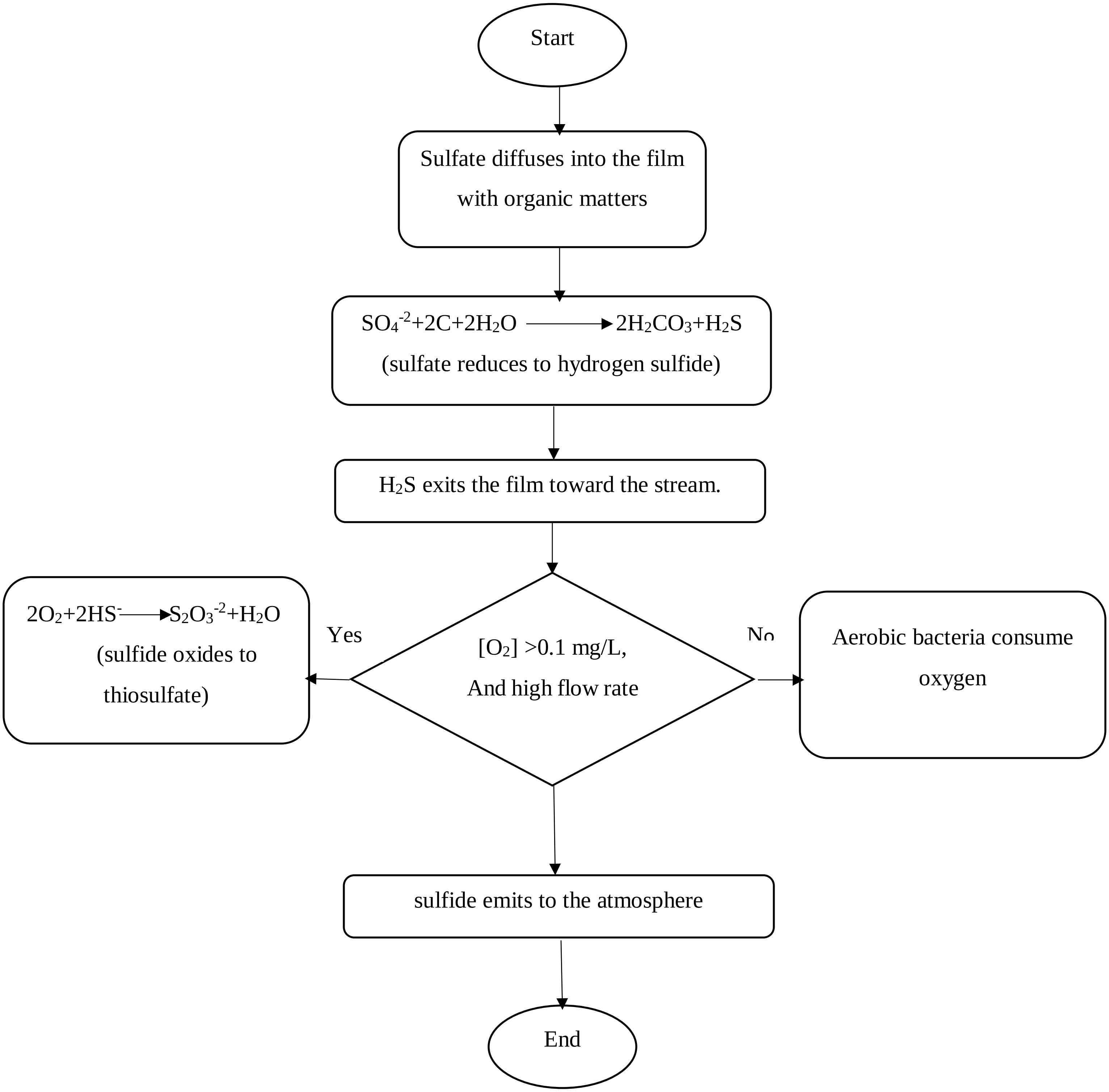


Figure 4: Sulfide development in partially submerged pipes (Parker. 1951, Pomeroy and Richard, 1974).

1.3.4 Erosion Mechanism

After a brief description of the main factors responsible for erosion (i.e. sulfide), understanding the mechanism by which the sulfide in wastewater being an active member in serviceability deterioration is highly important for further studies. There are many kinds of literature related to this. According to (Ahammed and Melchers. 1994), there are two general observations of corrosion, neither of these two causes a strength reduction, however, they cause serviceability loss.

1. General corrosion: observed as a uniform decrease in wall thickness in the section and it is recognized by the loss of the effectiveness of the protective layer.

2. Pitting or crevice corrosion: localized corrosion (no uniform) in the section, does not cause any significant reduction in strength.

According to (Silva and Rosowsky. 2008), microorganisms have significant role in accelerating the deterioration process; microorganisms may be sorted and ranked according to their impacts on the concrete surface.

1. Because of the high alkalinity of concrete after casting pH (12-13) that results from $CaOH_2$; this prevents the growth of microorganisms (Ribas-Silva. 1995). This stage is defined as Abiotic Neutralization (Wells. et al. 2009) in which high alkaline environment pH (12-13) prevents any chance of micro-activity, however, the sulfate-reducing bacteria (SRB) reside in the biofilm which exists along the perimeter of the submerged surface act as a reducing agent that reduces sulfate (SO_4^{-2}) into hydrogen sulfide and these bacteria is oxidized to form carbon dioxide (CO_2).

$$Organic\ matter + SO_4^{-2} \longrightarrow H_2S + CO_2 \ldots\ldots Eq\ 4$$

Once the pH drops to 9 and with a sufficient existence of nutrient and oxygen, sulfur reducing bacteria (e.g., thiobacillus) starts to colonizing the concrete surface and as they grow, they facilitate the oxidation of the sulfur ions S^{-2} in the sulfuric acid to form hydrogen sulfate acid (H_2SO_4).this acid will further react with the concrete surface to drop the pH more. This is known as Biotic corrosion as displayed in (Figure 5).

$$H_2S + 2O_2 \xrightarrow{NOSM} H_2SO_4 \ldots\ldots Eq\ 5$$

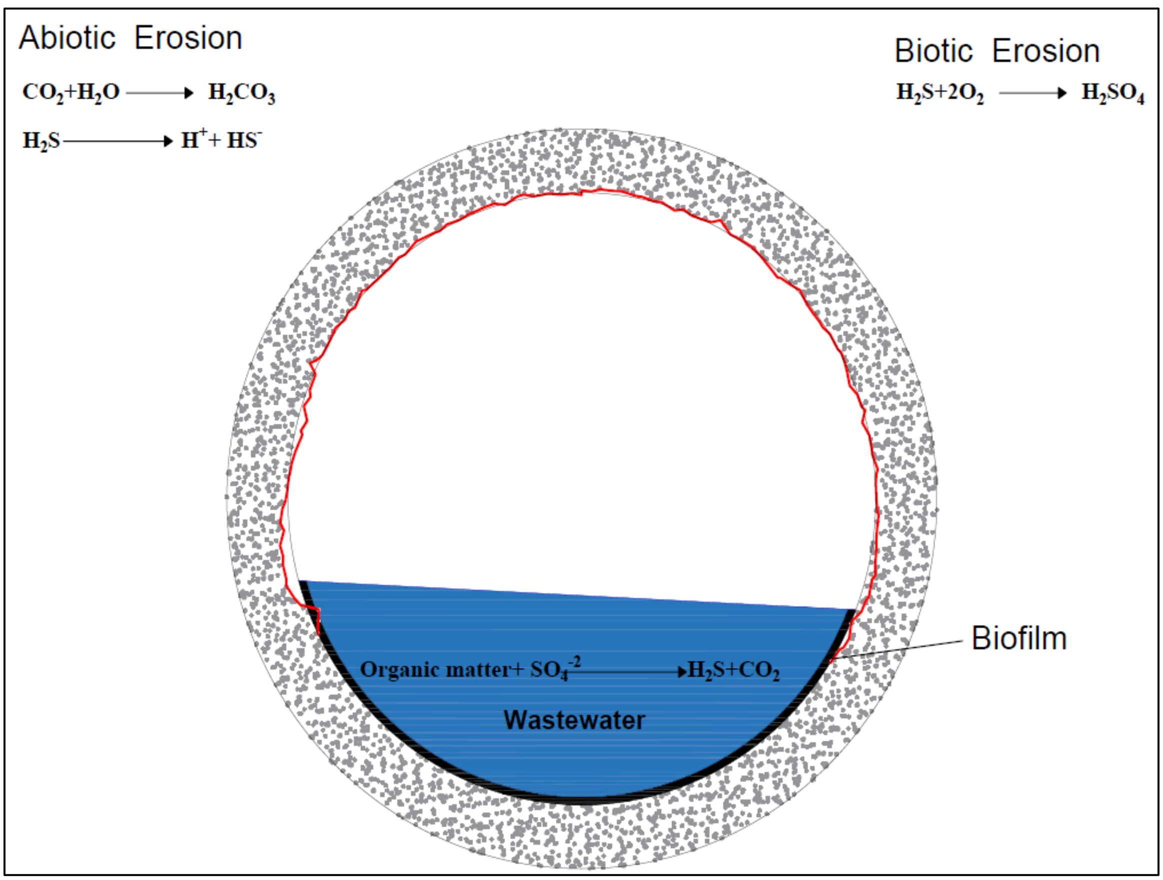


Figure 5: Abiotic corrosion and Biotic corrosion (Wells. et al. 2009)

2. Acidophilic bacteria colonization (ASOM):

   These bacteria start to grow once the pH drops to 4, it has the same role as the previous one (NOSM) also it oxidizes the elemental sulfur and the thiosulfate ($S_2O_3^{-2}$) this process will further drop the pH to (1-2).

3. Thickness losses initiation:

   The H_2SO_4 the result from the oxidation of the H_2S by the ASOM bacteria reacts with carbonate and silicate products in concrete mix to produce calcium sulfate $CaSO_4$ (gypsum) which accumulate on the perimeter of the unsubmerged surface. Figure (6) shows the chronological order of microorganism's growth with their corresponding pH drop and cover loss.

$$H_2SO_4+CaO.SiO_2.2H2O \longrightarrow CaSO_4+Si(OH)_4+H_2O \ldots\ldots Eq\ 6$$

$$H_2SO_4+CaCO_3 \longrightarrow CaSO4+H_2CO_3 \ldots\ldots\ldots\ldots\ldots Eq\ 7$$

$$H_2SO_4+Ca\ (OH)_2 \longrightarrow CaSO_4+2H_2O \ldots\ldots\ldots\ldots\ldots\ldots Eq\ 8$$

$$CaSO_4+3CaO.AL_2O_3.6H_2O+25H_2O \longrightarrow 3CaO.AL_2O_3.3CaSO_4.31H_2O..Eq\ 9$$

The formed gypsum will further react with the tricalcium aluminate to form ettringite ($3CaO.Al_2O_3.3CaSO_4.31H_2O$).

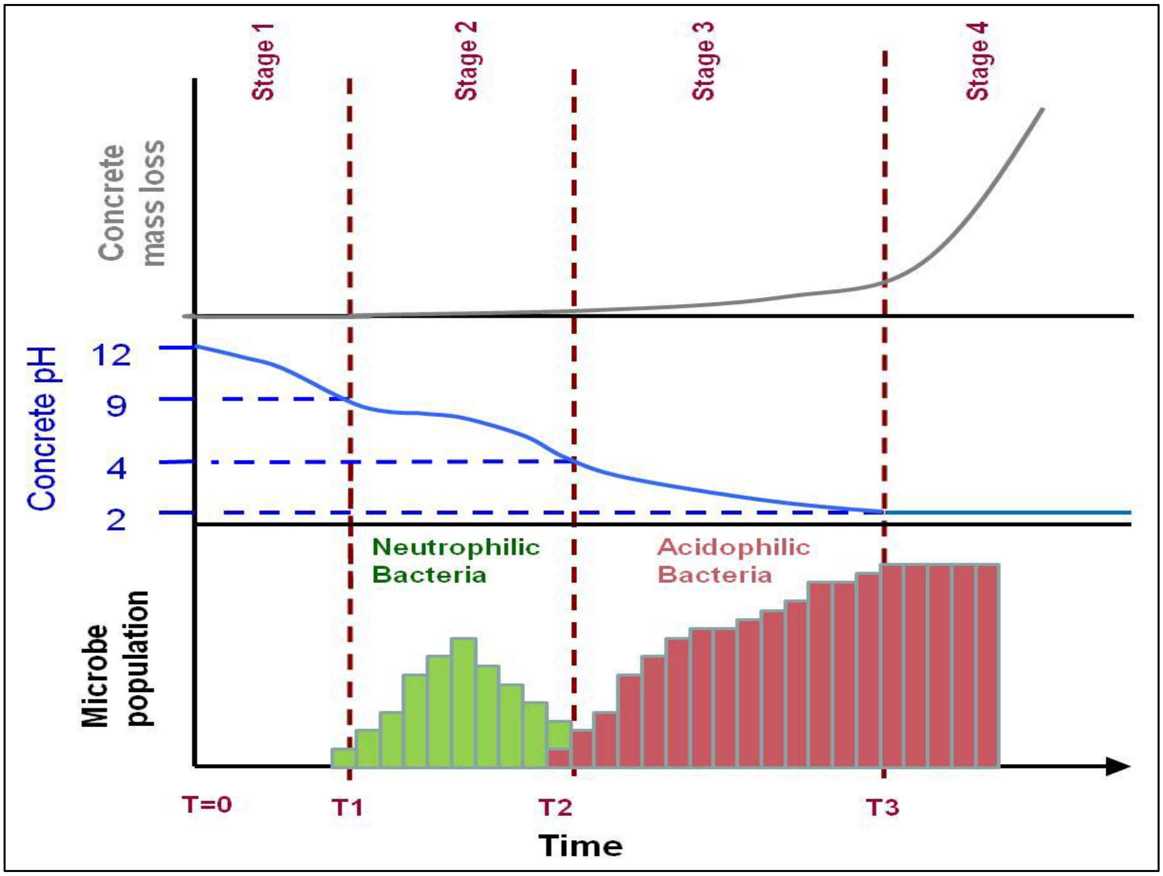


Figure 6: Progression of microorganism's growth with their corresponding pH drop (Wells. et al. 2009)

The gypsum is easily observed on the concrete surface as a white material with a weak bond to the surface, however, it acts as an isolator that prevents the H_2SO_4 from reaching the concrete (Okabe. et al, 2007), meanwhile the Ettringite is observed where cracks exist (Mori. et al. 1991; Mori. et al, 1992) because it causes a volume expansion of 127% and may reach to 600% according to (Monteny.et al, 2000) and (Parande. et al, 2006).

After addressing sulfide contribution in the erosion process, there are other factors that alter it:

1. The higher the resident time and the energy loss of the flow, the higher the BOD concentration which increases the activity of the ASOM and NSOM (Tator. 2003) (facilitate oxidation).

2. The pH is a factor that has a role in the equilibrium equation of hydrogen sulfide the less the pH the more transfer of H_2S gas rather than the disassociation in the liquid HS^- and $S^{-2}$and increase the micro-activity.

3. Transformation of sulfide (HS^- and S^{-2}) from the liquid phase to gas phase (H_2S) is also affected by both temperature and the turbulence of the flow (Monteny. et al. 2000; Lahav. et al. 2006; Parande. et al. 2006).

4. Washing of concrete pipes diminishes the micro-activity, however, within a few weeks these bacteria colonize again (Nielsen. et al, 2008).

5. Water to cement ratio (W/C) has a great impact on the erosion rate; the lower the W/C ratio the greater the erosion rate, however low porosity tends to act against corrosion rates because it prevents the hydrogen sulfate from reaching carbonate and silicate products in the concrete mix (Islander. et al. 1991).

6. The aggregate type also affects; calcareous material provides a buffering environment (pH neutralizer) against oxidation (Hewayde. et al, 2007).

The erosion of the pipe does not start from the time of installation; however, it starts from the point by which the pH drops below 6 (Wells and Melchers. 2015) regardless of the environmental conditions. This is also has been enforced by (Thistlethwayte. 1972) and (Okabe et al. 2007). But the time required to reach this point (initiation period) depends on the aggressiveness of the environmental conditions (Temperature, Humidity and H_2S concentration).

(Wells and Melchers, 2015) performed a test on samples of RC pipes. This test investigates a new sample (zero age) and an old sample (70 years old samples) in Australia to estimate the required time for erosion initiation and they find that this period ranges from 9 up to 36 months. Concrete pipes last for more than 50 years so this period is having no influence on the service of the pipe.

1.3.5 Estimation of Erosion Rate

After the explanation of the erosion mechanism in concrete pipes, literature concern is to forecast the erosion rate. This will help in anticipation of erosion at any time. Erosion rate depends on multiple factors including temperature, humidity and H_2S concentration which vary with time (Jiang. et al, 2014a, 2015), also (Jiang.et al, 2014b; Monteny et al., 2000) ; (Parande. et al, 2006) shows that the development of internal cracks in the pipes agitates to erosion rate; therefore, in order to understand the behavior of the erosion, erosion rate models are tested for validity with long-term erosion data.

1. According to (Pomeroy and Richard, 1974); erosion rate can be estimated using the following formula:

$$C\ \left(\frac{in}{year}\right) = 0.21952 * k * (s * u)^{0.375} * j * [DS] * \left(\frac{b}{p}'\right) * \left(\frac{1}{A}\right)\left(\frac{in}{year}\right) \ldots \ldots Eq\ 10$$

K factor: which is related to the rate of the acid formation and it ranges from 0.3-0.4 for rapid formation and approaching 1 for low rates.

J factor: is the ratio of sulfide presented as H_2S to HS^- and it depends on pH. From previous literature, the erosion process starts when pH drops below 6. From Table (2-3) (Pomeroy and Richard. 1974); j is equal to 1,

[DS]: sulfide concentration in water stream, this parameter varies even throughout the day,

A: which is the alkalinity of the pipe determined based on the composition of concrete pipe. most concrete pipe industry use aggregate made of limestone or dolomite (calcareous rocks) which has been found for most cases to have an alkalinity of 0.9 (Pomeroy, Richard, 1974).

2. Erosion model expressed by (Thistlethwayte.1972).

$$Cr\ \left(\frac{mm}{year}\right) = 19.9 * 10^6 * \frac{Ksa*PH_2S*Asa}{Z*m*Aaw} \ldots \ldots Eq\ 11$$

Where

K_{sa}: Rate of absorption of H_2S on pipe wall ($kg/m^2 * h$).

P_{H2S}: Partial pressure of H_2S (ppm).

A_{sa}: Ratio of the surface width of the stream to the exposed perimeter of the pipe wall above the water surface (m/m).

Z: Cement content of concrete (kg/m^3), m: Density of concrete (kg/m^3).

A_{aw}: The exposed perimeter of the pipe wall above the water surface (m^2/m).

3. Statistical methods are one of the methods used to model the initiation time for erosion and the erosion rates with independent variables of humidity, temperature, location, and H_2S concentration. Variables with significant factors less than 0.05 are eliminated to achieve minimum adequate model. (Jiang. et al. 2014b; Monteny. et al. 2000; Parande. et al. 2006) produce a multi-linear regression model to estimate the initiation time using long term erosion data set from a study done in three different cities in Australia considering different environmental conditions.

$$\text{ti} = 96.34 + 1.68 * \text{Location} - 0.18 * H_2S - 0.54 * \text{RH} - 0.84 * \text{T} \ldots\ldots \text{Eq 12}$$

This model has a coefficient of variation value R^2 of 0.54; which means 54% of the variation in the dependent variable is expressed in this model.

4. Artificial neural network modeling (ANN): this model has three layers of variables; the first layer is the input layer (any given data that is expected to influence the results), the second layer is the hidden layer which represents the model that transit the input data to the third layer which is the output layer (Liu. et al. 2017). This model contains four main steps:

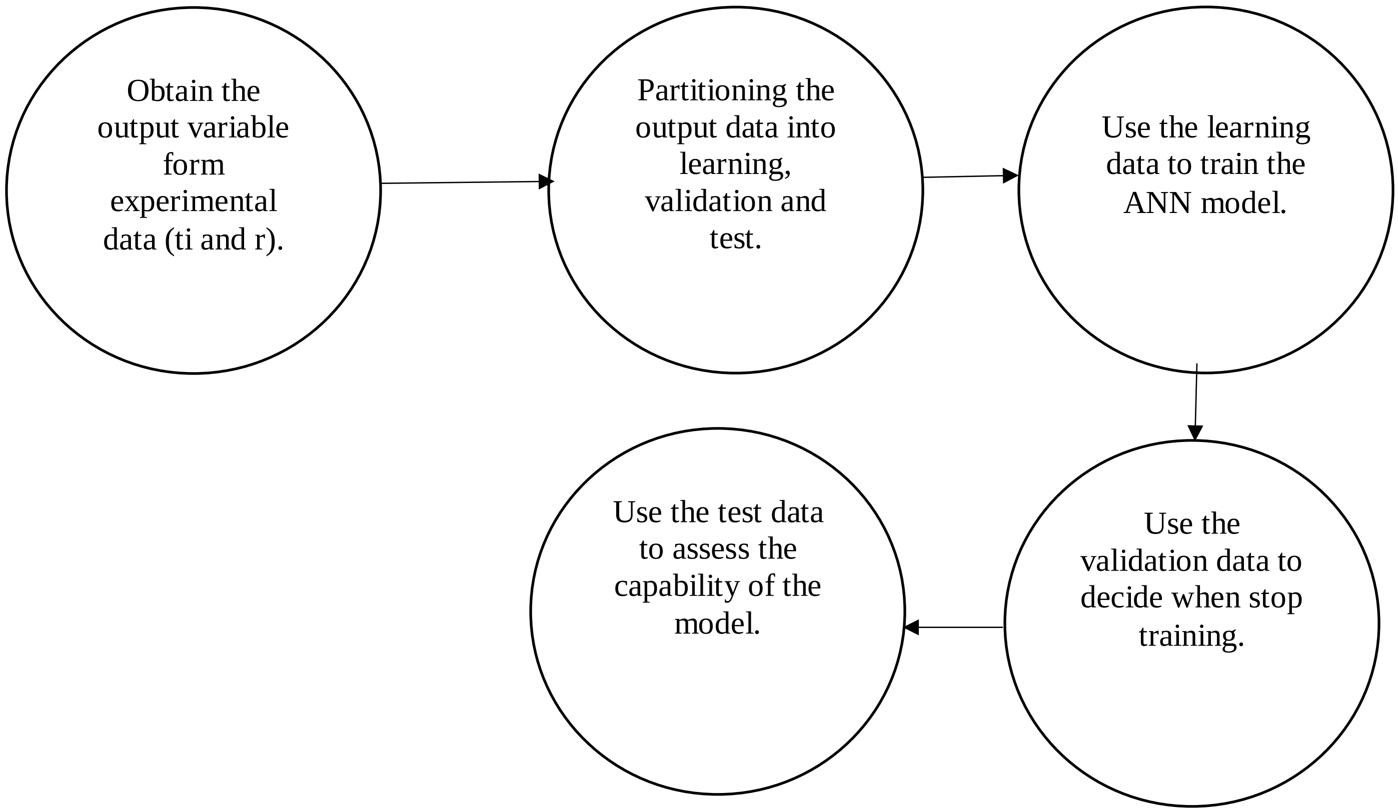


Figure 7: progression of Artificial neural network modeling (ANN) (Liu. et al. 2017).

Using the multi-linear regression backward selection process, (Liu. et al. 2017) estimates a linear equation for erosion rate for both partially submerged (near water level) Eq 13 and for gas (at the crown) Eq 14 respectively.

$$r\left(\frac{mm}{year}\right) = 1.03 - 0.45 * Location + 2.82 * 10^{-2} * H_2S \ldots\ldots Eq\ 13$$

$$r\left(\frac{mm}{year}\right) = -0.63 - 0.45 * Location + 2.82 * 10^{-2} * H2S + 8.69 * 10^{-3} * RH + 1.5 * 10^{-2} * T..Eq\ 14$$

This model provides more accurate results since the R^2 value is 0.8291, however, the model for partially submerged pipes does not take into account any environmental factors, which may alter the time to initiation, moreover, this model was developed using laboratory data which has limiting conditions compared with field investigations, it also over predicting the erosion rate; for instant it ranges from (0.16-1.5 mm/year) when the H_2S is 0 ppm. Erosion rate at the crown is 0.9mm/year more than the one near the water level.

5. Bypass model: (Wells and Melchers. 2015) relies on a physical, chemical and biological process in generating the model. They verified the result using data from an investigation of new samples (zero age) and old samples (70 years old samples) of RC pipes in different cities in Australia. Temperature impact is due to biological effect (Franzmann. et al. 2005; Nielsen. et al. 2006), humidity cause pores to fill out with moistures allowing the more microbial activity. Because the oxidation of H_2S effects the erosion rate; (Nielsen. et al. 2014) suggests that the oxidation of the sulfide follows an order of (n). (Wells and Melchers. 2015) estimate (nth) to be equal to 0.5 according to their experimental data.

$$C\left(\frac{mm}{years}\right) = A * [H_2S]^{0.5} * \frac{(0.1602*H-0.1355)}{(1-0.977*H)} * e^{(\frac{45000}{RT})} \ldots\ldots Eq\ 15$$

A: An empirical constant that relate field data to the model.

$[H_2S]$: Concentration of hydrogen sulfide (mg/L).

H: Relative humidity in sewer.

T: Temperature (k).

R: Universal gas constant (8.314 J/mole/k).

1.4 Reliability Analysis

Reliability of the structures holds different definitions; according to (ISO 2394. 2015), it is the ability of the structure to fulfill the design requirements during it’s expected design life. Reliability of the structures covers durability, load capacity, and serviceability of the structure (EN. 1990). Every structure is designed to sustain up to different level, whether in loading or in serviceability but based on the importance of the structure and economic considerations, designers set this level by choosing a specified value of probability of failure or reliability index.

Design methods of civil structures developed throughout the years incorporate the reliability in their methodologies; like the permissible stress design method ($\sigma_{max}<\sigma_{citical}/k$), global safety factor design method ($X_{resist}/X_{act}=S$). In these two methods, both actions (E) and resistances (R) are determined based on different design parameters like material properties, actions, and model uncertainties, also the (k) factor and the safety factor (S) reflect the reliability of these structures. Calculation of this factor is based on the desired probability of failure; therefore, probabilistic design method was addressed in (ISO 2394, 1998) in which designer specifies an allowable probability that structure should not exceed it during its expected service life ($P_f<P_t$). The probability of failure is calculated using computational (limit state function) in which resistance and action are functions of performance variables [X_1, X_2, X_3, X_4.X_n]. Generally, the probability of failure is the probability that the limit state function value (g(X)) is less than zero (resistance<action), where g(x) function is shown below.

$$g(x) = R(x) - E(x) \dots\dots Eq\ 16$$

Limit state is the point after which the structure is classified as unsafe, unserviceable or failed, based on the proposed limit state function (Eurocode, 1990:2002). In most common cases, limit state functions can be limited to vertical deflection, yielding point or any variable. The action on the structure increase until the limit state point, however, sometimes it is very hard to define this point, therefore, it is more convenient to define the limit state as an interval in which the structure loses its performance or reliability under a specific rate rather than losing it abruptly. Generally, when addressing a reliability issue or limit state function, the action and resistance are expressed in one of the following forms:

1. Resistance or action is a random variable: in this case, resistance is a constant number (independent on performance behavior) (r) and the action is a random variable of some performance factor and vice versa. The probability of failure is described as the following:

   $$P_E = P(E < r) = \Phi_E(r) \ldots \ldots . Eq\ 17$$

   In which Φ_E and P_E are the probability distribution function of the action random variable and probability of exceedance respectively.

2. Both action and resistance are random variables: these random variables can be described by different random distributions. The probability of failure is described in the following equation.

   $$P_E = \int_{-\infty}^{\infty} \Phi_R(x) * \Phi_E(x)\ dx \ldots \ldots . Eq\ 18$$

   In which Φ_R is the probability distribution function of the resistance random variable and Φ_E is the probability density function of the action random variable. This integration can be done numerically or Monte Carlo simulation.

Limit state function are classified based on the type of deterioration; losing of serviceability or safety:

1. Ultimate limit state: this limit associates with the safety of the structure and the safety of people. The limit state in most cases is defined as the failure of the structure and it can be described as an excessive deformation happens before the collapse, collapse can be also the limit state point. (Holicky. 2009) says that the ultimate limit state must be considered in case of loss of equilibrium, rupture, or changes in the behavior of the structure into a new system.

2. Serviceability limit state: this limit state concerns with the comfort of the user, the function of, and the appearance of the structure. This limit can be reversible or irreversible depends on the ability of the structure to recover from the permanent or temporary action.

Because structures exhibit different failure mode, it is hard to define failure or reliability using one limit state function; therefore, limit states representing failure modes are combined in one system. This system incorporates ultimate and serviceability limit states that are applied and act in parallel or in series with respect to each other (Holicky. 2009). Limit states act in parallel if the failure of the structure occurs when all the limit states are exceeded, meanwhile, limit states act in series if the failure of the structure occurs when at least one limit state is exceeded (Holicky. 2009). The concept of interaction and union are applied for parallel and series limits states respectively when calculating probability of failure. (Eq 19), (Eq 20), and (Eq 21) are samples of probabilities of failure for systems in which limit states acts in series, parallel, and combined respectively.

$$P_f = \left(P_{f1} \cup P_{f2} \cup P_{f3}\right) \ldots \ldots . Eq\ 19$$

$$P_f = (P_{f4} \cap P_{f4} \cap P_{f5}) \dots \dots . Eq\ 20$$

$$P_f = (P_{f4} \cap P_{f4} \cap P_{f5}) \cup (P_{f1} \cup P_{f2} \cup P_{f3}) \dots \dots . Eq\ 21$$

Different kinds of literatures use reliability analysis in different subjects related to pipelines and infrastructures in general (Mahmoodian and Alani. 2014), (Khan and Tee. 2016) and (Skrzypczak. 2017). (Mahmoodian and Alani. 2014) present a system of limit states for concrete in (Figure 8). As shown, the flexural and shear failures are ultimate limit states and they act in series which means the occurrence of one of them means a total failure in the structure, meanwhile, serviceability limit states like cover loss and crack control do not represent failure, therefore they act in parallel.

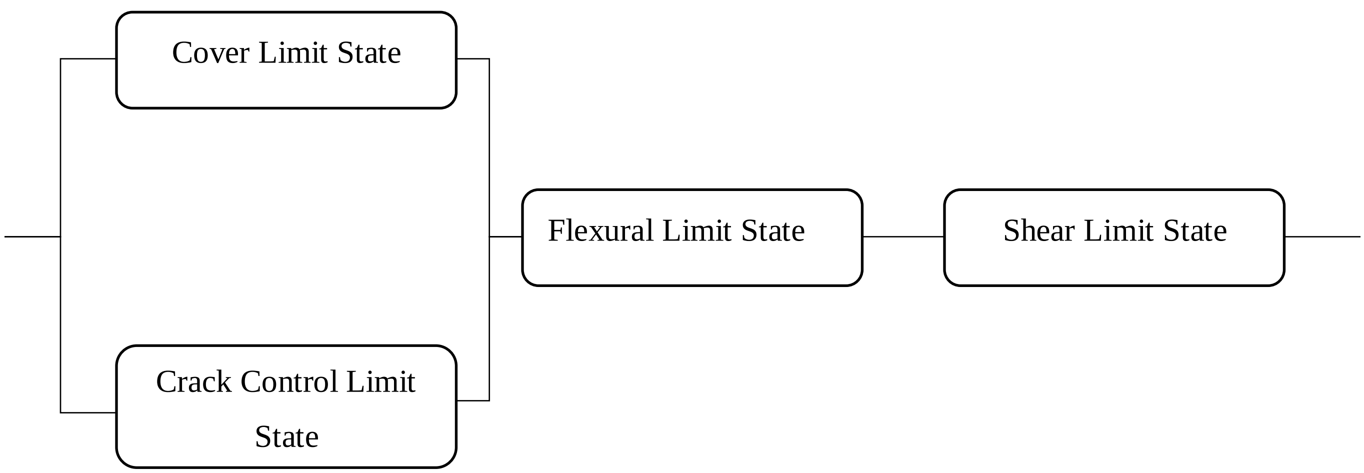


Figure 8: System of reliability for reinforced concrete pipe (Mahmoodian and Alani, 2014).

. (Khan and Tee. 2016) evaluate the risk cost of pipelines using subset simulation i.e. (a reliability method) and it is based on the conversion of optimization problem (maximum or minimum event) into probabilistic method (any event). This method overcomes barriers that is common in reliability analysis like; uncertainty about future conditions and the limitation or the validity of previous methods due since they were built using local random variables. (Skrzypczak. 2017) evaluates the probability of failure using common three reliability methods. The first method is a non-probabilistic or linear limit state functions are used and it is available in structural codes and standards, this method is used when all analysis parameter is known. The second method has two parts; second and first order reliability analytical method (SORM/FORM) which are used for calibration of the first approach. The third approach includes statistical analysis and stochastic simulations (Monte-Carlo simulation).

1.4.1 Risk Analysis and Consequence of Failure

Pipelines transfer wastewater throughout an integrated sewer system are susceptible to damages and even failure. Because these pipes are built into the ground, their conditions cannot be monitored continuously and there is no appearing evidence until the consequences commence, moreover, failure or even a small damage consequence cannot be tolerated due to the toxic nature of the wastewater and their impact on the surrounding environment, human public health society and the economic concerns. Because these pipes are distributed all over the city, it will be hard for the decision makers and the responsible agencies to prevent all the damages in the whole pipes system around the city. This is of courses is an uneconomical solution and impractical, therefore, decision-makers need to prioritize the rehabilitation of defected pipes based on kinds of parameters. In common engineering practice, risk is the desirable variable.

Risk is the expected consequence of an activity to reflect on the society, economic value and environment (Holicky. 2009), also it’s a function of the probability of failure and the consequences of this failure (eHuang. 2009, Aven. 2011). In general, risk is expressed in two ways; the first way is to express the risk as a quantity results from the product of the probability of failure and the consequences. This approach is suitable when there is no ambiguity or certainty in the consequences of failure, mainly in the regards of environmental and social impacts and expressing the consequences in a monetary term is preferable (Salman, and Baris. 2010; Anbari. 2016).

In sewer line, the consequences are related to environment and social impact, therefore, it is not economical to express the consequences quantitively and the second approach will be more reliable in which the risk is explained using linguistic values. Because risk is a combination of the probability of failure and the consequences, estimation of these Parameters is researchers concern. Different methodologies have been developed; for instant, Water Environment Federation/ASCE (WEF/ASCE. 2009) groups consequences of failure in sets based on the criticality of the three main impacts (environmental, economic and public heath), other researcher goes more further by incorporating more impact factors like; (McDonald and Zhao, 2001) who incorporates location, size, the type of soil, and the functionality and the consequences of each factor is categorized into different class level. Sewer, (Hahn et al. 1999) and (Hahn. et al, 2002) developed cataloging, retrieval, and prioritization system in which socioeconomic and reconstruction impacts are considered and the information related to this system are collected from groups of publics. Furthermore, the influence of different impact factors (age, pipe length, diameter and slope of the pipe) using the Monte Carlo simulation methods has been investigated by (Khan et al. 2009). In addition to all mentioned above, (Baah, Kelly. et al. 2015) evaluated consequences and risk using risk matrix and multi-criteria decision matrix and this study consider not only structural failures but also hydraulic failures.

The other significant component in finding risk is the condition of the asset at a given time. The condition of the assets can be estimated using either deterministic or probabilistic models and both models can be used to estimate the remaining life of the assets based on the time required to reach a predefined probability or condition, common methods to estimate the condition of the structure is shown in (Table 3) (Salman. 2010).

Table 3: Deterministic and probabilistic methods to estimate the condition of the assets (Salman. 2010).

Referenced Study	Method	Variables of Interest
(Chughtai and Zayed. 2008).	Multiple Regression.	Pipe material, depth, length, age, diameter, material class, bedding factor and street category
(Ariaratnam et al, 2001).	Logistic Regression.	Age, diameter, material, waste type, and an average depth of cover
(Najafi and Kulandaivel.2005).	Artificial Neural Networks.	Length, size, material type, sewerage, depth of cover, slope, and sewer type
(Wirahadikusumah et al. 2001).	Markov Chains – Nonlinear optimization.	A categorized dataset in terms of material type, groundwater table, backfill soil type, depth of cover
(Sinha and McKim. 2007).	Markov Chains – Nonlinear optimization.	Not specified
(Kleiner. et al. 2001).	Semi-Markov	Expert opinion, age
(Kleiner et al. 2004).	Fuzzy Rule-Based Markov Chains.	Age
(Micevski et al. 2002).	Markov-Chains – Metropolis-Hastings Algorithm.	A categorized dataset in terms of diameter, material type, soil type, exposure classification (distance from the coastline) and serviceability
(Baik et al. 2006).	Markov Chains – Ordered Probit.	Length, size, material type, age, and slope of the pipe

(Le Gat. 2008)	Markov Chains – Gompit	Diameter category, sewer type, installation period category
(Baur and Herz. 2002)	Survival Functions	Age, material, function, type of pipe, the shape of the profile, gradient, street category
(Ruwanpura et al. 2004)	Rule-Based Simulation	Age, material, and length

1.5 Research Objectives

In this study, the objective is to estimate the service life of RC pipes using the cover loss serviceability limit state function considering erosion of the concrete cover. Real data that have been collected from field inspection of pipes at different locations within the city of Arlington, TX, USA using Laser-based scanning is incorporated herein. Additional efforts related to finding the risk of losing serviceability of this pipe using methods provided by previous literature, is also presented. The output of this study represents the remaining service life corresponds to an acceptable probability of failure and the risk value of 9 ft. segments within pipelines after several years of operation.

Chapter2

2.1. Data Collection Methods

Pipes after installation are subjected to deteriorations due to different factors, therefore, it is mandatory to inspect these pipes to document defect and justify maintenance or replacement. Pipes are inspected using a high-resolution video recording equipment;circuit television system (CCTV). The minimum requirement for this equipment is to provide a clear image with good lighting for interior wall, runs at the center of the pipe and move with a speed, not greater 30 ft/minute (Inspection Manual for Concrete Pipes. 2014).

In order to evaluate the current pipe status, a non-destructive evaluation is desirable. There are a lot of options to provide an enough review without any destruction and they are listed in (Table 4) with their corresponding common observations.

Table 4: Pipes inspection techniques with their observations (Makar. 1999).

Technique	Where to Use	What Will Be Found	Purpose of Inspection
Conventional CCTV	empty pipes, partially filled pipes above the water surface	surface cracks, visible deformation, missing bricks, some erosion, visual indications of exfiltration/infiltration	Inspection of the Inner Pipe Surface
Stationary CCTV	Pipes with less than 50 m. distance between manholes	As CCTV	
Light line CCTV	Pipes where deformation is an issue	Better deformation measurements + CCTV results	
Computer Assisted CCTV	As CCTV, currently small diameter pipes only	As CCTV, but with quantitative measurements of damage	

Laser Scanning	partially filled pipes, empty pipes	surface cracks, deformations, missing bricks, erosion losses	
Ultrasound	Flooded pipes, partially filled pipes, empty pipes	deformation measurements; erosion losses; brick damage	
Micro deflections	Rigid sewer pipes	overall mechanical strength	Inspection of Pipe Structure and Bedding Condition
Natural Vibrations	Empty sewer pipes	combined pipe and soil condition, regions of cracking, regions of exfiltration	
Impact Echo	larger diameter, rigid sewers	combined pipe and soil condition, regions of wall cracking, regions of exfiltration	
Spectral Analysis of Surface Waves	larger diameter, rigid sewers	regions of wall cracking, overall wall condition, variations in soil condition, regions of exfiltration	
Ground Penetrating Radar	inside empty or partially filled pipes	voids and objects behind pipe walls, wall delamination's, changes in water content in bedding material	Inspection of Bedding

Regarding erosion measurements, filed data can be obtained using either one of the following options knowing that erosion only occurs above water level along the perimeter of the pipe wall.

2.1.1 Closed-Circuit Television (CCTV)

Most of the sewers need to be inspected visually using circuit television system (CCTV) and human inspectors (Water Research Centre. 1995), however, due to access difficulty in some pipes especially for small diameter pipes, it is more favorable to use a camera mounted over the robot (CCTV). CCTV can be stationary (attached to the manhole) to detect defects surrounding manhole within camera ranges, so it's hard to report defects in the middle of the sewer lines, however, it can refer which part of the sewer lines should be inspected using mobile CCTV. In this inspection, a camera is attached to the robot while moving along the pipe axis to examine the entire pipe length between two manholes. Although the advantages of the mobile CCTV overcome stationary CCTV in reporting defects along the pipeline, stationary CCTV is cost less; since cleaning the pipes for easing the movement of the robot is not required (Makar. 1999).

2.1.2 Laser-Based Scanning Systems

Laser scan is only valid for the portion above the water line; however, it is more precise in reporting defects that cannot be reported by CCTV accurately; for instant deposit and erosion level along the perimeter of the pipe. These defects can be observed by CCTV recording but they cannot be quantified, also small deformations and shape changes affecting the pipe cannot monitoring through the CCTV (Gibert. 1997, Hibino. et al. 1994). To emphasize the accuracy of this method, the laser scan does not require human bean action or processing since all laser data are captured and analyzed using computer software.

The laser is measured using either image processing, distance triangulation and time of flight measurements. Laser robot assembles measured data into a 2D cross-section then it renders these data into a 3D profile. Common profilers are listed below.

1. Rotational Profiler

    a. Use triangulation principles and time of laser flight to measure distances.

    b. To obtain a 2D profile; laser dots originates from the center of the pipe to the wall, and because the distance to the wall with it is corresponding triangulations is known, we can obtain the coordinates of the profile.

c. To obtain a 3D profile; combine 2D profilers into the best cylindrical shape.

2. Continues Ring Profiler

    a. Laser light illuminates from the pipe axis radially, then the illuminated ring is captured by high definition digital camera.

    b. Counting the number of pixels from the center pipe, many radial measurements can be obtained.

    c. The output is many 2D profilers that are combined to generate a 3D profiler.

3. Lidar

    a. It scans the backward and forward of a plan, and measure the distances based on the elapsed time that the laser takes to travel from it's origin to the wall.

    b. Multi 2D cross sections are formed from ring measurements using measured pair distances.

    c. 3D profiler is obtained simultaneously using Multi 2D cross section.

This study uses multi-sensor inspection robot (MSI) (see Figure 8) with aid from profiler software and Fly movie provided by (RedZone Robotics. 2018) to form 3D laser profilers along pipes. MSI RedZone has different types of equipment each has different properties. This study relies on HD profiler which has a floating platform for pipe ranges in diameter from 20'' to 84'. It provides an HD image for visual inspection and clear measurements of deposits, erosion, ovality, and debris based on topographical flat data. As presented in (Figure 9); data are presented using a color code between two manholes in which blue color refers to deposits or debris attached to the pipe wall, meanwhile red to orange color refers to erosion or missing wall thickness.

Figure 8: Multi-sensor inspection robot (MSI) (RedZone Robotics. 2018).

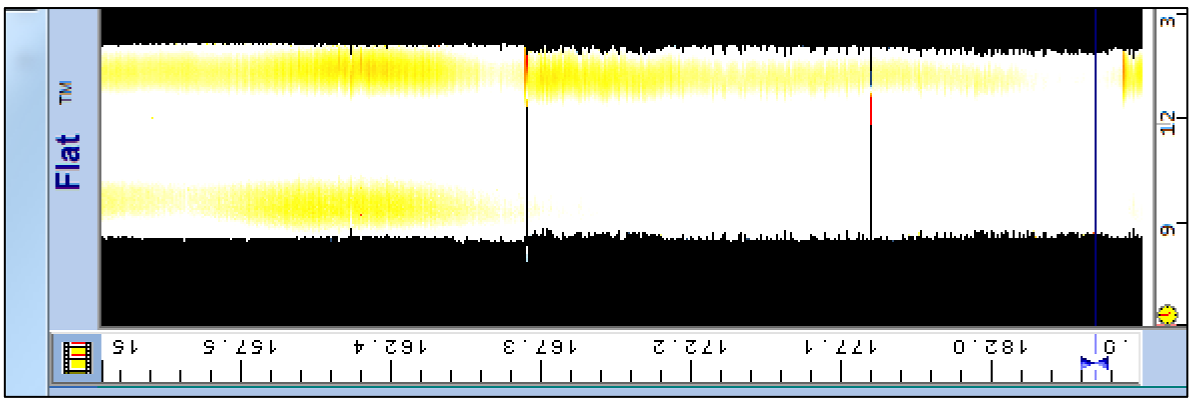


Figure 9: Topographical flat data for pipe between two manholes.

2.2 Methodology

Erosion is one of the service life limitation factors and it represents the loss of thickness along the perimeter of the wall above the water level. Thickness loss rate varies as the erosion rate varies under different conditions explained in chapter 1 and because of the difficulty of providing continues measurements of these highly flocculating and unpredictable conditional variables, previous literature assumes that the erosion rate is constant starting from the point of initiation.

In this study, inspection of reinforced concrete pipes located in the city of Arlington was done and they have been under service since the second half of the previous century. Lines are divided into different inspections each one assigned to a different part of the city, in each inspection part of the pipes are RCP. In cooperation with the municipal of the city of Arlington and RedZone, RedZone inspects all inspections using multi-sensor inspection robot (MSI). Following that, data analysis is done by the University of Texas at Arlington Team.

2.2.1 Erosion Data

Using the multi-sensor inspection robot (MSI), erosion data is observed by the CCTV recording and Laser-Based Scanning Systems which helps to quantify pipe erosion as loss of thickness. The following points are the steps for erosion data collection

1. After robot installation, the robot moves in the direction of the stream and ejecting laser that scans the perimeter of the pipe wall every 0.1 ft. laser scan and CCTV recording are then imported into Fly Movie software in which inspectors cuts the video between two manholes. Still, from this point, no values or measurements are yet available.

2. Laser data is interpreted as dot points arranged every 2- degree out of 360 – degree points around the laser shape lines as shown in (Figure 10). This can be shown by exporting the laser file into the profiler software. The main task of this software at this step is to convert the dot points for every 0.1 ft. section into a solid semi-circle with known Cartesian coordinates (Recording process).

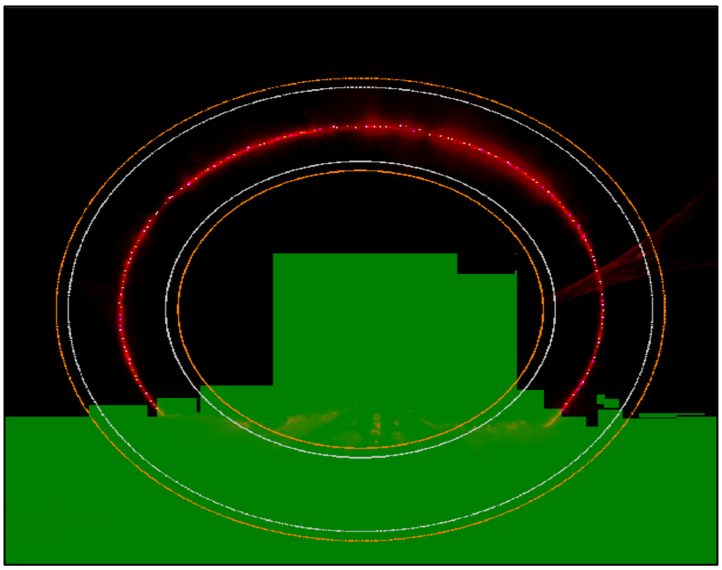


Figure 10: 2D laser shape line of a cross-section.

3. Due to the lateral movement of the robot when it runs through the pipe, the recorded semi-circles are not aligned into a straight pipeline shape, therefore, this semi-circle (0.1 ft. increment laser sections) must be aligned using a true undeteriorated circle. In order to provide accurate results, an intensive awareness and quality assurance in addition to a general understanding of the types of deterioration and defects monitored by the laser lines. For instants, RC pipes are rigid pipes, this means that there is no or rarely observed case of deflection in comparison to fixable pipes, also since RC pipes are eroded continuously, the diameter for the undeteriorated circle should be less than

the diameter of the semi-circle laser and deposits and suspended objects can be identified by a wired projection toward the pipe interior.

4. The output of the alignment process is an excel spreadsheet file which presents the Cartesian coordinates (x, y) for each 2-degree along the section. Data in the spread file are for 3 ft consecutive sections; each section data is the average of the 0.1 ft increment sections.

5. Using programming software like MATLAB R2018, these data can be utilized to quantify erosion and deposit at each 2-degree point on a section. Erosion is the positive difference between laser points and the true diameter, meanwhile, the deposit is the negative difference. To implement this step, use the code mentioned in appendix A 2. This code is explained in detail in section 3.1.

6. The result is a matrix with several rows equal to the number of sections and several columns equal to 180.

2.2.2 Erosion Data Processing

After data collection, these data are presented in a random phase, so it is difficult to understand their behavior. Each section has a set of erosion data and has maximum, minimum values in addition to different statistical definitions (means, median, standard deviation, etc.….). It is better to describe these data using histogram; which is the distribution of data based on their frequencies, this method is useful especially when describing random variables possessing a large number of discrete observations, it also provides a clear visualization of data compared to another interpreter like tables or text.

Before fitting data into histogram, it is important to understand the data boundaries; since odd values or unreasonable data alter the distribution of data in the histogram in, also they alter statistical variables like mean and standard deviation, for example, large standard deviation reflects a large spread of data around the expected value or mean which can overestimate or underestimate output variables (in this case, the remaining life of the structure); therefore, data should be refined in order to reduce discrepancy and standard deviation as much as possible. Refinement or cleaning is basically removing any unexpected values based on the nature of the data that might be raised from different sources. A list of unexpected value is shown below:

1. Deposits: laser scan doesn't distinguish between deposit and erosion, therefore, it's our task to eliminate deposit data by understanding how erosion is presented (loss of thickness (Refer to step 5 in section 2.2.1).

2. Noise: represent any obstacles (water splash, deposits, etc.…) attached to the lens of the device leads to unclear laser shape along the perimeter of the pipes. This will affect the recording process since it will be hard to arrange the points around disturb and unclear laser line. This issue can be overcome while recording (Refer to step 2 section 2.2.1) by either masking the unclear portion of the laser, increasing the laser sharpness, reduce the picked-up data or reducing the zone where laser recording happens.

3. Unexpected ovality: RC pipes are rigid pipes, so they are rarely deformed or deformed slightly, however, at some laser frame deformation is diagnosed because of the improper location of the robot; sometimes the robot might stick to the one side of the wall which shows an excessive deformation on the opposite wall. To avoid this kind of

error, inspectors should try to maintain the robot position directly at the middle of the pipe.

4. Manufacturing errors: due to manufacturing errors, pipes segments may have different diameters. To overcome this issue either choose the most repetitive diameter or simply take the average during the alignment process (Refer to step 3 section 2.2.1).

5. Flocculation: flocculation of water level during inspection time reduce the amount of laser since laser can not penetrate water, therefore, the inspector should inspect the pipe at the time of steady flow (laminar flow).

6. Alignment: inaccurate alignment process (step 3 in section 2.2.1) because the alignment process is not automated, a significant amount of human error is anticipated.

7. By eliminating all expected error, the histogram will be more accurate (represents reasonable erosion data).

Erosion data along each section is a continues random variable (attaining any values within a given interval or domain), thus it is better to describe all possibilities using probability density function. There are different types of probability distribution functions, however, data may, or may not fit a given density function, therefore, there are different tests to measure the goodness of fitting. In this study, the Chi-square test is used in which the distribution of a sample data is tested to see if it is consistent with the hypothesized distribution for the population or not (Holický. 2009). The test is done as explained in the following steps:

1. Arrange data into categories, each interval has an upper limit, a lower limit, and a corresponding frequency, which is the repetition of data within a certain interval. The frequencies have observed values of (O_1, O_2, ……., O_n).

2. Assume that data follow a certain distribution (the null hypothesis), we can obtain the probability corresponding to each observed value (P_1, P_2,……., P_n). The expected frequency values then will be (E_i=P_i*total number of observations).

3. Find the statistic X^2 according to

$$\sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i} \dots \dots . Eq\ 22$$

4. Knowing the available degree of freedom (number of categories-1) and the level of significance α which is the probability of rejecting the null hypothesis knowing that it is true, we can define the critical $X^{\cdot 2}$.

5. To accept the null hypothesis, the critical X^2 should be greater than the statistic X^2 or by using the definition of p-value which is the probability under the null hypothesis of obtaining a result equal to or greater than the observed one (P ($X^2_{critical}$> $X^2_{statistical}$)). If P-value is greater than the hypothesis, this means that the null hypothesis is satisfied.

