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Reliability Assessment for Corroded Pipelines in Series Considering Length-Scale Effects

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ABSTRACT

This paper presents a method for assessing the reliability of a corroded pipeline placed in series, with special consideration given to the effect of the length scale imposed by each segment of the pipe. The features of corrosion in different pipe segments are statistically correlated; thus, a failure in one section may impact the adjacent sections. Herein, using a correlation distance parameter, such statistical correlation is described considering the length-scale effects. The reliability of the corroded pipeline is presented in the form of a failure probability. The results show that analysing a corroded pipeline by considering length-scale effects produces a higher failure probability compared with the case where such effects are excluded, even when the parameters that govern corrosion in a pipeline are included in the analysis.

Keywords: Reliability; system; pipeline; series; corrosion.

INTRODUCTION

Probabilistic approaches are being increasingly adopted by various industries, in particular, the oil and gas industries, where cost optimisation is the key factor for achieving sustainability. A probabilistic approach allows the reliability of any operational structure to be estimated, including pipelines. A typical pipeline incurs high operational costs during its lifetime; thus, the associated costs of maintenance, repair, and replacement should be kept to a minimum without compromising safety. The easiest way to ensure both the safety and reliability of a pipeline is to prevent leaking from it. Most leaks are caused by thinning of the pipe wall, which usually results from corrosion and occasionally from erosion.

However, managing corrosion is problematic, especially for long pipelines laid in deep waters. A long pipeline is composed of many connected pipe segments, each 12 m long; therefore, a pipeline is best described as a serial structure. Utmost care should be taken when dealing with multiple segments or components because the failure of one can cause others to fail too. Because of its serial alignment, a pipeline may also be prone to effects associated with the length of its sections. Previous studies have investigated the effect of sectional length on structures operating in series, e.g., flood- and sea-defence structures [1, 2].

Therefore, this paper aims to investigate how length-scale effects manifest themselves in a pipeline and their impact on the overall failure probability of the structure. Figure 1 shows an example of a pipeline in which each section has a different failure probability P_f; it is noteworthy that the overall failure probability is greater than any of the sectional failure probabilities. Thus, it becomes problematic to specify the reliability of a corroded pipe precisely. This paper attempts to provide insights into determining the reliability in such cases. We also compare two pipeline reliability models: one with and the other without the influence of length-scale effects.

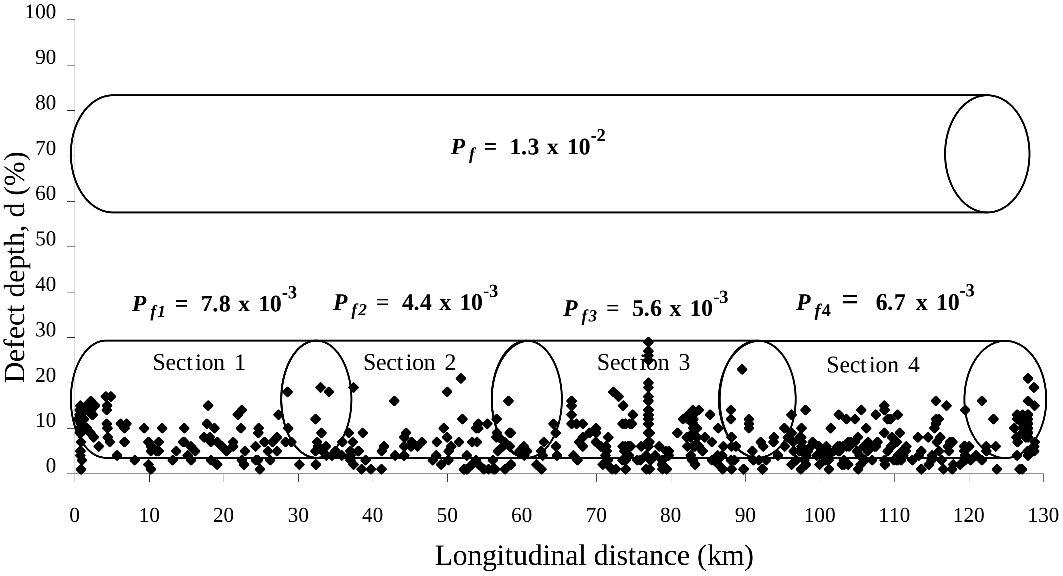

Figure 1. Variation in failure probability P_f computed for different sections of a corroded API 5LX-65 pipeline.