In this study, Chi-square test is done automatically using code mentioned in Appendix A 2. This code is explained in detail in section 3.1.

One of the most common distributions used in reliability theory is the Weibull distribution (Weibull, 1951). This distribution has the capability of estimating the failure of the structure using a small size sample, also it can take different shape based on the value of it's shape parameter. Weibull distribution can have one, two and three parameters. The following equation is the probability density function for 2- parameters Weibull distribution (Probability, Random Variables, and Stochastic Processes 4th ed.):

$$f(x;\lambda,k) = \begin{Bmatrix} \frac{k}{\lambda} * \left(\frac{x}{\lambda}\right)^{k-1} * e^{-\left(\frac{x}{\lambda}\right)^{k}} & x \geq 0 \\ 0 & X < 0 \end{Bmatrix} \ldots \ldots . Eq\ 23$$

Where;

k: is the shape parameter.

λ: is the scalar parameter (λ>0).

With different shape factors, Weibull distribution can exhibit multiple shapes as presented in (Figure 12).

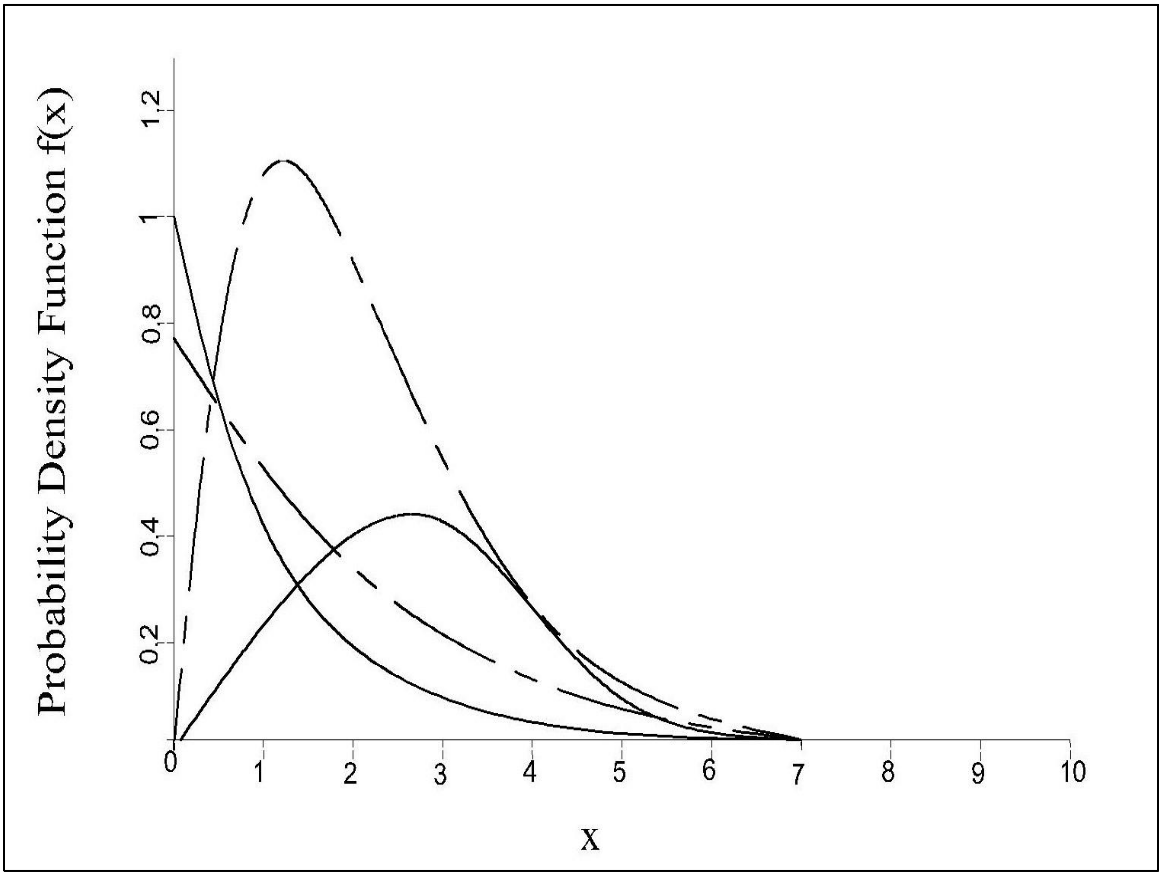


Figure 12: Possible shapes for probability density function of Weibull distribution.

Referring to step 3 in section 2.2.1, erosion data are different for every 3 ft. section; therefore, there will be multiple numbers of random variables and it will end with a hundred or more Weibull distributions; therefore, it is inconvenient to test each random variable using hand calculation. In this study, MATLAB is used which provides an automated test for fitting with all desired outcome for different distribution following the basic rule of statistics (MATLAB reference).

The code in Appendix A 2 describes the process of erosion data collection, in addition to test for fitting using the Chi-square test; it mainly determines the number of sections that follow Weibull distribution.

The following notes should be taken into consideration when running this code:

1. Points along the perimeter of the wall and have zero erosion data are exempt and do not invade into the distribution.

2. To reduce error, any erosion points greater than the mean plus 3 times standard deviation in one section is eliminated.

3. Each section will be first fit into a 2-parameter Weibull distribution.

4. Then each section will go under a Chi-square test with a significant level of 1% assuming the null hypothesis is the 2-parameter Weibull distribution. The code output will be (number of sections * 2) matrix; the first column has two discrete input; either zero which means acceptance of the null hypothesis and one for rejecting the null hypothesis, while the second column reflects the P-value for each section; P-value should be larger than 0.01 to fail to reject the null hypothesis. More details are described in section 3.1 and (Figure 15) which presents the histogram of the erosion data a section.

2.2.3 Forecasting of Erosion

Determination of the erosion data and fitting them to Weibull distribution is not enough for estimation of the service life of each section within a pipe. Since erosion is a deterioration phenomenon, we expect that it increases at a rate as the time elapsing. If all influencing factors described in section 1.3.2 remain unchanged during the lifetime of structure, then the rate of deterioration will be constant. This assumption has been agreed on by different literature because of flocculating nature of these factors during the study period or even through a single day.

Referring to section 1.3.5, any of the proposed methods can be used, however, all the methods assume that erosion rate is constant because of the uncertainties of other variable. The uncertainties rise from the hardness of measurement or the non-linear behavior of these variables. In this study only the age of the pipe at the time of the inspection is available and with the assumption of constant rate of erosion, the rate can be found according to the following equation:

$$Er\ \left(\frac{in}{year}\right) = \frac{Erosion\ at\ the\ time\ of\ inspection}{Age\ of\ the\ pipe\ at\ the\ time\ of\ inspection} \ldots\ldots.Eq\ 24$$

The code in the appendix 3, estimates the erosion rate for each point within section according to the previous equation, then it utilizes the rate for forecasting the erosion at each point for each year increment and fit them to Weibull distribution. This code is explained in detail in section 3.1.

2.2.4 Probability of exceedance

Despite the variety of models that can be used to simulate the deterioration of the pipe see (Table 3), our approach is simply fitting the deterioration data at a given age into Weibull probability distribution function for the ease of relating them to the resisting agent.

Each section within the pipe has a specific resistance (R) against the corresponding of action (E), but these sections cannot last forever since it is under action continuously. Generally, a structure is expected to fail when the action overcomes the resistance. The point by which the action utilizes the whole resistance is known as the limit state point and its described in the following equation.

$$G(t) = R(t) - E(t) = 0 \ldots\ldots Eq\ 25$$

In this study, the resistance of each section is the reinforcements' cover (Reston. 2007). This cover protects the reinforcements from corrosion by isolating them from the surrounding environment i.e. (humidity, air), meanwhile, the action is the erosion at the points above the water level. The resistance (concrete cover) is uniform at each point, so it can be expressed as a single value and its equal to 1 in for typical concrete pipes according to (ASTM C76. 2015), however, the erosion at each point within a section is different; therefore, erosion in a section at a certain year is presented as a random variable that follows Weibull distribution function; see (Figure 13).

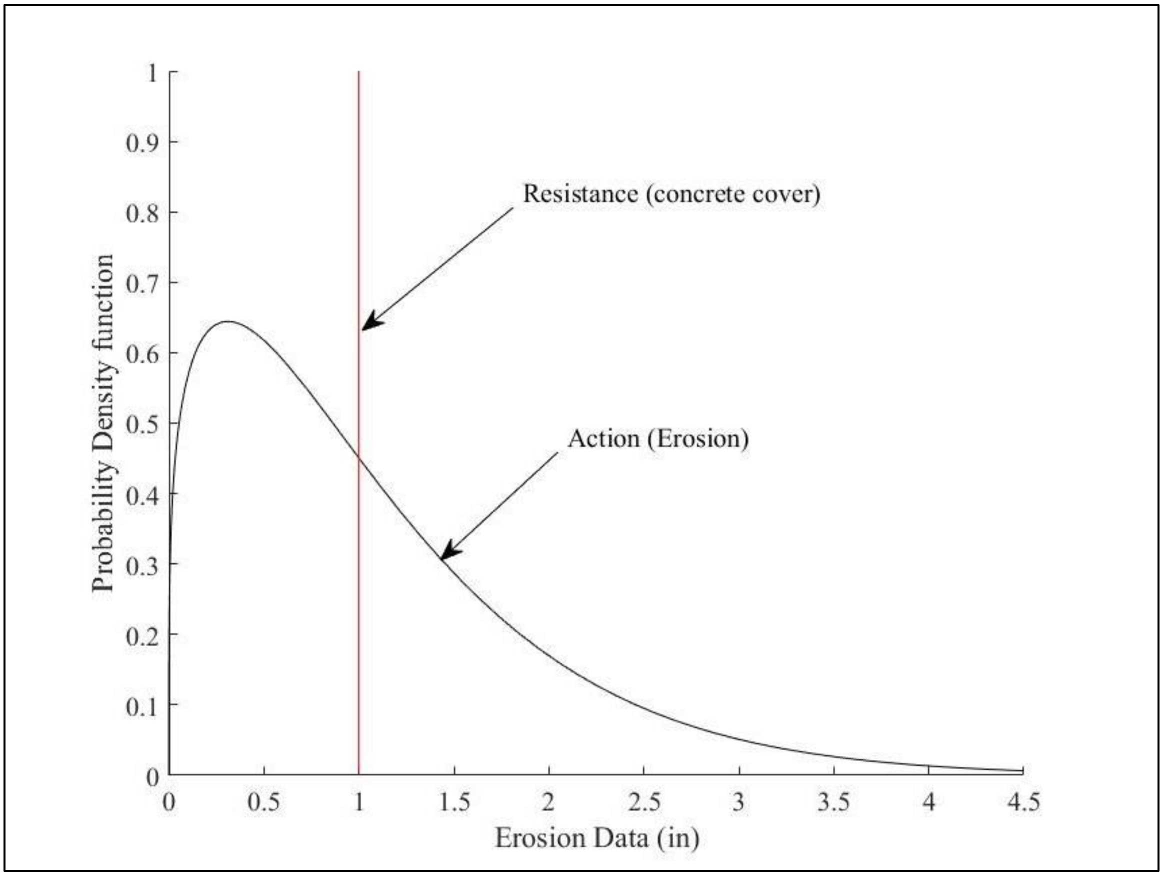


Figure 13: Probability distribution of action random variable with resistance value.

By looking to (Figure 13), a portion of the action lies on the right side of the resistance (E (t_i)>R (t_i)). This portion shows the points that already lost their resistance. Using probability definition i.e. (area under probability density function curve), the probability of points exceeding the limit state or losing their resistance is the area enclosed between the action's probability density curve and the resistance where the action lies on the right side of the resistance and it is known as probability of exceedance. Probability of exceedance (P_E) is interpreted using the following integration. This probability is the base for service life estimation and risk assessment as described in the next sections.

$$P_E = \int_1^{\infty} f(x)\, dx \ldots\ldots.. Eq\ 26$$

2.2.5 Estimation of the Service Life

The final step is the estimation of the service life. The service life is that time at which the structure demands maintenance; however, this time doesn't reflect the ultimate failure of that structure. In this study, the erosion rate (section 2.2.3) along with the probability of exceedance (section 2.2.4) is used to estimate the service life of pipes, hence using the age of the pipe at the time of inspection we can estimate the residual service life of the pipe. The following steps explain the procedure precisely with the aid of the code in appendix A 3 explained in section 3.1:

1. Calculate the erosion rate in (in/year) as in (Eq 24) for all sections that already fit Weibull distribution.

2. For each year, calculate the erosion for each accepted section assuming constant erosion rates and fit them to Weibull distribution.

3. This process is repeated for a consecutive number of years, and the result will be a matrix (year number X section number).

4. To reduce the complexity of the problem and for the purpose of simplifying the results, probability of exceedance after several years is averaged out for 3 consecutive sections. This will help to estimate the remaining age for a 9 ft segment rather than for 3 ft. sections separately.

5. Finally, a cumulative distribution function (CDF) of segments' age which is a function of time is drawn (Figure 14); this figure belongs to line number 18 (E13SL0103) in (Table 6). Based on the decision-makers' preferred probability of exceedance, they can estimate the service life of a pipe's segment.

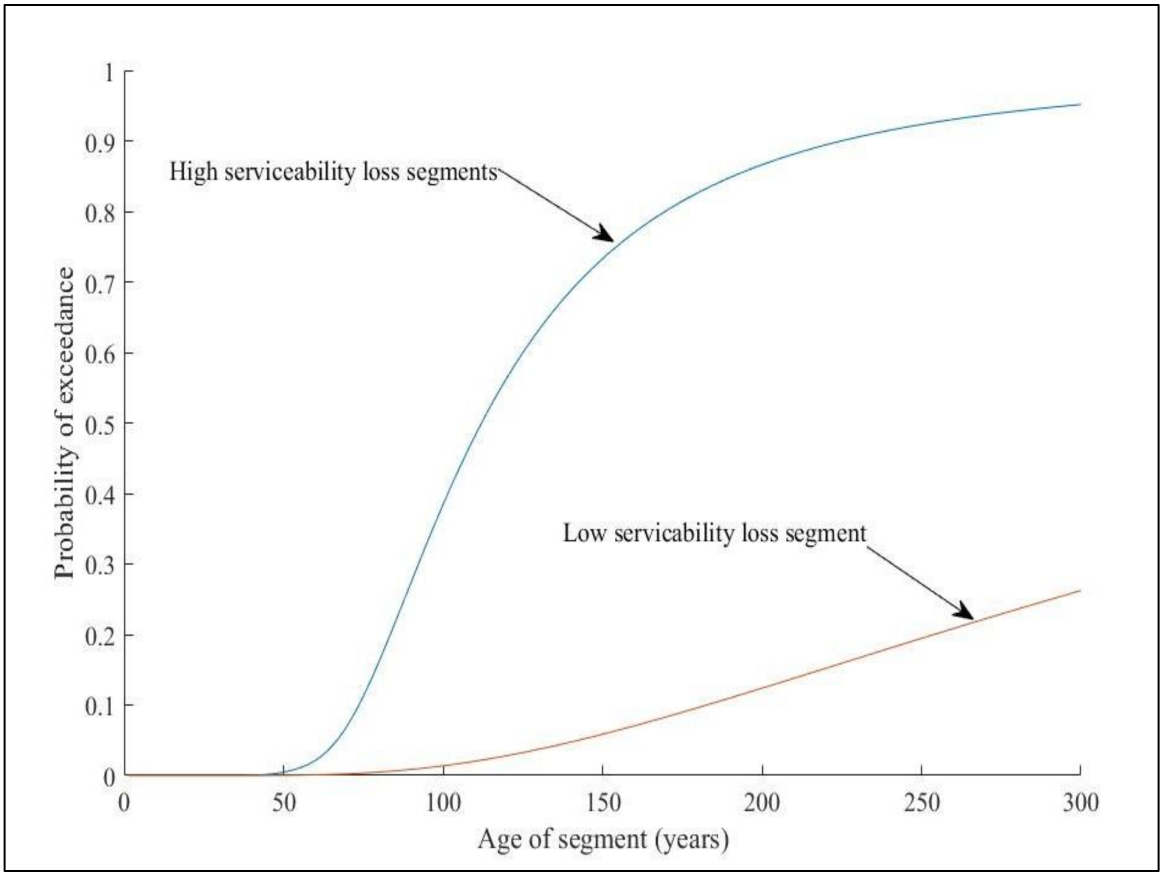


Figure 14: Cumulative distribution function (CDF) of segments' age

Since pipes consist of multiple segments, some of these segments will be in a more severe condition compared with other segments. (Figure 14) present two different behaviors i.e. (two CDFs); the blue curve represents the highest serviceability loss rate case in which a steep slope leading to almost the same expected service life for all probability of exceedance, meanwhile, the orange curve represents the lowest serviceability loss rate in which flat slope provides a large variety of expected service life between successive probabilities.

The estimated service life of a pipe is the mean of segments' service life, in which the service life of segments is the age of the segment corresponding to a probability of 10%.

2.2.6 Risk Assessment

Pipe replacement or maintenance is not an easy decision to be made, it requires justifications to convince the sponsors to allocate funds for it. Hundreds or even thousands of pipes require maintenance or replacement while some of these pipes demand that promptly, therefore, it is preferable to prioritize any action against these pipes based on the severity of the consequences resulting from the ignorance or delaying the action. Assessing the risk behind the consequences is one of the ways for helping decision makers to set a schedule for actions.

According to (Salman, and Baris. 2010), risk assessment involves two parts; the first part is related to the deterioration of the pipe or the condition of it. This can be expressed using the probability of exceedance explained earlier due to the erosion action on RC pipe. The second part talks about the consequences of failure (COF) or the expected outcome of the actions on the environment, the society, and economics.

The probability of exceedance or the condition state of pipe segments is based on the erosion action and the total consequence of failure is the weighted average of the consequences index. (Javad et al. 2017) provides more details.

$$T_c = \frac{\sum_{i=1}^{n} W_i \, CI_i}{\sum_{i=1}^{n} W_i} \ldots \ldots . Eq\ 27$$

Where

T_c: Total consequences of failure.

CI_i: is the consequence index of the i^{th} impact factors for a certain consequence of failure.

W_i: is the weight of the i^{th} impact factors for a certain consequence of failure.

Typical values for Wi and CIi are found in Table (8) and Table (9) in Appendix (B).

Following the estimation of both probability and the (COF), the risk level can be estimated either quantitatively (multiplication of probability of exceedance with (COF)) or linguistically (either Risk matrix or fuzzy inference system) (Salman. 2010). Due to the reasons mentioned in section 1.4.1, it is more convenient to express risk in linguistic terms using four descriptions (low, moderate, semi-high, high) (Javad et al. 2017). To do so each of the probability of exceedance and the (COF) must be converted to a ordinal scale in which a scale of one represents the lowest range of probabilities of exceedance and this scale correspond to the lowest range of consequences of failure, meanwhile, a scale of 4 represents the highest range of probabilities of exceedance and this scale correspond to the highest range of consequences of failure. The final output will be a (4x4) matrix in which risk can be defined as in (Table 5).

Table 5: Risk matrix description as a combination of probability of failure and consequences of failure.

Probability of Failure	Consequences of Failure (COF)			
	1(0-0.25)	2 (0.26-0.50)	3 (0.51-0.75)	4 (0.76-1)
1 (0-0.25)	Low	Low	Fair	Moderate
2 (0.26-0.5)	Low	Fair	Fair	Moderate
3 (0.51-0.75)	Fair	Fair	Moderate	Moderate
4 (0.76-1.0)	Moderate	Moderate	High	High

At the mean age of segments, each pipe segment's probability of exceedance will be categorized in groups from 1 to 4. Risk of a given segment within a pipe is the combination of its probability of exceedance interval with it's corresponding (COF) of the pipe. a flow chart (Figure 15) describes the procedure from raw data collection until risk evaluation.

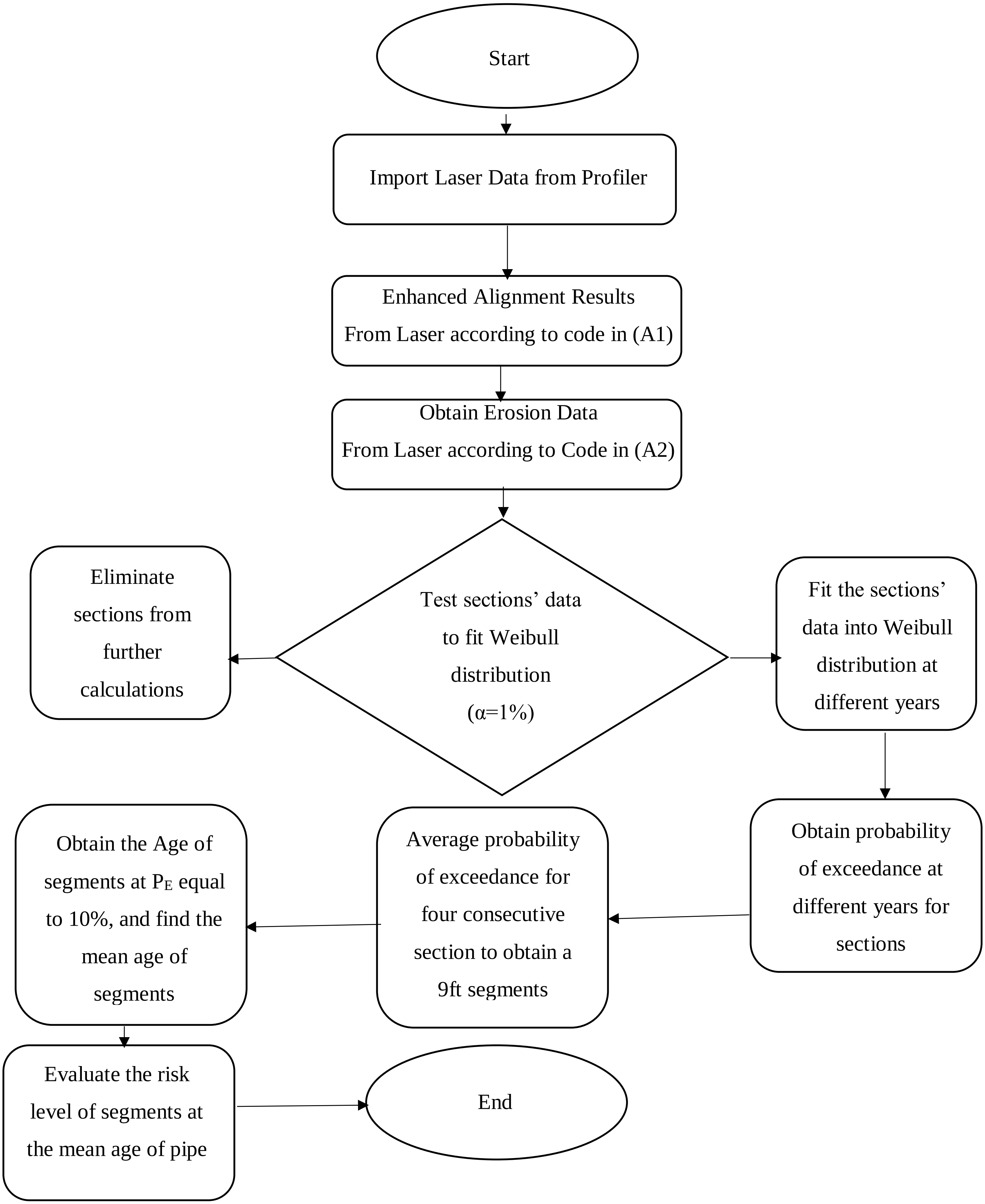


Figure 15: Flow chart of the approach steps.

Chapter3

3.1. Summary

In this study, reinforced concrete pipes located in the city of Arlington were inspected using CCTV, Laser-based scan and Sonar scan operated by the multi-sensor inspection robot (MSI) by (RedZone Robotics. 2018). These pipes were installed in the late 20th century or even older and they have been under operation since these old days, therefore, decision-makers in the city want to utilize the data collected from inspection in its different types to diagnose the condition of these pipes in order to set priorities for rehabilitation. Because one of the most important deterioration aspects in concrete pipes is the erosion, we choose this parameter as the independent parameter to estimate the current status and to anticipate the status in the future. Rather than presenting the status of the pipes in term of erosion or thickness loss that seems vague to the most of people who may not be engineers or even experienced in sewer industry, it is more desirable to evaluate the condition of the pipe using the service life that is more comprehensible to the public.

Estimation of service life is done throughout the reliability analysis using the concrete cover service limit state function provided by the ASCE. However, estimation of the service life is not adequate to define a plan for rehabilitation or maintenance, because if a number of pipes possess the same expected service life, it will be financially inefficient to repair all the pipes at the same time and may result in extra financial burdens, that's why decision-makers need to think for other criteria for giving priorities within pipes groups. In common practice, risk analysis is performed for aiding the decision makers for opting the proper decision.

3.2. Result

The sewer system in the city of Arlington has a lot of reinforced concrete pipes, some of these pipes are inspected and some are not, therefore in this study we are limited with only 30 lines with different lengths, a pipe is defined as the pipe that connecting two consecutive manholes and its designated by an assets number. Pipes enrolled in this study are presented in (Table 6)**,** each of these pipes has distinct features related to diameter, length, age, and other characteristics that are related to the functionality, proximity to the public area, rivers or water assembly, and roadways; however all pipes are main pipes and for domestic purposes. This information is important in risk analysis following the methodology described in chapter 2.

Table 6: Geographical properties of reinforced concrete pipes to be considered for the estimation of the service life.

Asset Number	Length (ft)	Age (Years)	Importance of the Surrounding Building	Surrounding Roadway	Located Under or Adjacent to Railway	Proximity to Public Places
E14SL0255	1191.7	31	Important Public Center	Local Street	No	Public Places
E15SL0140	680.629	31	Residential	Highway	No	Public Places
E15SL0146	525	31	Residential	Highway	No	Public Places
E15SL0253	569	31	Important Public Center	Local Street	No	Public Places
E15SL0254	877.8	31	Important Public Center	Local Street	No	Public Places
F16SL0249	510.1	37	Residential	Alley	No	Public Places
F16SL0250	458.45	37	Residential	Alley	No	Public Places
F15SL0146	642.39	37	Residential	Local Street	No	Public Places
F15SL0161	384.05	31	Residential	Local Street	No	Public Places
F15SL0346	41.63	14	Residential	Local Street	No	N/A
F15SL0347	84.1	14	Residential	Local Street	No	N/A
F15SL0348	354.5	14	Residential	Local Street	No	N/A
E12SL0011	1647.31	31	Residential	Alley	No	N/A

Table 6: Geographical properties of reinforced concrete pipes to be considered for the estimation of the service life (continued).

Asset Number	Length (ft)	Age (Years)	Importance of The Surrounding Building	Surrounding Roadway	Located Under or Adjacent to Railway	Proximity to Public Places
E12SL0292	180.2	31	Residential	Alley	No	N/A
E12SL0330	588.05	31	Residential	Alley	No	N/A
E13SL0093-E13SL0165	933	31	Residential	Local Road	No	N/A
E13SL0099	580.25	31	Residential	Local Road	No	N/A
E13SL0103	912	31	Residential	Alley	No	N/A
E13SL0104	1104	31	Residential	Alley	No	N/A
E13SL0203	108.05	31	Residential	Local Road	No	N/A
E12SL0294	54	31	Residential	Alley	No	N/A
D09SL0052-D09SL0051	1017.1	32	Residential	Highway	No	N/A
D09SL0087	1014.5	32	Residential	Highway	No	N/A
D10SL0062	819	32	Residential	Highway	No	N/A
D10SL00124-D10SL0125	1353	32	Residential	Highway	No	Public Places
D10SL0140	780	32	Residential	Highway	No	Public Places
D09SL0169	954.05	32	Main	Domestic	Residential	Highway

Table 7: Evaluation of total consequences of failure (TC) for risk assessment.

Asset Number	Diameter (In)	Located Close to River (Ft)	Ci*Wi (Importance of The Surrounding Building)	Ci*Wi (Roadway Type)	Ci*Wi (Proximity to Public Places)	Ci*Wi (Diameter)	TC (Equivalent Scale)
E14SL0255	33	700	480	160	600	455	3
E15SL0140	33	2000	240	640	600	455	3
E15SL0146	33	1645	240	640	600	455	3
E15SL0253	33	1058	480	160	600	455	3
E15SL0254	33	2700	480	160	600	455	3
F16SL0249	33	N/A	240	80	600	455	2
F16SL0250	33	N/A	240	80	600	455	2
F15SL0146	33	N/A	240	160	600	455	2
F15SL0161	33	N/A	240	160	600	455	2
F15SL0346	36	N/A	240	160	600	491	2
F15SL0347	36	N/A	240	160	0	491	2
F15SL0348	36	N/A	240	160	0	491	2
E12SL0011	39	N/A	240	80	0	531	2
E12SL0292	39	N/A	240	80	0	531	2
E12SL0330	39	N/A	240	80	0	531	2
E13SL0093-E13SL0165	39	1122	240	80	0	531	2
E13SL0099	39	1475	240	160	0	531	2
E13SL0103	39	1671	240	160	0	531	2
E13SL0104	39	N/A	240	80	0	531	2
E13SL0203	39	1916	240	160	0	531	2
E12SL0294	39	N/A	240	80	0	531	2
D09SL0052-D09SL0051	48	N/A	240	640	0	632.5	3

Table 7: Evaluation of total consequences of failure (TC) for risk assessment (continued).

Asset Number	Diameter (In)	Located Close to River (Ft)	Ci*Wi (Importance of The Surrounding Building)	Ci*Wi (Roadway Type)	Ci*Wi (Proximity to Public Places)	Ci*Wi (Diameter)	TC (Equivalent Scale)
D09SL0087	48	N/A	240	640	0	632.5	**3**
D10SL0062	48	N/A	240	640	0	632.5	**3**
D10SL00124 -D10SL0125	48	N/A	240	640	600	632.5	**3**
D10SL0140	48	N/A	240	640	600	632.5	**3**
D09SL0169	48	N/A	240	640	600	632.5	**3**

For each line, the MATLAB programming codes in Appendix (A1, A2, A3 & A4) will be run successively. Duties and outputs of each code are explained in the following points and presented in appendix (A 5) for each line individually, also for more convenient results, CCTV photos for each line are presented in Appendix B.

1- The code in Appendix A1

After processing the data described in section 2.2.1, the result will be a CSV file that represents the Cartesian coordinate for each point along the wall perimeter. This code imports the data from the CSV file for further processing; enhance the alignment by adjusting the X- coordinates for every two points which are mirroring each other about the Y-axis so that the centroid of the horizontal line connecting these two points match the X-coordinate of the circle. No changes are done to the Y-coordinate for each point since laser scan doesn't give data for the portion of the section beneath the water. The output of this code is the adjusted CSV matrix.

2- The code in Appendix A2

This code is a multi-task, the first task is to obtain the erosion data form every 3 ft. successive section. Since erosion is the positive difference between the arm length from the center to point on the section and the true radius, any negative difference is recognized as a deposit and its irrelevant to the study, therefore, its omitted, furthermore, any illogical positive difference (e.g. difference >1) is omitted to, then these data are rounded to 4 significant digits. The second task is to filter eroded sections; which means the determination of the number of sections that fit 2-parameter Weibull distribution with a significant level (α=1%) using Chi-square test with a null hypothesis defined as data to Weibull distribution (see Figure 15); this figure belongs to line number 18 (E13SL0103) in (Table 6). The blue bars represent the histogram of erosion data in a section and the red line is the Weibull distribution function. The output is a matrix that shows which section passed the test and which didn’t. Failed sections are not considered in further analysis.

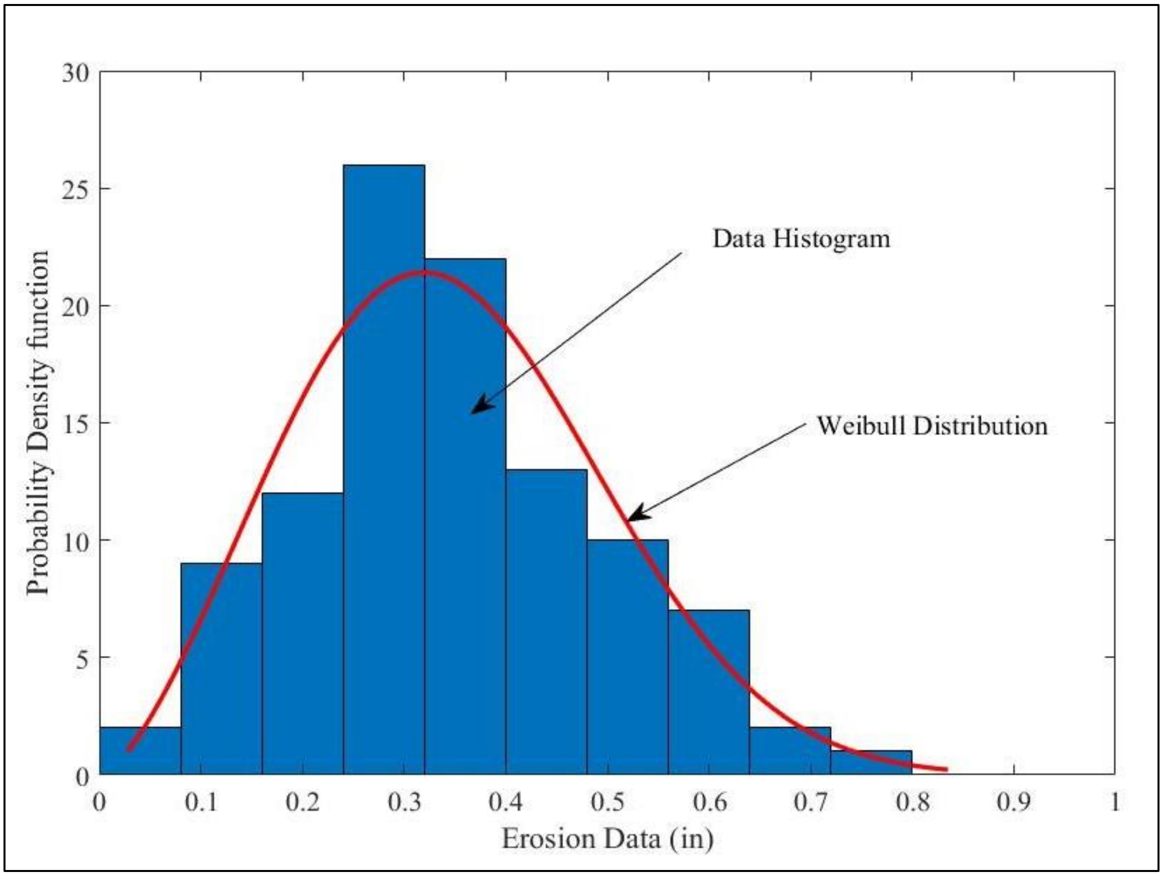


Figure 15: Probability density function of erosion data within a section.

3- The code in Appendix A3

This code is the final step to estimate the remaining service life of the pipe. First using the assumption that the erosion rate is constant, the erosion rate is found according to (Eq 24) for each point along the section, then for each year the process in code (A2) is repeated and the probability of exceedance is found as proposed in section 2.2.4. Rather explaining the results in term of sections, it is more desirable to combine every three sections into one segment of 9 ft length and the probability of exceedance for each segment is simply assumed as the average for the sections. The output of this code is cumulative density function (CDF) graph for the age of the worst and the best segment within a pipe as in (Figure 14). The segment's expected service life is the age of the segment corresponding to the acceptable probability level i.e. (Pa=10%). Pipe service life is the mean of segments' service life. Segments service life is assumed to follow normal distribution.

4- The code in Appendix A4

The purpose of this code is to ease the risk analysis according to the methodology in chapter 2, the outcome of this code is the risk values for (9 ft.) segments at the expected service life of the pipe that is already obtained from the code in Appendix (A3). Result of risk is interpreted in graph that illustrate segments' risk level along the pipe's length (see Figure 16); this figure belongs to line number 18 (E13SL0103) in (Table 6).

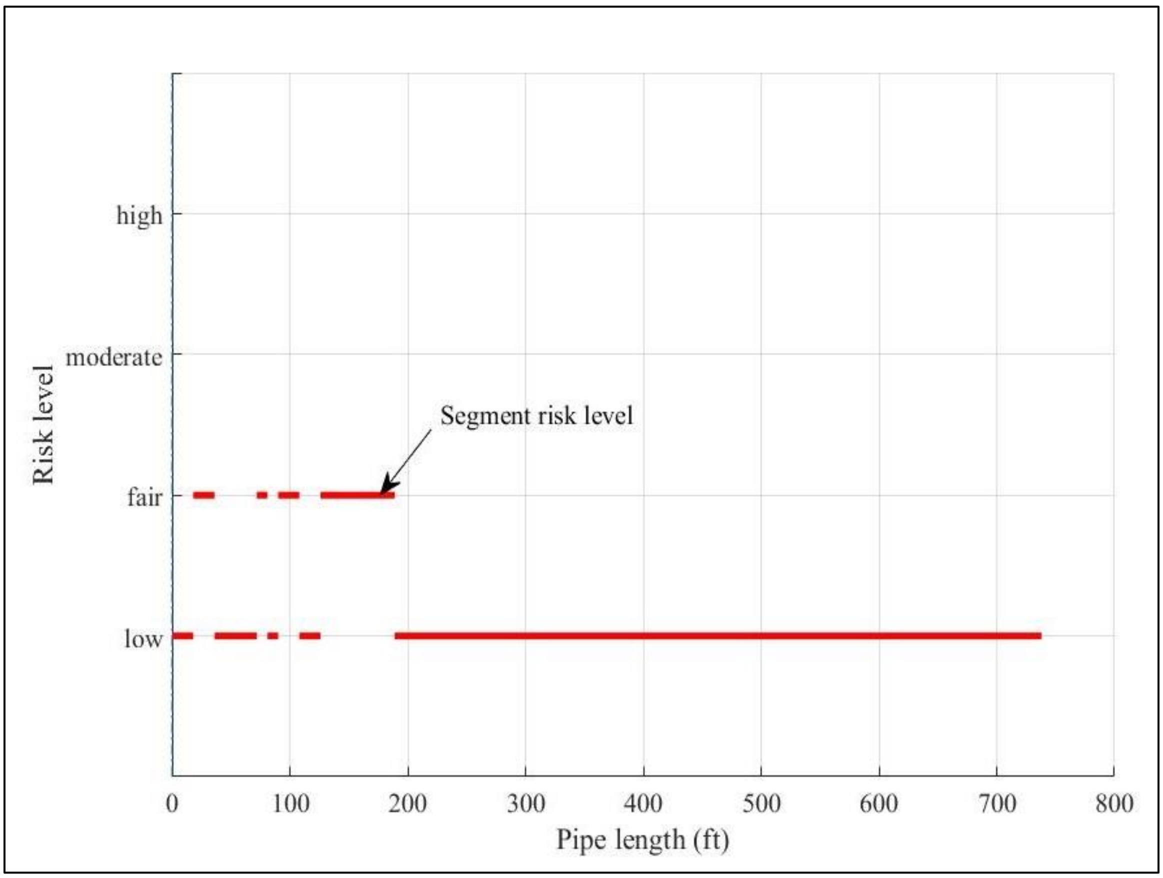


Figure 16: Risk level of pipe segments along the total pipe length.

Chapter 4

4.1 Discussion

After running the codes provided in the appendices using MATLAB R2018, the mean service life and one standard deviation beyond the mean are estimated for 9 ft. segments along the pipe length and they are presented in (Table 7). Pipes are divided into different inspections and in each inspection, pipes almost have the same conditions i.e. (erosion level, service life, and risk level). By referring to (Table 7), it is obvious that the most crucial inspection in this study is inspection 5 since it exhibits the lowest remaining service life among other inspection, moreover; because the erosion rate is constant, pipes exhibit high erosion at the time of inspection (e.g. Inspection 5) will continue to gain this amount of erosion with a constant rate each year regardless to any changes in the surrounding environment. This basic assumption might either underestimate the service life or overestimate it since it's hard to anticipate the changes in environmental conditions.

Not even pipes among an inspection differ in their condition, but also segments within the pipe itself have distinct attitudes. For each pipe, the probability of exceedance profile shows a variation between the worst and the best segments. This variation is due to different reasons, for instant; erosion in pipes is a localized type defect which means either it may be observed in a given segment more than other, or it may not be observed at all, also one of the most common reasons is the alternation of the observed diameter of segments within the pipe; this will result in different erosion reading, hence different probabilities.

By examining the risk values of segments at the estimated mean service life, for most of the pipes, segments' risk level ranges from low to fair condition depending on their probability and pipe's consequences of failure.

Table 8: Reinforced concrete pipes estimated mean, mean plus standard deviation service life.

Asset Number	Line Number	Numbers of Segments	Inspection Number	(μ) Service Life (Years)	(μ+Ϭ) Service Life (Years)	Remaining (μ) Service Life (Years)
E14SL0255	1	89	3	122	163	91
E15SL0140	2	24	3	152	187	121
E15SL0146	3	37	3	114	145	83
E15SL0253	4	17	3	128	149	97
E15SL0254	5	40	3	117	148	86
F16SL0249	6	15	3	126	131	89
F16SL0250	7	31	3	125	137	88
F15SL0146	8	17	2	171	218	134
F15SL0161	9	25	2	161	204	130
F15SL0347	10	7	2	74	27	60
F15SL0348	11	28	2	106	124	92
E12SL0011	12	77	7	86	118	55
E12SL0292	13	14	7	74	104	43
E12SL0017	14	89	7	62	76	31
E12SL0330	15	41	7	67	87	36
E13SL0093-E13SL0165	16	66	7	89	101	58
E13SL0099	17	42	7	100	117	69
E13SL0103	18	62	7	107	129	76
E13SL0104	19	76	7	82	119	51
E13SL0203	20	7	7	82	92	51

Table 8: Reinforced concrete pipes estimated mean, mean plus standard deviation service life (continued).

Asset Number	Line Number	Numbers of Segments	Inspection Number	(μ) Service Life (Years)	(μ+Ϭ) Service Life (Years)	Remaining (μ) Service Life (Years)
E12SL0294	21	3	7	64	71	33
D09SL0162	22	10	5	38	52	6
D10SL0120	23	27	5	49	66	17
D10SL0142	24	58	5	50	63	18
D09SL0052-D09SL0051	25	77	5	52	64	20
D09SL0087	26	80	5	44	53	12
D10SL0062	27	62	5	46	66	14
D10SL00124-D10SL0125	28	96	5	60	98	28
D10SL0140	29	56	5	61	77	29
D09SL0169	30	69	5	60	82	28
E12SL0294	21	3	7	64	71	33
D09SL0162	22	10	5	38	52	6
D10SL0120	23	27	5	49	66	17
D10SL0142	24	58	5	50	63	18
D09SL0052-D09SL0051	25	77	5	52	64	20
D09SL0087	26	80	5	44	53	12
D10SL0062	27	62	5	46	66	14
D10SL00124-D10SL0125	28	96	5	60	98	28
D10SL0140	29	56	5	61	77	29
D09SL0169	30	69	5	60	82	28

4.2 Future Work

Service life estimation and risk assessment of RC pipes are done by utilizing inspections output i.e. (laser scan), geographical information i.e. (locations, proximity to important places, etc.…), and pipes properties i.e.(diameter, length, material specifications), in addition to implement reliability theory, probabilistic and risk assessment principles, however, the accuracy of the results can be increased by taking under consideration the following points:

- Search for results outputs of previous inspections, notes and comments regarding significant previous operations i.e. (rehabilitation, or replacements).
- Do more inspections for these lines in the future to know more about lines' status, also to validate the approach used in this study or previous ones.
- Provide more measurements regarding influencing parameters like; temperature, velocity, sulfide concentration and oxygen concentration below water level.
- Try to enhance or use more accurate scan devices that provide adequate lateral movement restrictions and perfect alignment.
- Try to simulate the conditions exist in a group of pipes in the lab. This will help in building up more robust model even though sometimes it exaggerates the problem.

4.3 Conclusion

Reinforced concrete pipes in Arlington, Texas were inspected using CCTV, laser-based scan and sonar scan via a multi-sensor inspection robot (MSI) by (RedZone Robotics. 2018). Utilizing laser scan, erosion is estimated for every 3 ft section and used as a deterioration parameter against serviceability. But in order to make our result more valuable, readable, and explicit to decision-makers, pipes are divided into segments units rather than sections units. By Implementing reliability theory and service limit state function along with probabilities principles and kinds of literature the following have been obtain:

- Service life of a pipe is the mean of segments' service life, in which the service life of segment is the age of segment when the cover limit state is 10% exceeded by the mean erosion of segment.
- Risk level of segments within a pipe is interrelated to the probability of exceedance for segments at pipe's service life and consequences of failure.
- From all the inspected pipes, pipes in inspection 5 have the least service life and high-risk levels among other inspections.

This study gives an estimation in regards of serviceability and risk for reinforced concrete pipes; however, it doesn't provide 100% accurate results because of the limited outputs of inspection results; like wastewater properties, environmental conditions, and results of the previous inspections if any.

Appendix

Appendix (A1)

This code is concerned with importing the Cartesian coordinates of points along the perimeter of sections within the pipe, also it enhances the alignment process for each section to provide more accurate results. More details are in section 3.1

```
clc
filename='Asset Number.xlsx';
Data=xlsread(filename,'E3:GB20000');
[k,l]=size(Data);
sectionnumb=k/2; %sections number in the pipe
Dobsereved=xlsread(filename,'GD1:GD1');
th=pi/90:pi/90:2*pi;
x=Dobsereved/2*sin(th);%formation of eroded section
y=-Dobsereved/2*cos(th);%formation of eroded section
xcl=mean(x);
ycl=mean(y);
Data1=Data;
for j=1:2:k
    for i=1:180
    if(Data1(j,i)==0)
        Data1(j,i)=x(1,i);
    end
    if(Data1(j+1,i)==0)
      Data1(j+1,i)=y(1,i);
    end
     end
end
cent=zeros(k,180);
for j=1:2:k
    for b=1:90
    cent(j,b)=(Data1(j,b)+Data1(j,(180-b)))/2;

    end
end
cent(:,91:180)=cent(:,1:90);
    for i=1:k
    for j=1:180
        if (Data(i,j)~=0)
            Data2(i,j)=Data1(i,j)-cent(i,j);
        elseif(Data(i,j)==0)
             Data2(i,j)=Data1(i,j);

        end
    end
    end
```

```
for i=1:k
 for j=1:180
    if (Data(i,j)==0)
        Data2(i,j)=0;
    end
end
end
```

Appendix (A2)

This code utilizes the laser data to obtain erosion data and to eliminate any odd data, also it tests the validity of erosion data per section to follow a 2 parameter Weibull distribution function with (α=1%). More details are provided in section 3.1.

```
clc
sectionN=sectionnumb;
Erosion=zeros(sectionN,180);
Robserved= zeros(sectionN,180);
k=0;
for i=1:sectionN
    for j=1:180
        Robserved(i,j)=sqrt(Data2(2*k+1,j)^2+Data2(2*k+2,j)^2);
        Rexpected(j)=sqrt((x(j)^2)+(y(j)^2));
    end
    k=k+1;
end
difference=Robserved-Rexpected;
for i=1:sectionN
    for j=1:180
   if (difference(i,j)>0)
       Erosion(i,j)=(difference(i,j));
   elseif(difference(i,j)<0)
       Erosion(i,j)=0;
   end

    end
end

Erosion(Erosion==0)=NaN;
Erosion( ~any(Erosion,2), : ) = [];
Erosion( :, ~any(Erosion,1) ) = [];
[m,n]=size(Erosion);
for i=1:m
    for j=1:n
       mu=nanmean(Erosion(i,:));
       st=nanstd(Erosion(i,:));
         if (Erosion(i,j)>(mu+3*st))
           Erosion(i,j)=0;
         elseif (Erosion(i,j)<(mu-3*st))
            Erosion(i,j)=0;
         end
    end
end
Erosion=round(Erosion,4,'decimals');
Erosion(Erosion==0)=NaN;
```

```
a=zeros(m,2);
su=zeros(m,1);
for i=1:m
q=fitdist(Erosion(i,1:n)','weibull');
[h,p]=chi2gof(Erosion(i,1:n)','alpha',0.01,'CDF',q);
if(h==0)
su(i,1)=mean(q);
end
e(i)=h;
d(i)=p;
a(i,1)=h;
a(i,2)=p;
end
[E,O]=hist(a(1:m,1)')
Erosionf=zeros(m,n);
for i=1:m
    if(a(i,1)==0)
        Erosionf(i,1:n)=Erosion(i,1:n);
    end
end
Erosionf( ~any(Erosionf,2), : ) = [];
[u,c]=size(Erosionf)
figure(1)
histfit(Erosionf(:),30,'weibull')
xlabel('Erosion Data');
ylabel('Probability Density function')
xlim([0,2])
```

Appendix (A3)

This code uses the output of the previous code to estimate the probability of exceedance by applying concrete cover limit state function on each section, also it presents the result i.e. (probability of exceedance) in term of 9ft. segments instead of sections.

```
clc
warning off
[u,c]=size(Erosionf)
R=zeros(1,u);
R1=zeros(1,u);
Q=1/u;
r=u/4;
R=floor(r)
propaf2=zeros(300,R);
erosionrate=Erosionf/31;
for j=1:1:300
 erosion=erosionrate*j;
for i=1:u
 d=erosion(i,:);
 d( :, ~any(d,1) ) = [];
[r,t]=size(d);
 p=wblfit(d'); w=@(x) (p(2)./p(1)).*(x./p(1)).^(p(2)-1).*exp(-
((x./p(1)).^p(2)));
 propaf(i)=integral(w,1,inf);
end
x=1;
for i=1:4:R*4
    propaf1(x)=(propaf(i)+propaf(i+1)+propaf(i+2)+propaf(i+3))/4;
    x=x+1;
end
propaf2(j,:)=propaf1;
end
[maxval,segmentnum1]=max(propaf2(j,:));
[minval,segmentnum]=min(propaf2(j,:));
figure (2)
hold on
plot([1:1:300],propaf2(:,segmentnum1));
plot([1:1:300],propaf2(:,segmentnum));
xlabel('Age of the pipe (years)');
ylabel('Probability of Failure');
hold off
propaf2=round(propaf2,2,'decimals');
for i=1:R
    c=propaf2(:,i);
    Age(i)=find(c>=0.1,1,'first');
end
propaf3=propaf2(100,:);
```

```
figure(3)
histfit(Age,6,'normal')
xlabel('Expected service life (years)');
ylabel('Probability Density function');
q=fitdist(Age','normal')
mean_age=round(mean(q));
```

Appendix (A4)

This code uses the probability of exceedance per each segment along with the pipe properties to evaluate risk level for segments.

```
clc
probaoff=propaf2(mean_age,:);
Y = discretize(probaoff,[0,0.25,0.5,0.75,1]);
Risk=sym('R',[5,5]);
Risk(1,2)=1;Risk(1,3)=2,Risk(1,4)=3;Risk(1,5)=4;
Risk(2,1)=1;Risk(3,1)=2,Risk(4,1)=3;Risk(5,1)=4;
Risk(2,2)='low';Risk(2,3)='low',Risk(2,4)='fair';Risk(2,5)='Moderat
e';
Risk(3,2)='low';Risk(3,3)='fair';Risk(3,4)='fair';Risk(3,5)='Modera
te';
Risk(4,2)='fair';Risk(4,3)='fair';Risk(4,4)='Moderate';Risk(4,5)='H
igh';
Risk(5,2)='Moderate';Risk(5,3)='Moderate';Risk(5,4)='Moderate';Risk
(5,5)='High';
Z=sym('R',[1,R]);
for i=1:R
    z(i)=find(Y(i)==Risk(1:5,1));
    Z(i)=Risk(z(i),3);
end
Z=Risk(z,3)
for i=1:R
    if Z(i)=='low'
        P(i)=1;
    elseif Z(i)=='fair'
           P(i)=2;
    elseif Z(i)=='Moderate'
               P(i)=3;
    elseif Z(i)=='High'
               P(i)=4;
    end
end
pipe_length=[0:9:(R*12)];
hold on
figure(4)
grid on
j=1;
t=1;
for i=2:1:((R*4+1)/3)
line([pipe_length(i-
1),pipe_length(i)],[P(j),P(j)],'color','r','linewidth',3)
line([pipe_length(t),pipe_length(t)],[0,5],'linestyle','-.')
 j=(3*i-1)/4;
 j=floor(j);
 ylim([0,5])
```

```
 yticks([1,2,3,4,5])
yticklabels({' low',' fair','moderate','high'})
end
```

Appendix (A5): Research Output

In this appendix results regrading erosion data, service life and risk analysis for the 30 lines in (Table 6) are presented individually. Each line is expressed in a seperated section and in each section four main graphs:

1. The first graph is known as “probability density function of erosion data along the entire pipe”, the purpose of this graph is to provide a general view about the distrbution of the erosion data along the pipe length.

2. The second graph is known as “cumulative distribution function (CDF) of segments’ age”, this graph is already demonstrated in section 3.1 and it is used to obtain the service life of segments.

3. The third graph is known as “normal distribution of pipe segments expected service life”, this graph shows the histogram of the segments service life which is assumed to fit normal distribution and help to visualize the variation of the service life between segments.

4. The fourth graph is known as “risk level for pipe segments along the total length”, this graph is already demonstrated in section 3.1, and it clarifies the risk level of segments distributed along the pipe length.

A5.1 E14SL0255 Line

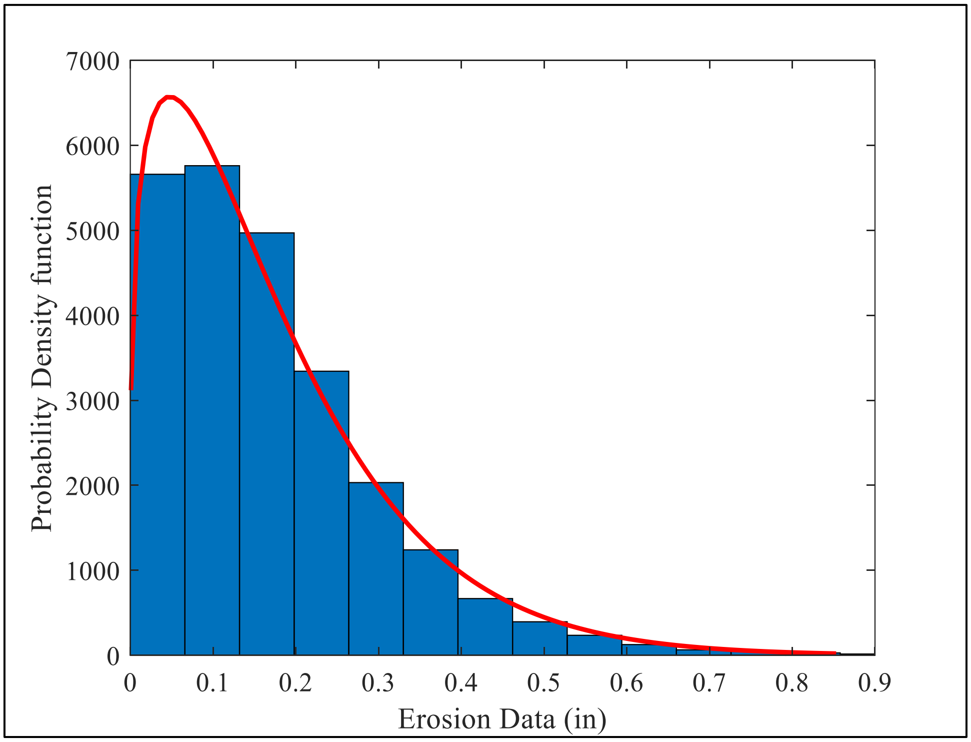


Figure 17: Probability density function of erosion data along the entire pipe.

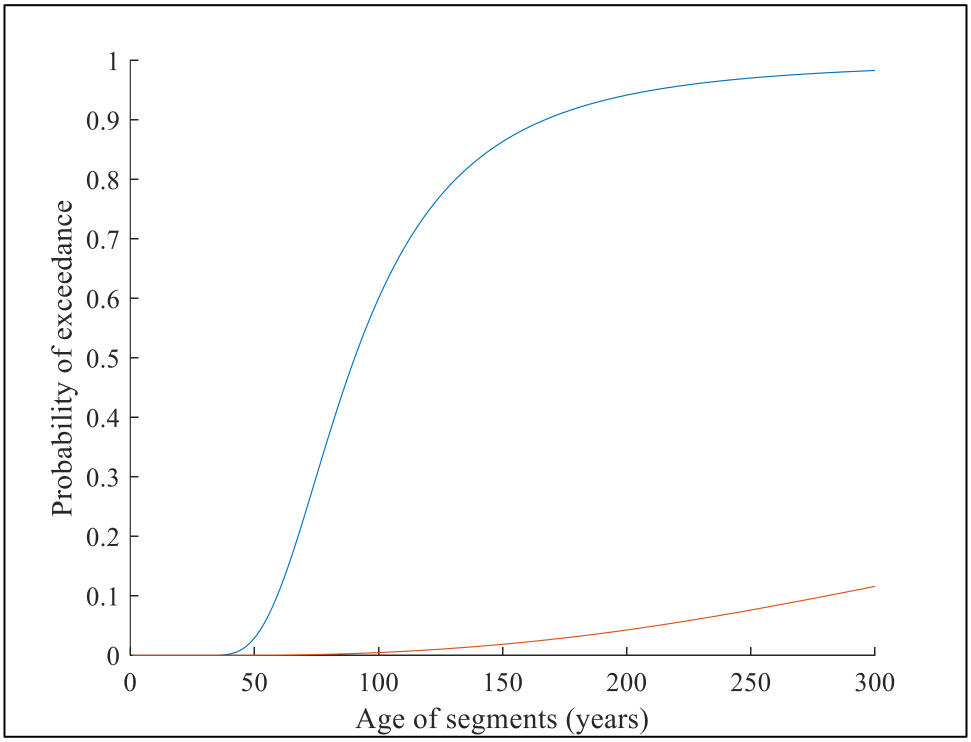


Figure 18: Cumulative distribution function (CDF) of segments' age.

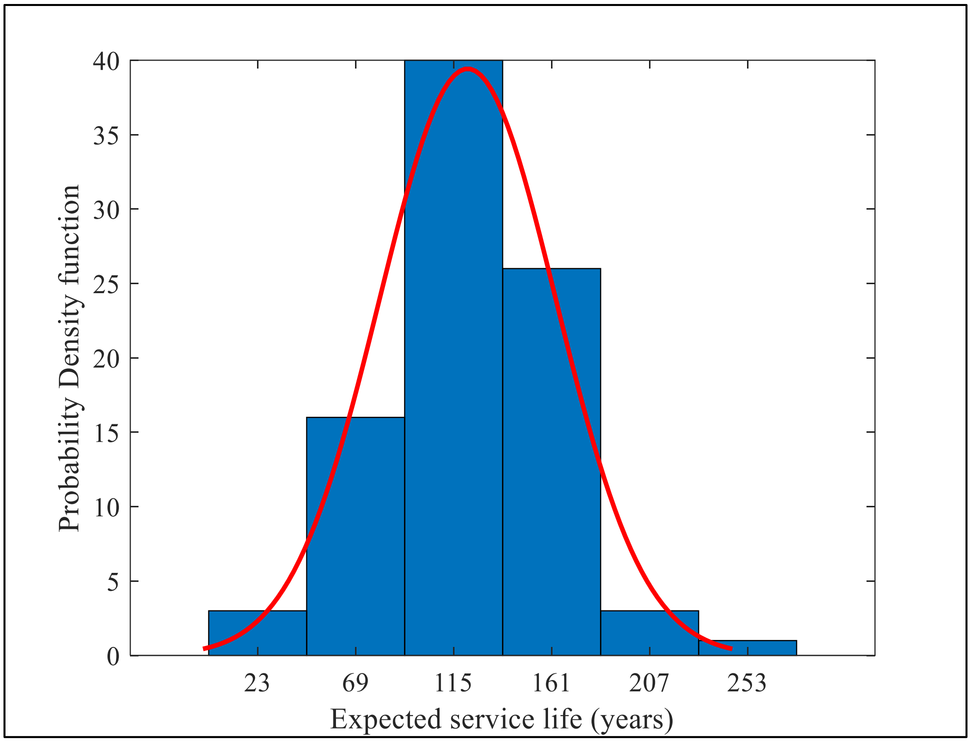


Figure 19: Normal distribution of pipe segments expected service life.

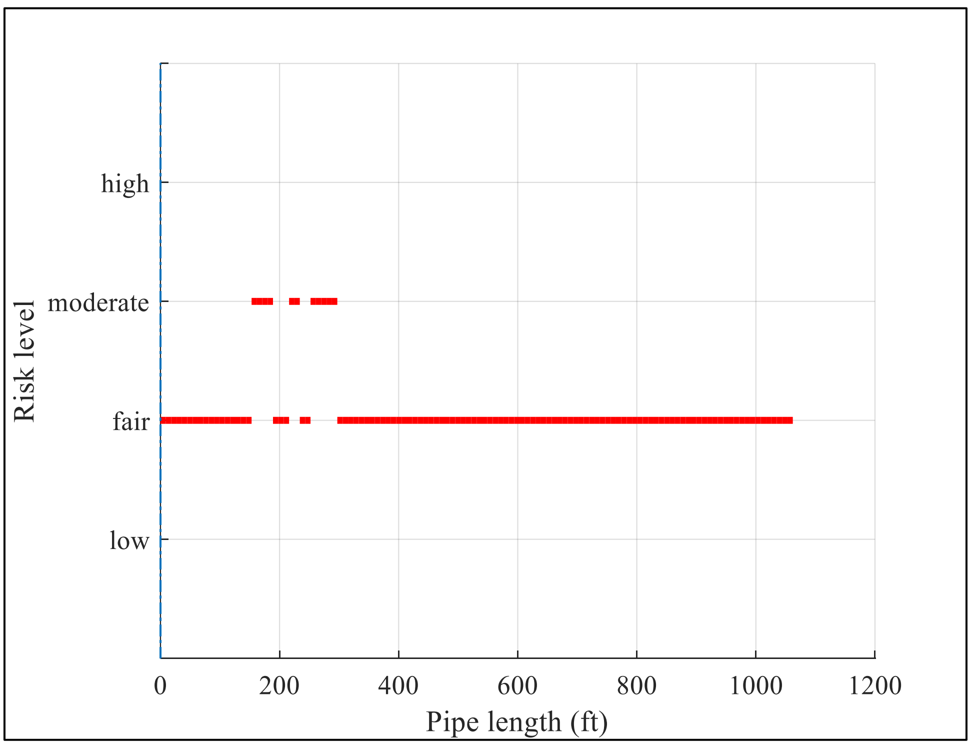


Figure 20: Risk level for pipe segments along the total length.

A5.2 E15SL0140 Line

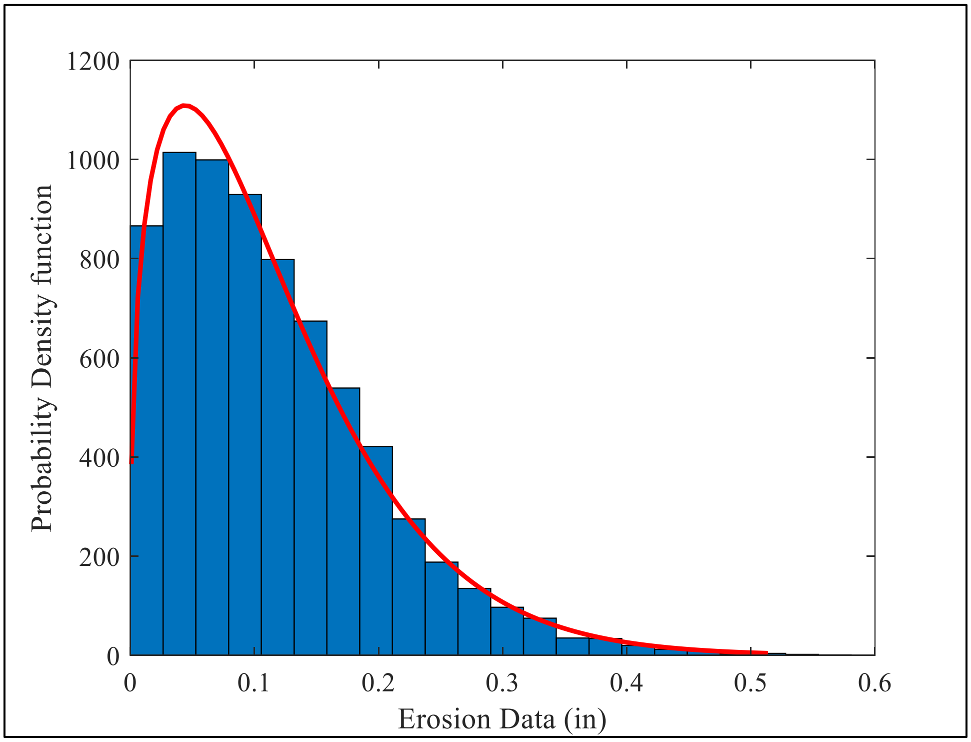


Figure 21: Probability density function of erosion data along the entire pipe.

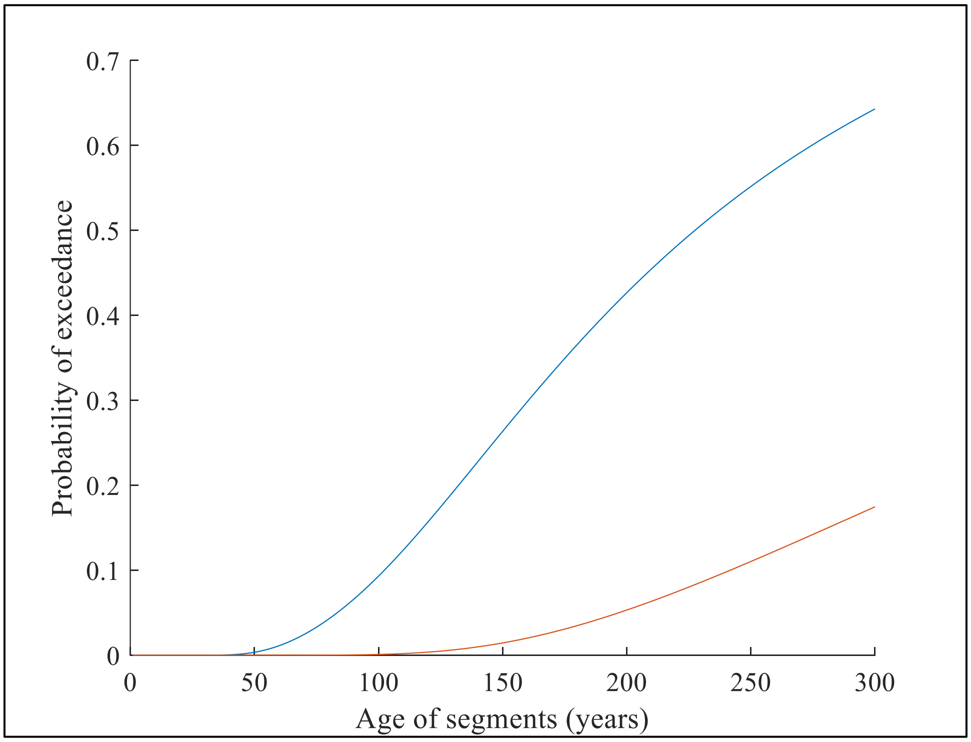


Figure 22: Cumulative distribution function (CDF) of segments' age.

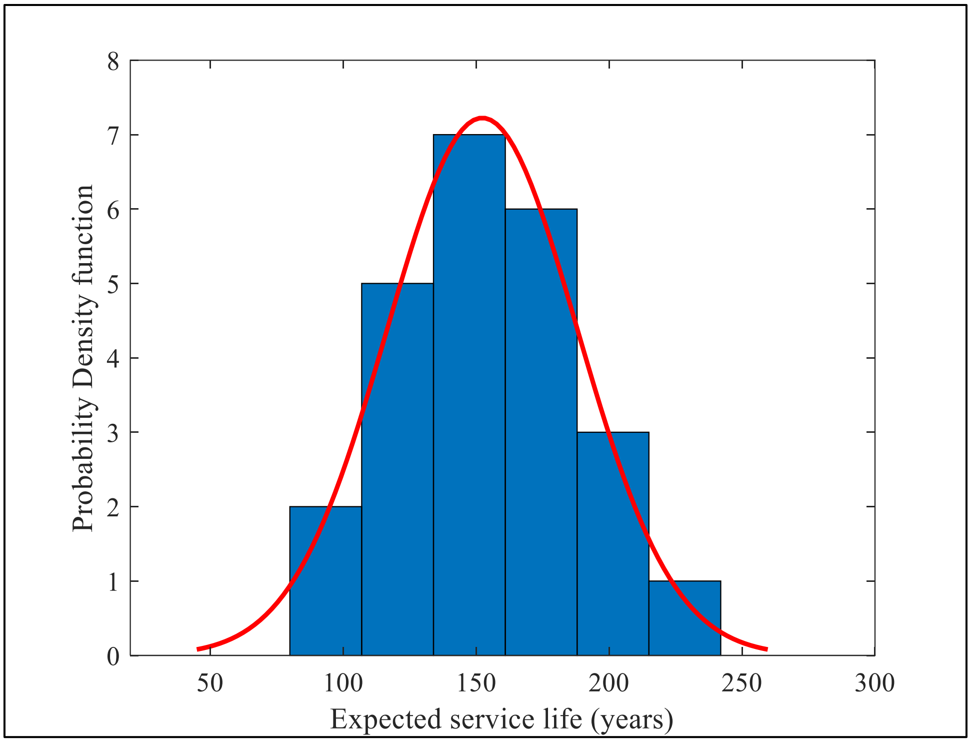


Figure 23: Normal distribution of pipe segments expected service life.

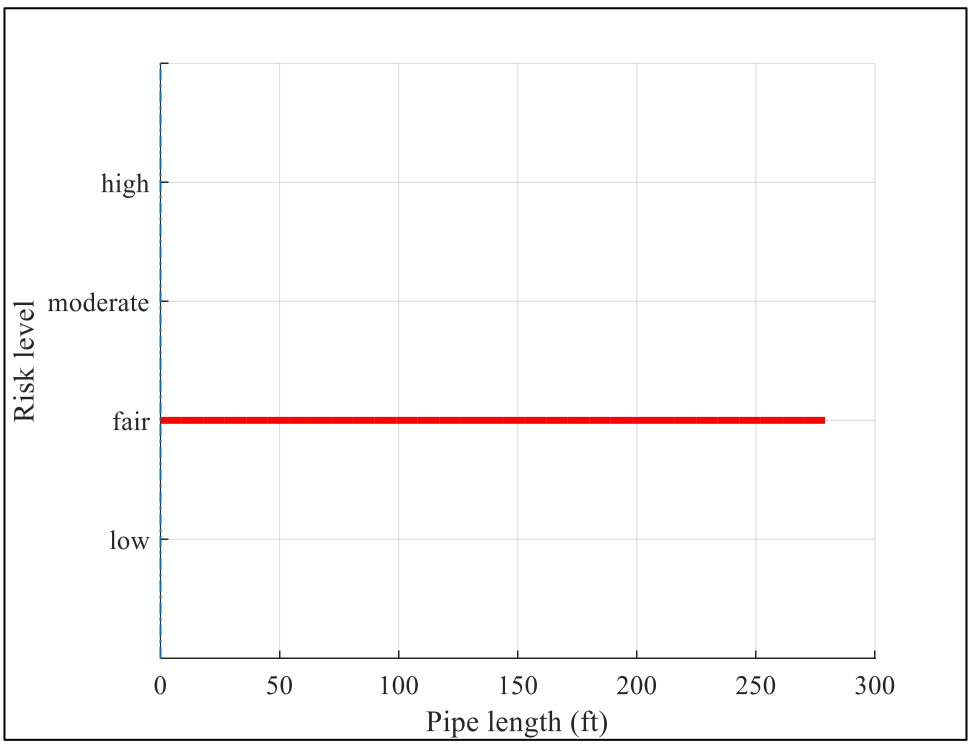


Figure 24: Risk level for pipe's segments along the total length.

A5.3 E15SL0146 Line

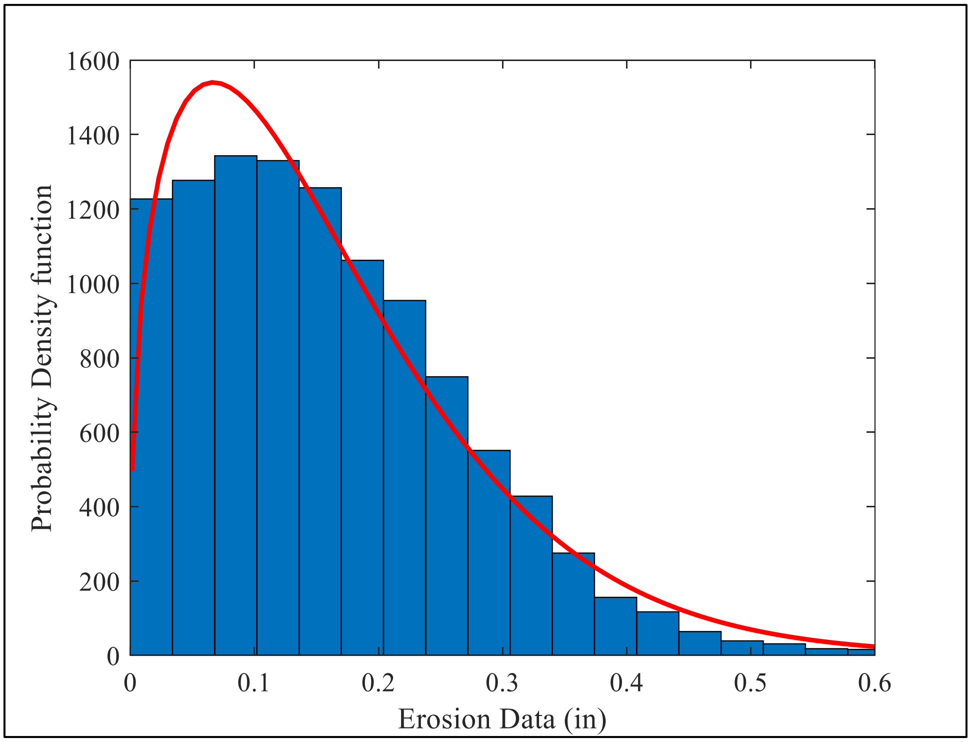


Figure 25: Probability density function of erosion data along the entire line.

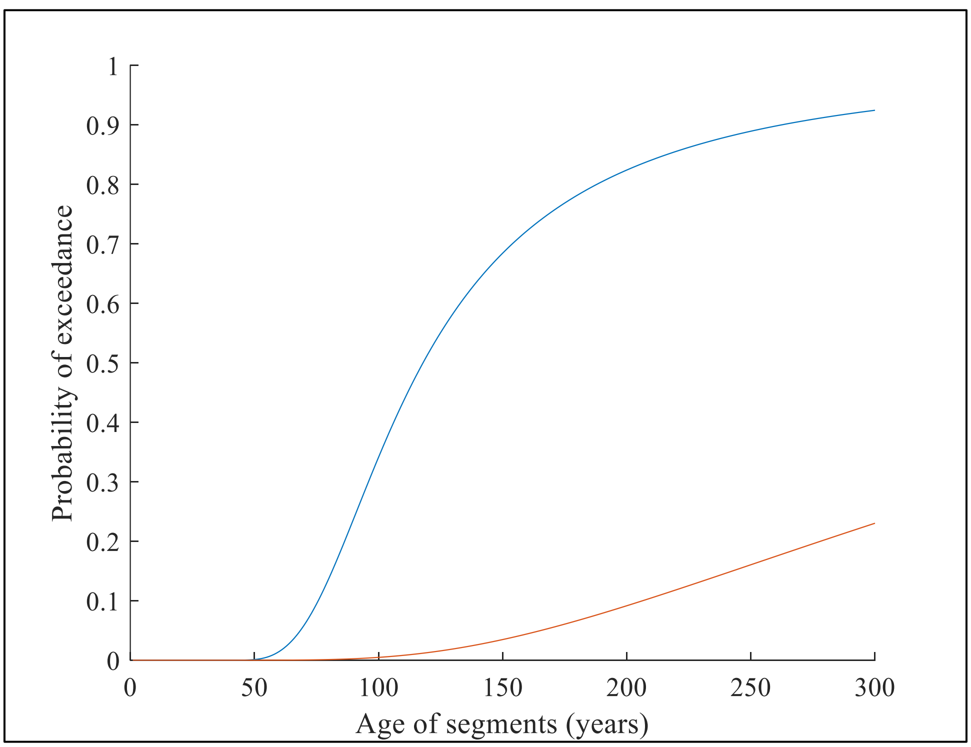


Figure 26: Cumulative distribution function (CDF) of segments' age.

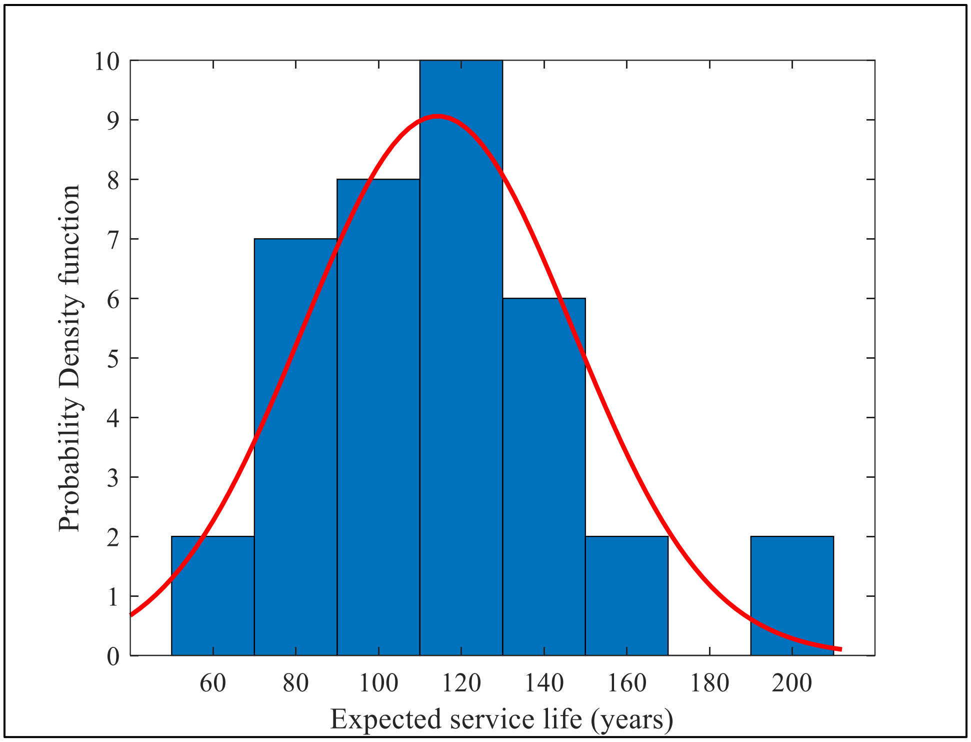


Figure 27: Normal distribution of pipe’s segments expected service life.

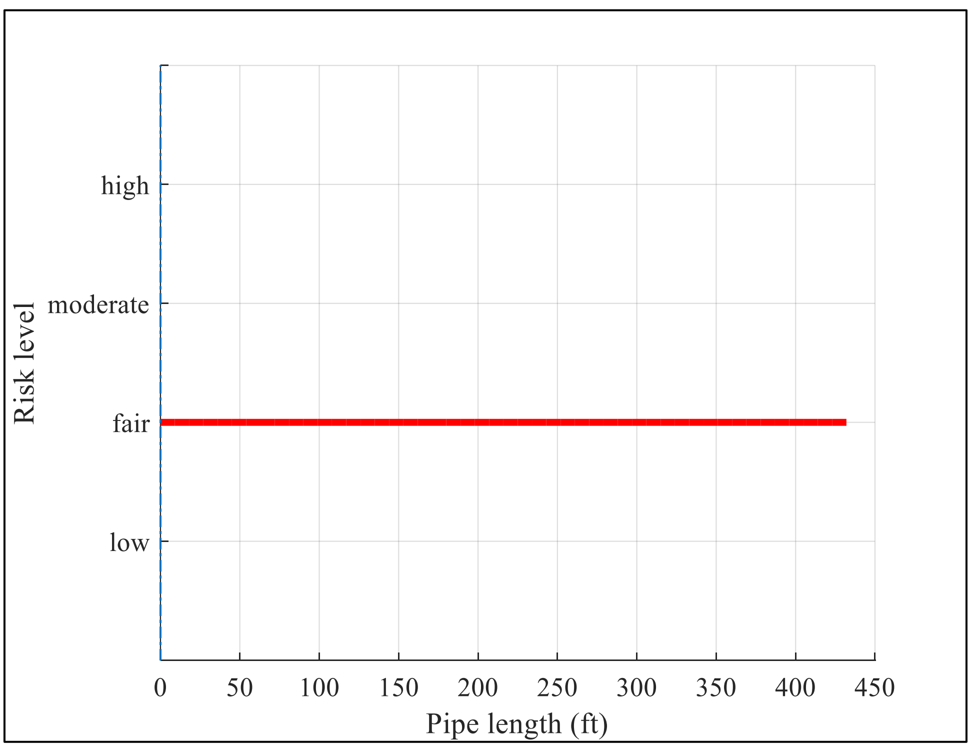


Figure 28: Risk level for pipe’s segments along the total length.

A5.4 E15SL0253 Line

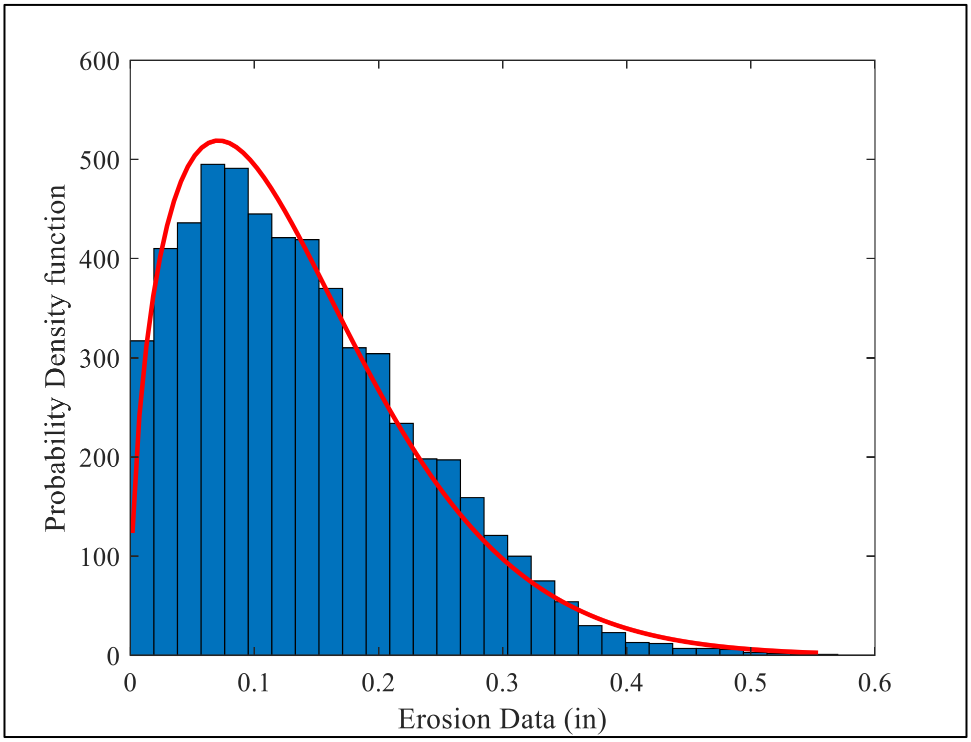


Figure 29: Probability density function of erosion data along the entire line.

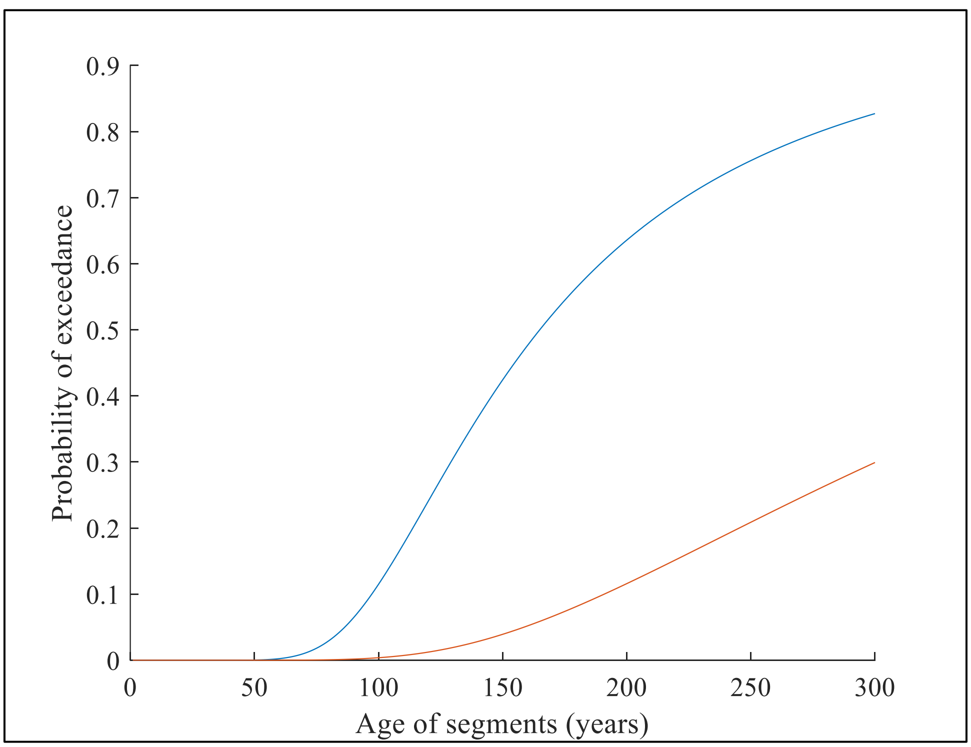


Figure 30: Cumulative distribution function (CDF) of segments' age.

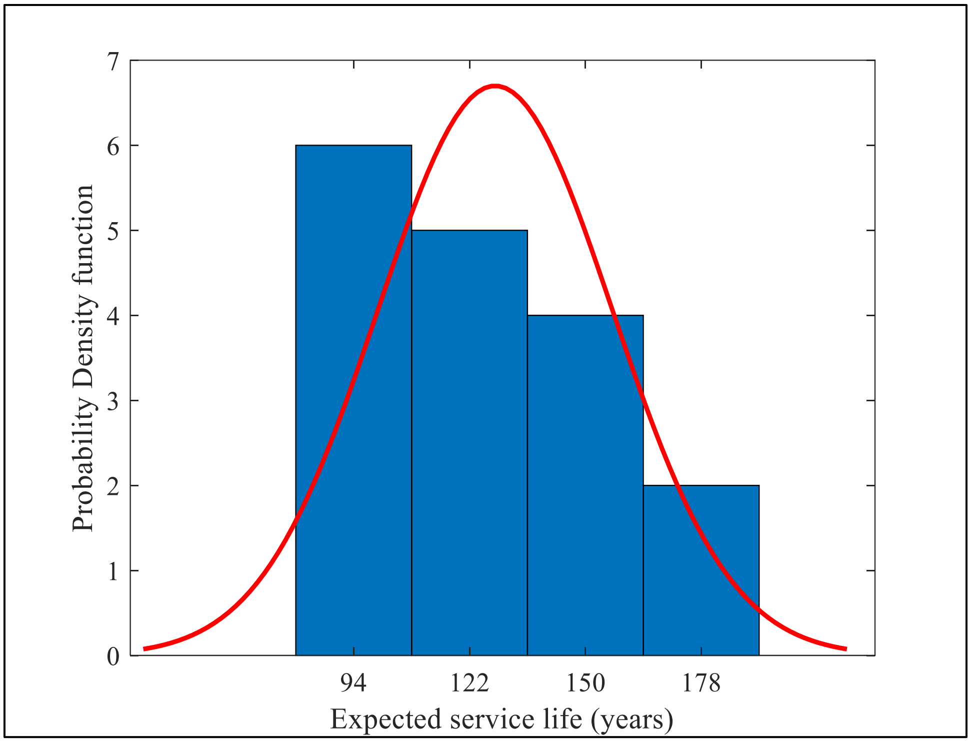


Figure 31: Normal distribution of pipe’s segments expected service life.

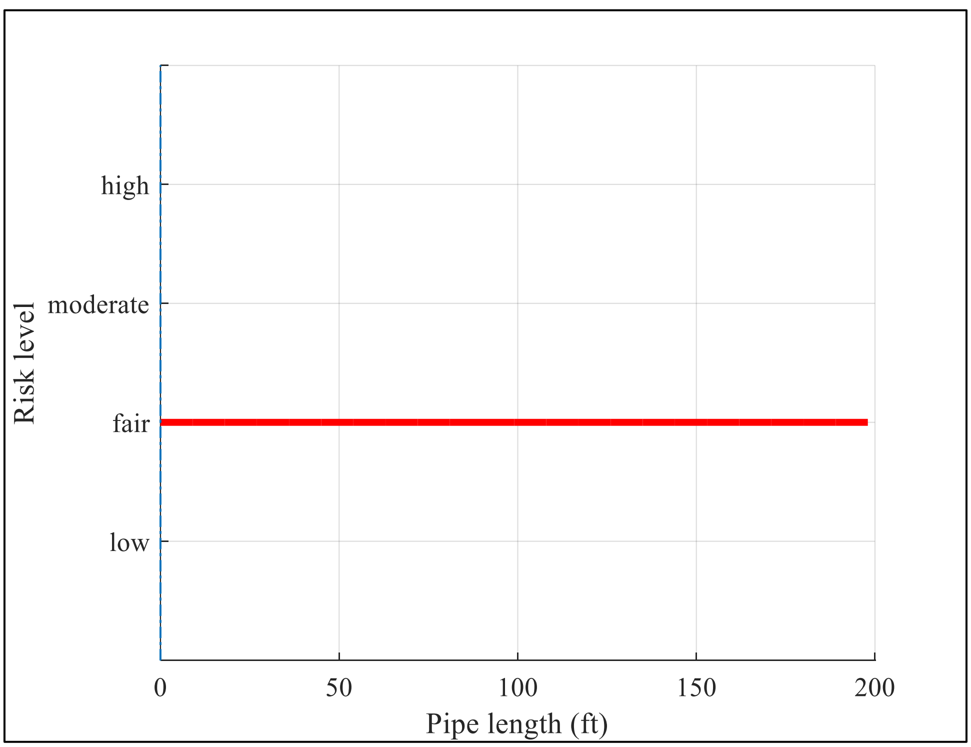


Figure 32: Risk level for pipe’s segments along the total length.

A5.5 E15SL0254 Line

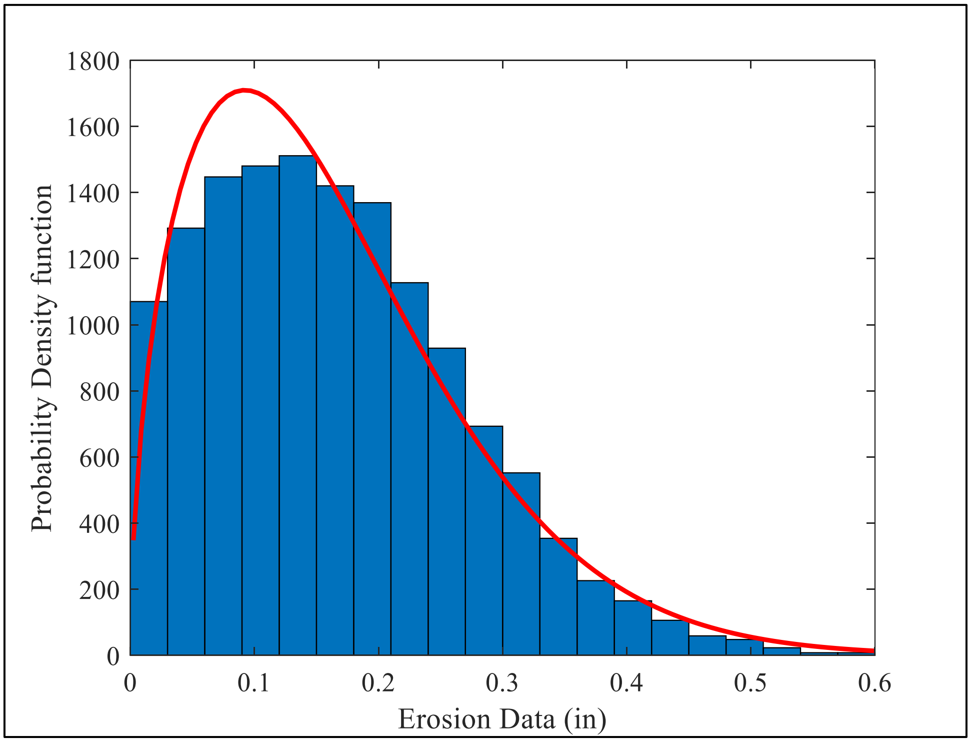


Figure 33: Probability density function of erosion data along the entire line.

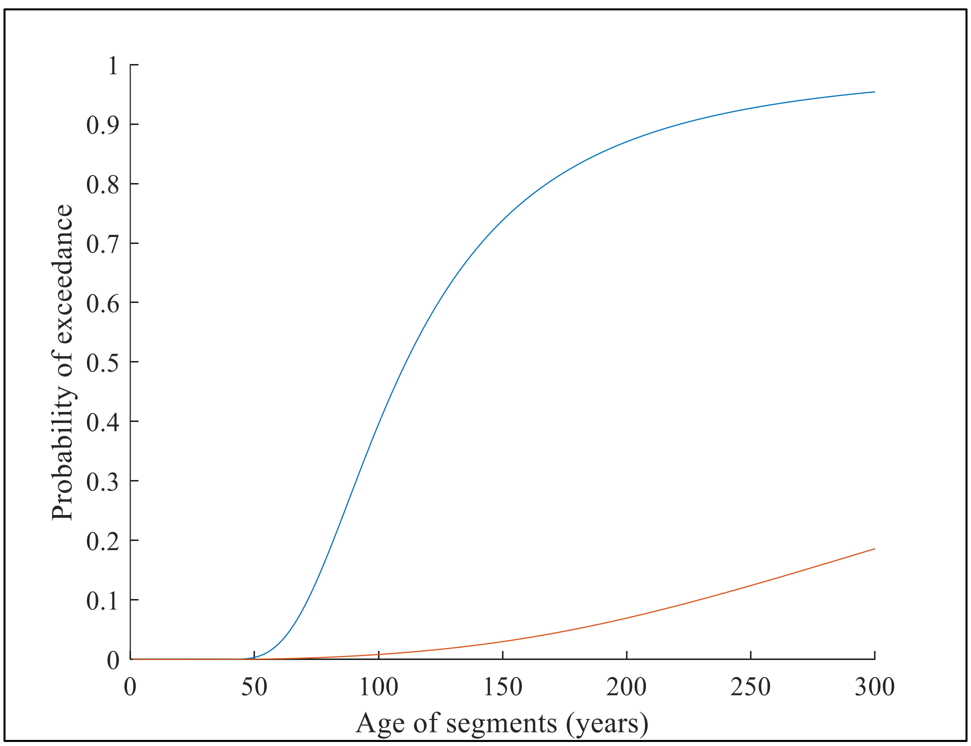


Figure 34: Cumulative distribution function (CDF) of segments' age.

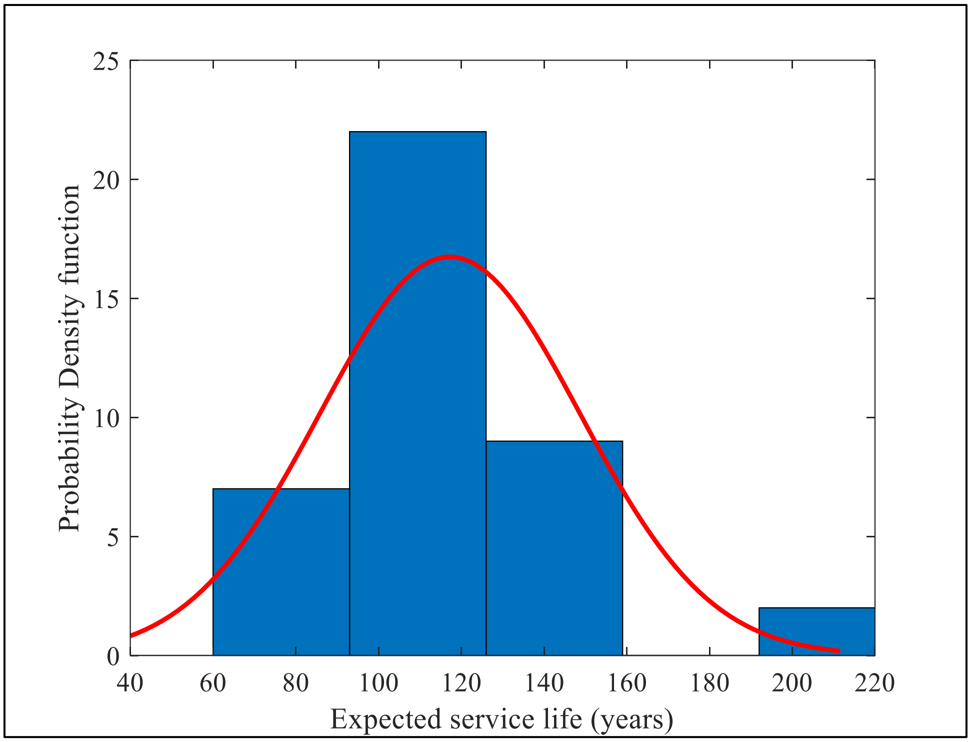


Figure 35: Normal distribution of pipe's segments expected service life.

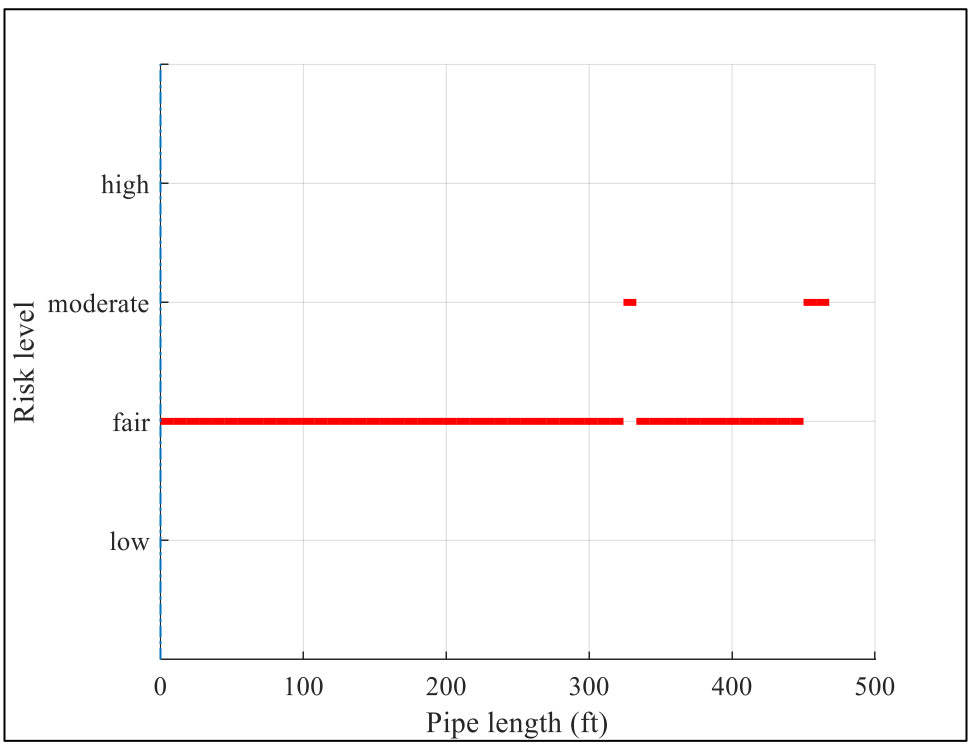


Figure 36: Risk level for pipe's segments along the total length.

A5.6 F16SL0249 Line

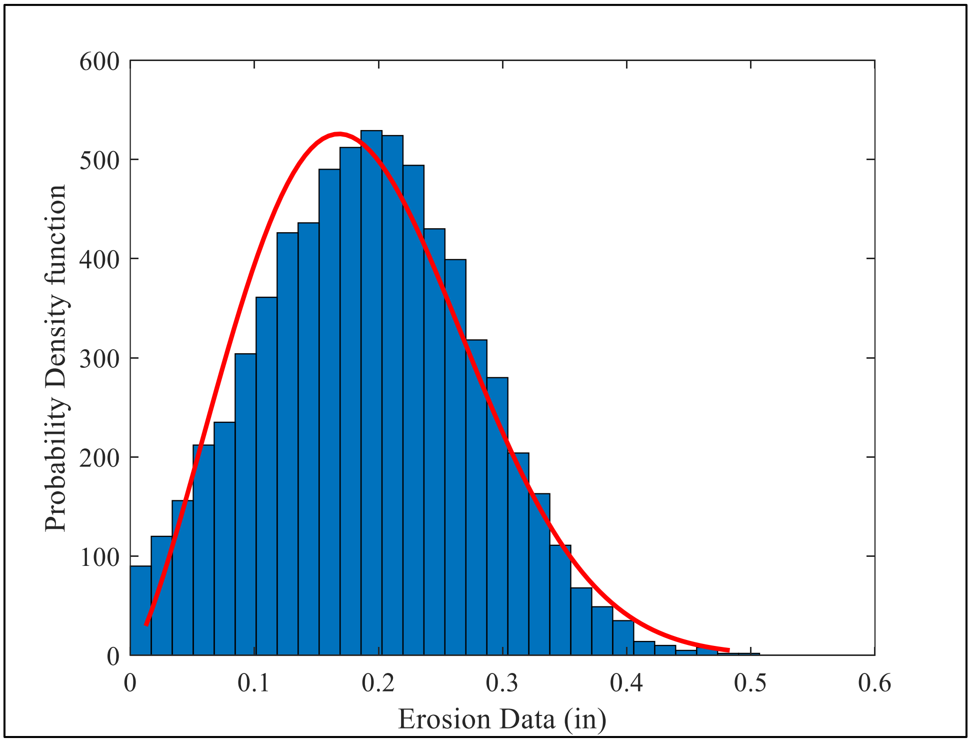


Figure 37: Probability density function of erosion data along the entire line.

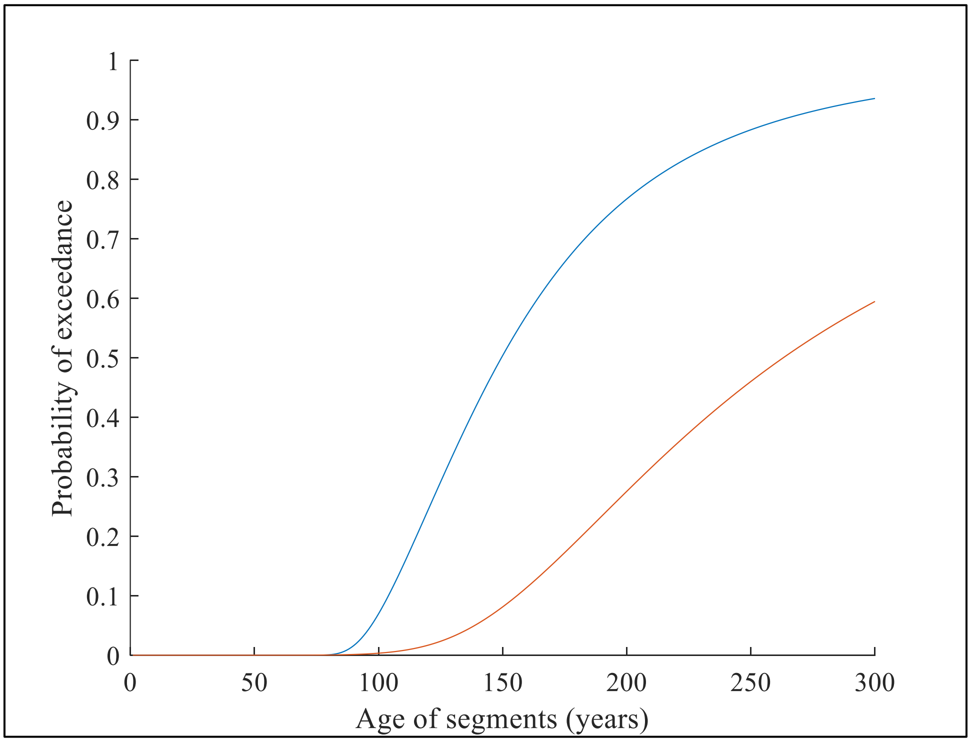


Figure 38: Cumulative distribution function (CDF) of segments' age.