LITERATURE REVIEW

Reliability of System

A system can be defined as “a group of elements or processes with a common objective” [3]. Many physical systems are composed of multiple components, and the reliability of a multicomponent system is a function of its redundancy [4]. If a system incorporates redundancy, its components can be either (i) participating [e.g., sharing loads (active redundancy)] or (ii) inactive until some other previously active component fails. Further details on this aspect may be referred to Ang and Tang [4]. A multicomponent system can be classified as being connected either in series or parallel.

Serial system

In a system whose components (elements) are connected in series (see Figure 2), failure of one or more components constitutes a failure of the entire system; therefore, serial systems have no redundancy and are also known as “weakest link” systems [4]. In other words, the reliability or safety of a serial system depends on none of its components failing.

Figure 2. Representation of a serial system.

If E_i denotes failure of component i, failure of a serial system comprising m components, denoted by E_s, is the event;

$$E_s=E_1\cup E_2\cup...\cup E_m \tag{1}$$

For a simple serial system that contains two components, the probability of component 1 failing (i.e., event E_1) or component 2 failing (i.e., event E_2) is given by:

$$P_f=P(E_1\cup E_2)=P(E_1)+P(E_2),\ P_f=P(E_1 \text{or} E_2) \tag{2}$$

Equation (2) shows that the probability of the system failing is a function of not only the probabilities of individual components failing but also of a conditional probability. This means that the statistical dependence of element failure is important [3].

Parallel system

In a system whose components or elements are connected in parallel shown in Figure 3, failure of the whole system requires the failure of all the components; in other words, if any one component survives, the system remains safe [4]. A parallel system is an obvious example of a system with redundancy. Failure of an m-component in a parallel system is denoted by the event. The probability of n components failing in a parallel system is given by Eq. (4).

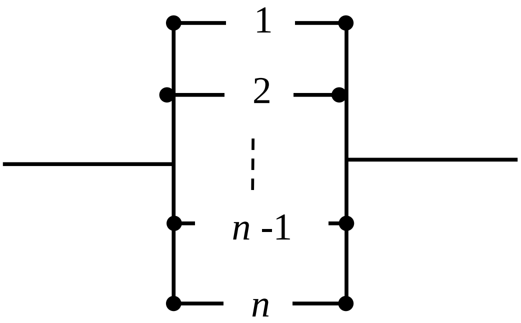

Figure 3. Representation of a parallel system.

$$E_s=E_1\cap E_2\cap...\cap E_m \tag{3}$$

$$P_f=P(E_1)P\left(\frac{E_2}{E_1}\right)P\left(\frac{E_3}{E_2},E_2\right)...P\left(\frac{E_n}{E}....E_{n-1}\right) \tag{4}$$

Background of Corrosion

Physics of CO_2 corrosion

Corrosion is a chemical or electrochemical reaction between material, usually metal, and its environment that produces deterioration of the material and its properties. This is because of the natural tendency for most metals to return to iron in the presence of moist air. Corrosions are normally classified into two categories; the sweet and sour corrosions. The sweet corrosion is defined as the deterioration of metal caused by contact with carbon dioxide (CO_2) in water. The sour corrosion, on the other hand, containing or caused by hydrogen sulphide (H_2S) or another acid gas. The corrosion assessment presented in this paper is only concerned with sweet corrosion. Herein, the electrochemical process of CO_2 corrosion involves the anodic dissolution of iron and cathodic evolution of hydrogen, as given below:

$Fe \rightarrow Fe^{++} + 2e^-$

while the cathodic reactions are described by,

$2H^+ + 2e^- \rightarrow H_2$

$2H_2CO_3 + 2e^- \rightarrow H_2 + 2HCO_3^-$

and finally, the overall reaction is then represented by,

$Fe + CO_2 + H_2O \rightarrow FeCO_3 + H_2$

Forms of corrosion

The electrochemical reactions between the metal and its environment would result in different forms of corrosion. While the most common one is pitting, others also include crevice, galvanic, intergranular, velocity- or microbially-induced corrosions, or even stress corrosion cracking and selective leaching as schematically shown in Figure 4. The corrosion data analysed in this paper, however, were not limited to any forms of corrosions as the nature of the data captured by the inspection tool was inclusive of all. In the context of this paper, such inclusion would allow the overall geometries of corrosion developed in the pipe to be assessed without having to assume certain impacts that each form could give.