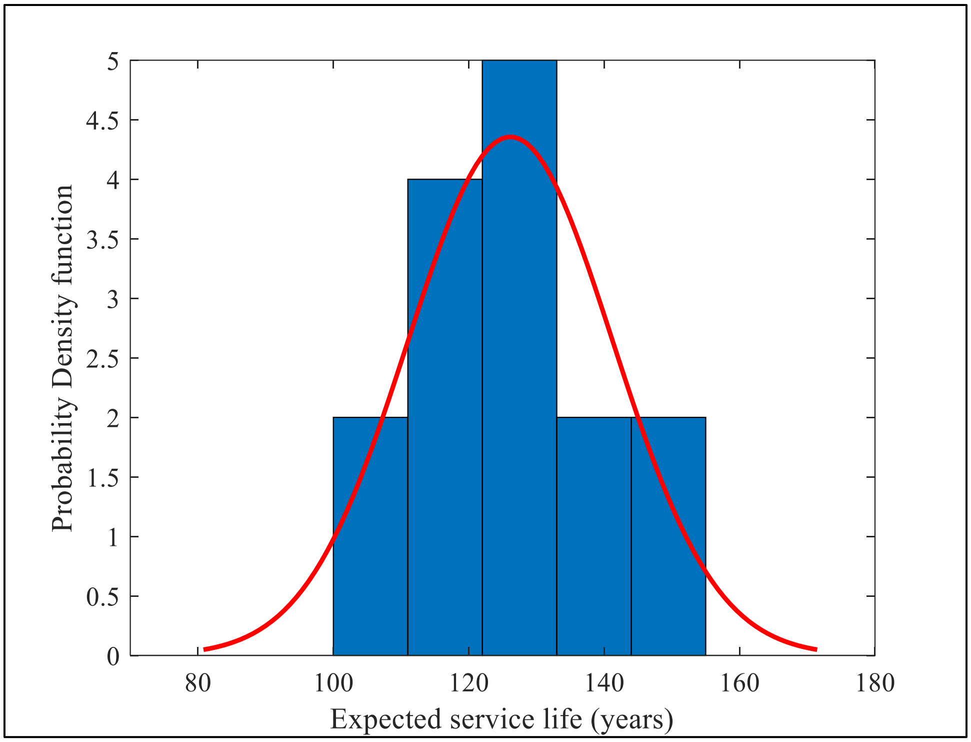


Figure 39: Normal distribution of pipe's segments expected service life.

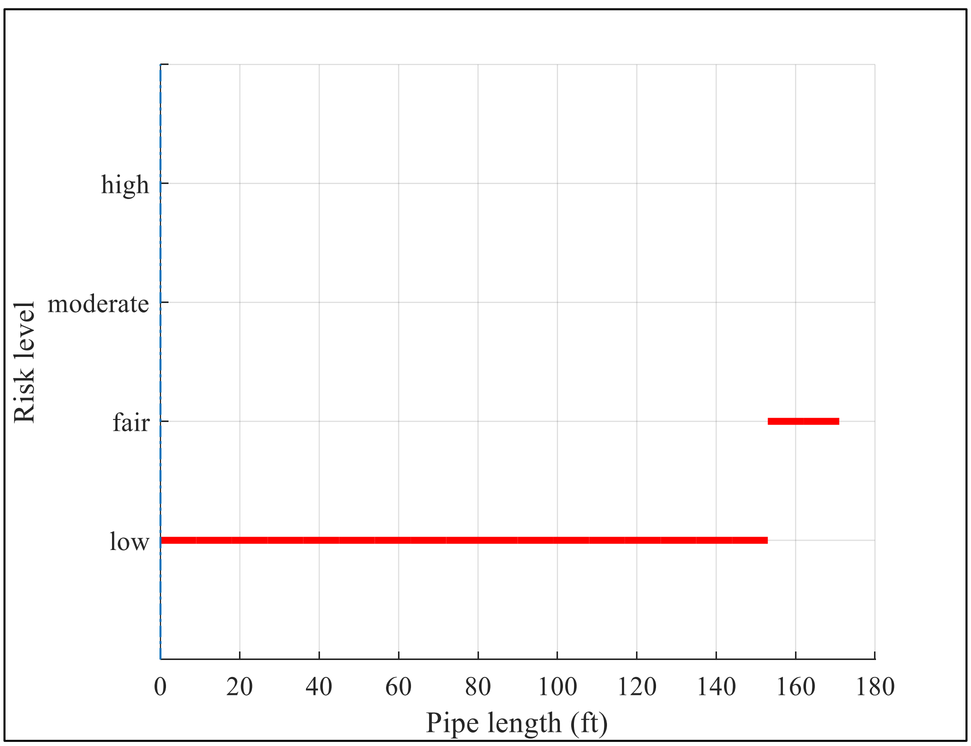


Figure 40: Risk level for pipe's segments along the total length.

A5.7 F16SL0250 Line

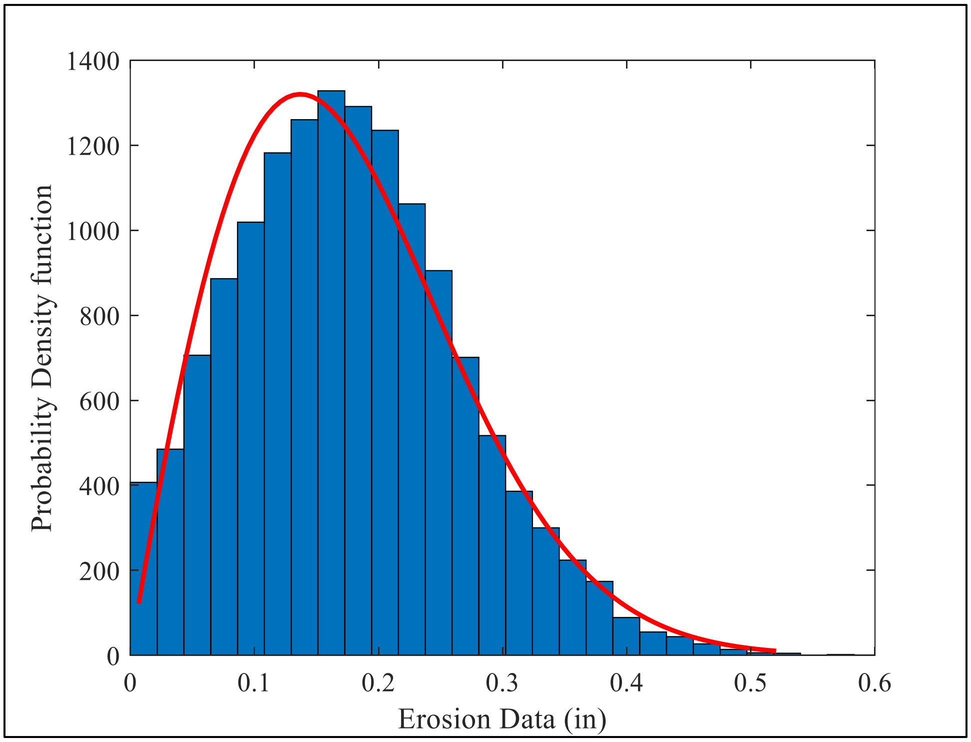


Figure 41: Probability density function of erosion data along the entire line.

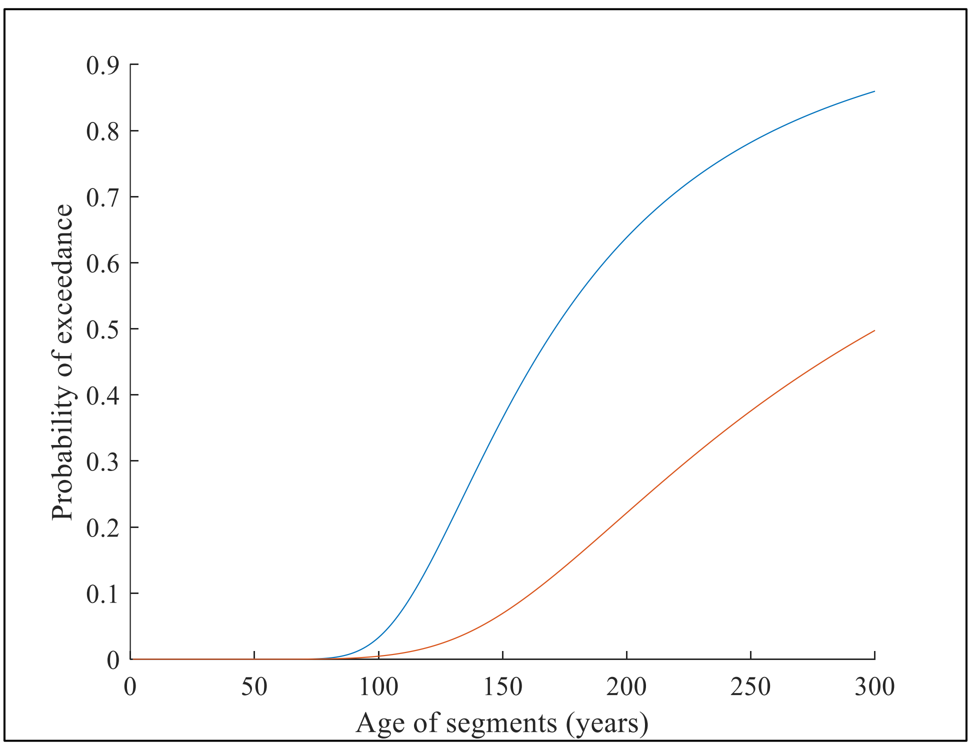


Figure 42: Cumulative distribution function (CDF) of segments' age.

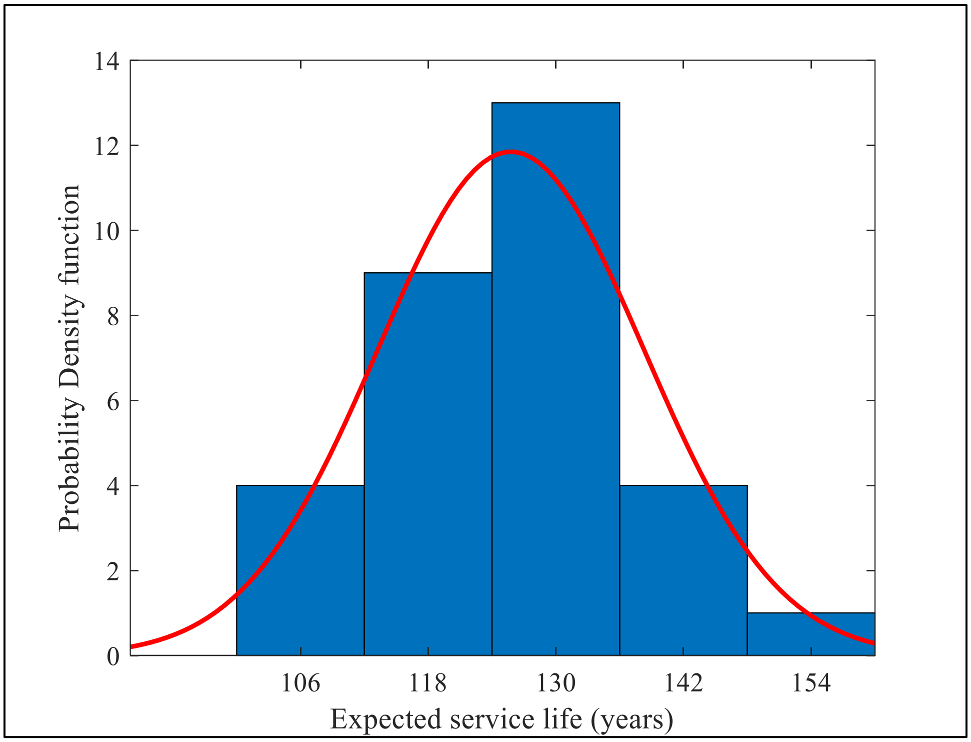


Figure 43: Normal distribution of pipe's segments expected service life.

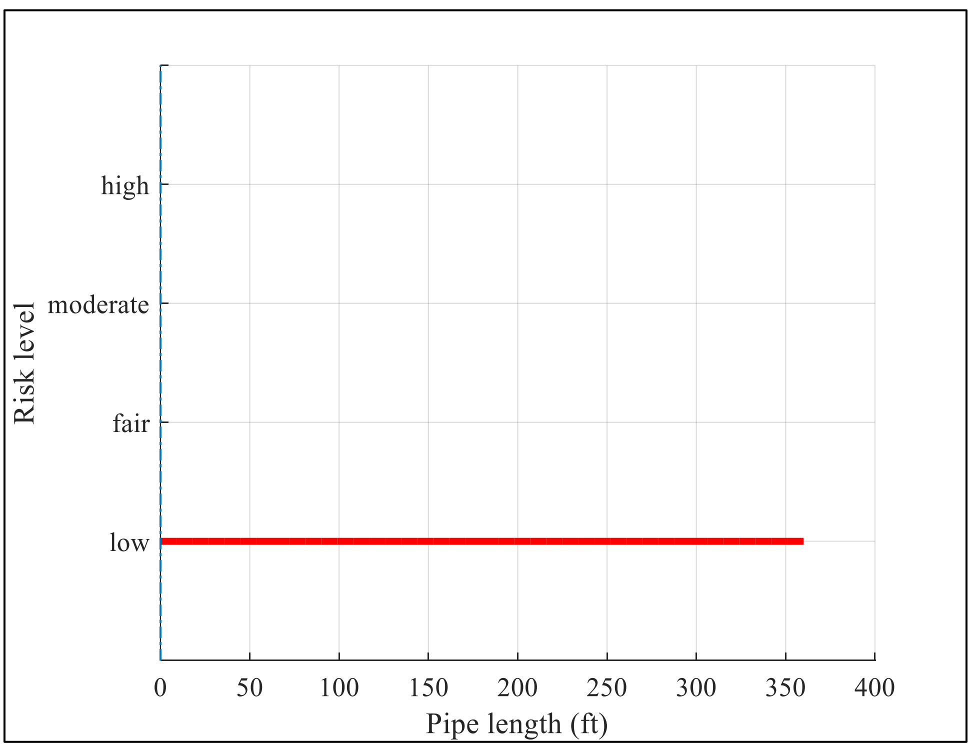


Figure 44: Risk level for pipe's segments along the total length.

A5.8 F15SL0146 Line

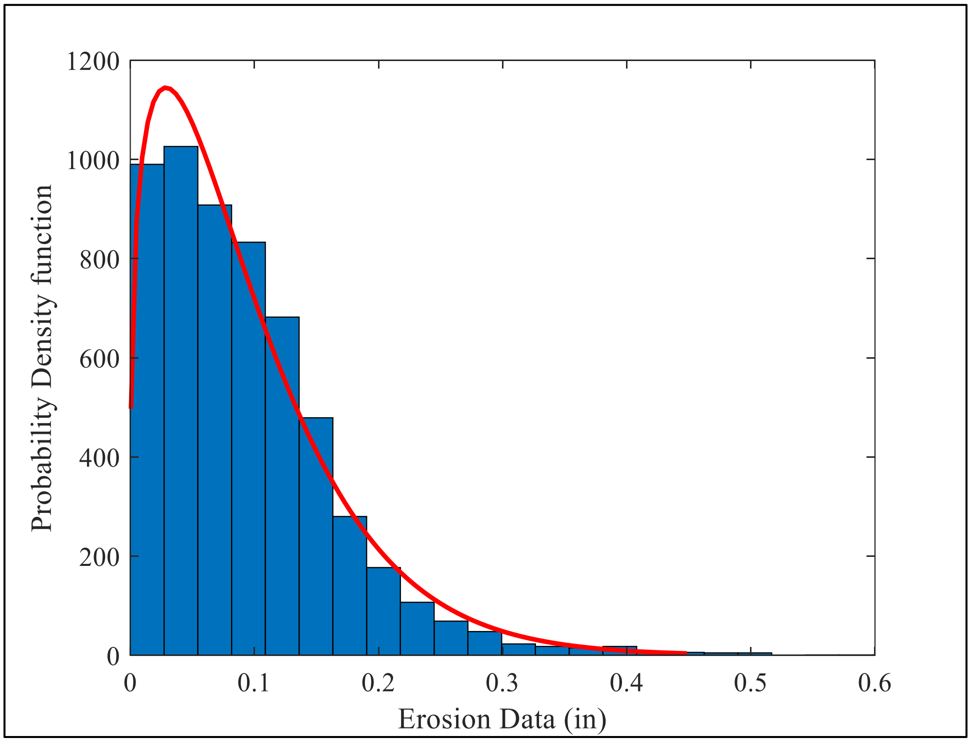


Figure 45: Probability density function of erosion data along the entire line.

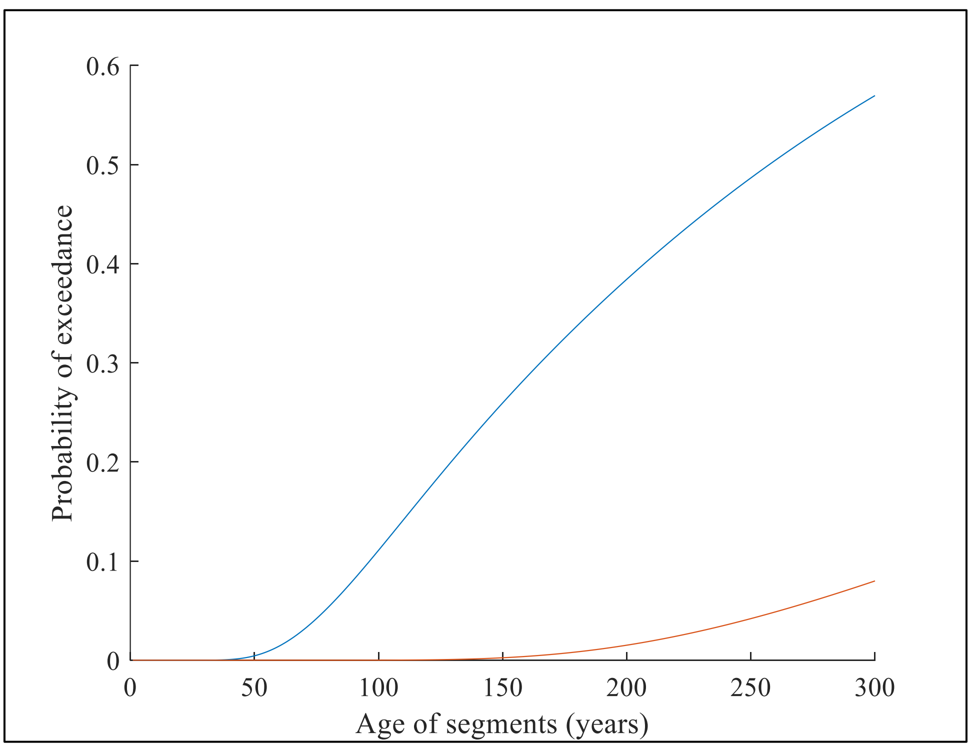


Figure 46: Cumulative distribution function (CDF) of segments' age.

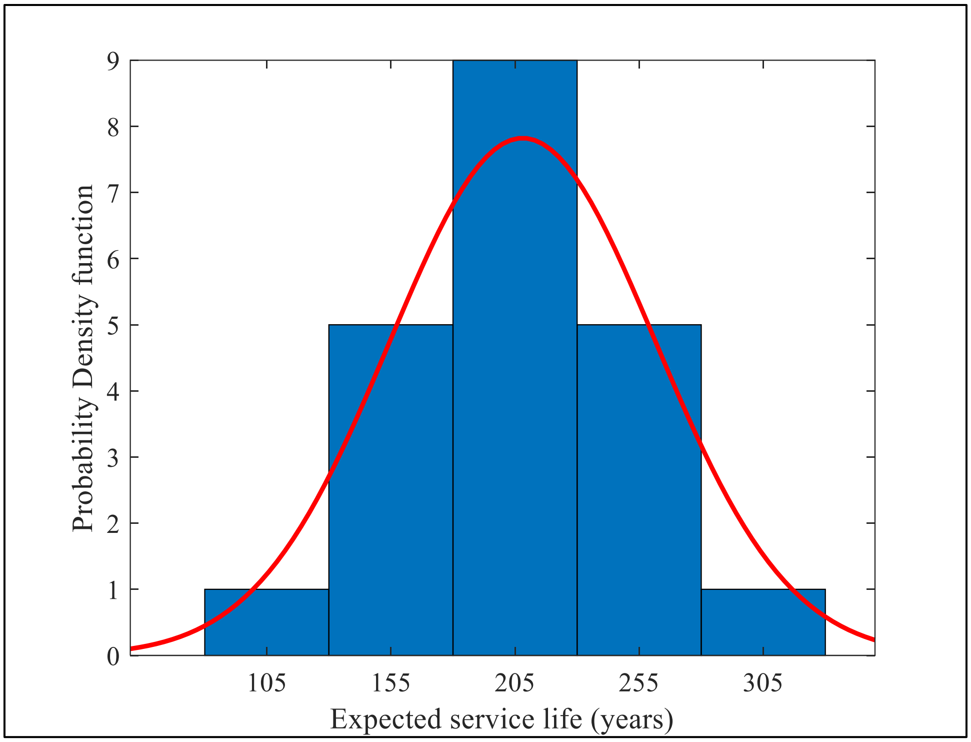


Figure 47: Normal distribution of pipe's segments expected service life.

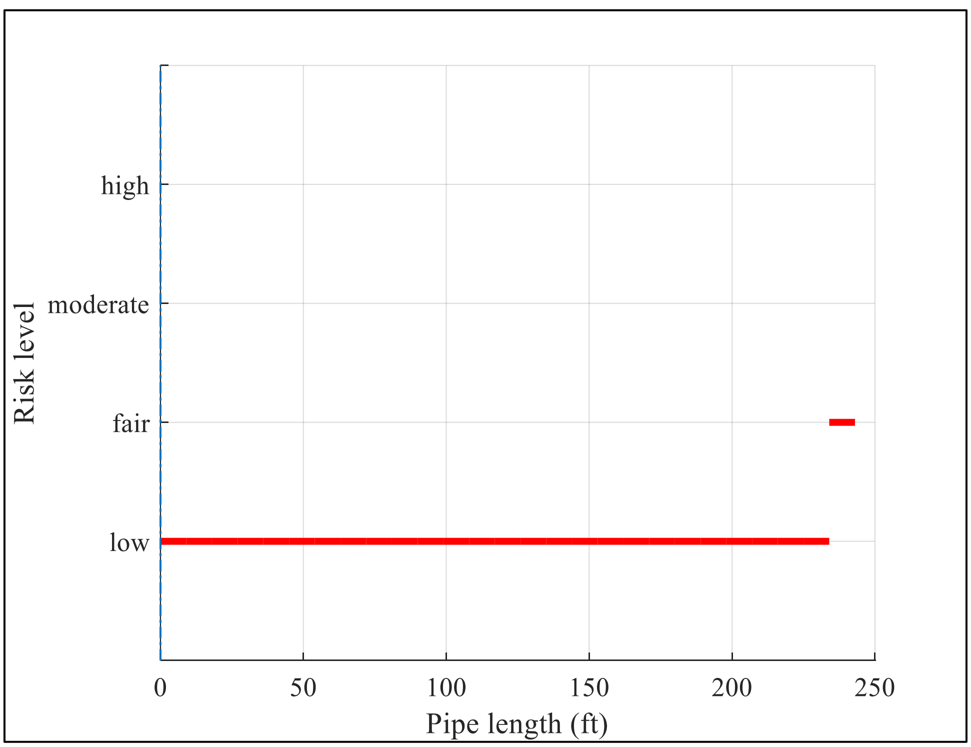


Figure 48: Risk level for pipe's segments along the total length.

A5.9 F15SL0161 Line

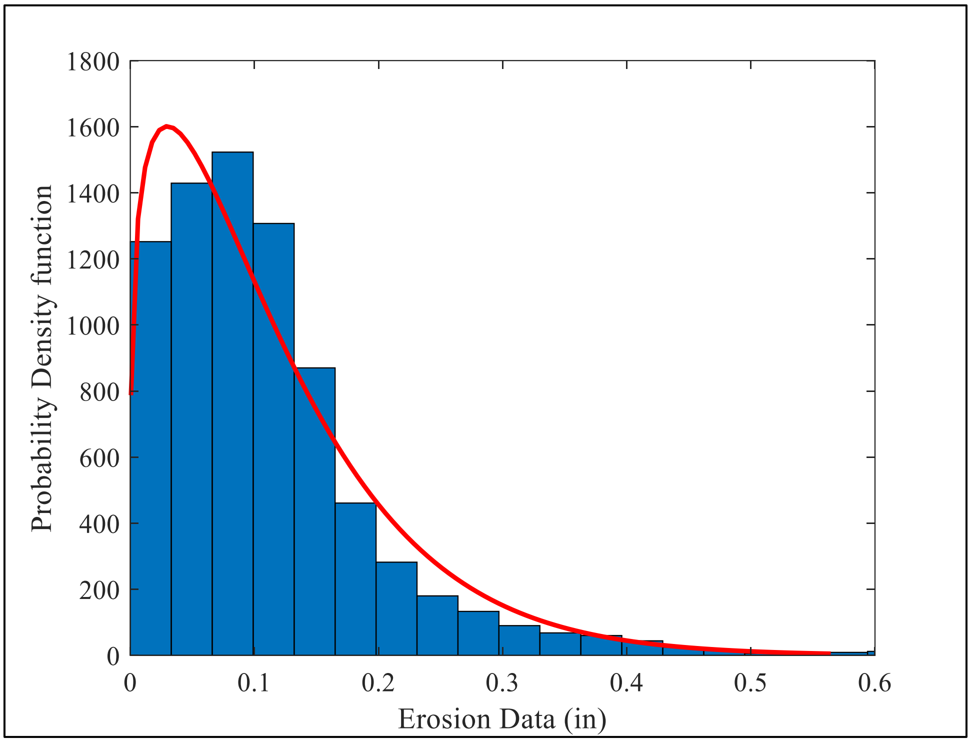


Figure 49: Probability density function of erosion data along the entire line.

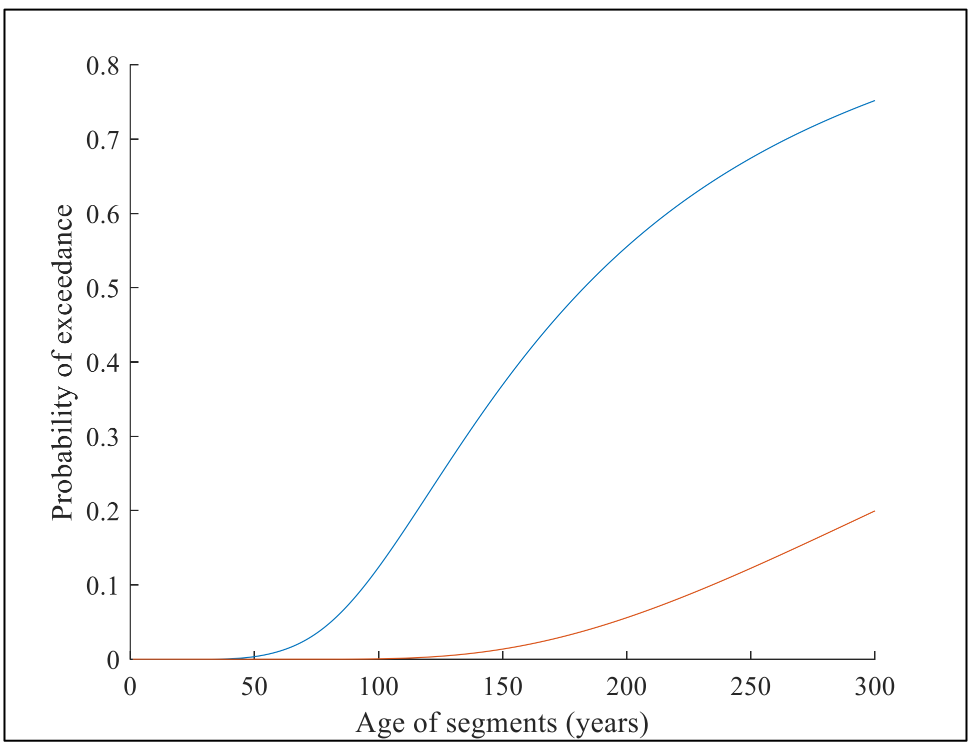


Figure 50: Cumulative distribution function (CDF) of segments' age.

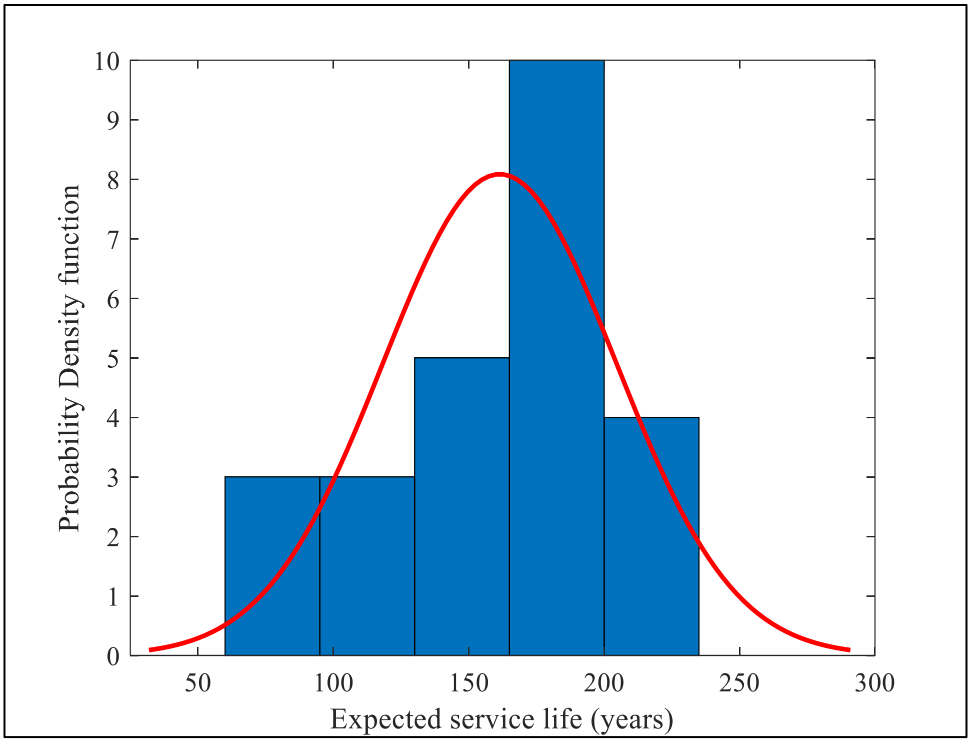


Figure 51: Normal distribution of pipe's segments expected service life.

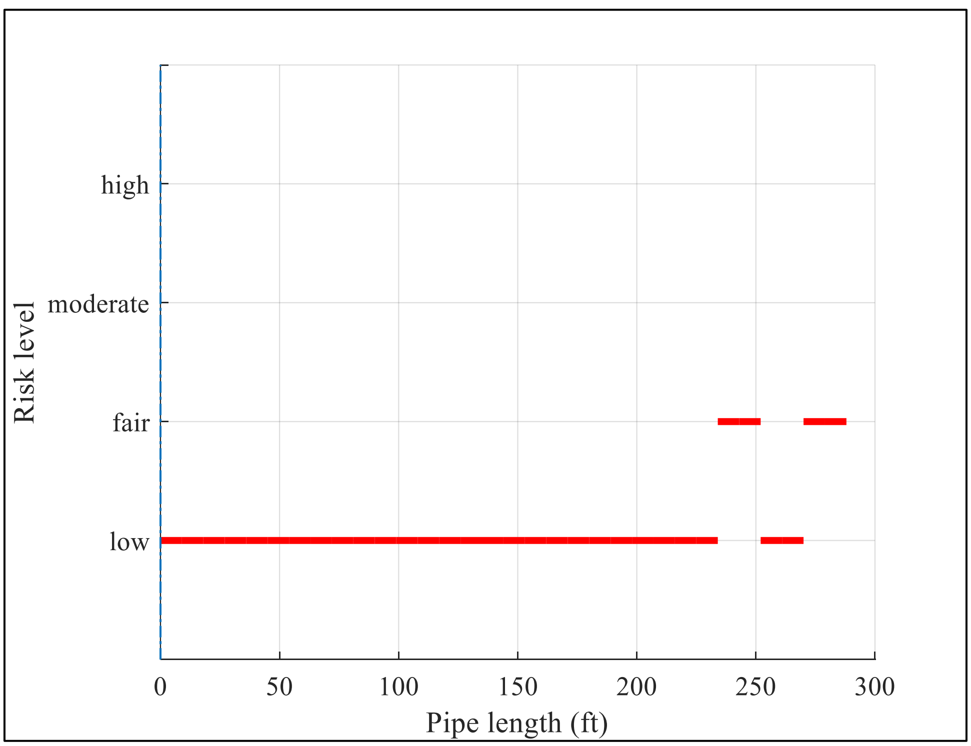


Figure 52: Risk level for pipe's segments along the total length.

A5.10 F15SL0347 Line

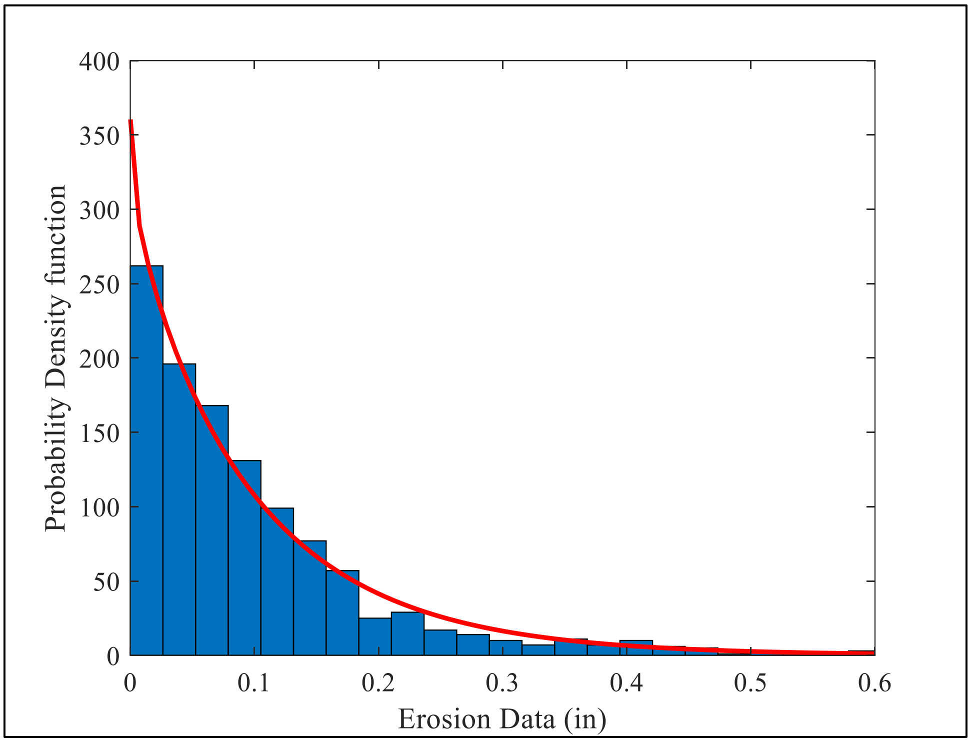


Figure 53: Probability density function of erosion data along the entire line.

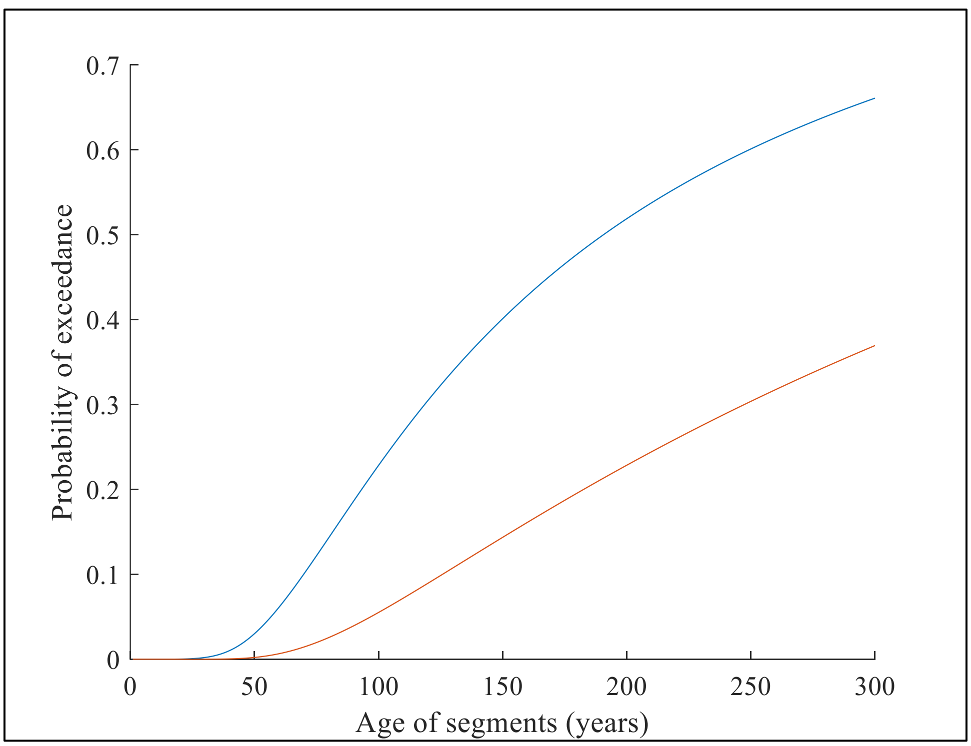


Figure 54: Cumulative distribution function (CDF) of segments' age.

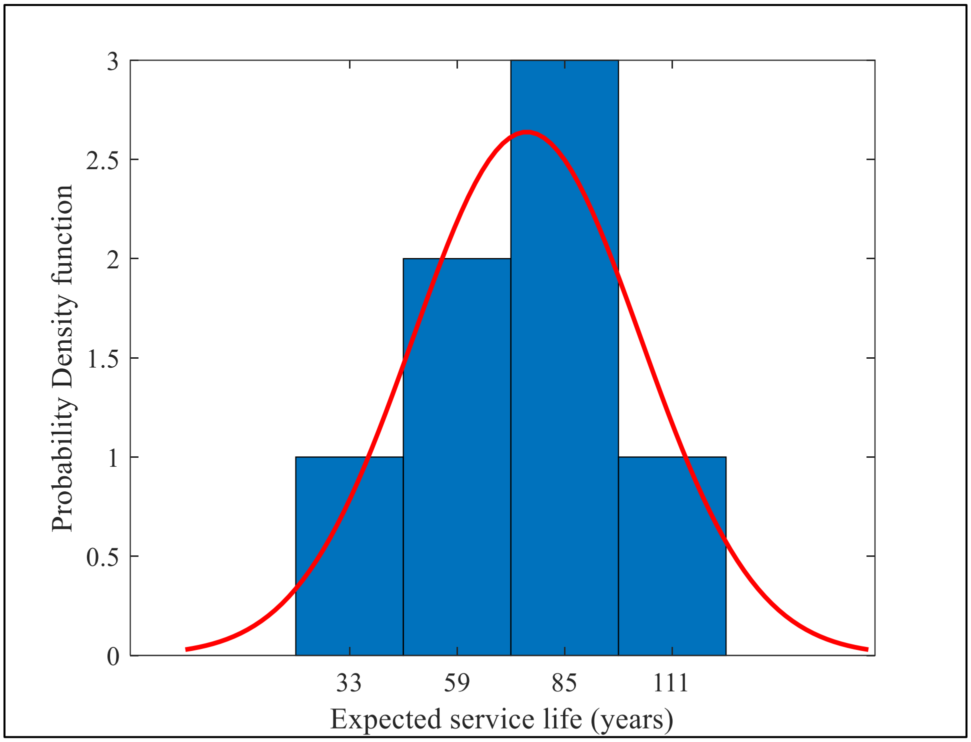


Figure 55: Normal distribution of pipe’s segments expected service life.

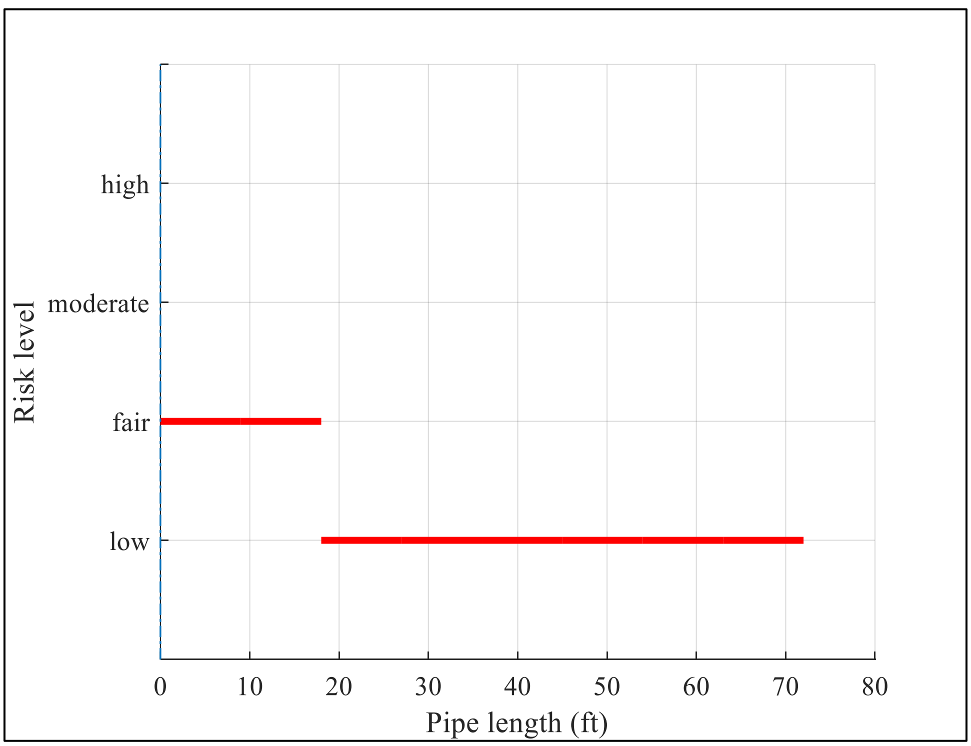


Figure 56: Risk level for pipe’s segments along the total length.

A5.11 F15SL0348 Line

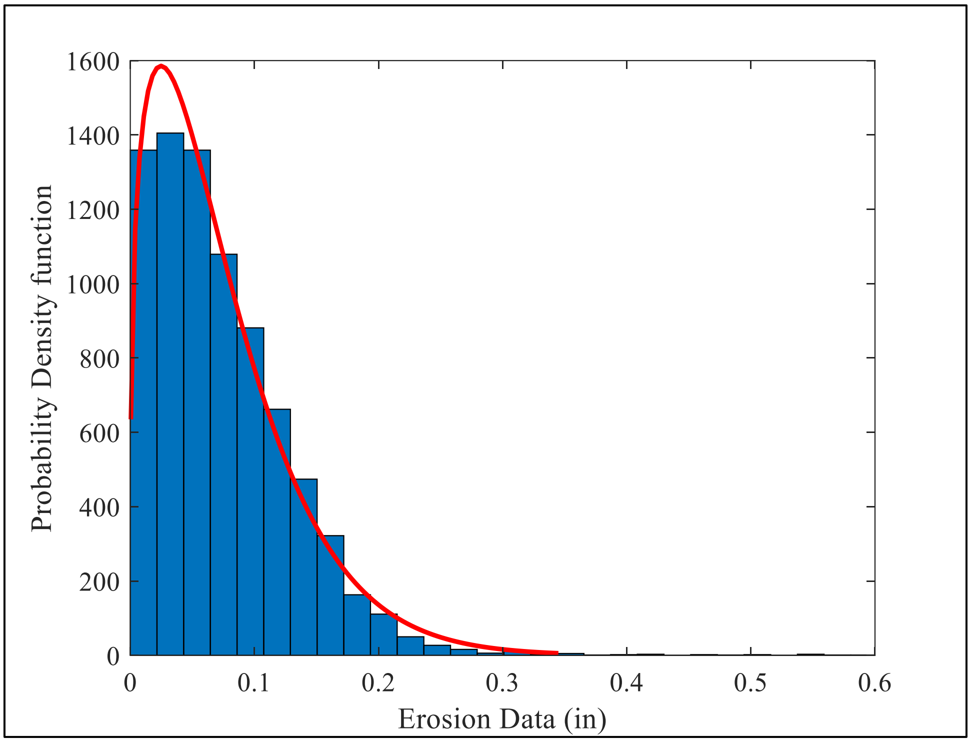


Figure 57: Probability density function of erosion data along the entire line.

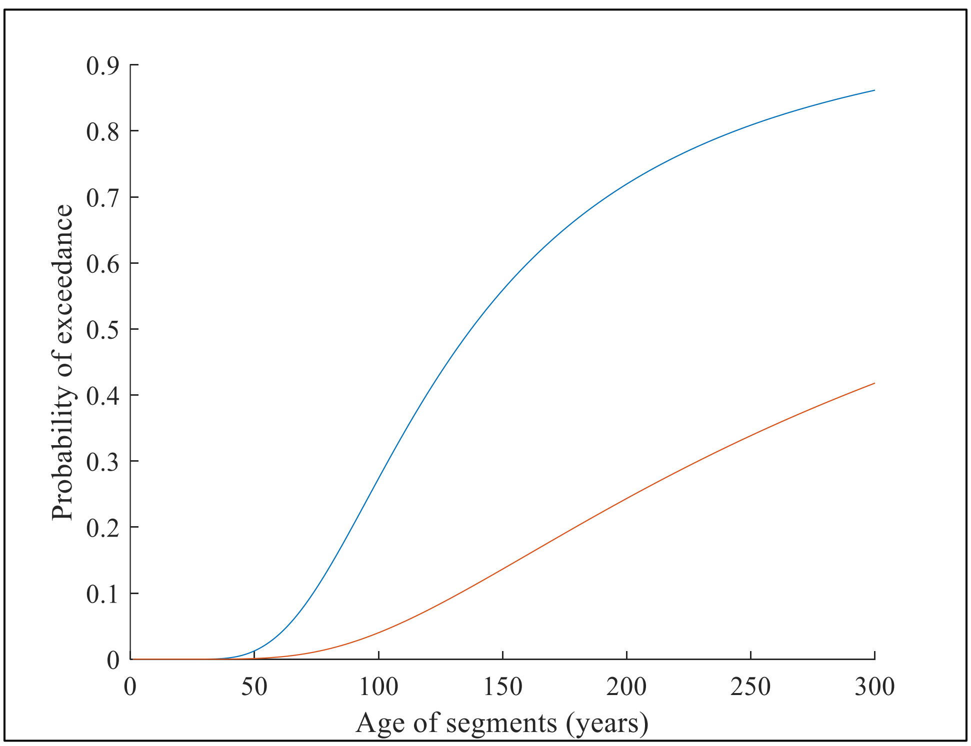


Figure 58: Cumulative distribution function (CDF) of segments' age.

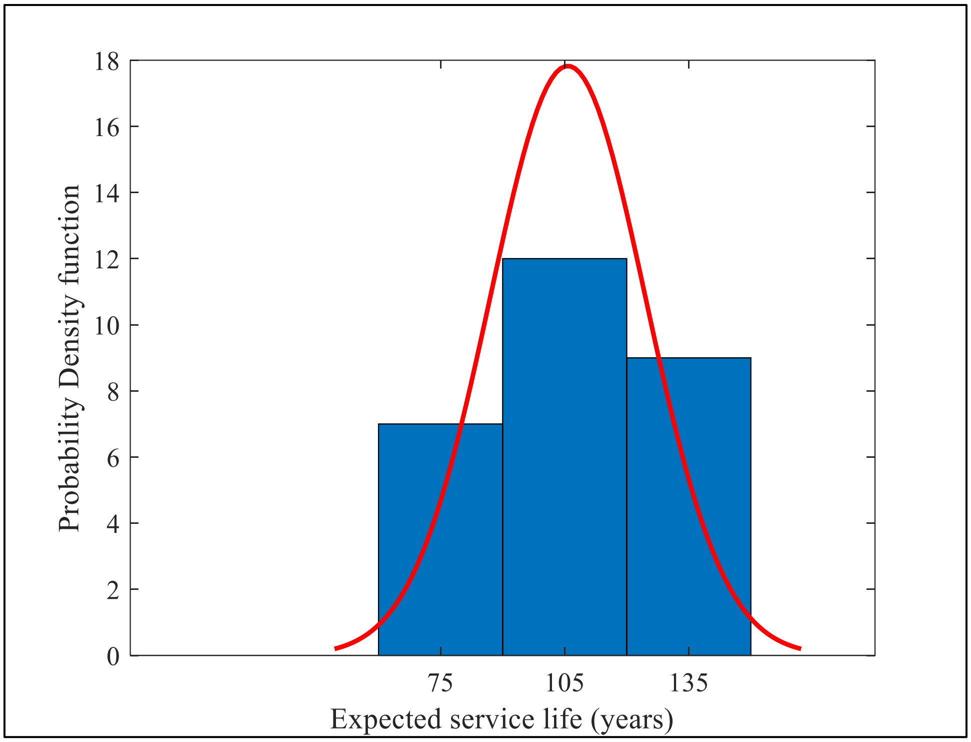


Figure 59: Normal distribution of pipe's segments expected service life.

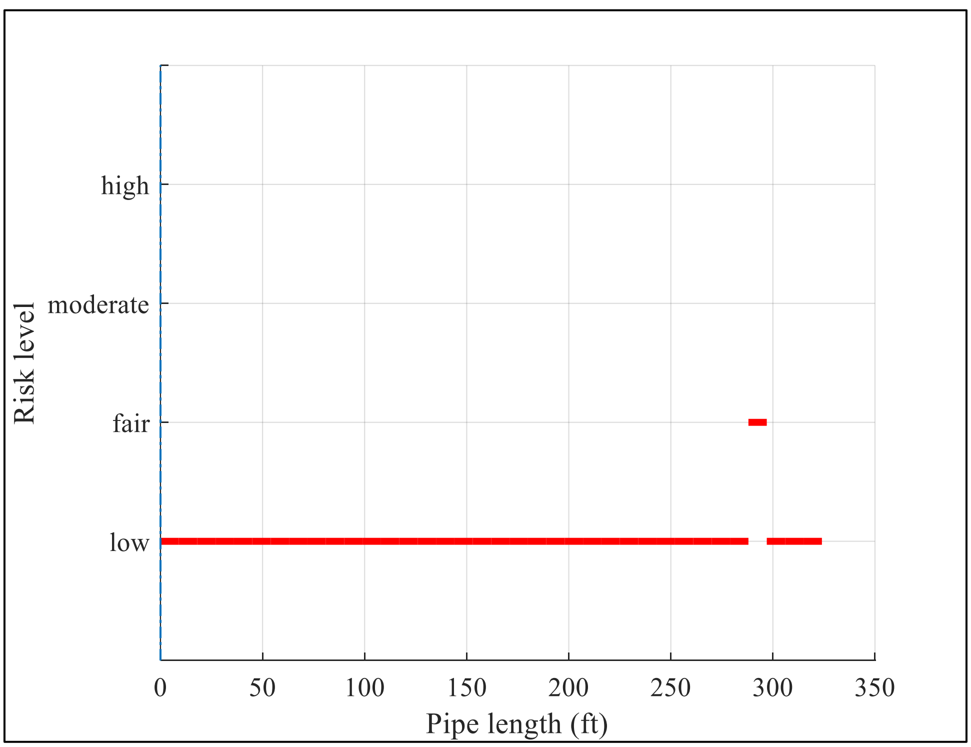


Figure 60: Risk level for pipe's segments along the total length.

A5.12 E12SL0011 Line

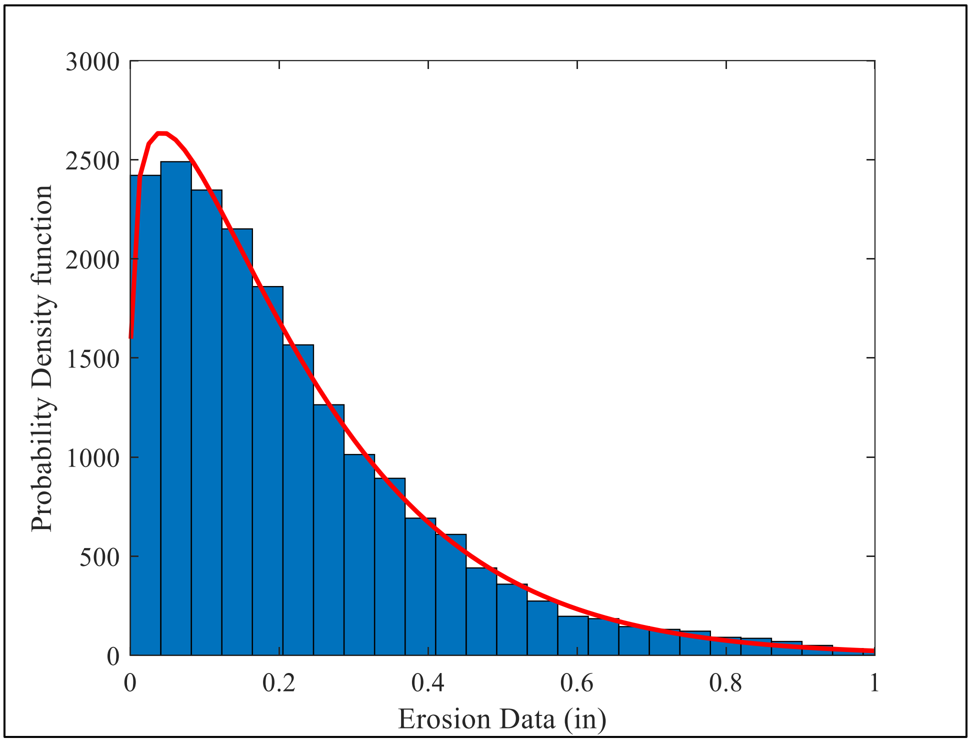


Figure 61: Probability density function of erosion data along the entire line.

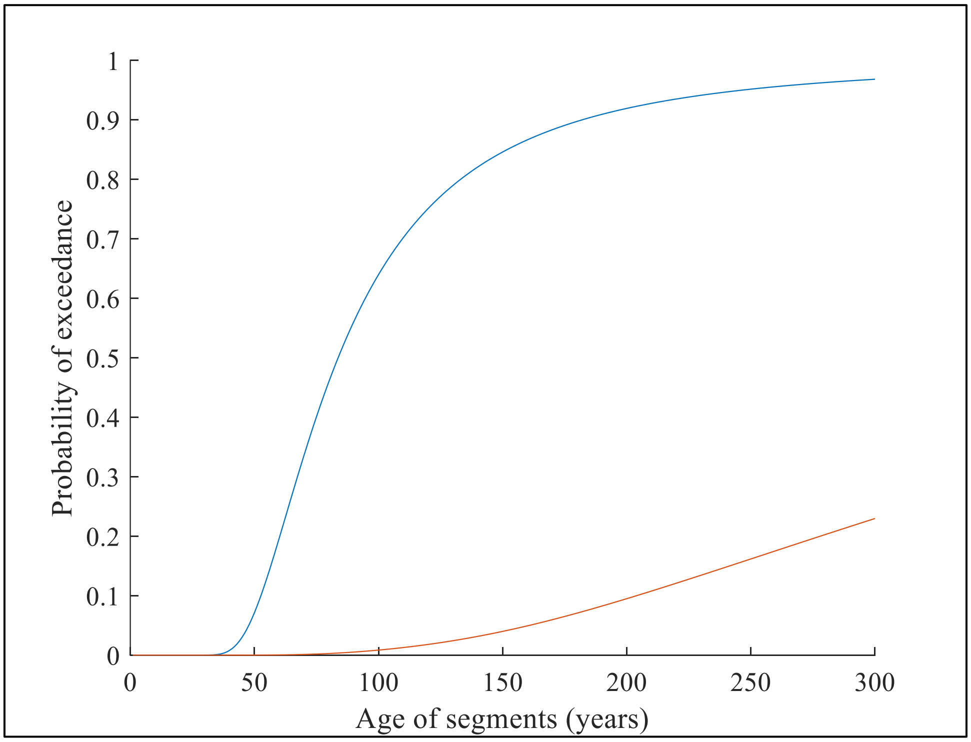


Figure 62: Cumulative distribution function (CDF) of segments' age.

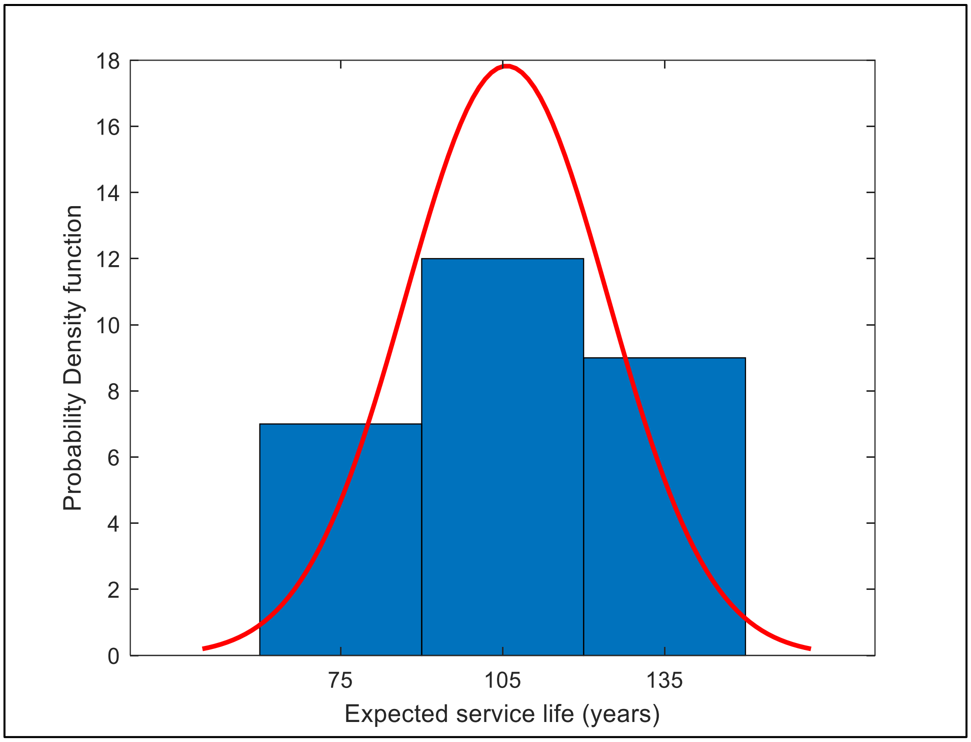


Figure 63: Normal distribution of pipe's segments expected service life.

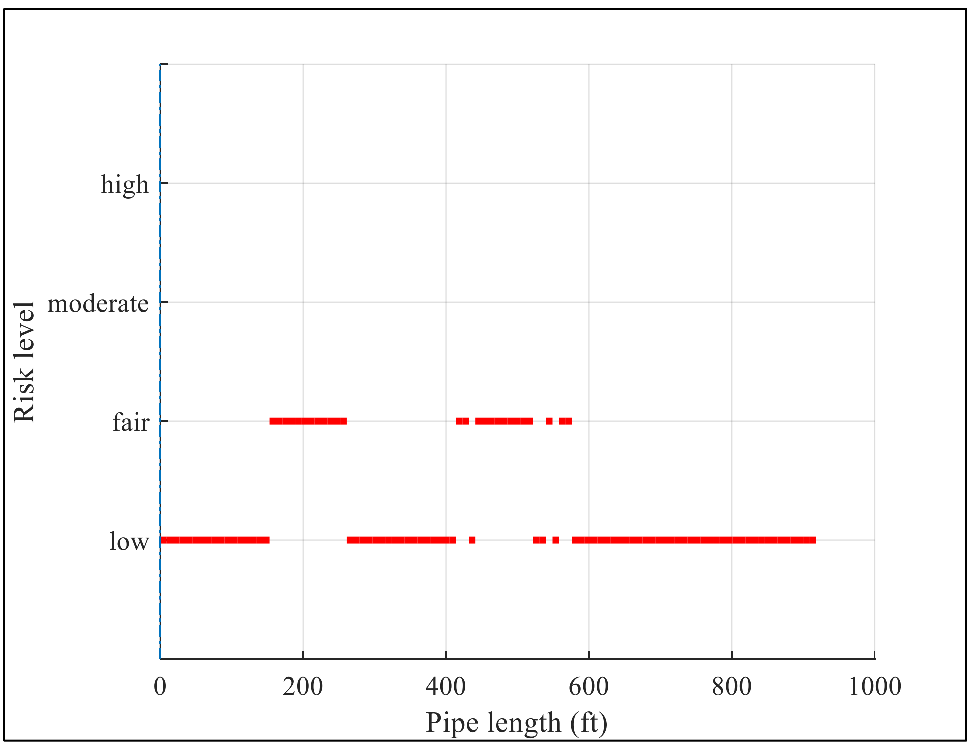


Figure 64: Risk level for pipe's segments along the total length.

A5.13 E12SL0017 Line

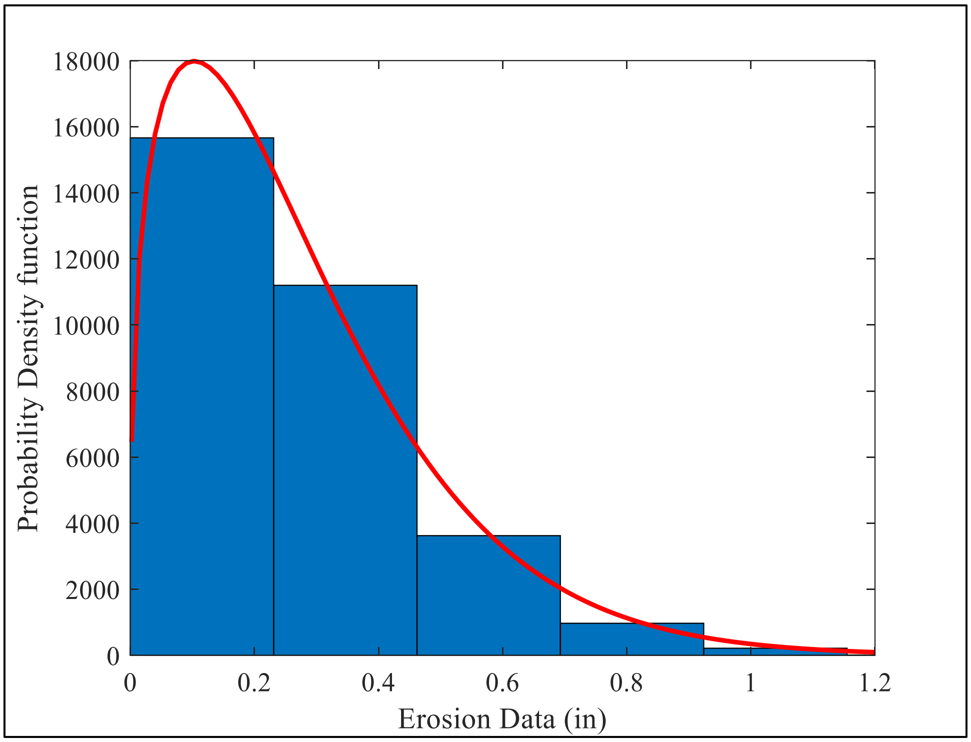


Figure 65: Probability density function of erosion data along the entire line.

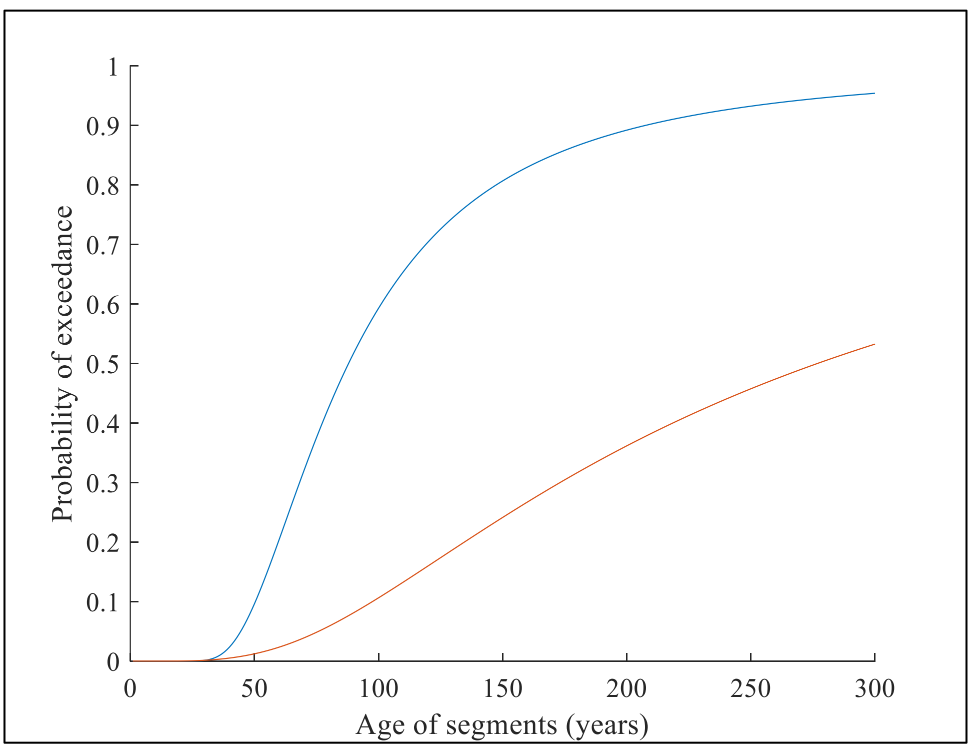


Figure 66: Cumulative distribution function (CDF) of segments' age.

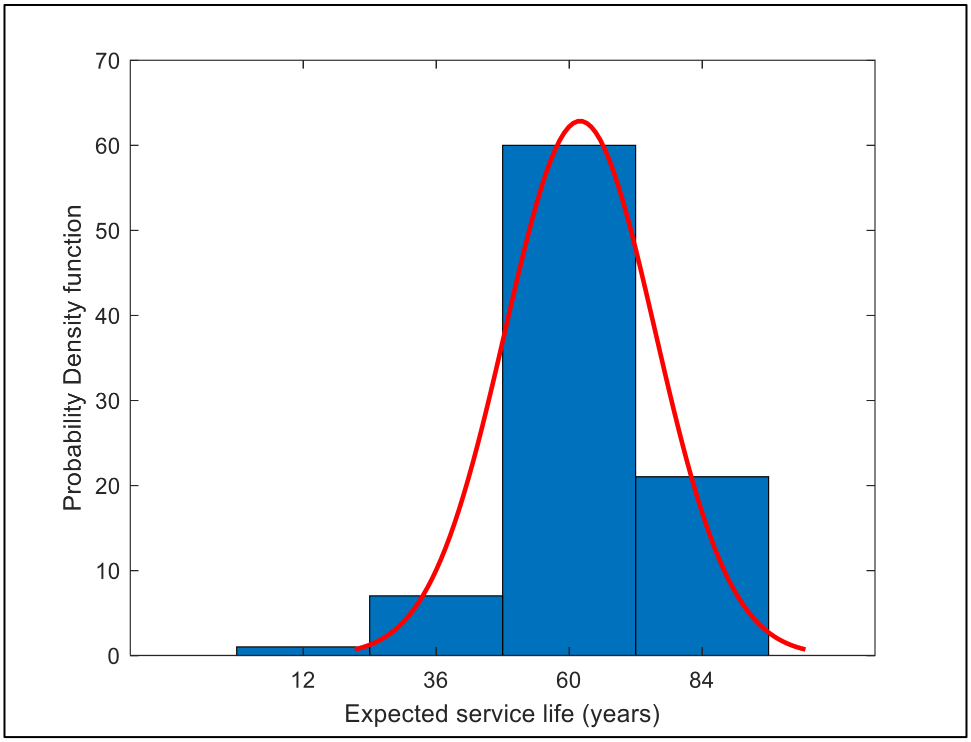


Figure 67: Normal distribution of pipe's segments expected service life.

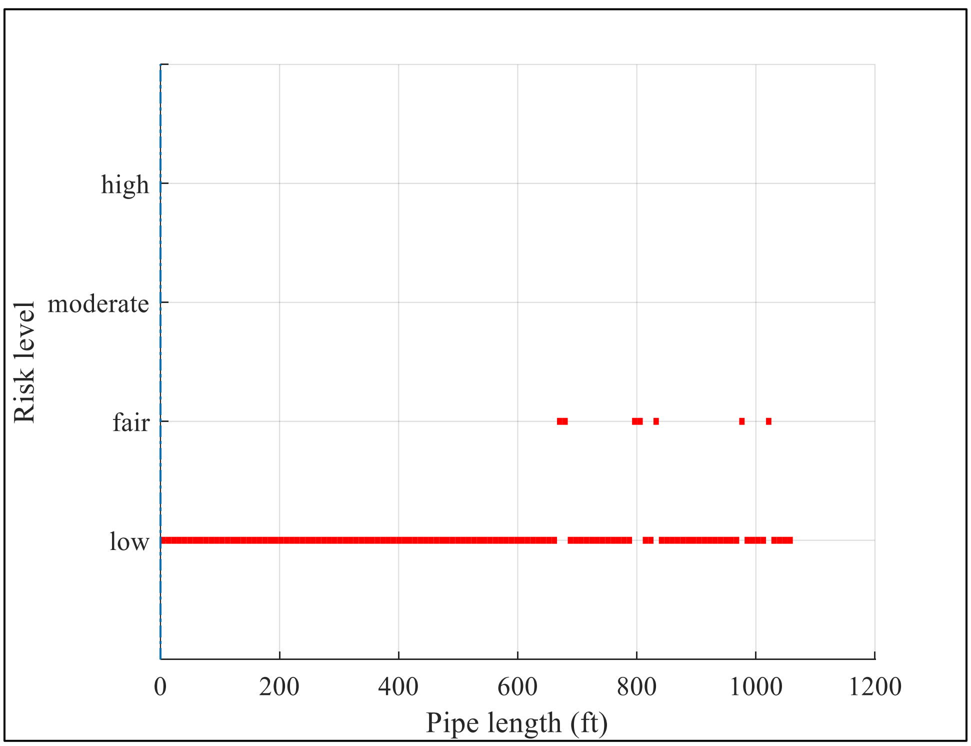


Figure 68: Risk level for pipe's segments along the total length.

A5.14 E12SL0292 Line

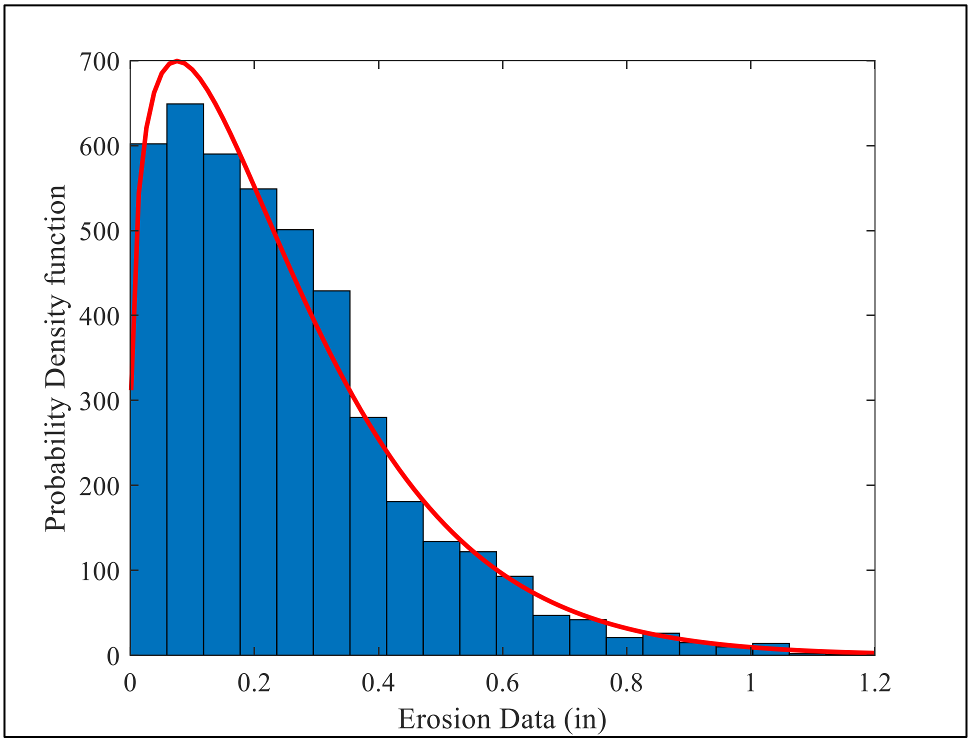


Figure 69: Probability density function of erosion data along the entire line.

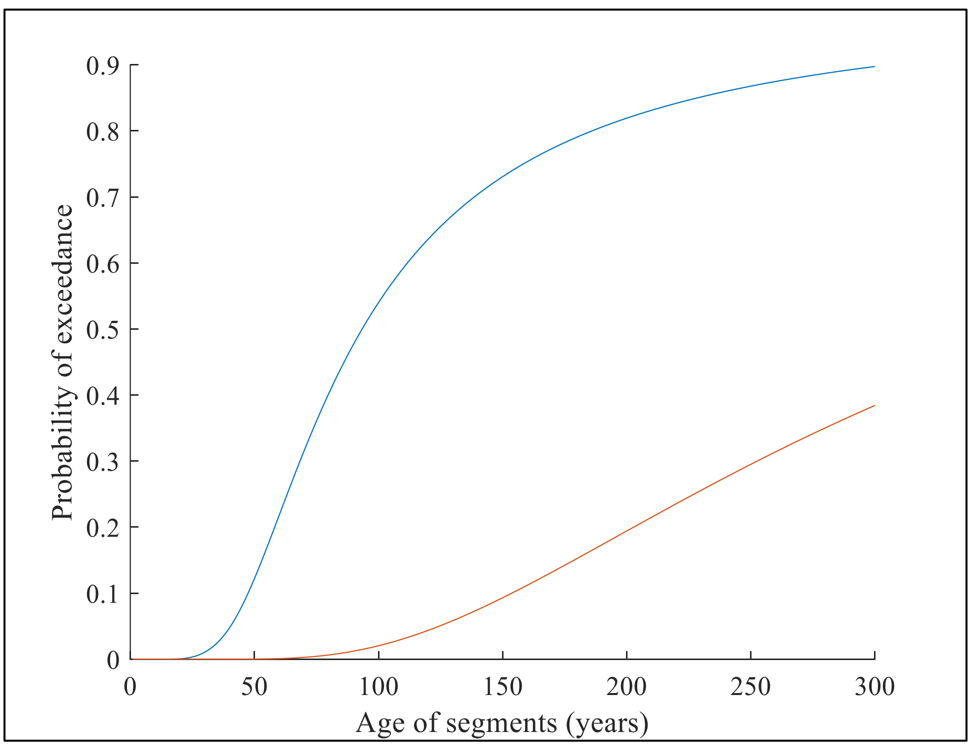


Figure 70: Cumulative distribution function (CDF) of segments' age.

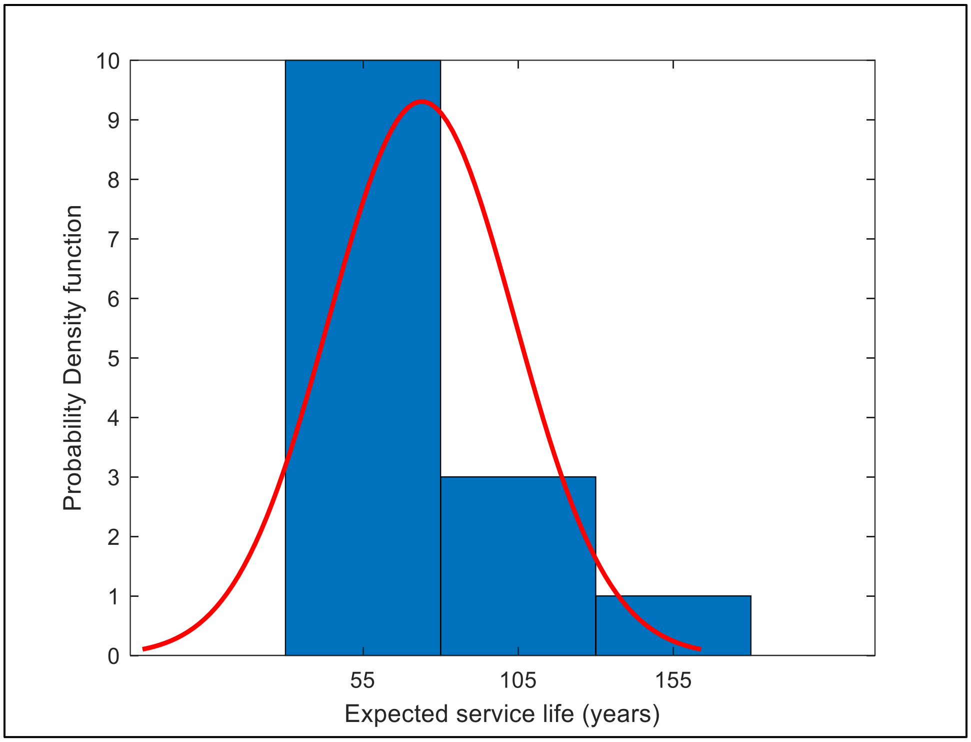


Figure 71: Normal distribution of pipe’s segments expected service life.

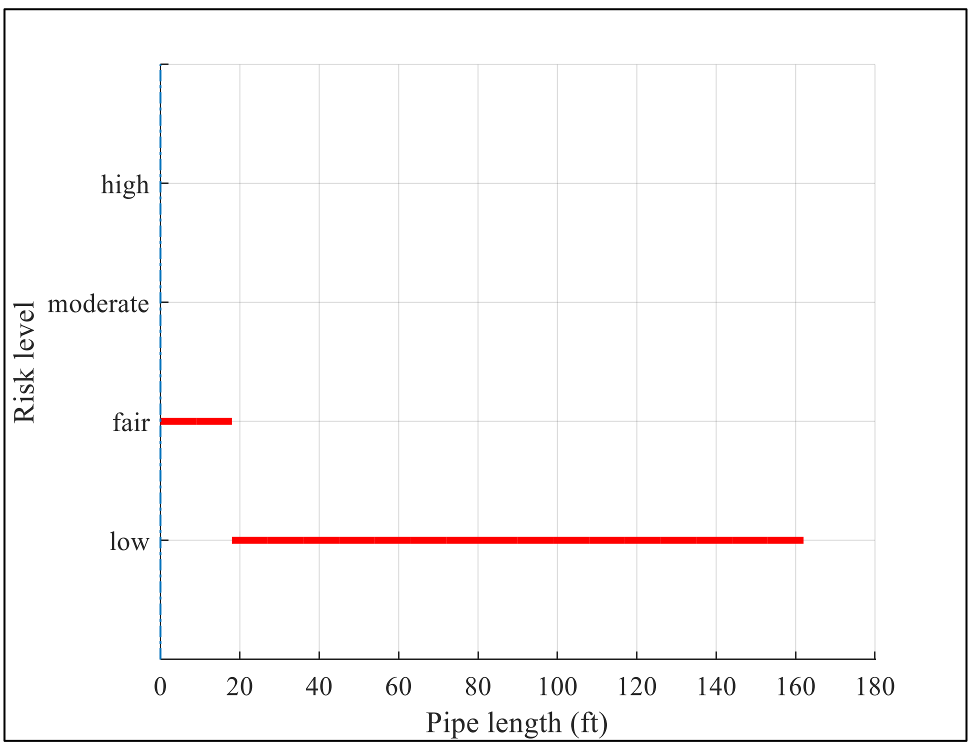


Figure 72: Risk level for pipe’s segments along the total length.

A5.15 E12SL0330 Line

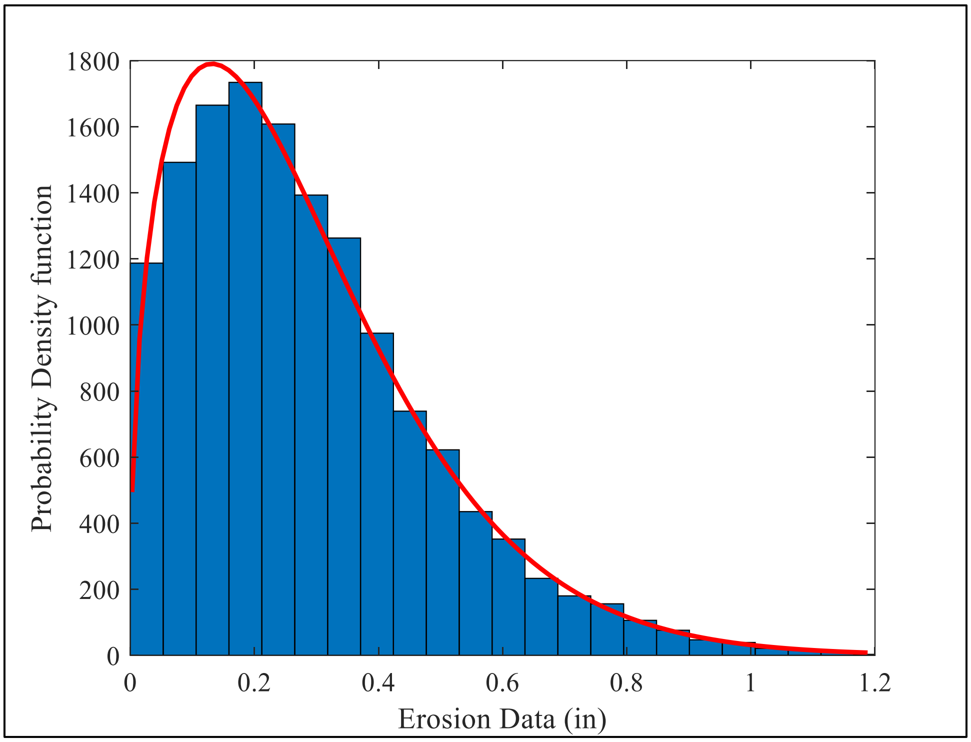


Figure 73: Probability density function of erosion data along the entire line.

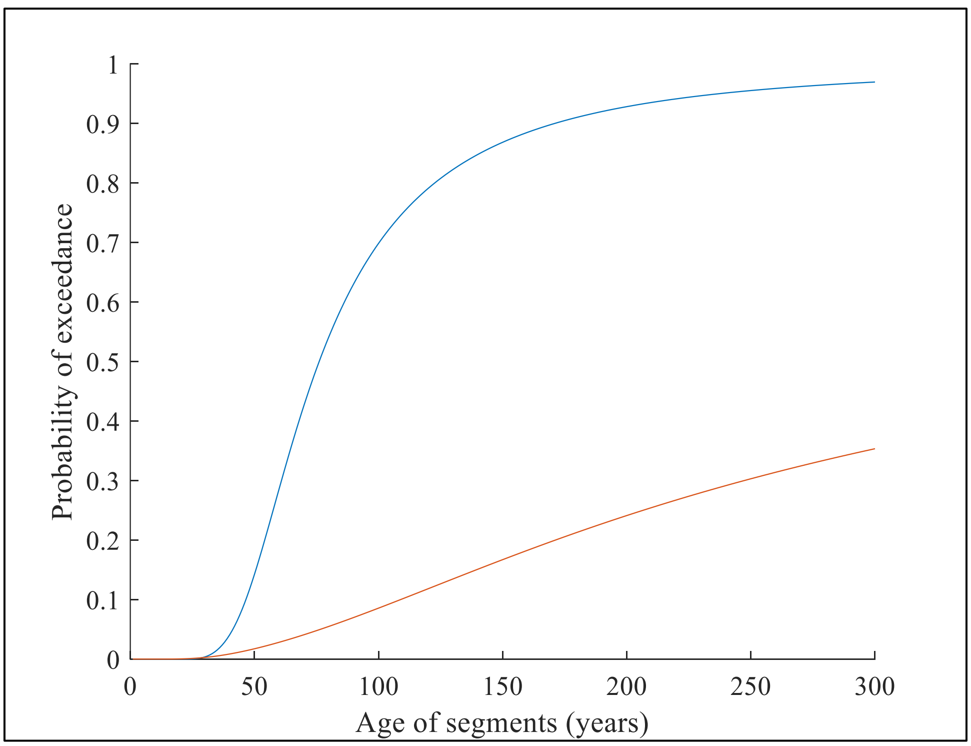


Figure 74: Cumulative distribution function (CDF) of segments' age.

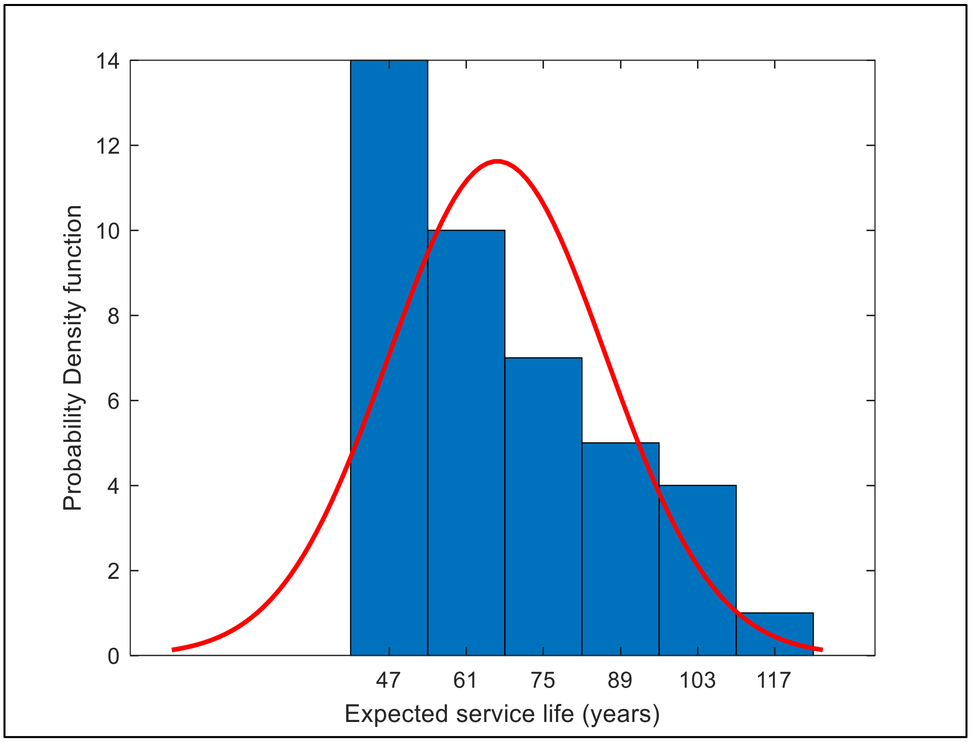


Figure 75: Normal distribution of pipe’s segments expected service life.

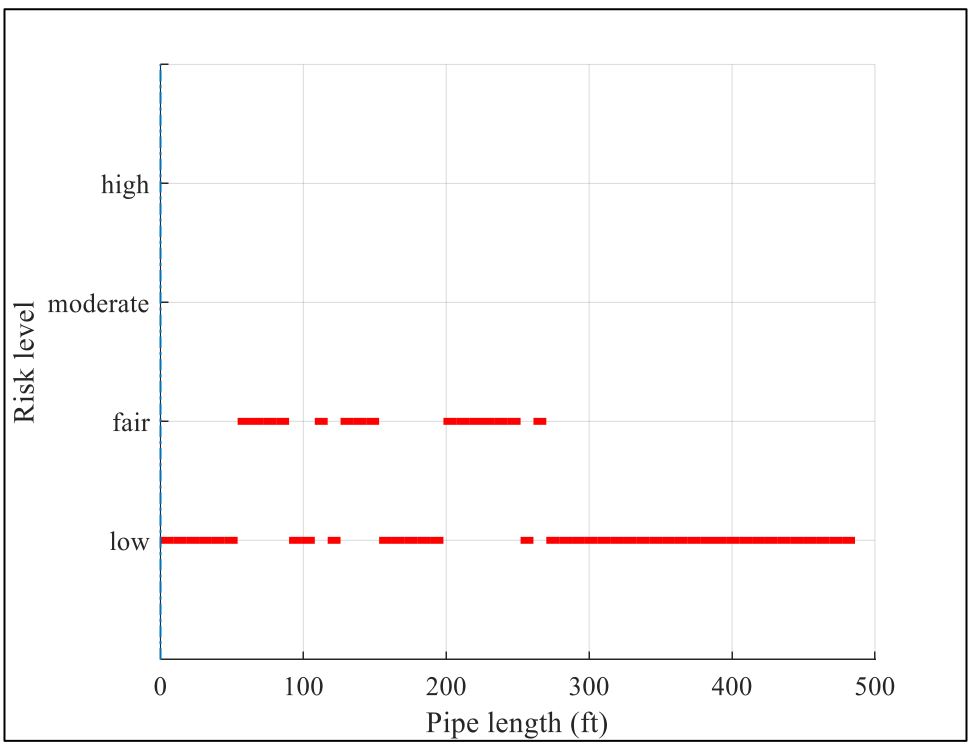


Figure 76: Risk level for pipe’s segments along the total length.

A5.16 E13SL0093-E13SL0165 Line

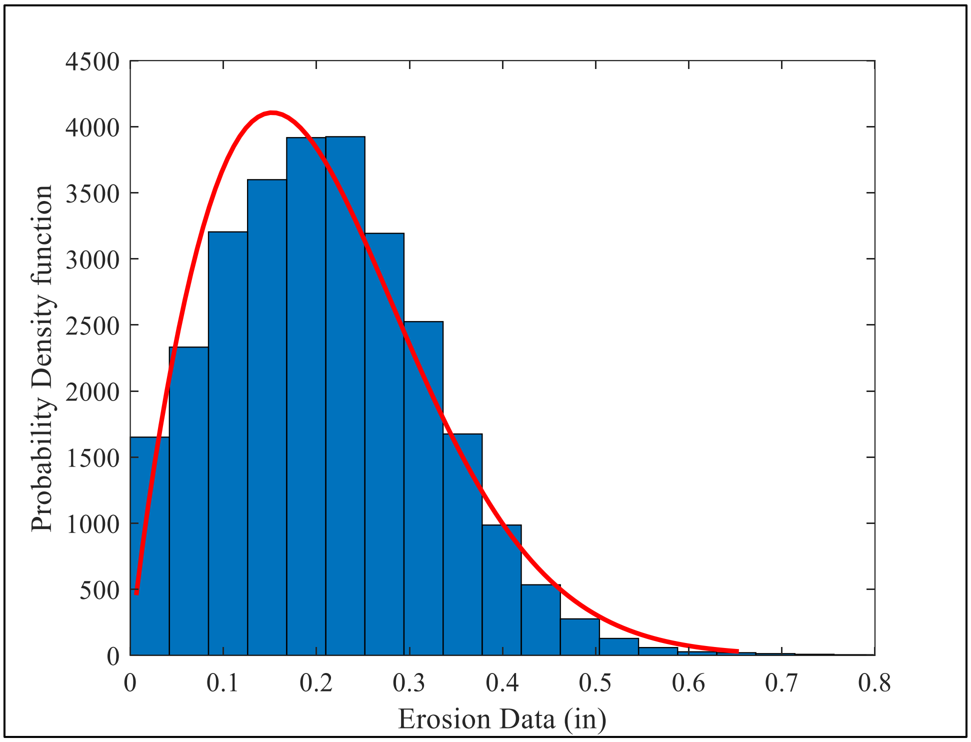


Figure 78: Probability density function of erosion data along the entire line.

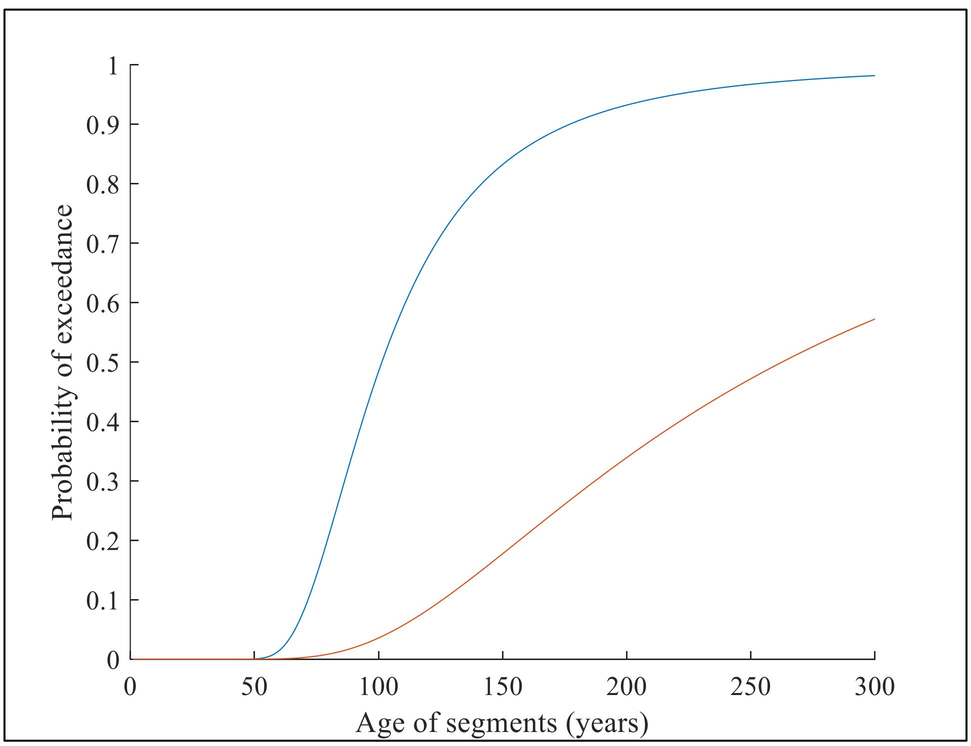


Figure 79: Cumulative distribution function (CDF) of segments' age.

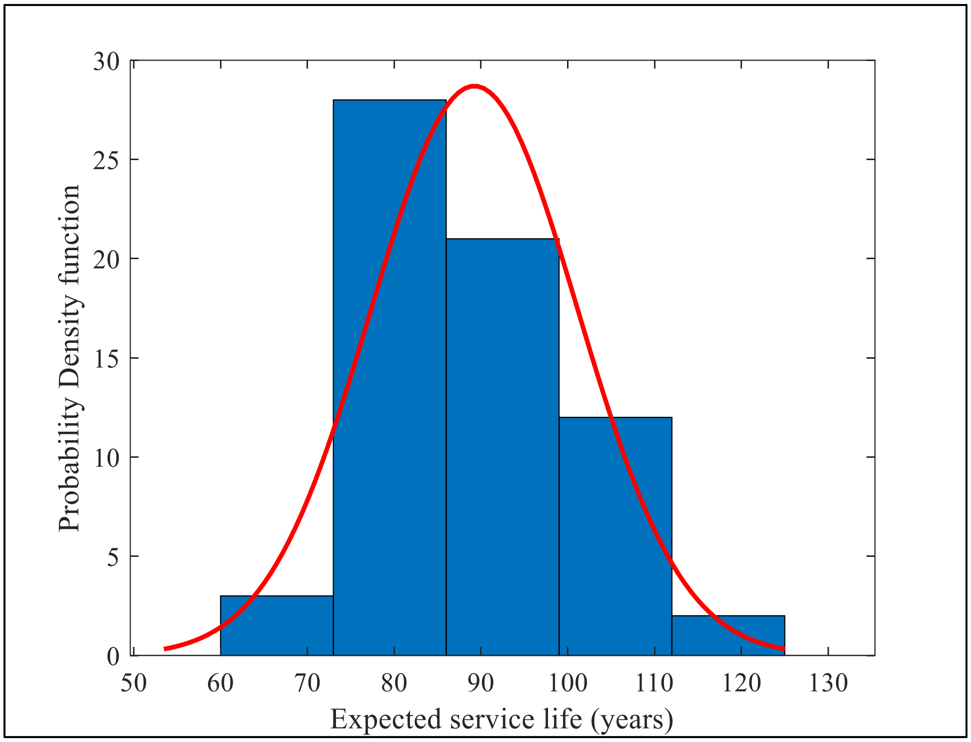


Figure 80: Normal distribution of pipe's segments expected service life.

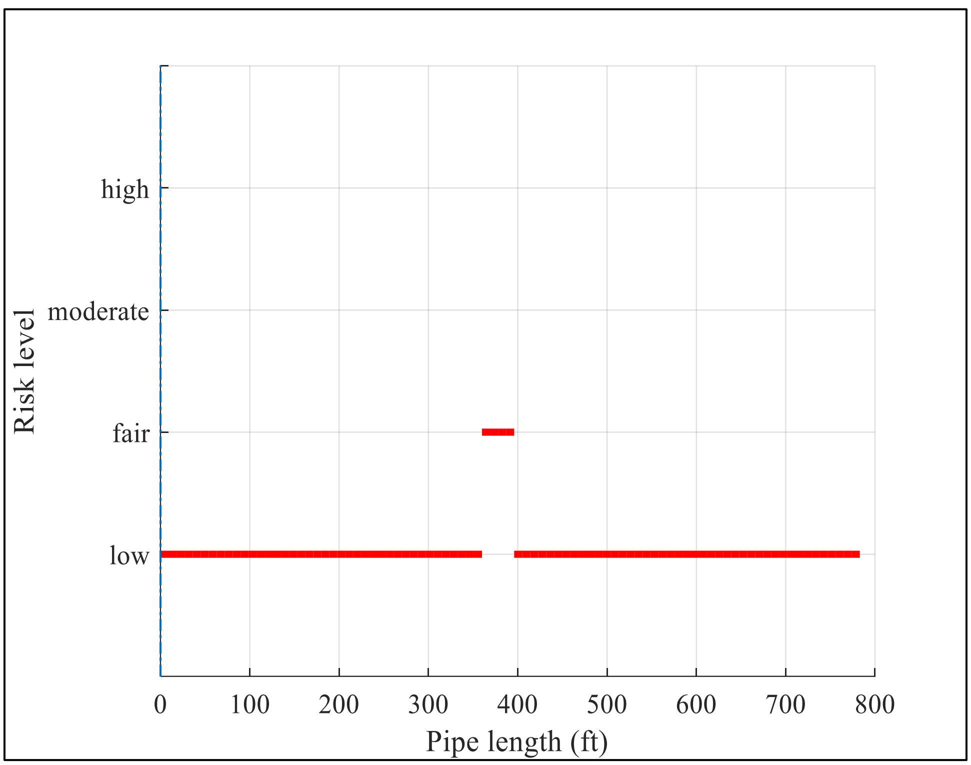


Figure 81: Risk level for pipe's segments along the total length.

A5.17 E13SL0099 Line

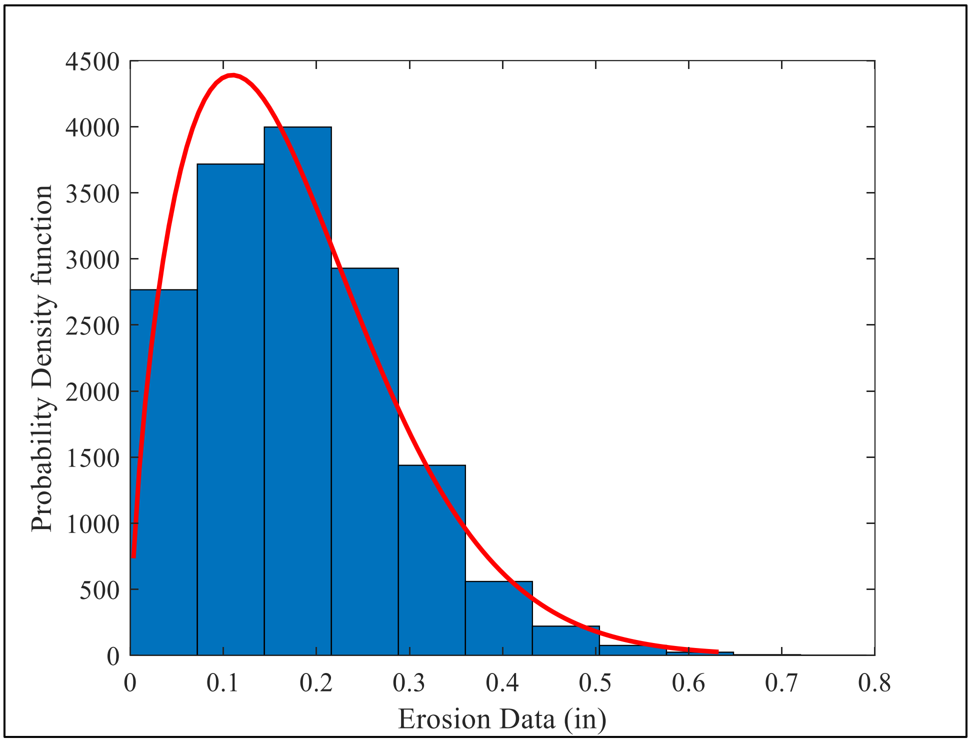


Figure 82: Probability density function of erosion data along the entire line.

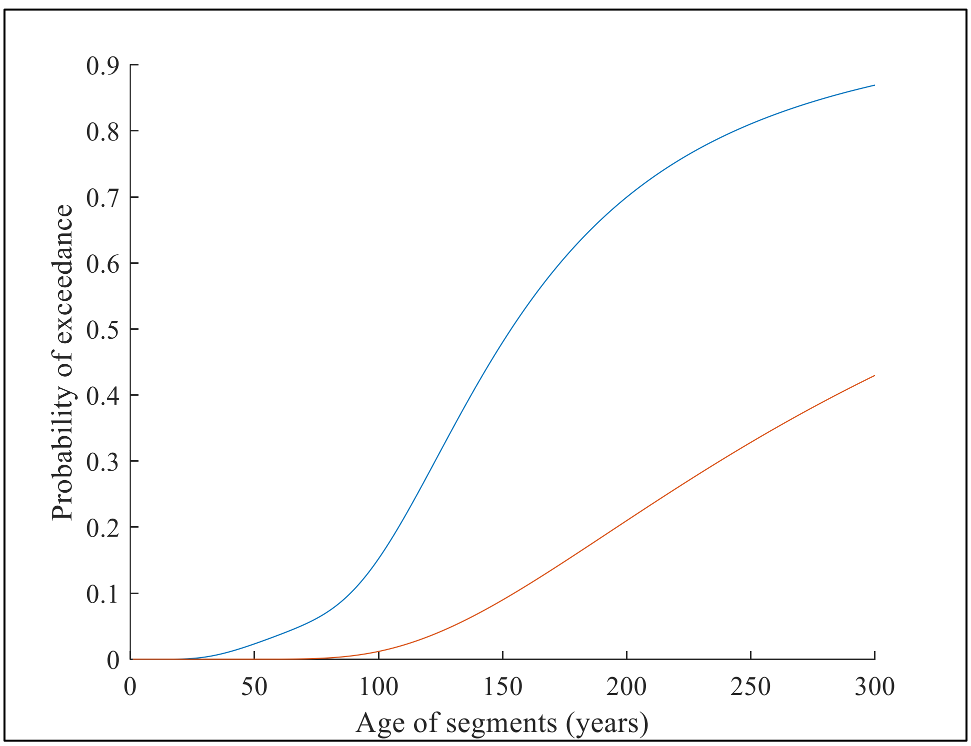


Figure 83: Cumulative distribution function (CDF) of segments' age.

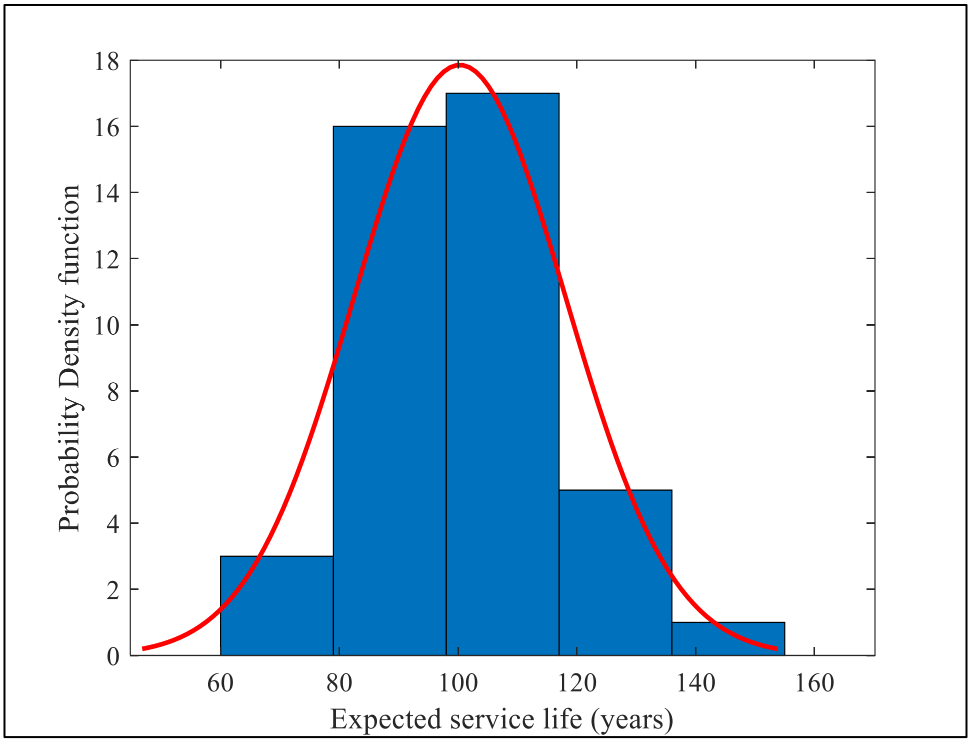


Figure 84: Normal distribution of pipe’s segments expected service life.

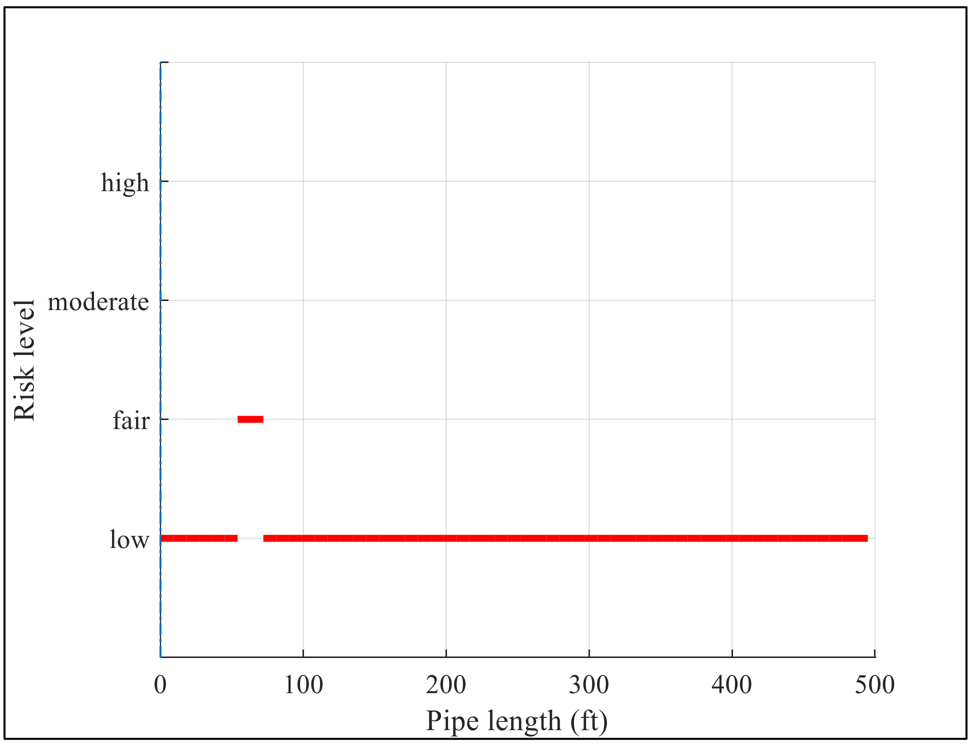


Figure 85: Risk level for pipe’s segments along the total length.

A5.18 E13SL0103 Line

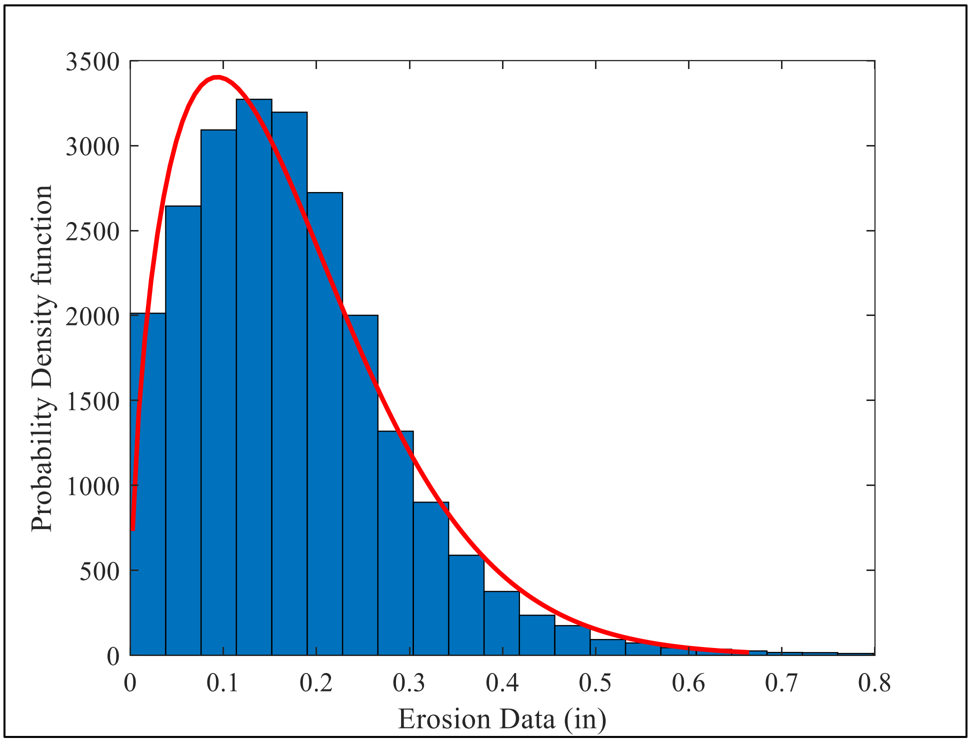


Figure 86: Probability density function of erosion data along the entire line.

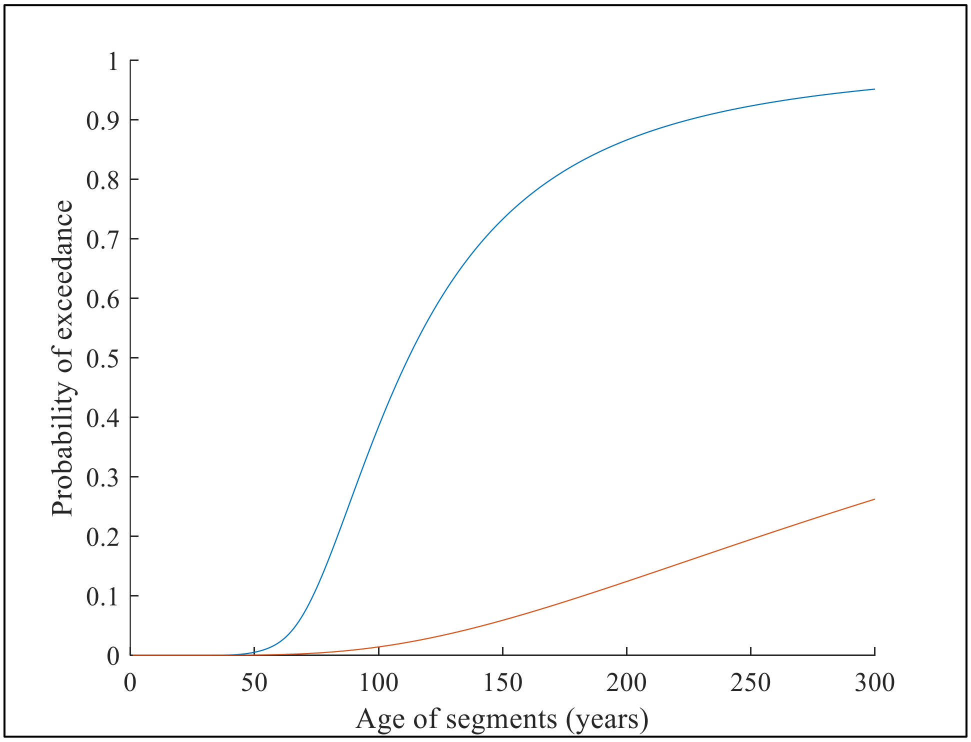


Figure 87: Cumulative distribution function (CDF) of segments' age.

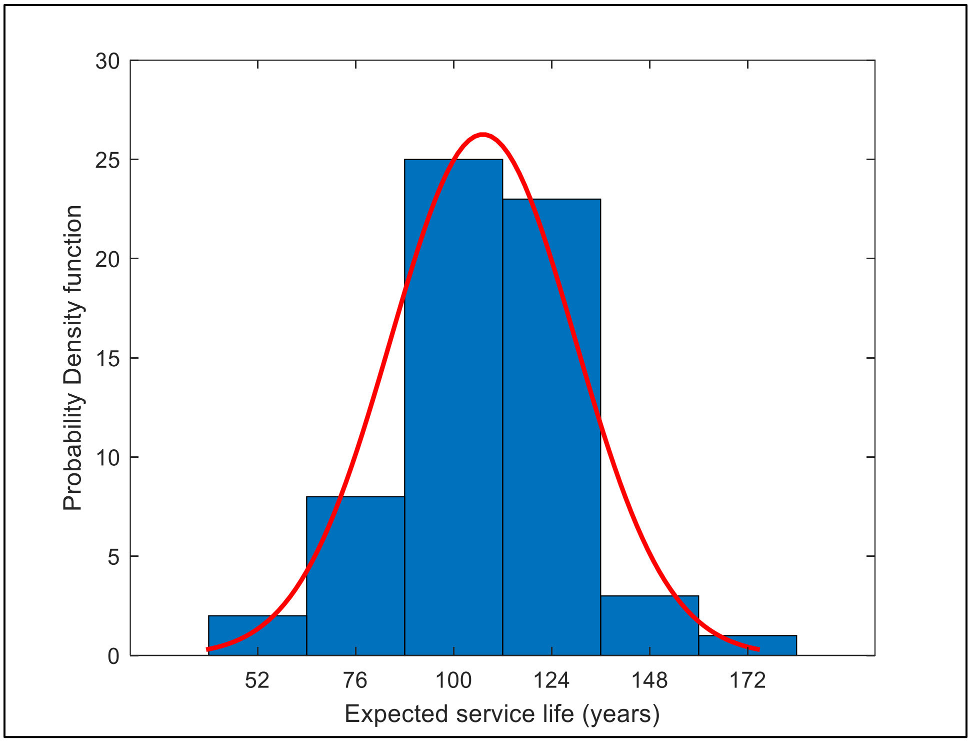


Figure 88: Normal distribution of pipe's segments expected service life.

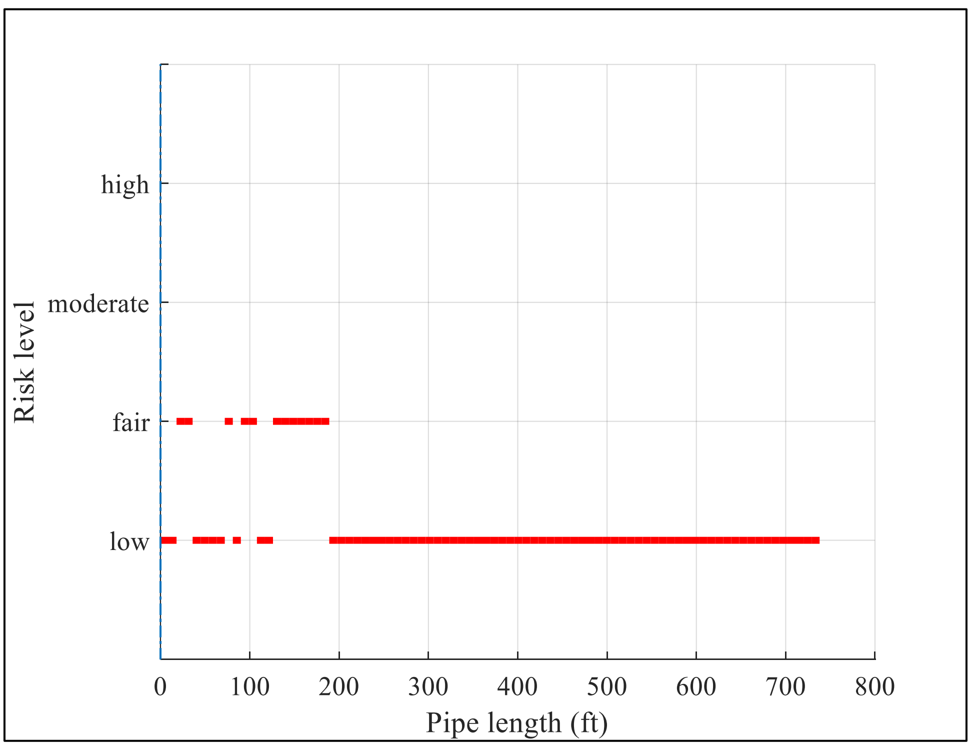


Figure 89: Risk level for pipe's segments along the total length.

A5.19 E13SL0104 Line

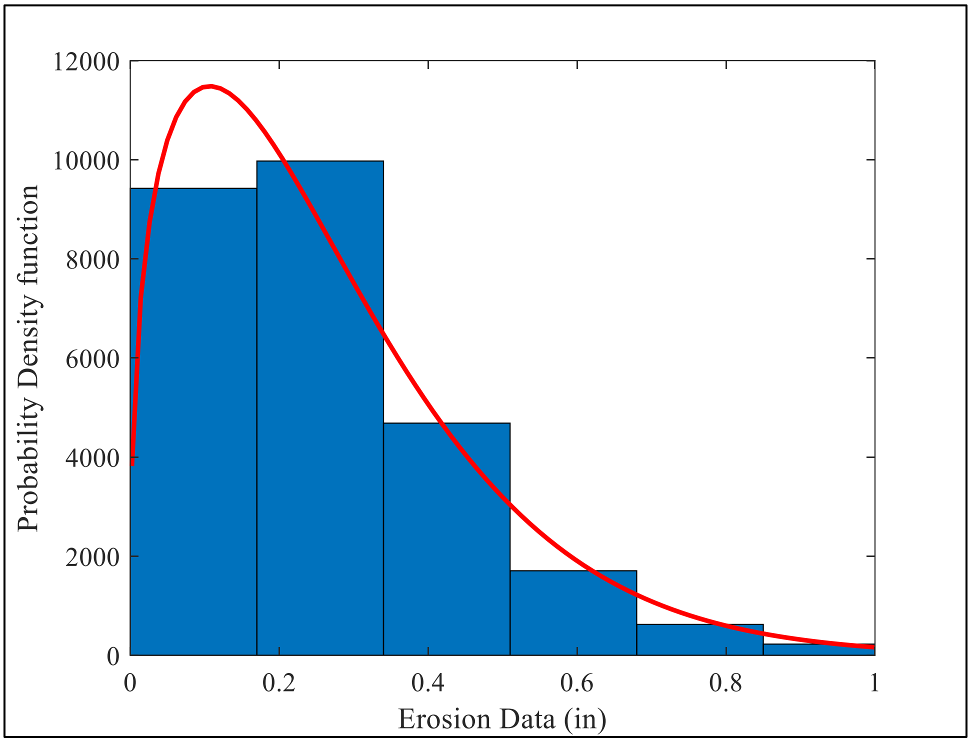


Figure 90: Probability density function of erosion data along the entire line.

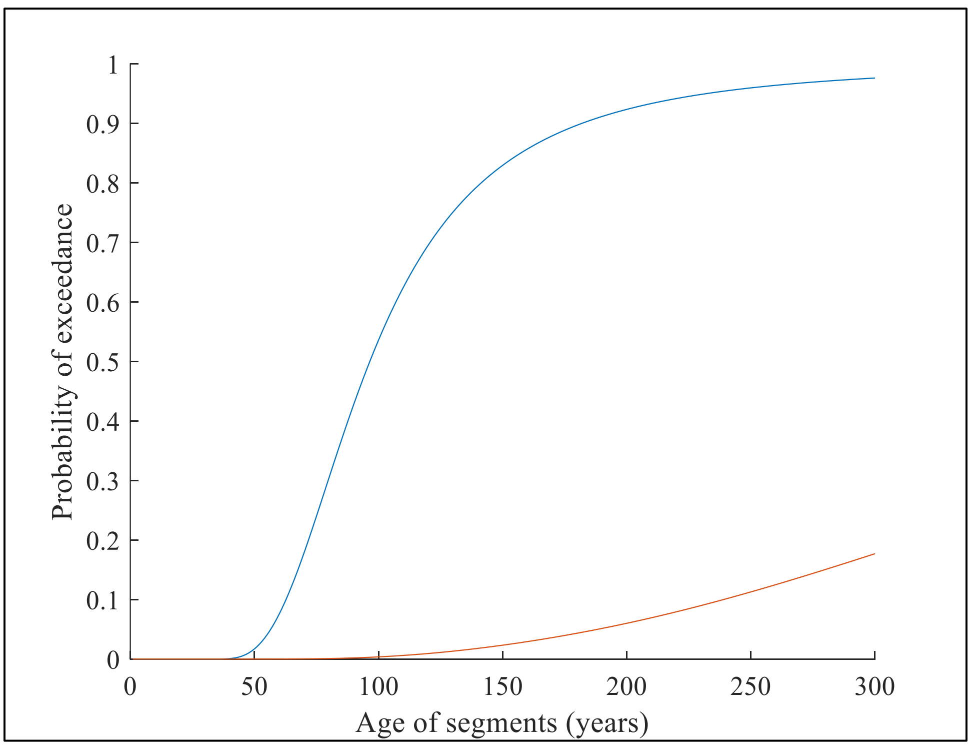


Figure 91: Cumulative distribution function (CDF) of segments' age.

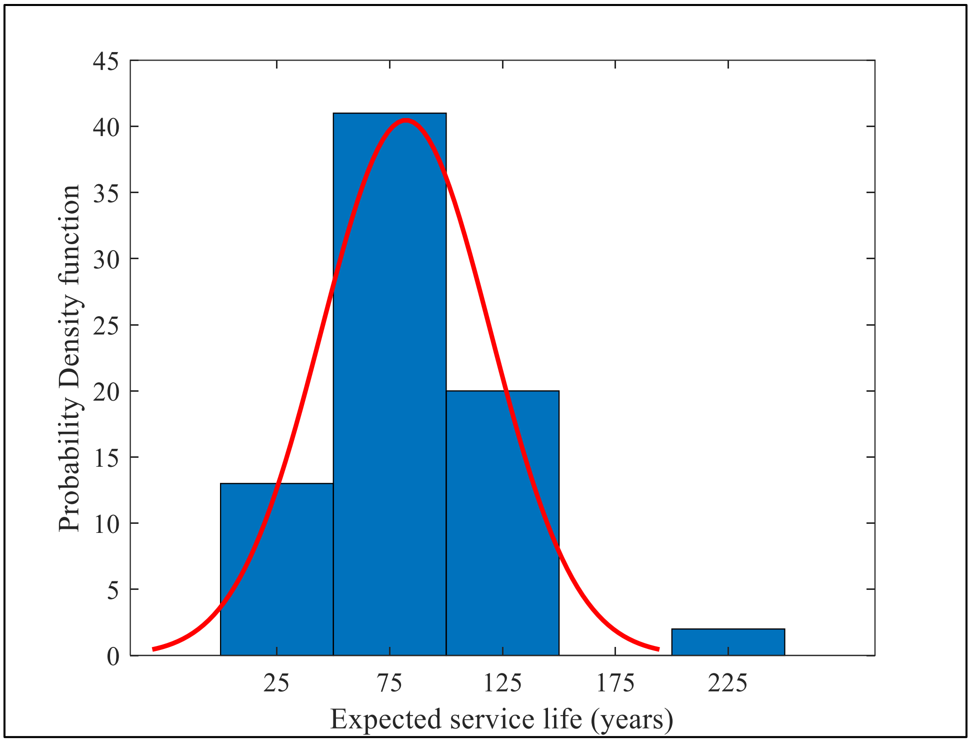


Figure 92: Normal distribution of pipe's segments expected service life.

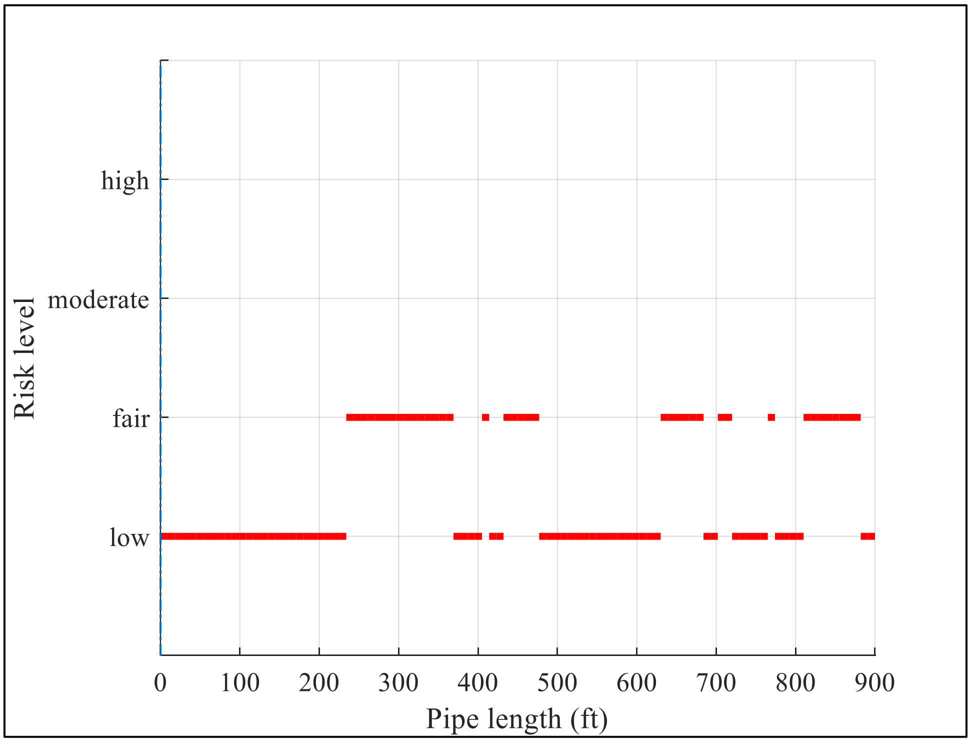


Figure 93: Risk level for pipe's segments along the total length.

A5.20 E13SL0203 Line

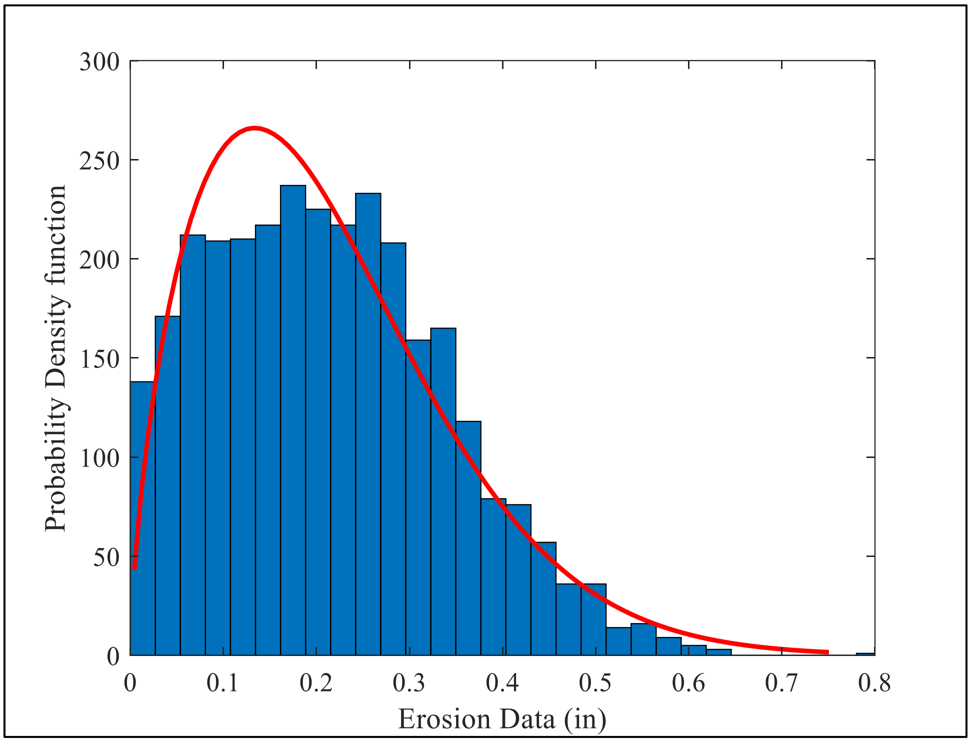


Figure 94: Probability density function of erosion data along the entire line.

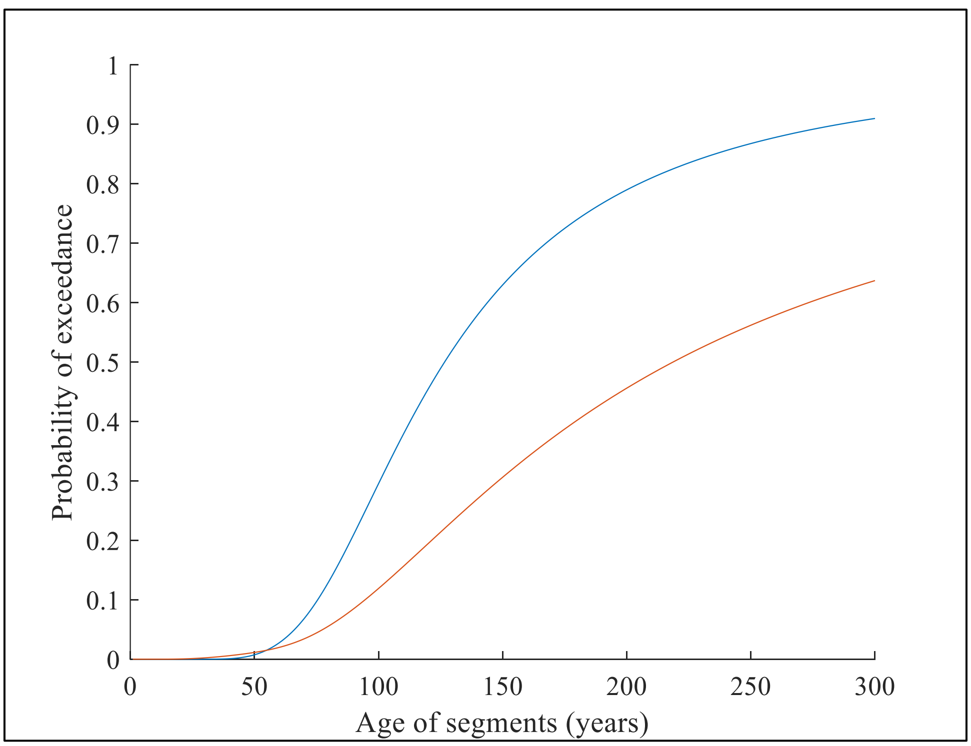


Figure 95 Cumulative distribution function (CDF) of segments' age.

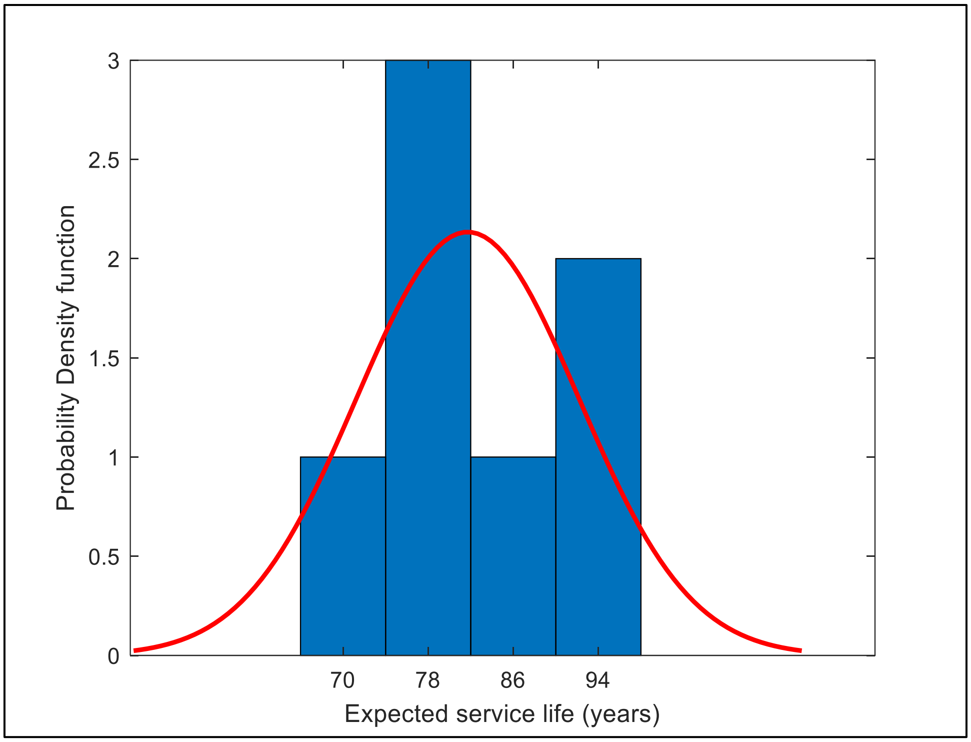


Figure 96: Normal Distribution of Pipe's Segments Expected Service Life.

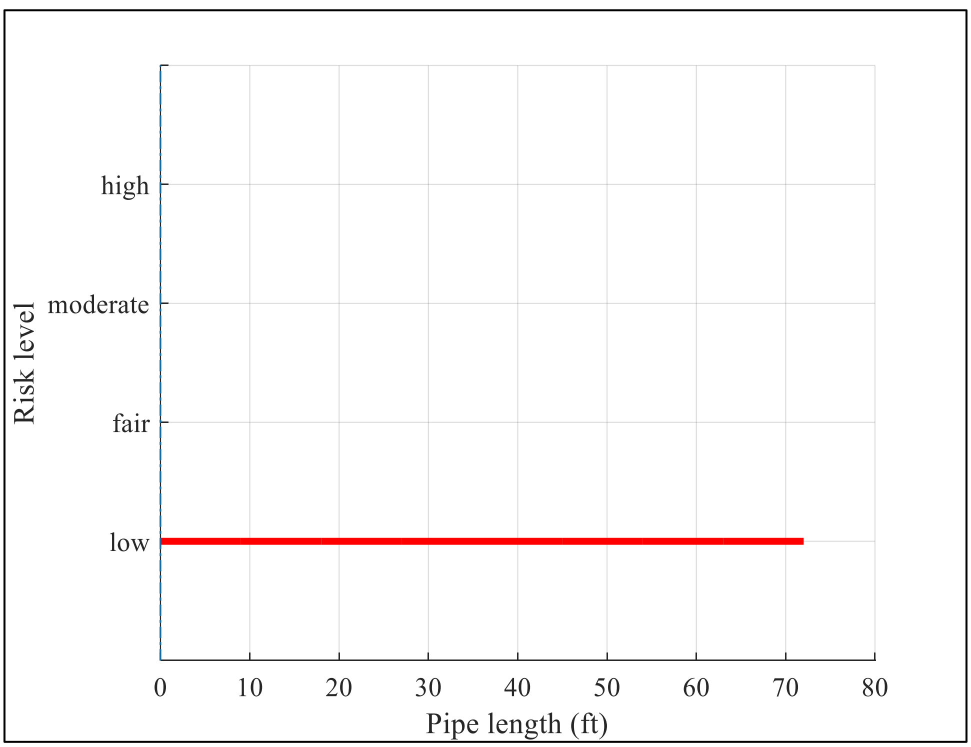


Figure 97: Risk level for pipe's segments along the total length.

A5.21 E12SL0294 Line

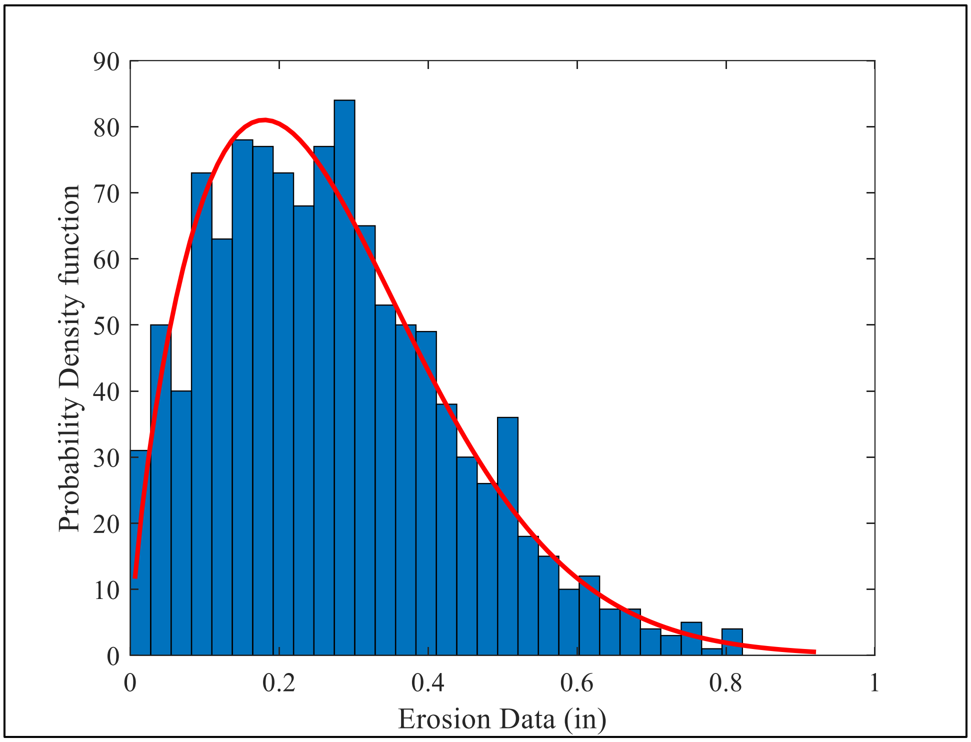


Figure 98: Probability density function of erosion data along the entire line.

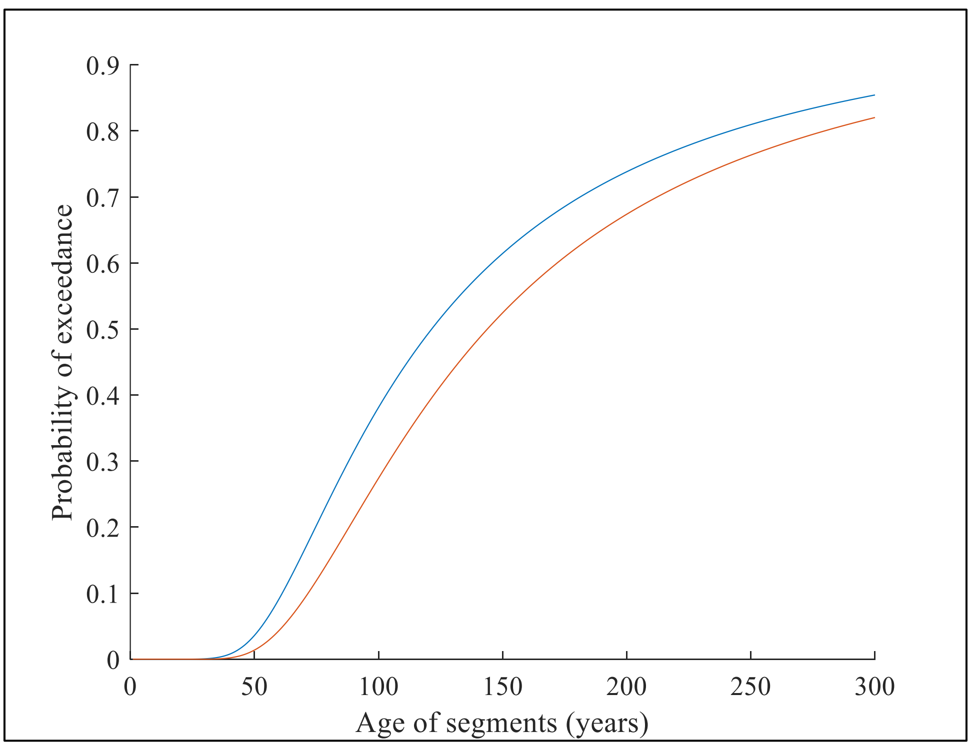


Figure 99: Cumulative distribution function (CDF) of segments' age.

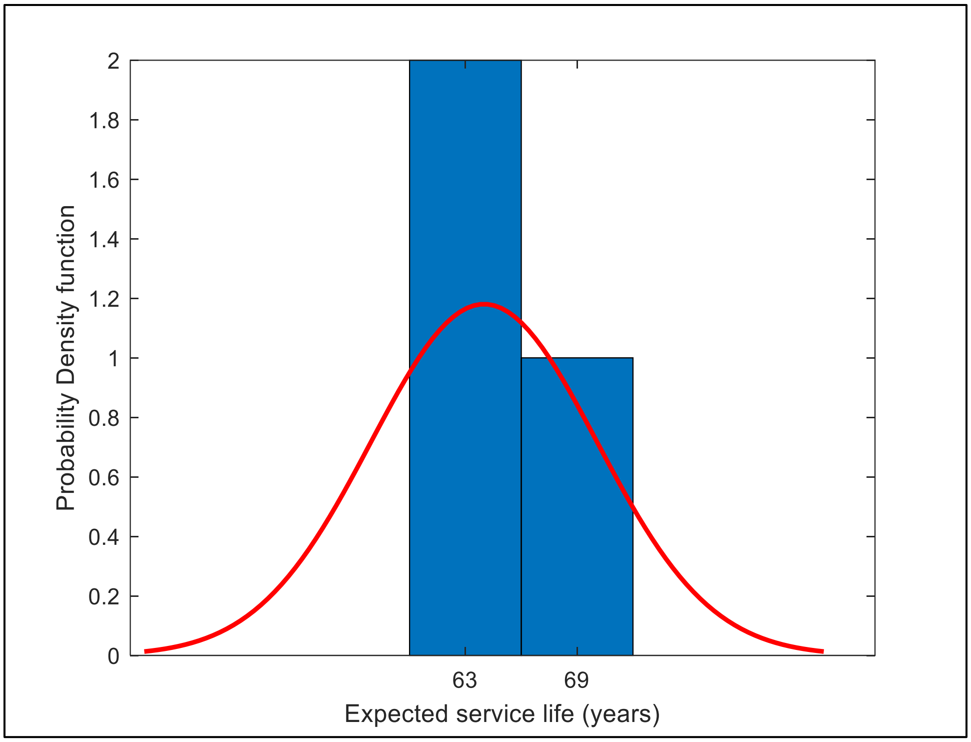


Figure 100: Normal distribution of pipe's segments expected service life.

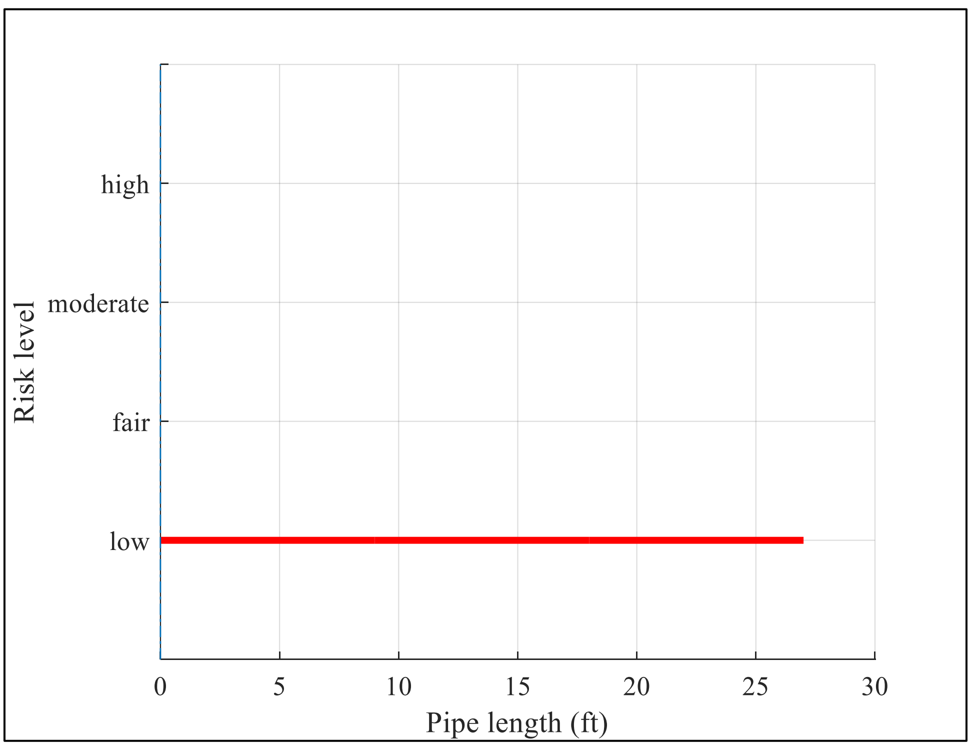


Figure 101: Risk level for pipe's segments along the total length.

A5.22 D09SL0162 Line

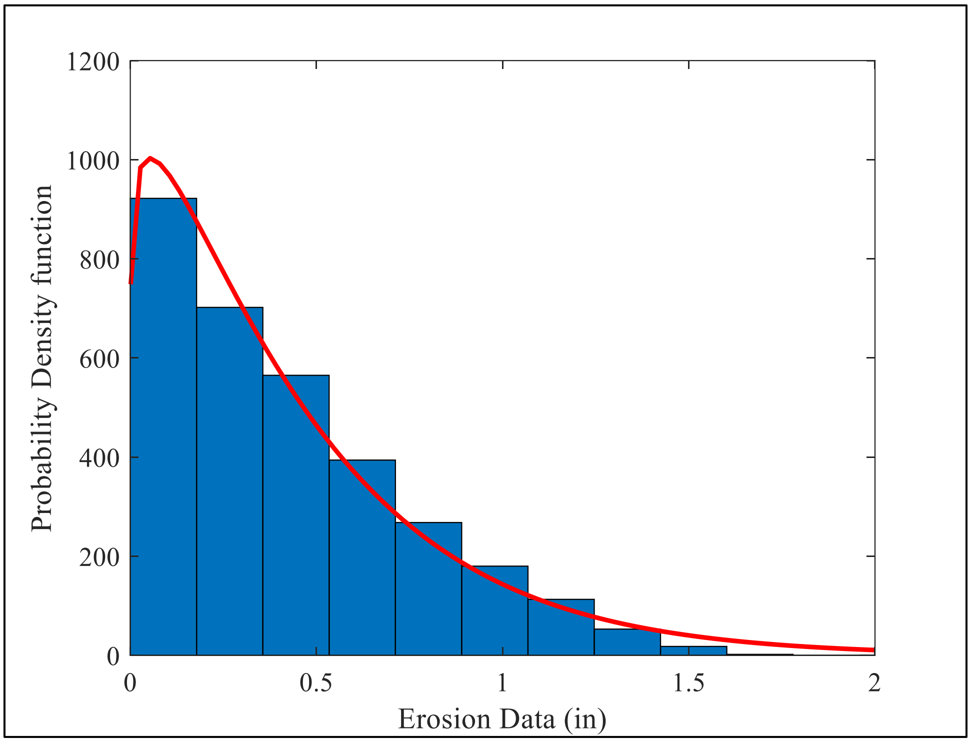


Figure 102: Probability density function of erosion data along the entire line.

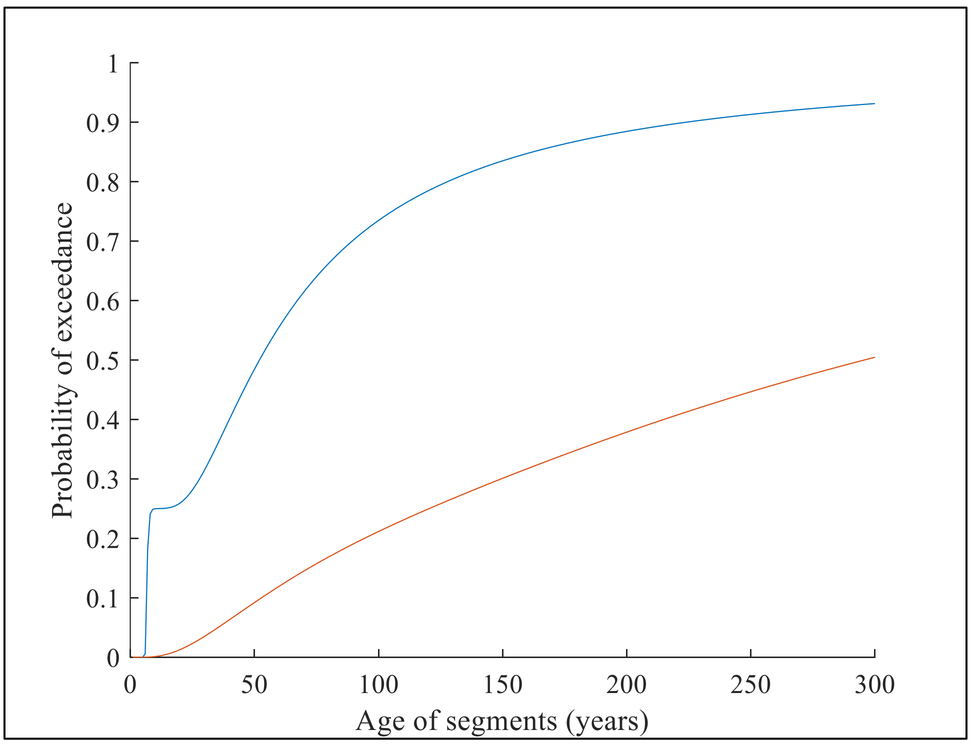


Figure 103: Cumulative distribution function (CDF) of segments' age.

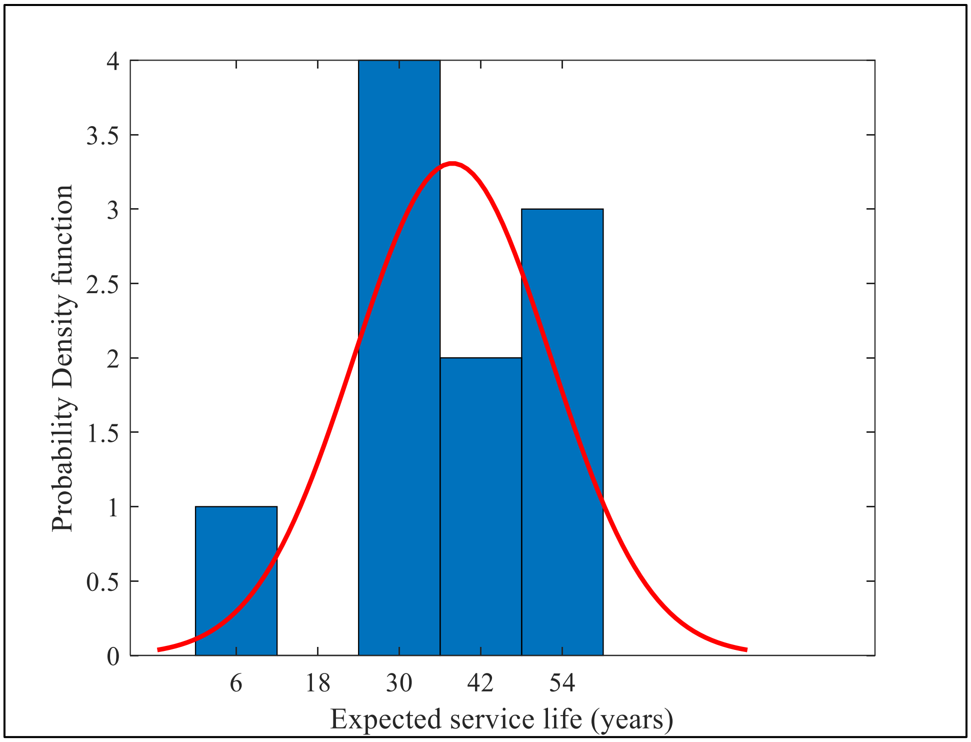


Figure 104: Normal distribution of pipe’s segments expected service life.

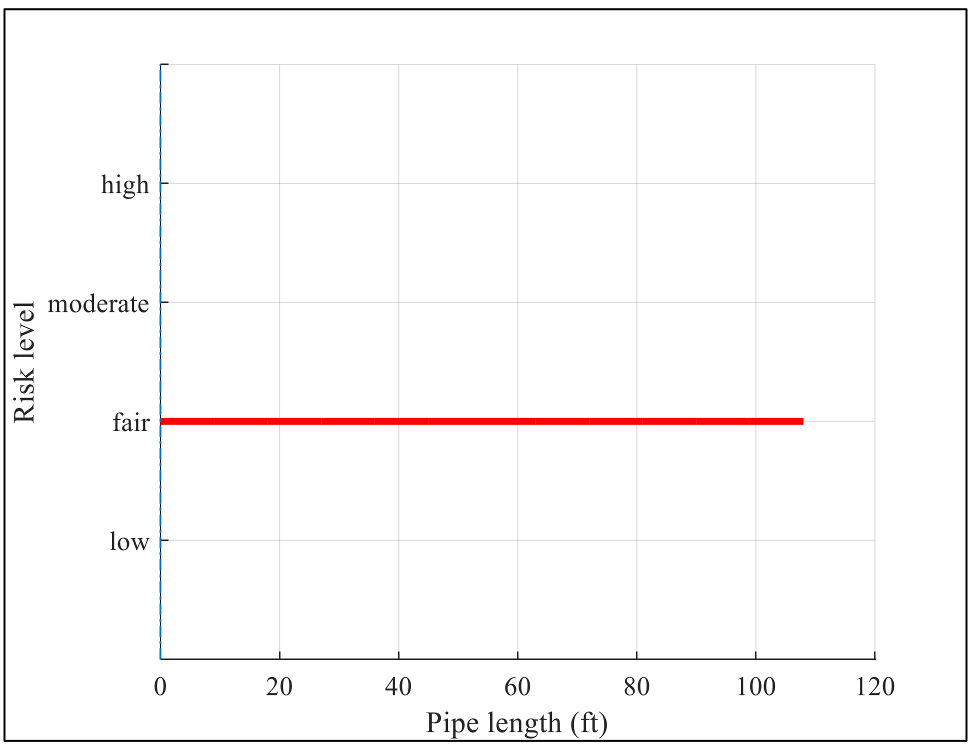


Figure 105: Risk level for pipe’s segments along the total length.

A5.23 D10SL0142 Line

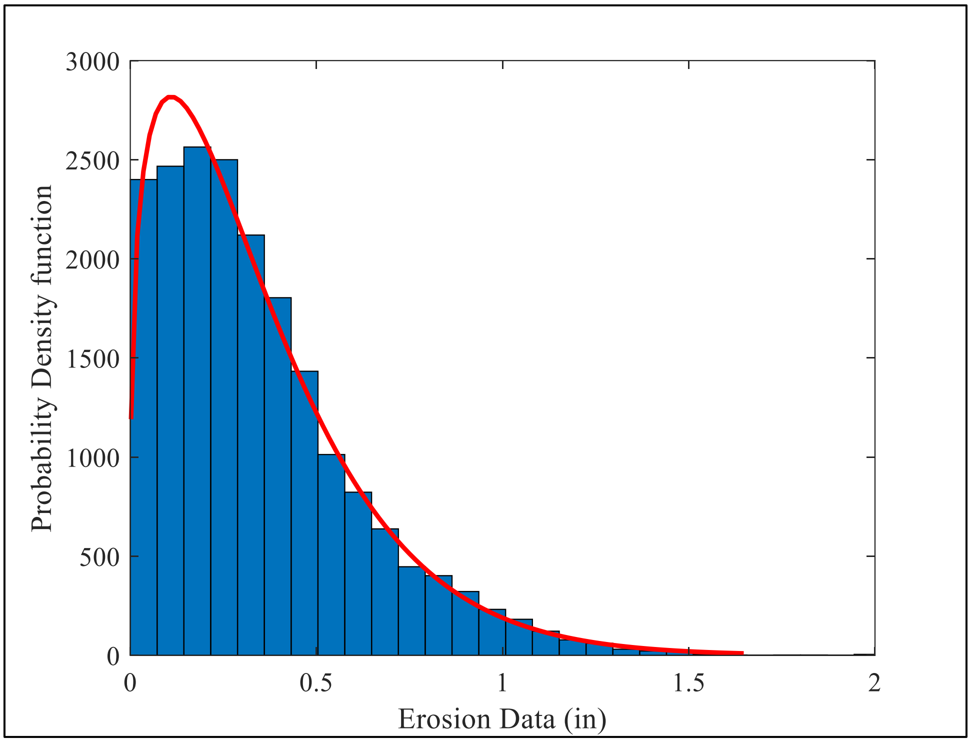


Figure 106: Probability density function of erosion data along the entire line.

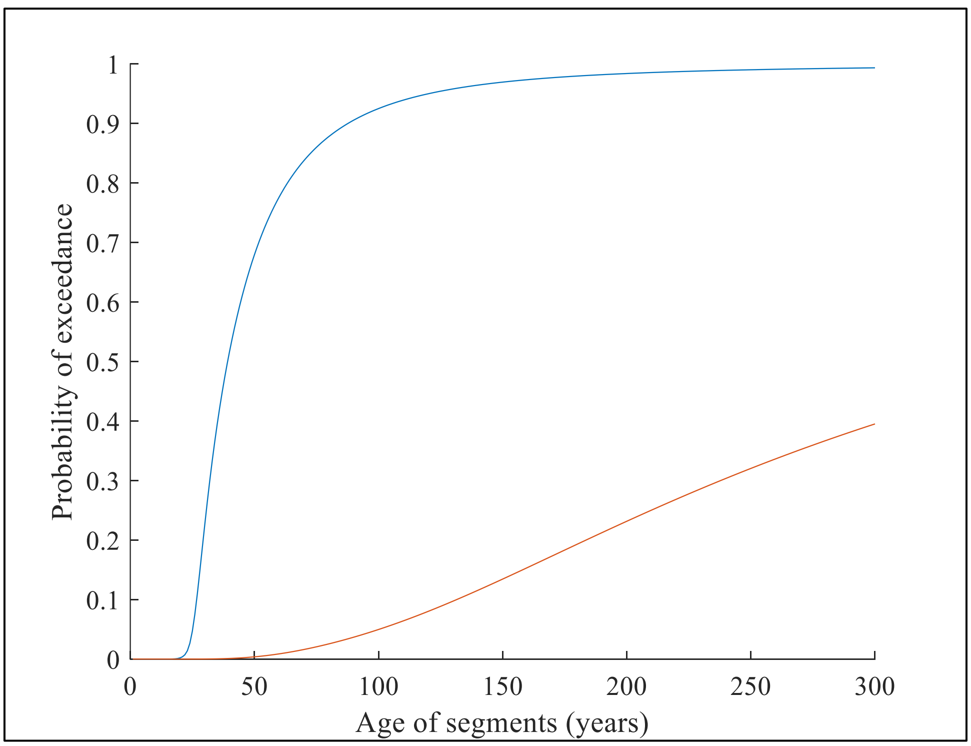


Figure 107: Cumulative distribution function (CDF) of segments' age.

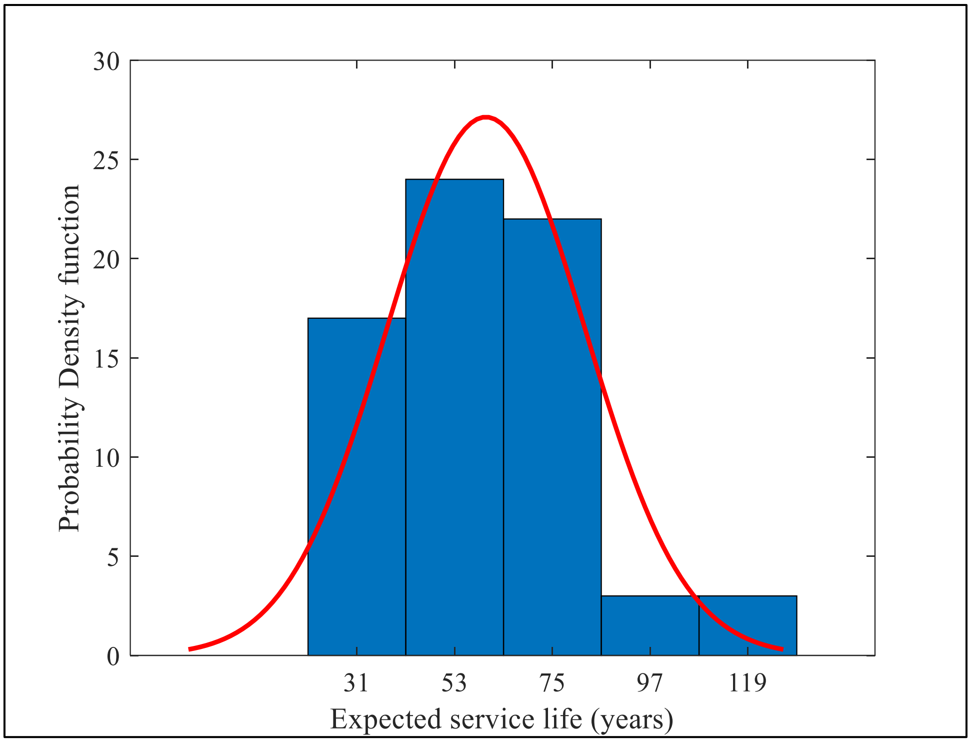


Figure 108: Normal distribution of pipe's segments expected service life.

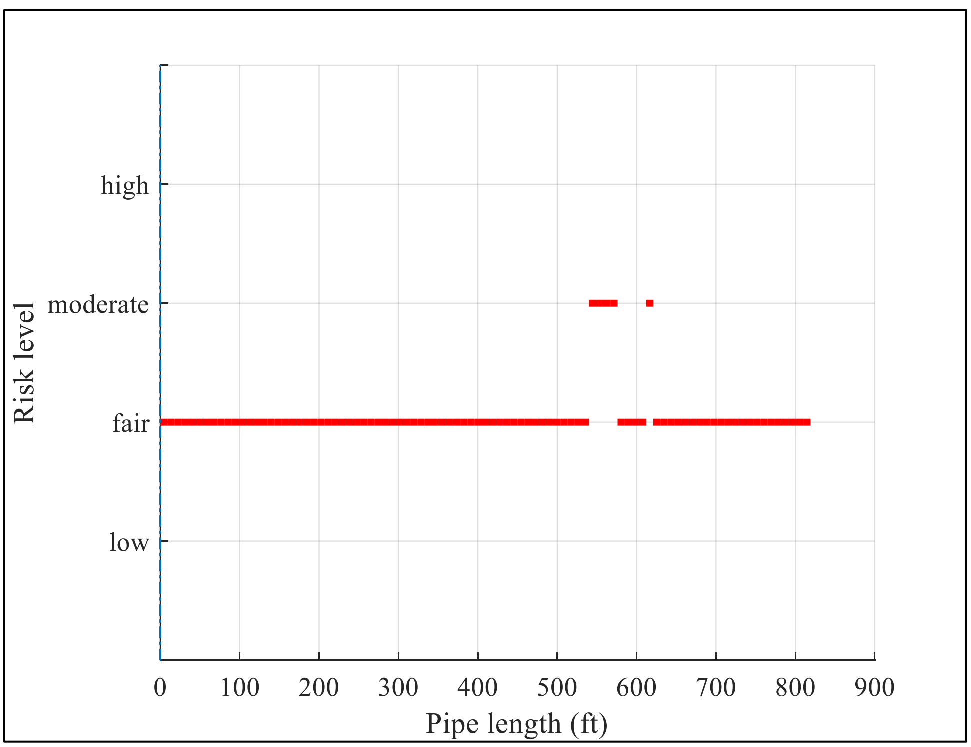


Figure 109: Risk Level for Pipe's Segments Along the Total Length.

A5.24 D10SL0120 Line

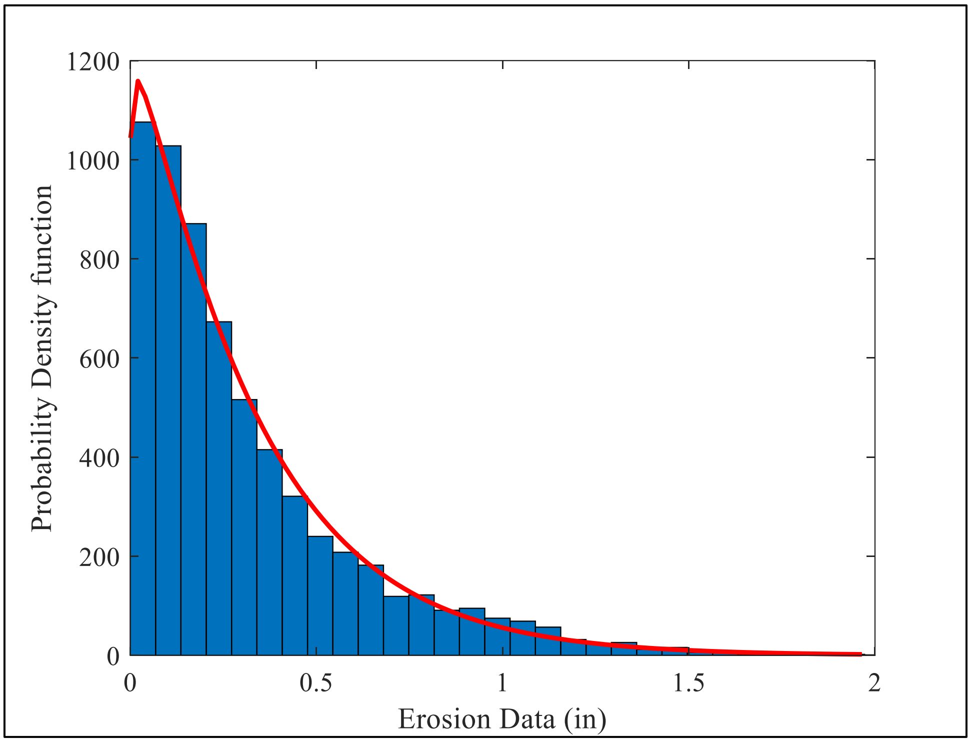


Figure 110: Probability density function of erosion data along the entire line.

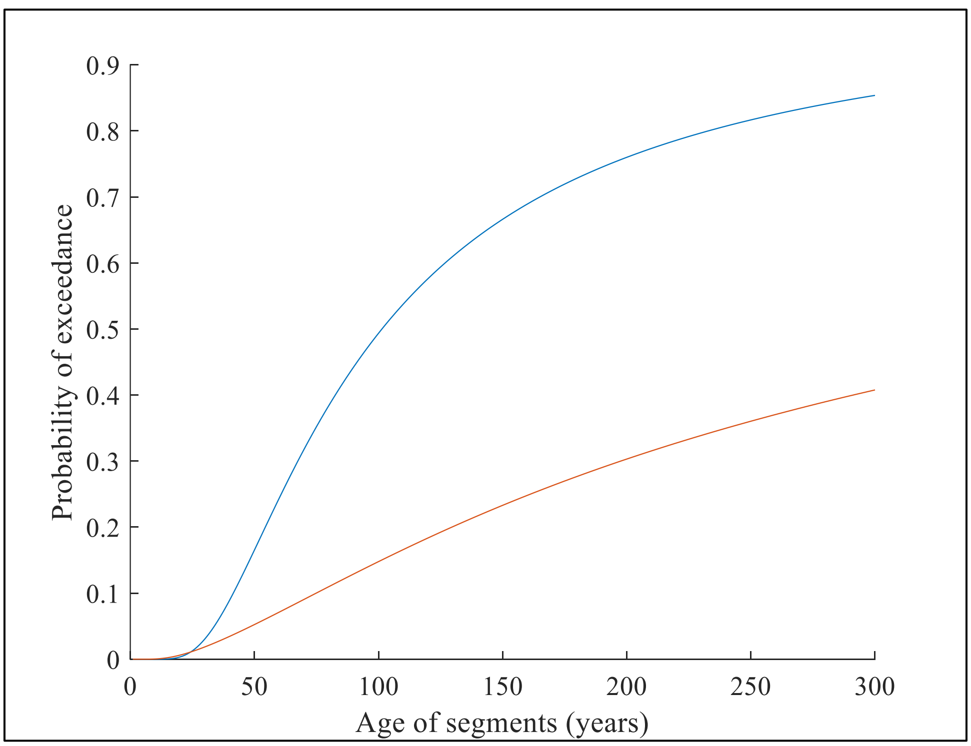


Figure 111: Cumulative distribution function (CDF) of segments' age.

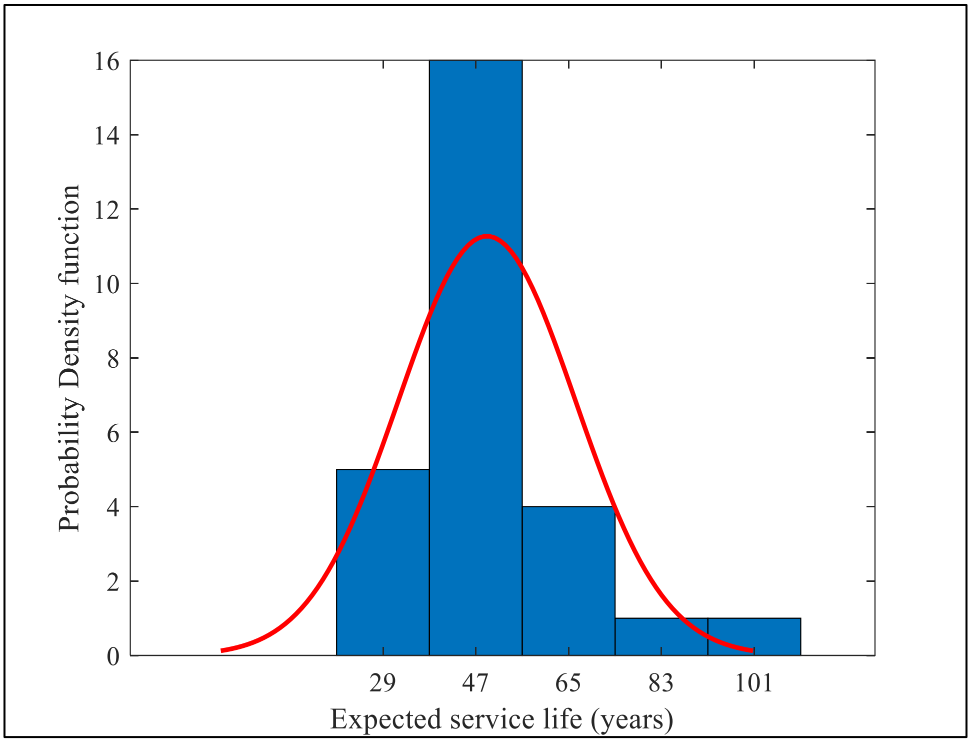


Figure 112: Normal distribution of pipe's segments expected service life.

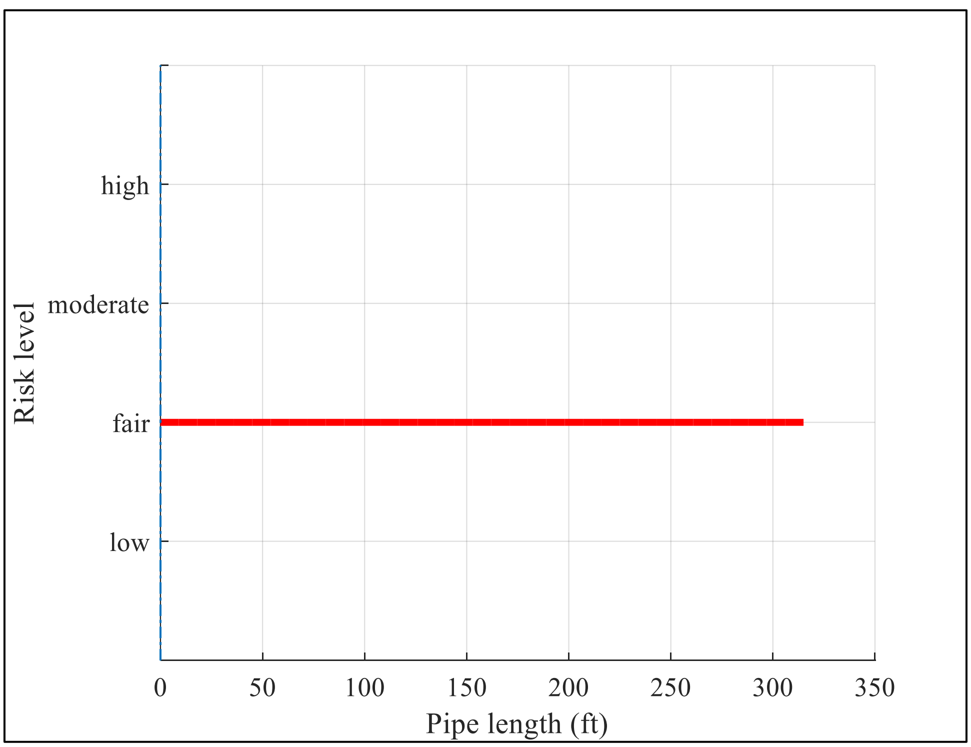


Figure 113: Risk level for pipe's segments along the total length.

A5.25 D09SL0052-D09SL0051 Line

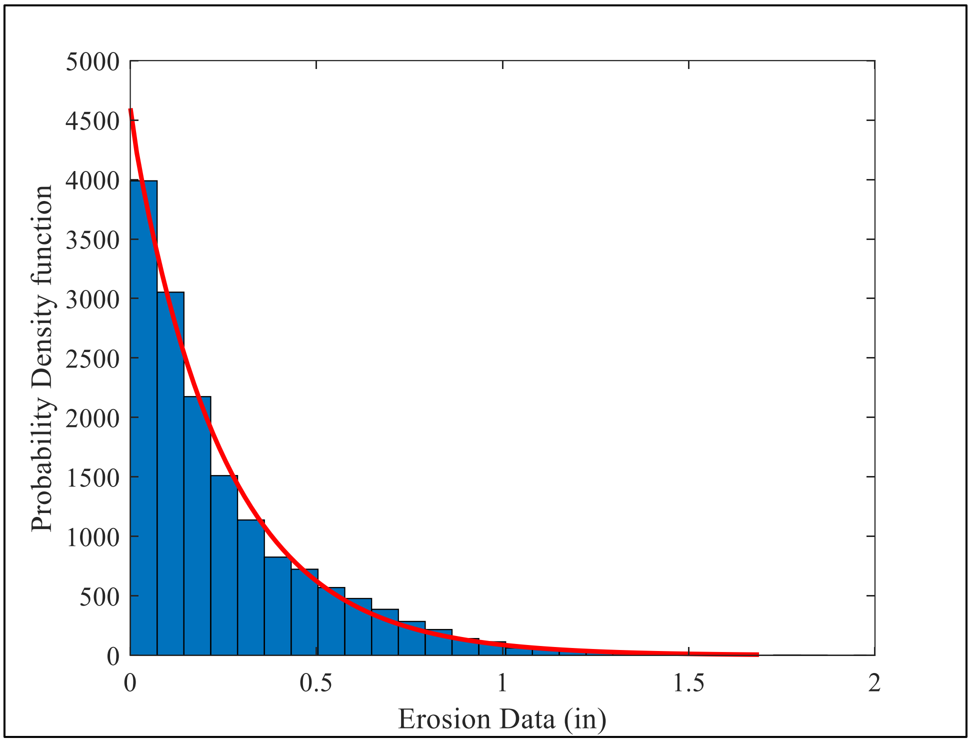


Figure 114: Probability density function of erosion data along the entire line.

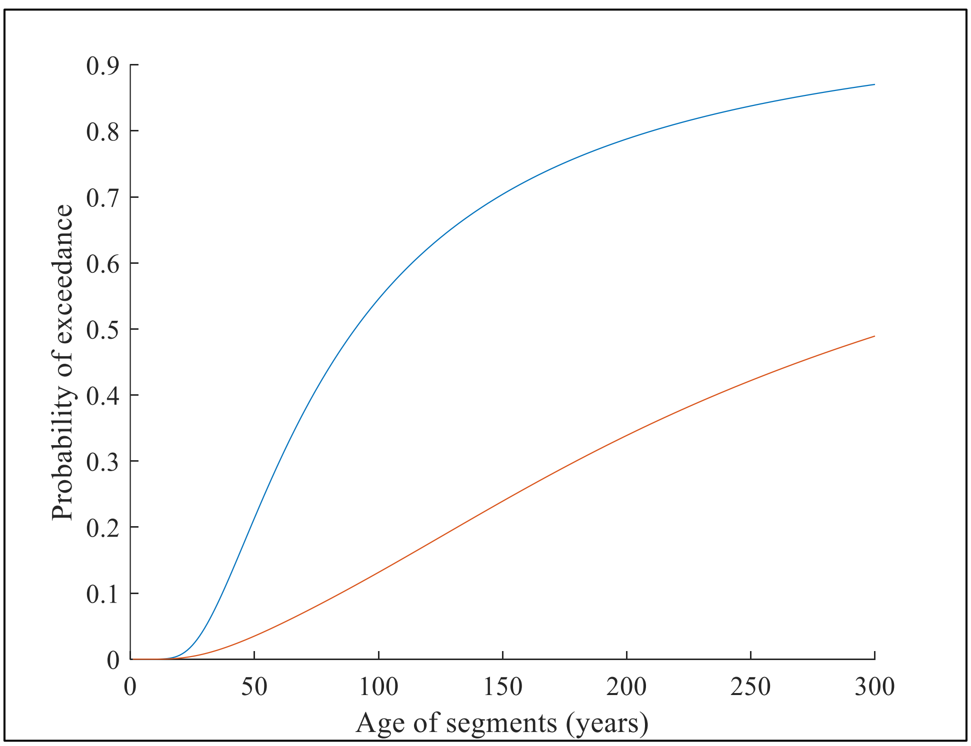


Figure 115: Cumulative distribution function (CDF) of segments' age.

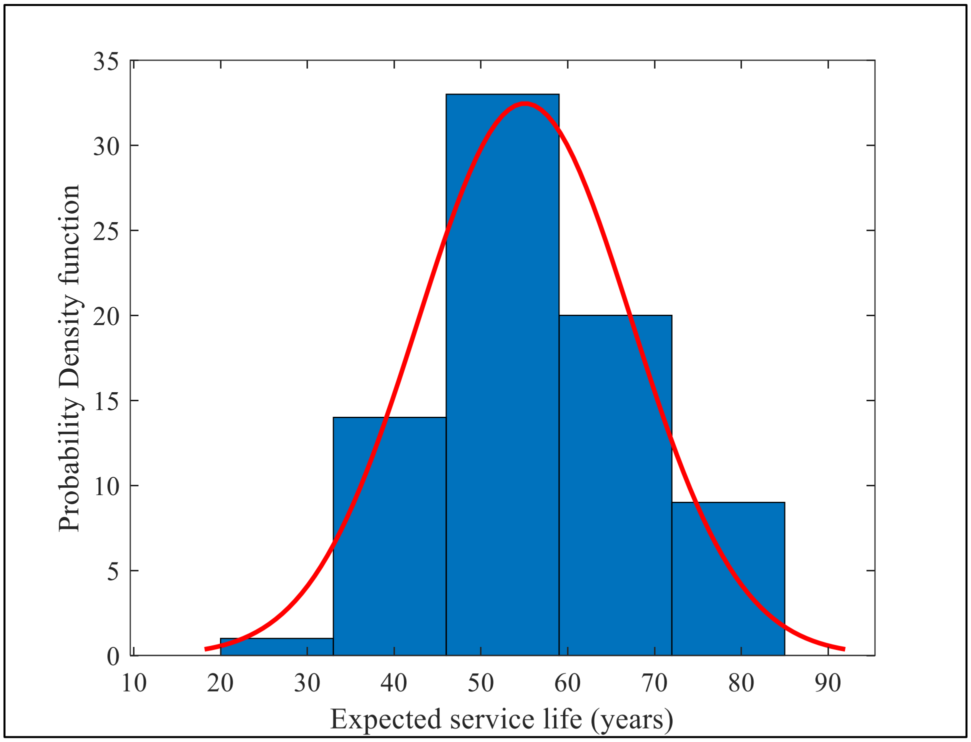


Figure 116: Normal distribution of pipe's segments expected service life.

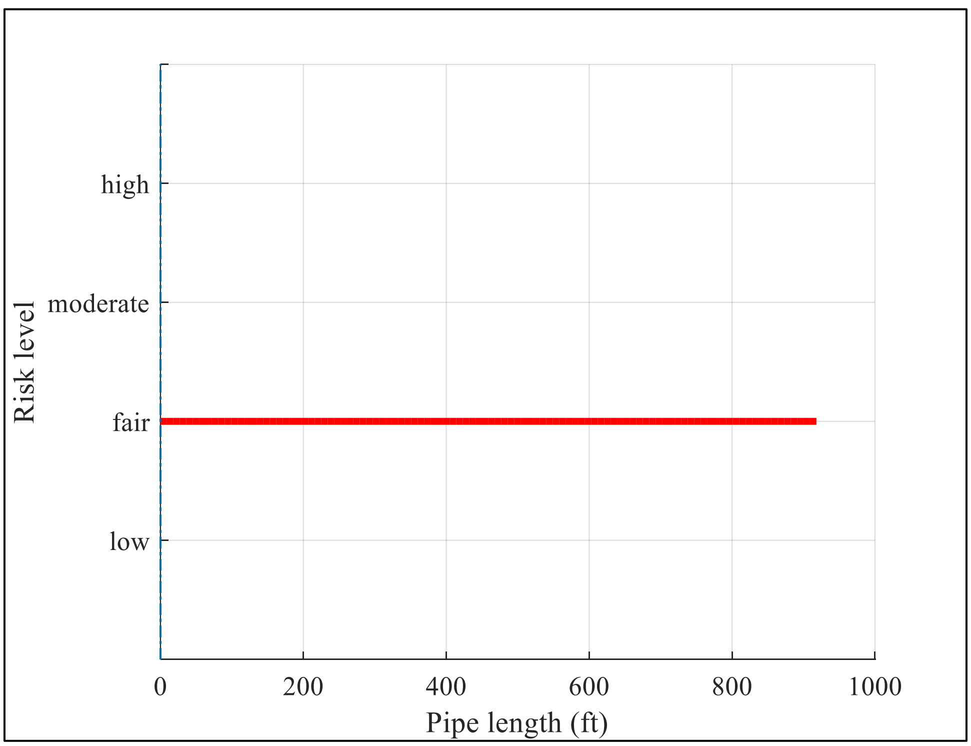


Figure 117: Risk level for pipe's segments along the total length.

A5.26 D09SL0087 Line

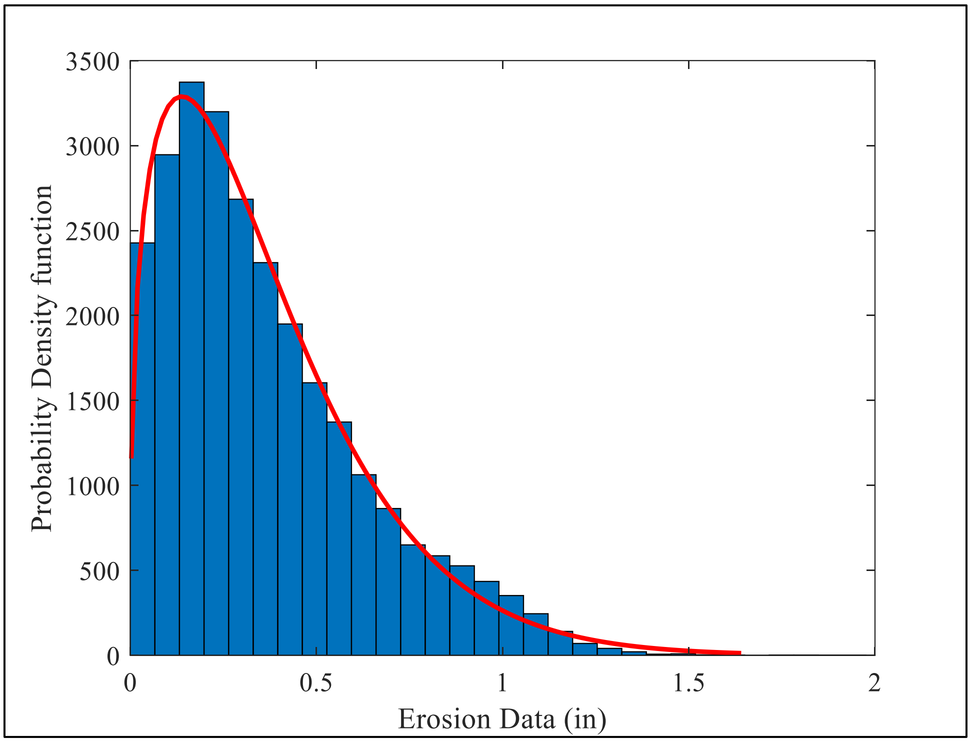


Figure 118: Probability density function of erosion data along the entire line.

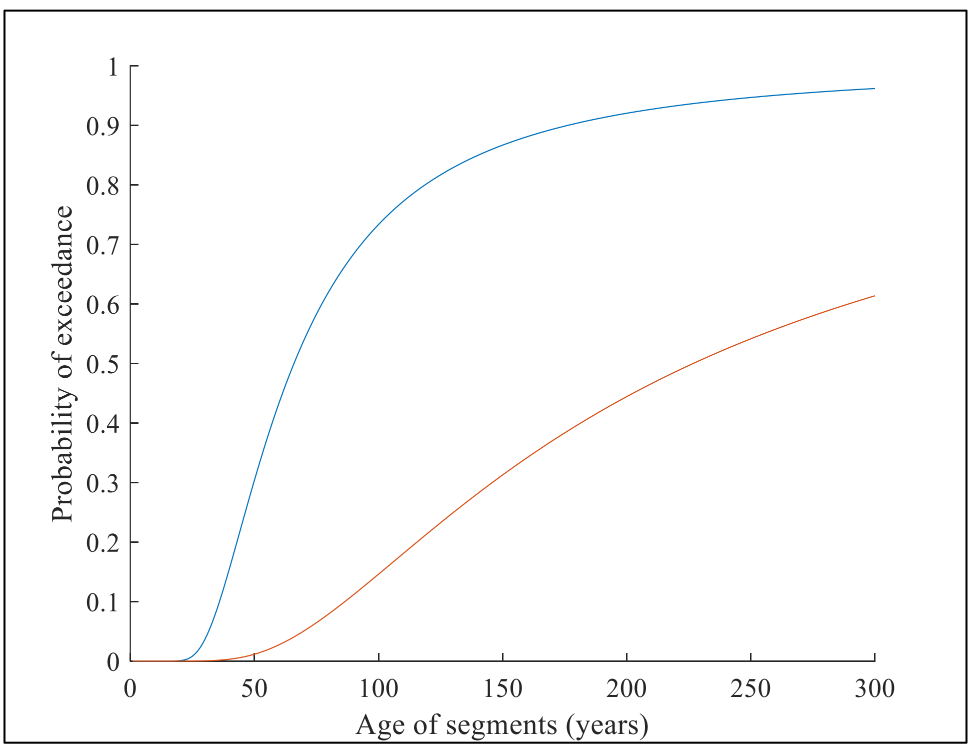


Figure 119: Cumulative distribution function (CDF) of segments' age

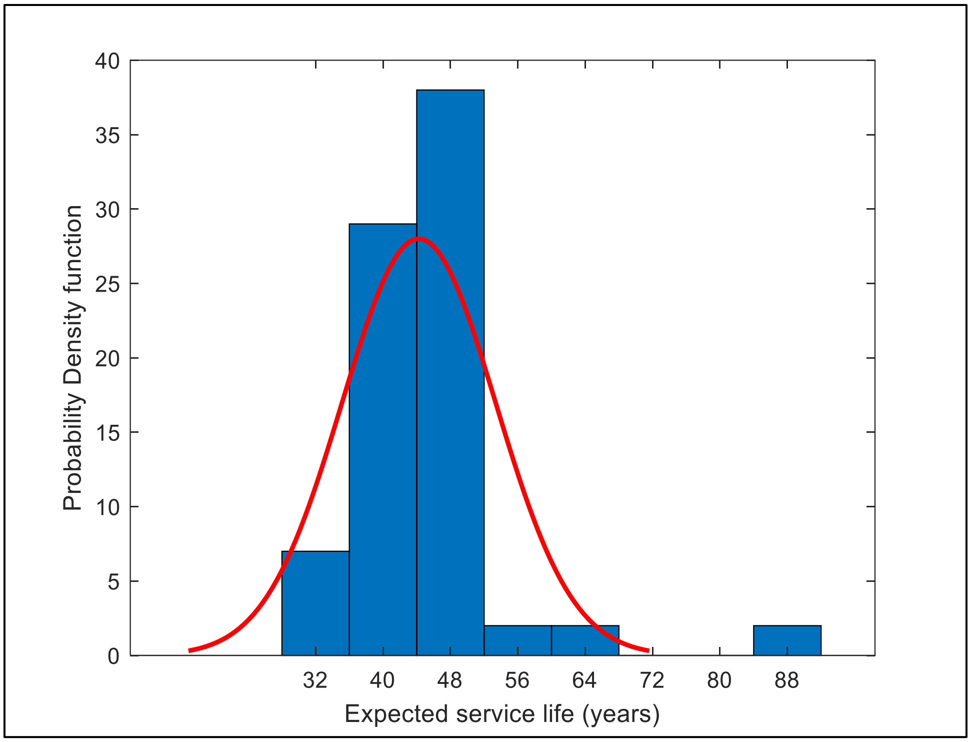


Figure 120: Normal distribution of pipe’s segments expected service life.

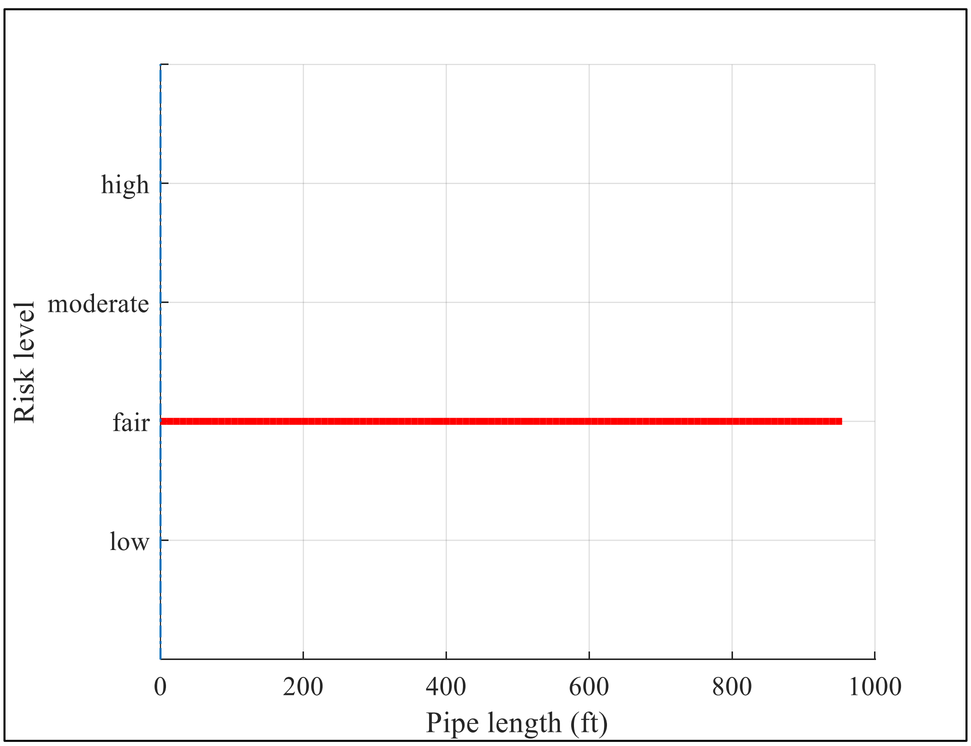


Figure 121: Risk level for pipe’s segments along the total length.

A5.27 D10SL0062 Line

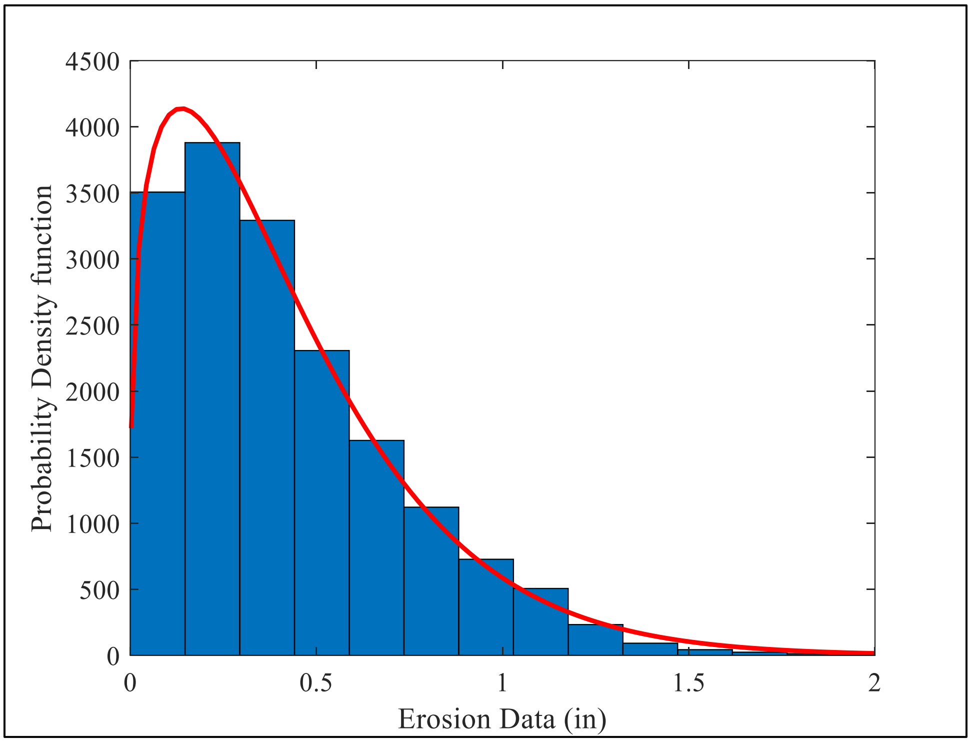


Figure 122: Probability density function of erosion data along the entire line.

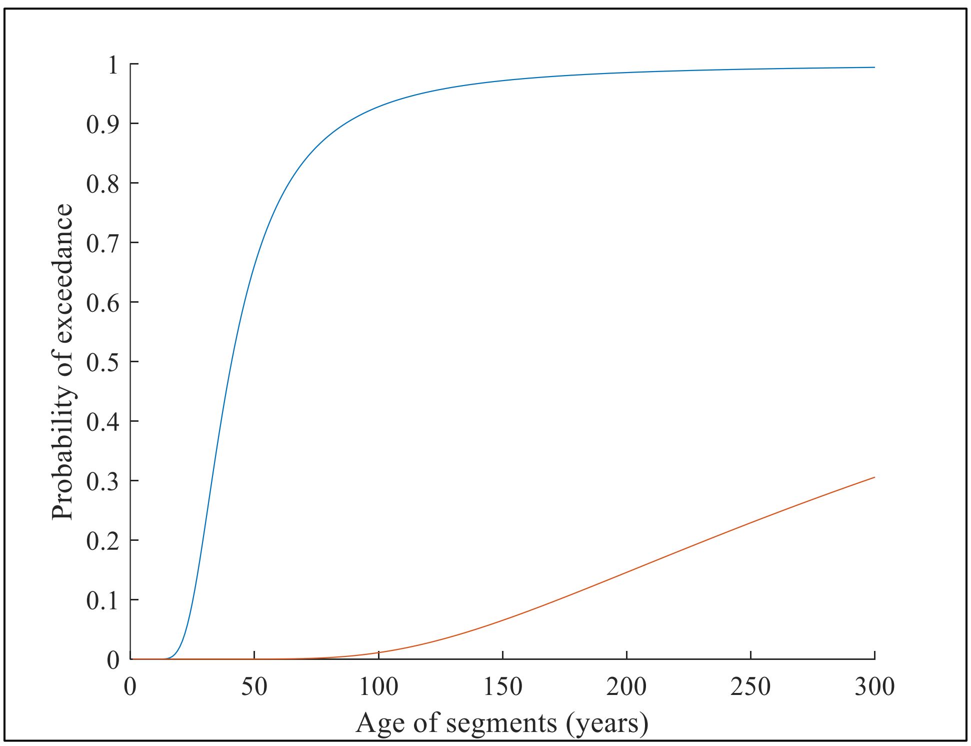


Figure 123: Cumulative distribution function (CDF) of segments’ age

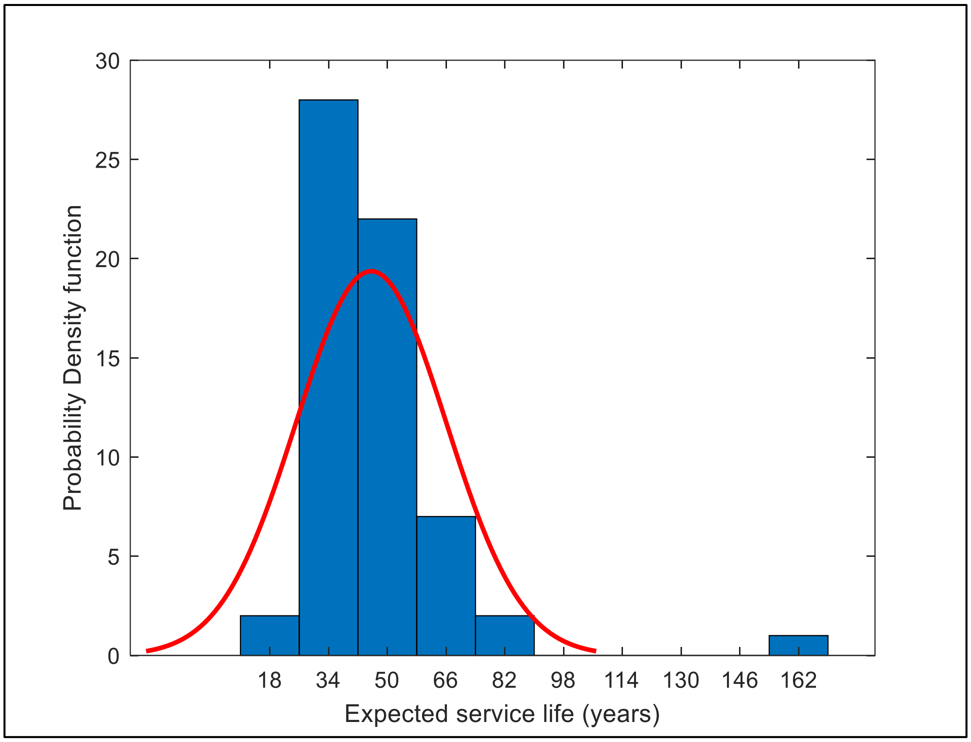


Figure 124: Normal distribution of pipe's segments expected service life.

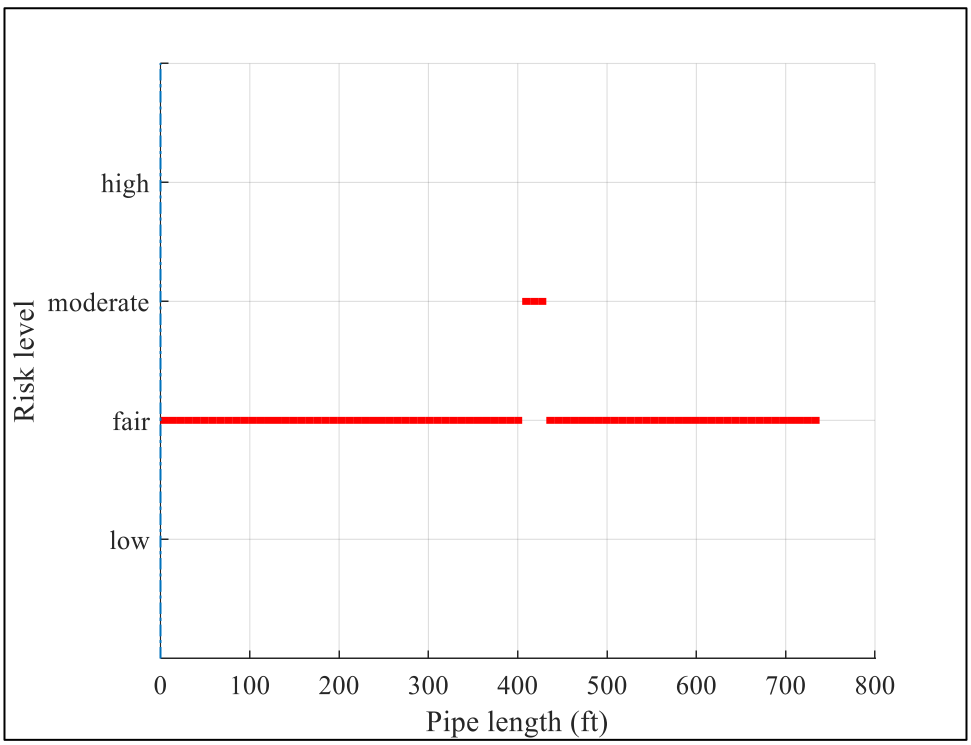


Figure 125: Risk level for pipe's segments along the total length.

A5.28 D10SL0124-D10SL0125 Line

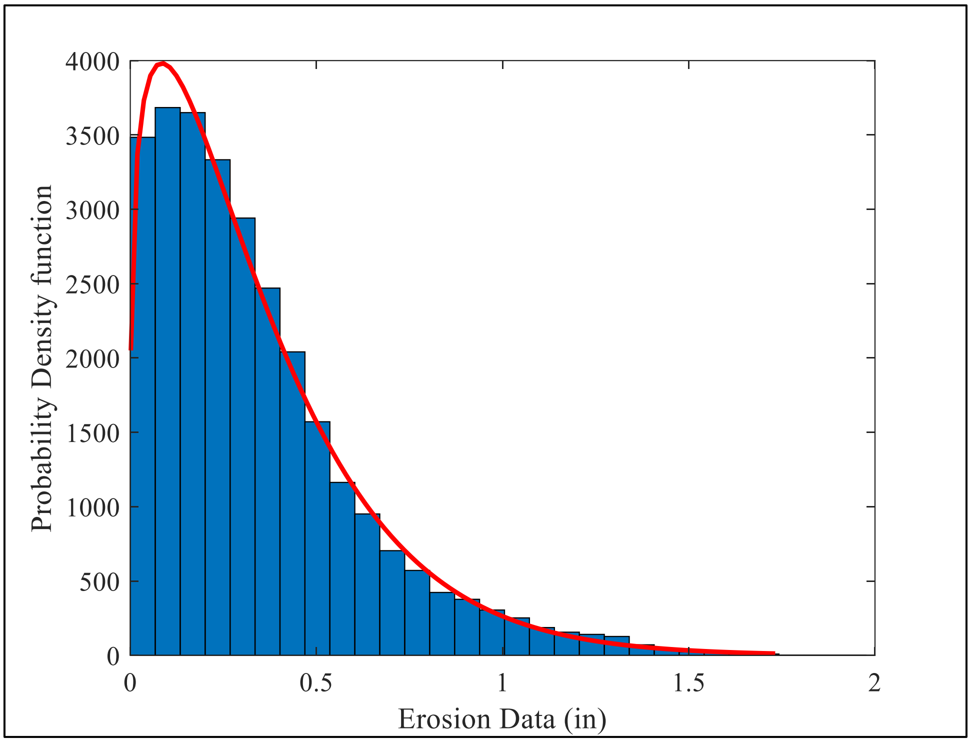


Figure 126: Probability density function of erosion data along the entire line.

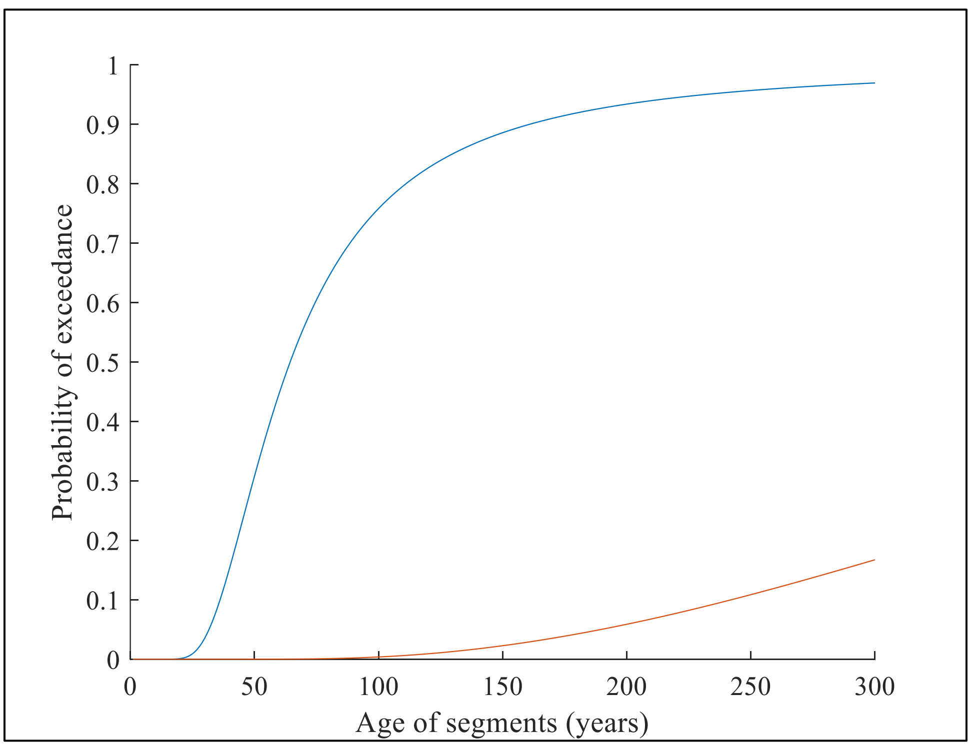


Figure 127: Cumulative distribution function (CDF) of segments' age.

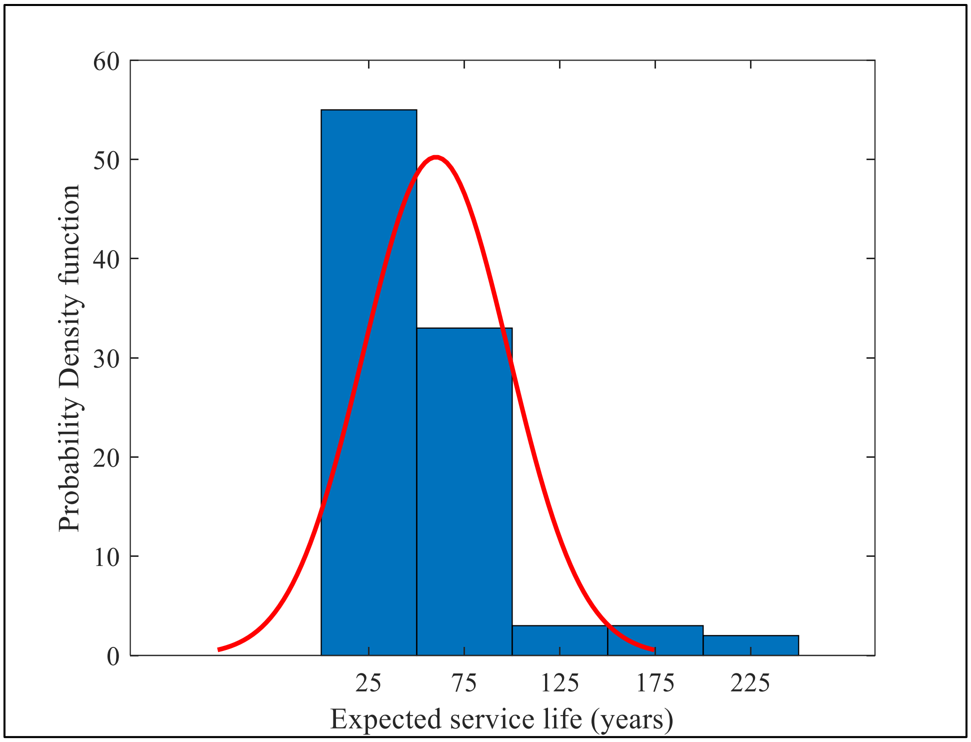


Figure 128: Normal distribution of pipe's segments expected service life.

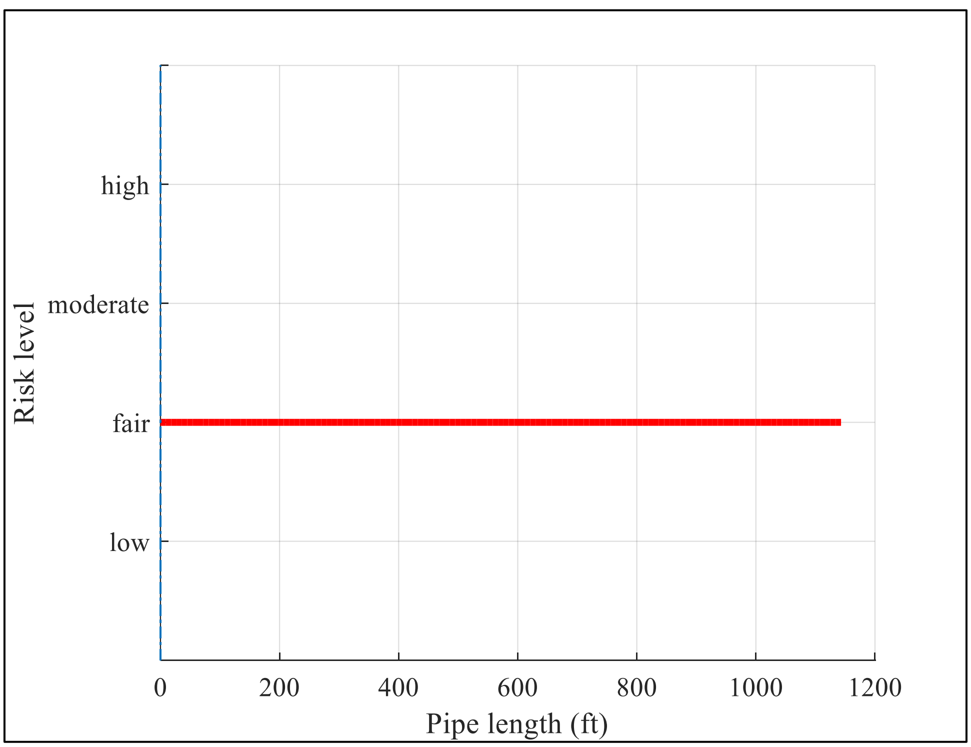


Figure 129: Risk level for pipe's segments along the total length.

A5.29 D10SL0140 Line

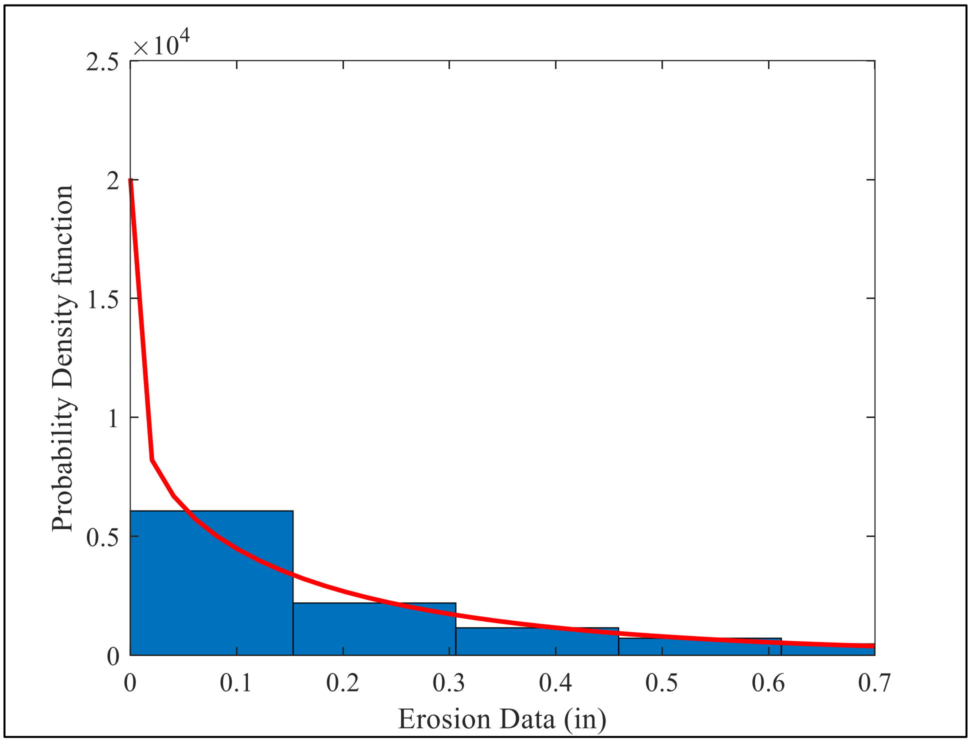


Figure 130: Probability density function of erosion data along the entire line.

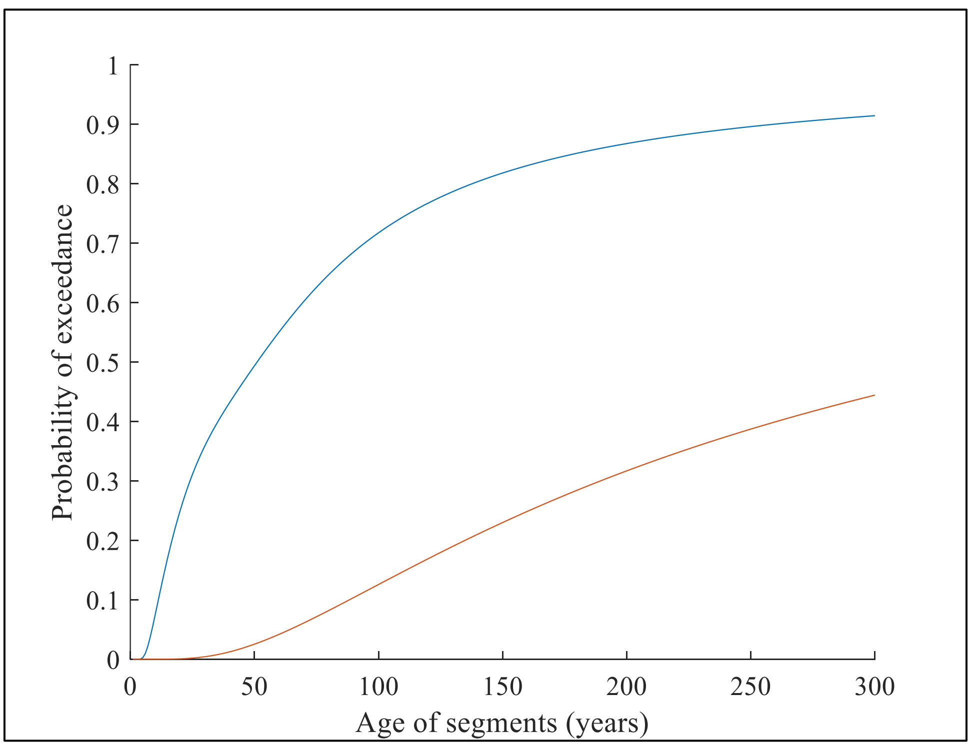


Figure 131: Cumulative distribution function (CDF) of segments' age

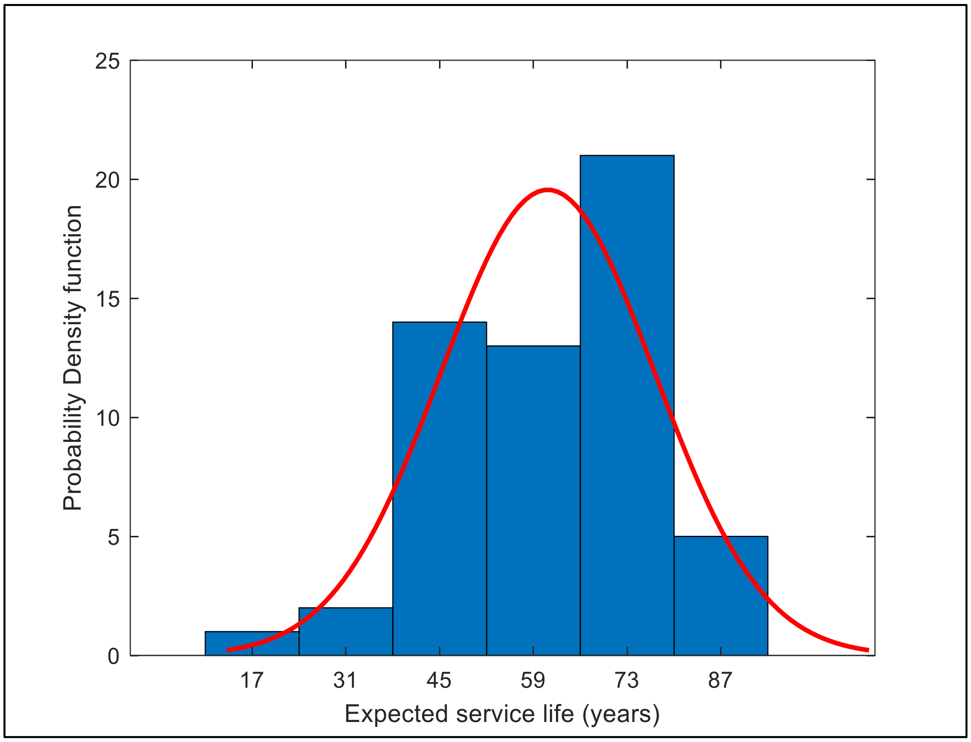


Figure 132: Normal distribution of pipe's segments expected service life.

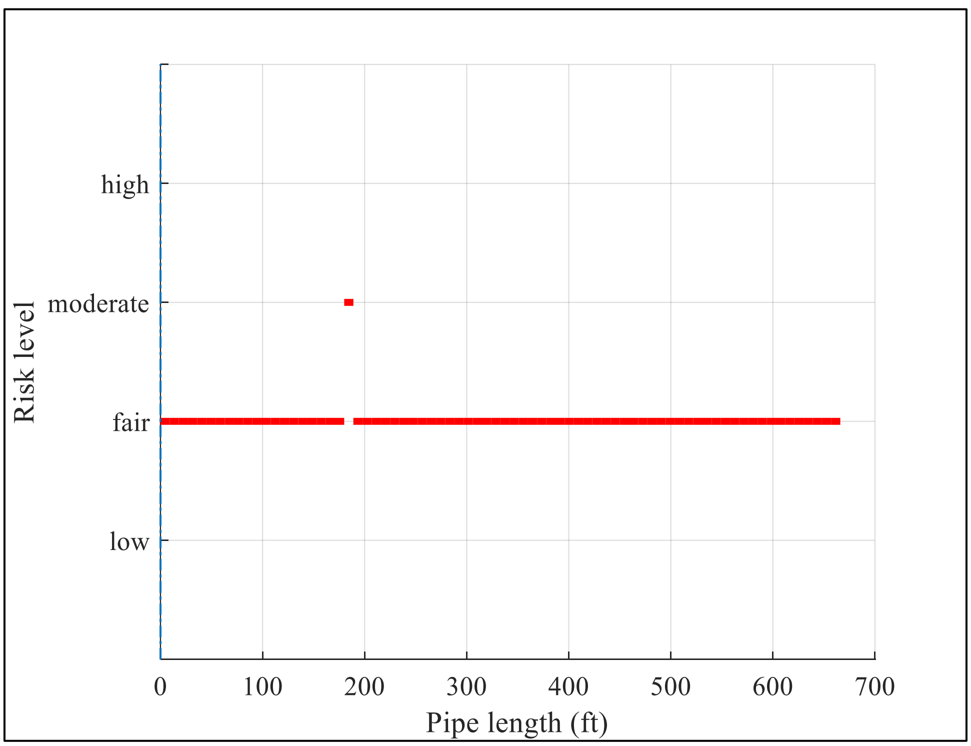


Figure 133: Risk level for pipe's segments along the total length.

A5.30 D09SL0169 Line

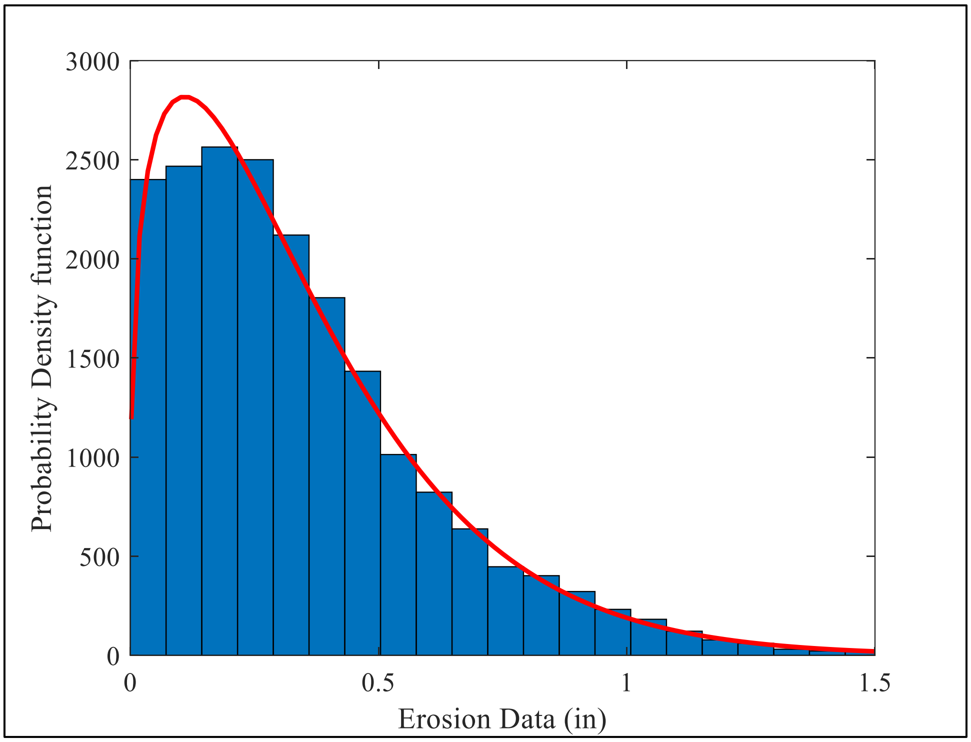


Figure 134: Probability density function of erosion data along the entire line.

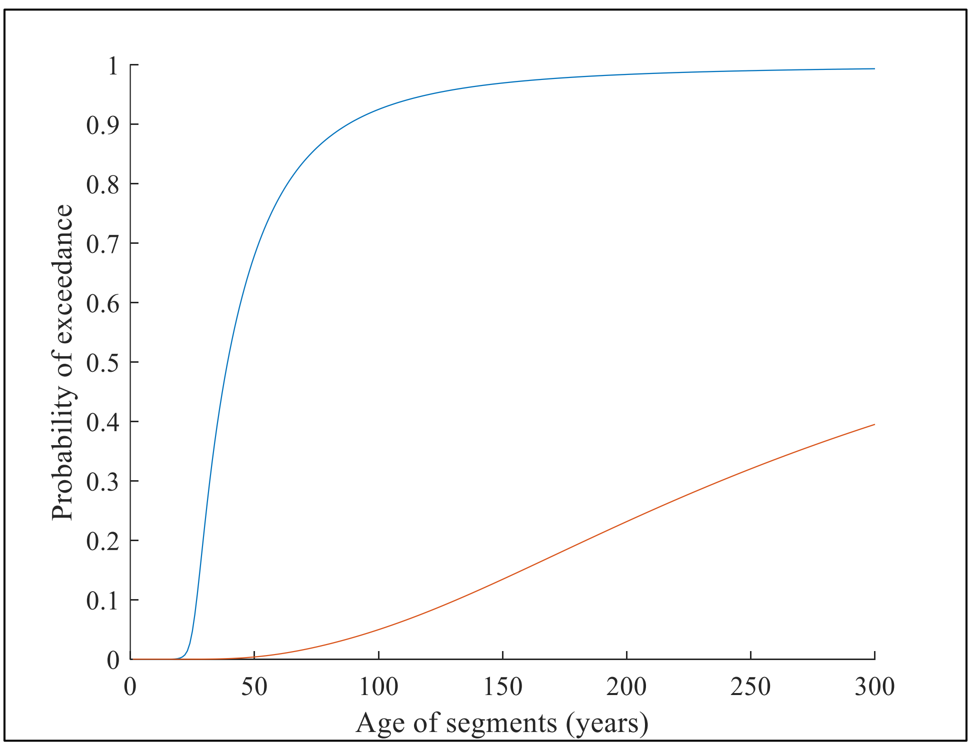


Figure 135: Cumulative distribution function (CDF) of segments' age.

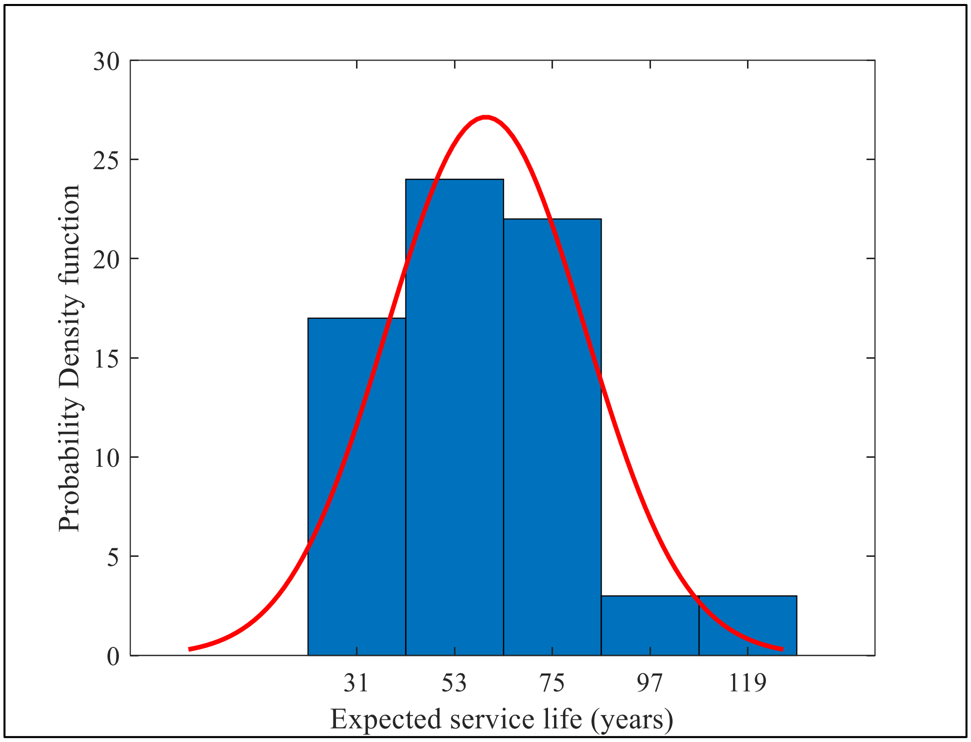


Figure 136: Normal distribution of pipe's segments expected service life.

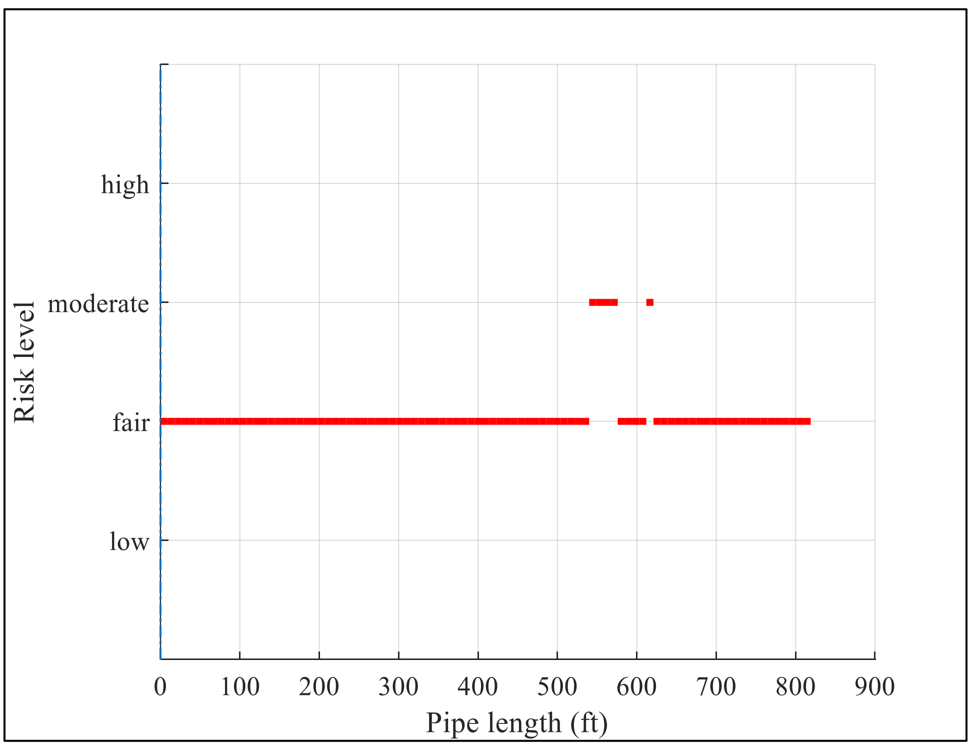


Figure 137: Risk level for pipe's segments along the total length.

Appendix B

Table 9: Weights and CIs for impact factors with discrete categories values.

Impact Factor	Weight (Wi)	CI
The cost of sewer pipe repair	8	Main sewer pipes: 100 Subsidiary sewer pipes: 50
Wastewater quality	6	Wastewater of industries and manufacturers of dangerous pollutants: 100 Hospital wastewater: 75 Wastewater of usual industries and manufacturers: 50 Domestic wastewater: 25
Located within the influence of wells	7	Yes: 100 No: 0
The importance of the surrounding buildings and the importance of Subscribers	6	Hospital and educational centers: 90 Important commercial and public centers, e.g. mosques, fire stations, malls, etc., and government buildings: 80 Industrial centers: 60 Miscellaneous public centers, e.g. hotels: 35 Residential buildings: 30
Roadway type	8	Freeway: 100 Collector road: 45 Ringway: 90 Local street: 20 Highway: 80 Alley: 10 Arterial road: 60 Not located under a roadway: 0
Located under or adjacent to railway lines	7	Yes: 100 No: 0

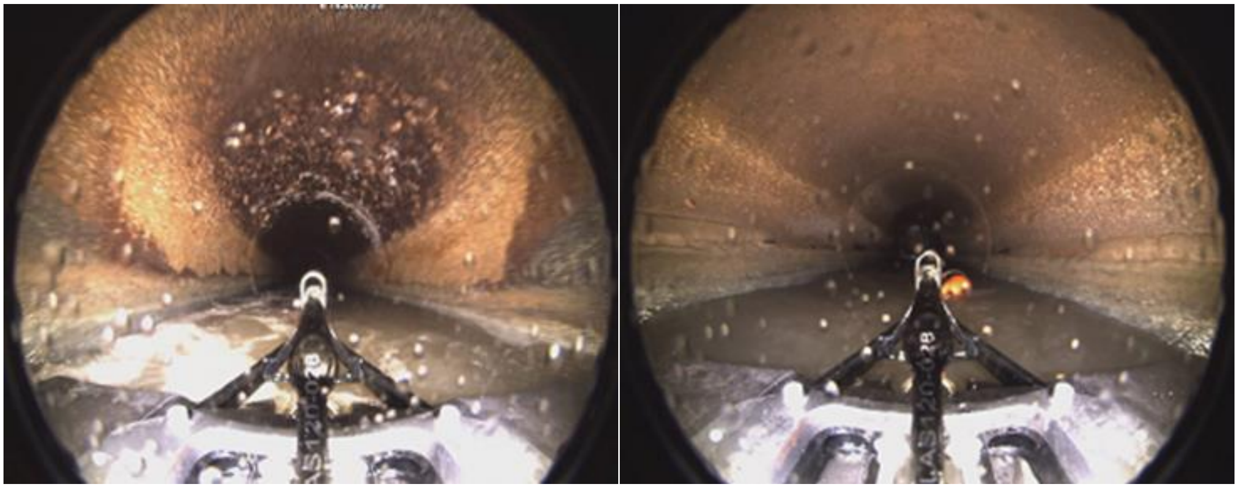
Proximity to public places (From the viewpoint of population involved)	7	Airport, subway, and terminals: 100 Parks, downtown and business centers (markets and malls): 75 Hospitals, educational centers and critical places, e.g. fire, aid and police stations: 70 Religious, cultural and sport places: 50 Other public and government places, e.g. municipality, banks, etc.: 45 Not located near a public place: 0

Table 10: Weights and CIs for impact factors with continuous variables.

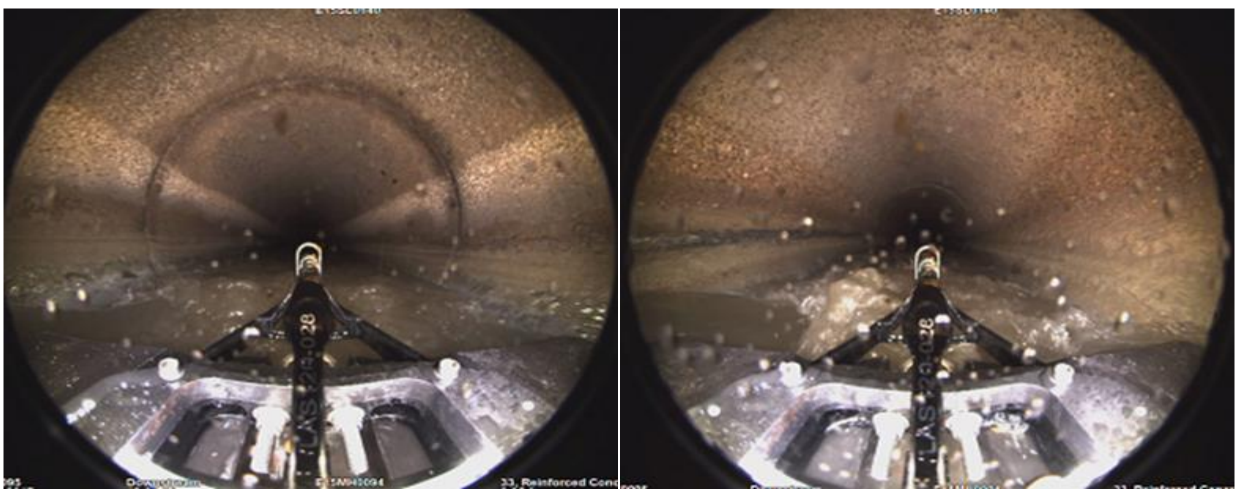
Impact Factor	Weight (Wi)	CI Eq.
Sewer distance (d) from groundwater level (m)	5	CI ¼ $0.0001d^4 - 0.0124d^3 + 0.4565d^2 - 9.1351d + 100$
Sewer pipe diameter (mm)	8	$CI=-2*10^{-10}d^4 + 6*10^{-7}d^3 - 0.0006d^2 + 0.2668d+0.1879$
Sewer distance from water pipe (cm)	5	$CI = 0.0071d^2 - 1.7186d + 99.963$
Sewer distance from river (m)	5	$CI = 4*10^{-5}d^4 - 0.0045d^3 + 0.182d^2 - 4.4603d + 100$

Appendix C: CCTV image for RC pipes

E14SL0255



E15SL0140



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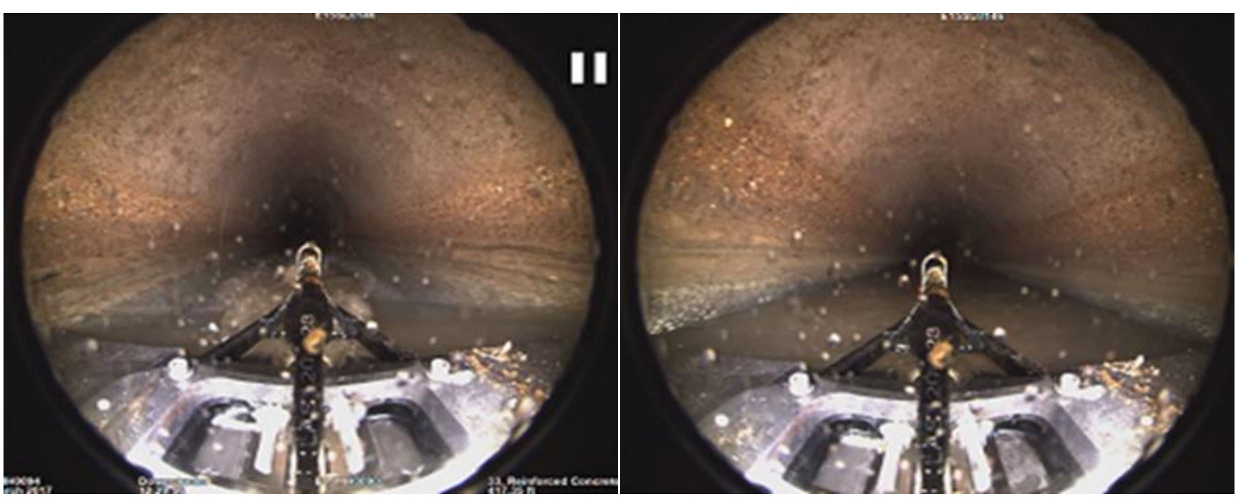
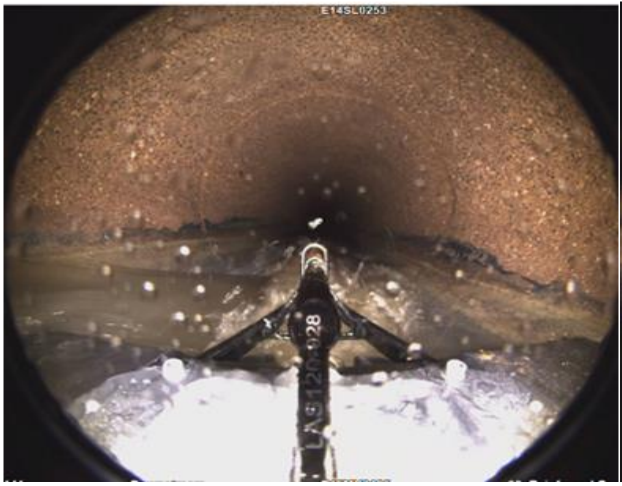
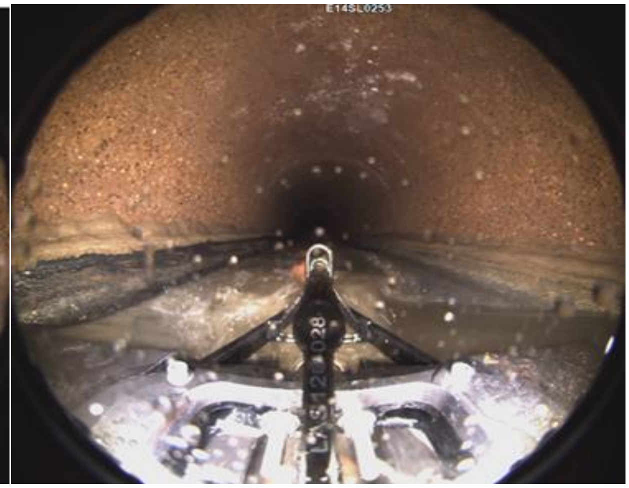


E14SL0253





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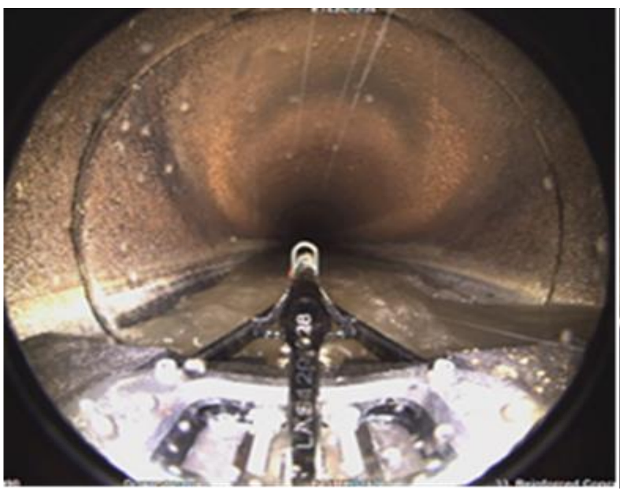
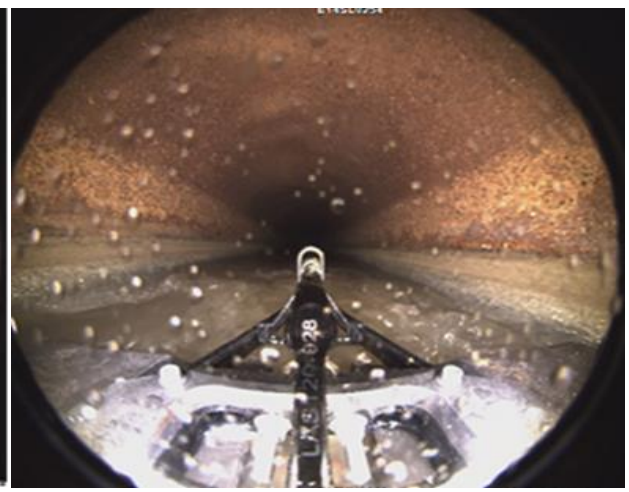
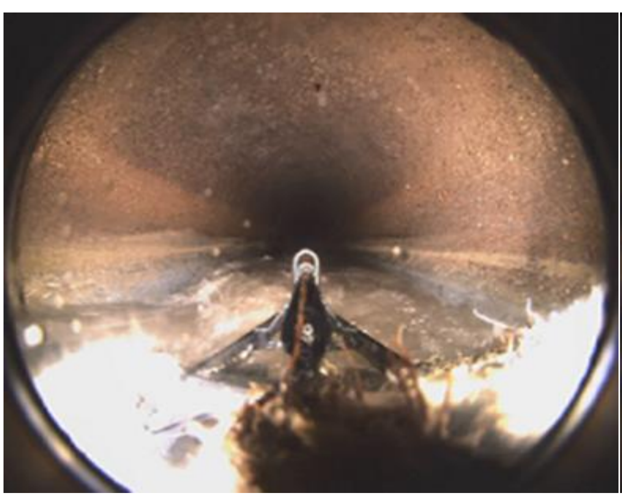




F16SL0249



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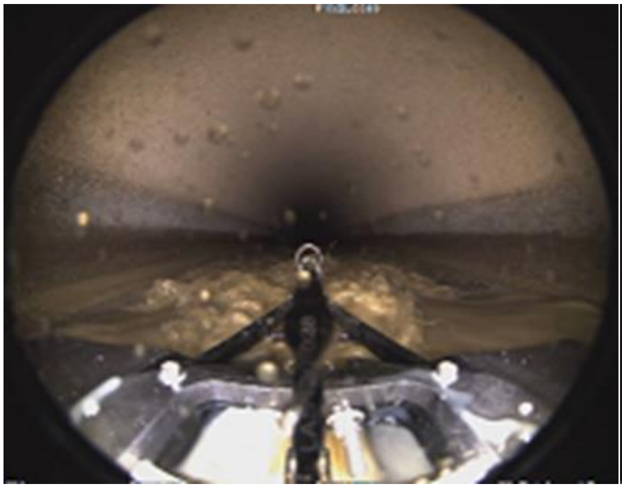

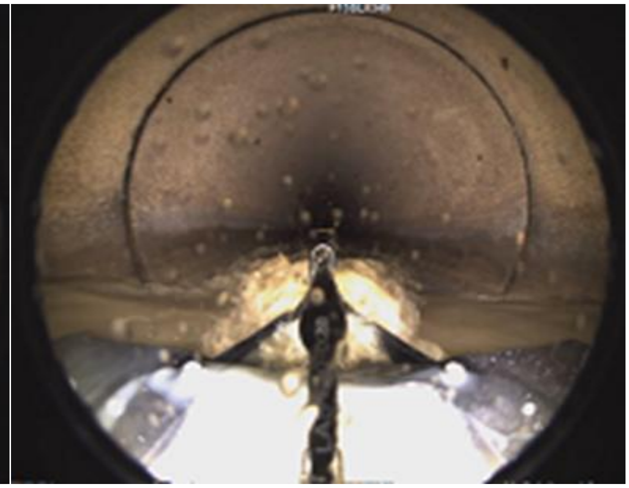

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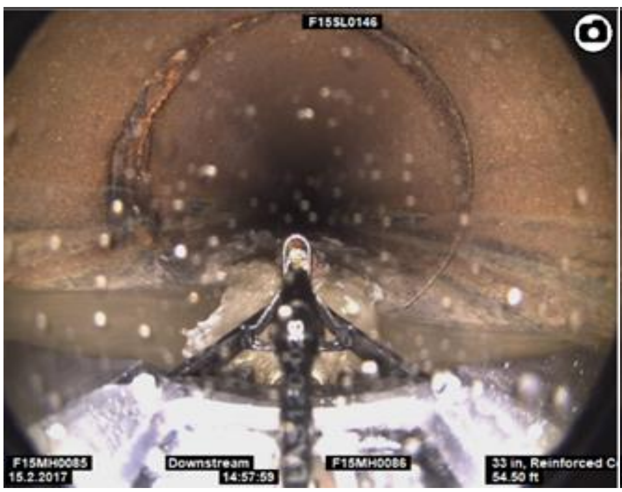

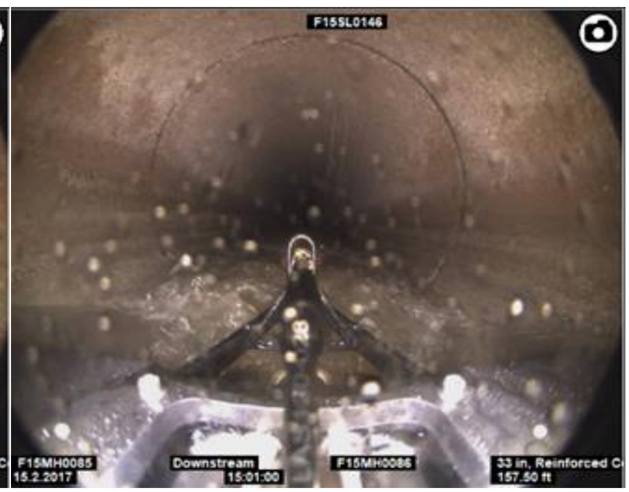

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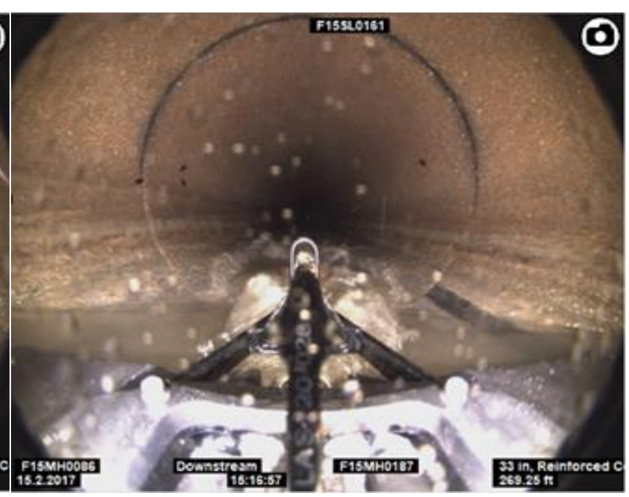

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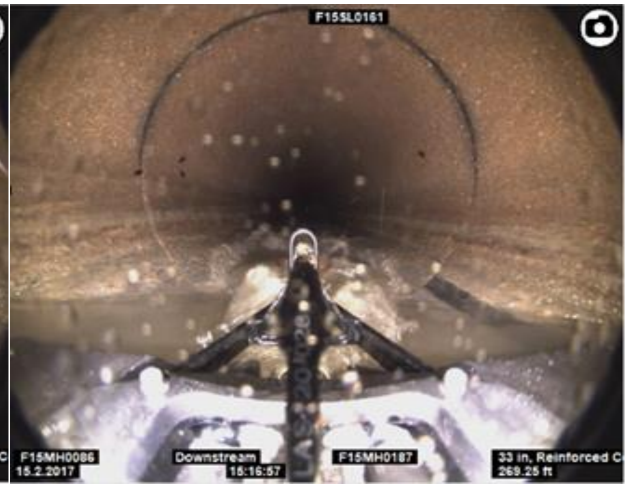

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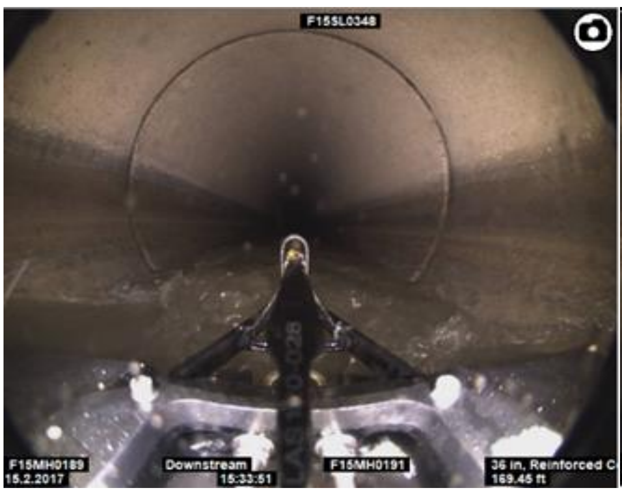
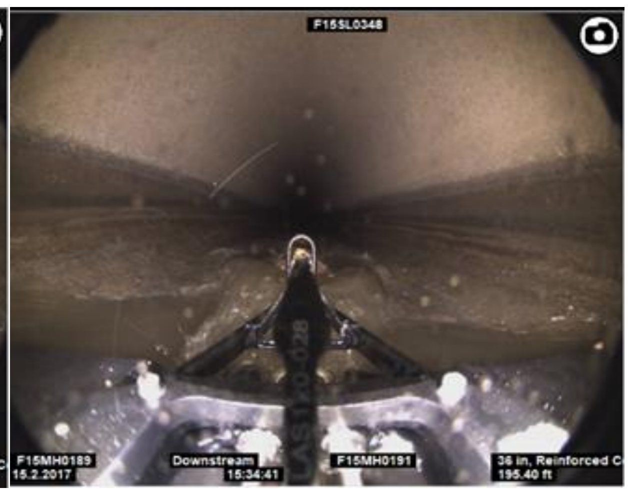
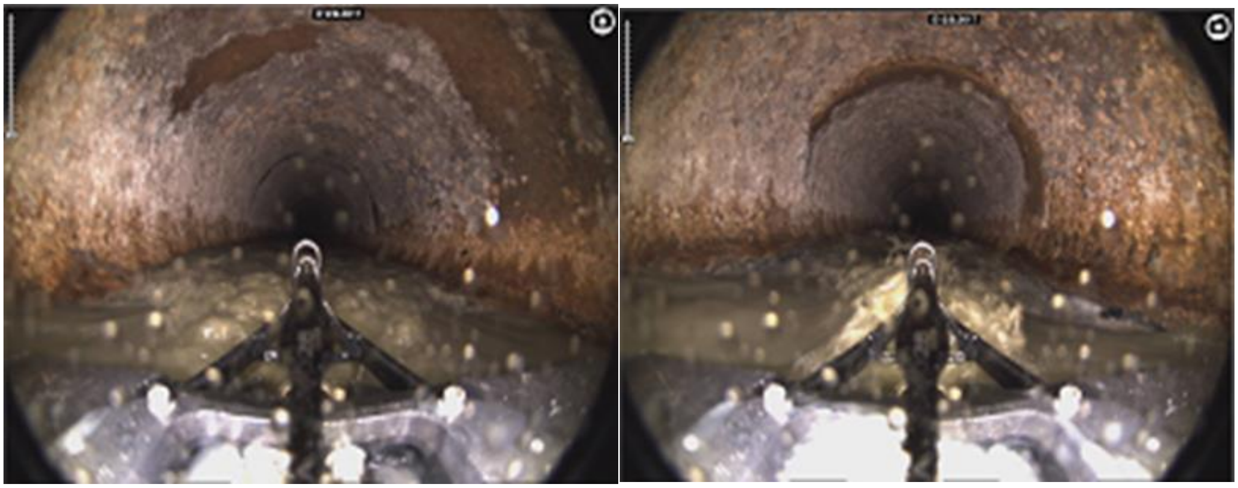


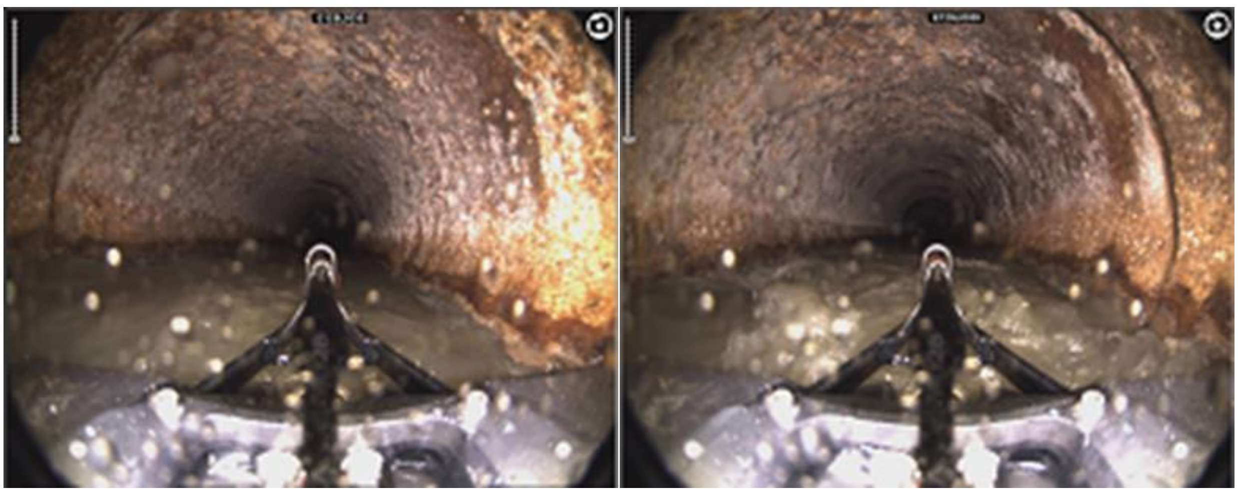


E12SL0011

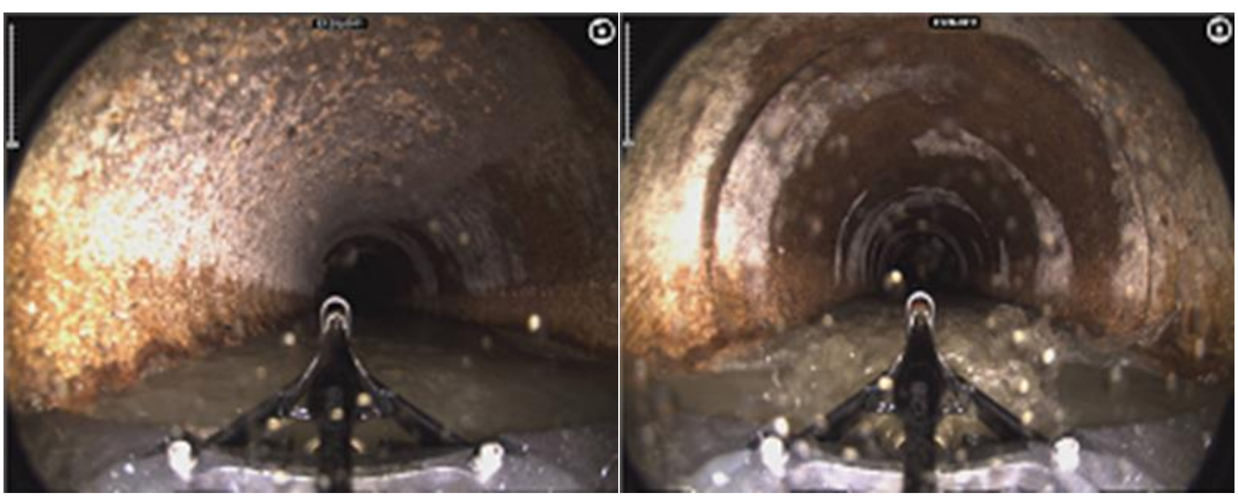
E12SL0017



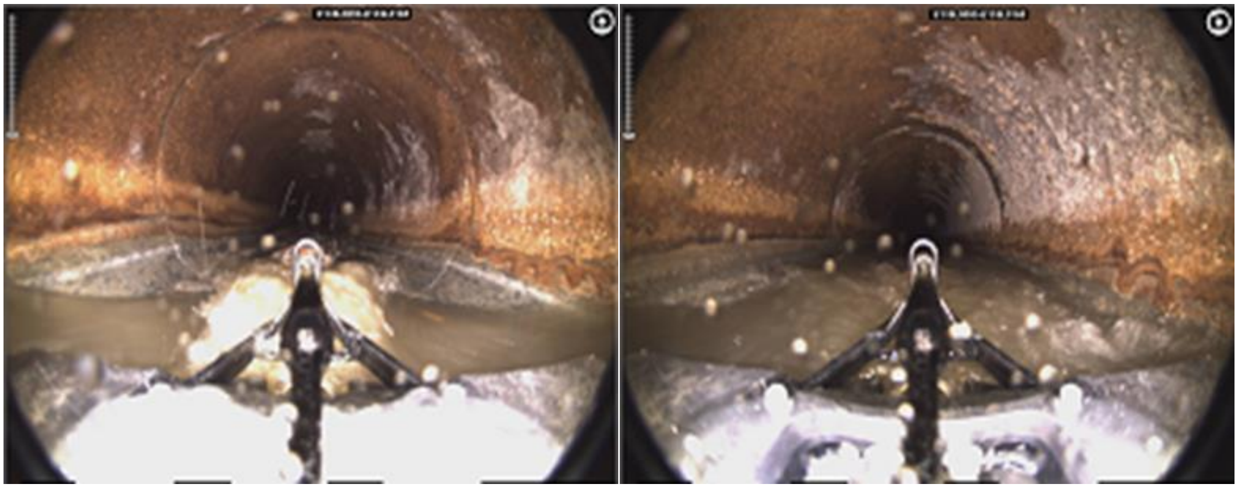
E12SL0330



E12SL0011



E13SL0093-E13SL0165



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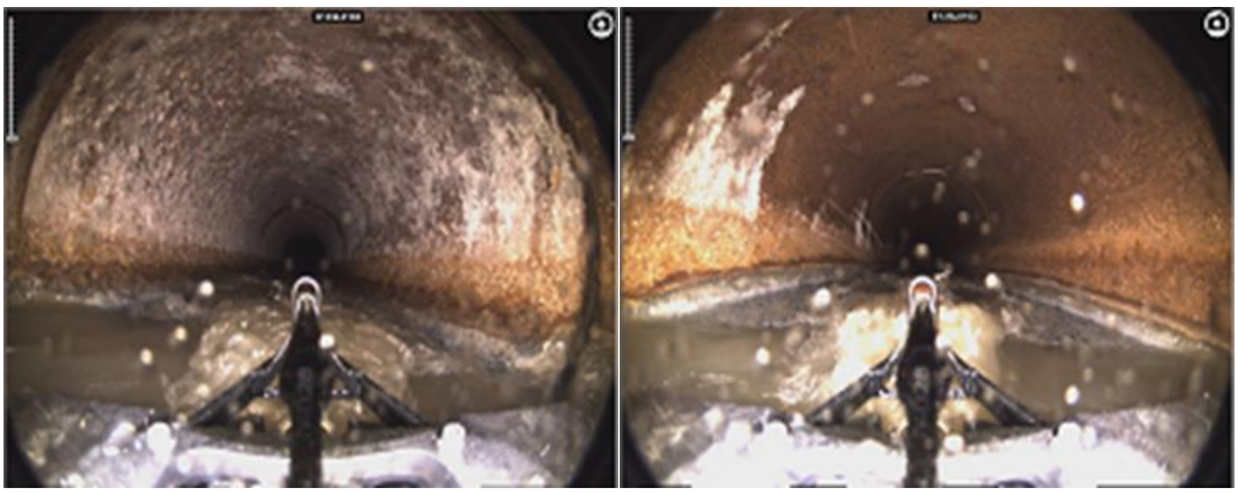

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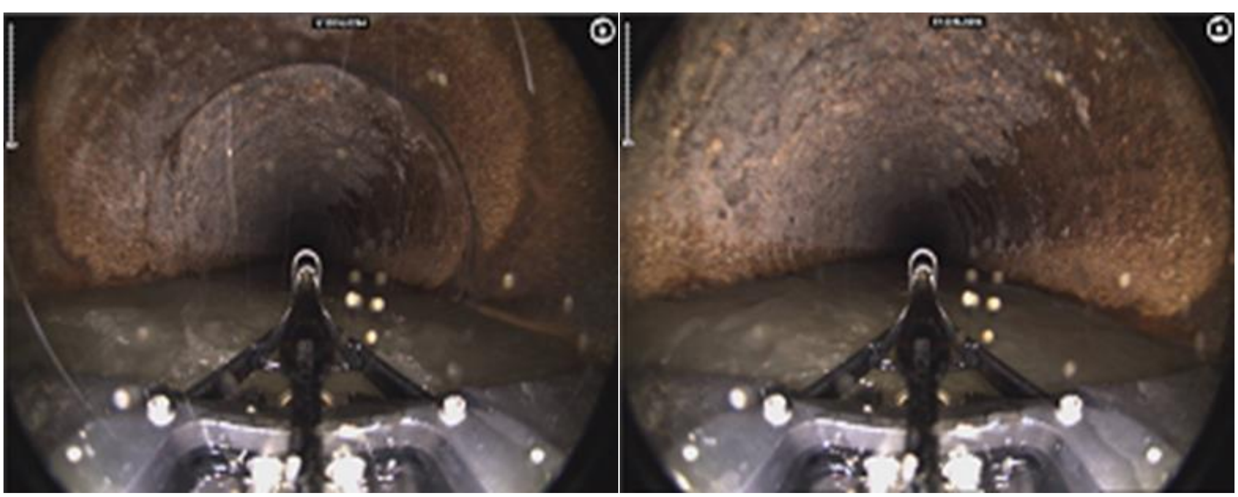

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