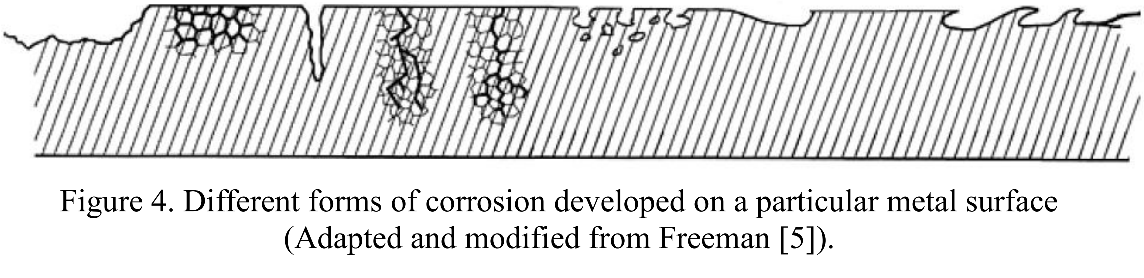

Figure 4. Different forms of corrosion developed on a particular metal surface (Adapted and modified from Freeman [5]).

Probabilistic physics-of-corrosion

Corrosion growth evolves with time, spreading in size and increasing in quantities. Most fundamental studies on corrosion science normally are experimental, where the growth of corrosions is critically studied based on a time basis. A work by Rivas et al. [6] and Valor et al. [7] for instance, were focused on experimental investigations on corrosion pits growth with time. In studies on corrosion science such as the works by these authors, it is quite common for a sample of material to be kept under certain controlled environments and later the growth of corrosion colonies would be inspected from time to time. At each inspection, the depth of each corrosion pit would be measured and recorded. Although the results (corrosion depths) for such growth could be made in different ways, presenting them in the form of probabilistic distribution functions (PDF) have been acceptable in describing its characteristics and patterns.

A sample of this presentation could be found in Figure 5, for instance. The figure summarizes (colonies of) corrosion evolvement with time, where at the beginning (1 day) the depth is less but becoming deeper by the end (30 days) of the experiment period. Note that the progression of depths is visible from the *x*-axis scale of the graphs. Not only the magnitude of the growth could be seen from here, but also the spread of corrosions. The spread is simply translated by the width of the PDF, indicating the increase in the number of corrosions. While ‘new born corrosion’ remains on the left tail of the PDF, the ‘older’ ones would move to the right tail holding deeper corrosion depths.

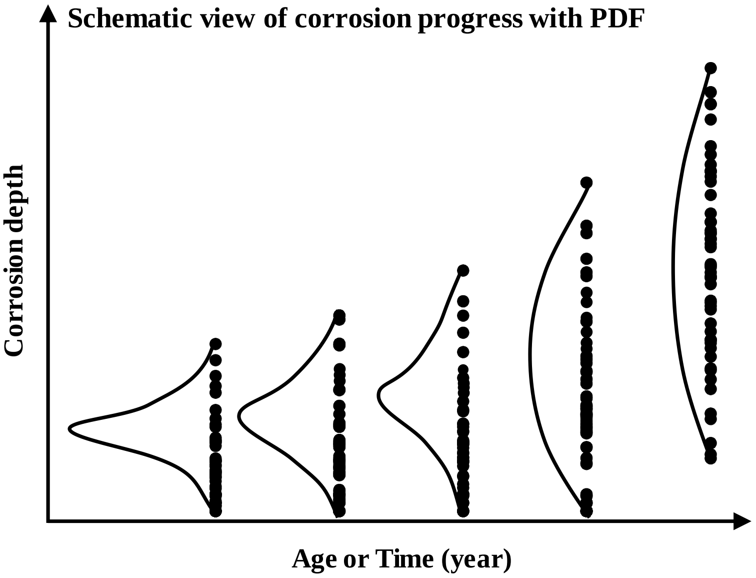

Figure 5. PDF presenting the growth of pit depth over time at different exposure times.

The above representation of PDF has paved the way to describe corrosion as random variables, which eventually allows the data to be interpreted statistically. Insights from the experimental works could then be directly applied to the actual site operations as well, in the present case is pipeline operation. This then conforms well with the scope of the paper, with the analysis projected further towards the reliability assessment of corrosion failures.

Corrosion models

It is well recognized that the prediction of the corrosion progress by time is necessary to run our facilities safely. Some studies have been conducted to develop the time-dependent corrosion wastage model by many researchers. Among the various types of corrosion shown in Figure 4, the pitting corrosion issue is continually reported by operation side. Recently, Bhandari et al. [8] conducted a wide range of the technical reviews on modelling of pitting corrosion in marine and offshore steel structures. With regard to pitting corrosion of carbon steel pipes, Wang and Melchers [9] conducted in-depth investigations.

Paik et al. [10] proposed a simplified technique to estimate the pitting corrosion rate by time which was applied to oil tanker [11] and bulk carrier [12]. Valor et al. (2010) proposed a stochastic approach to pitting-corrosion-extreme modelling based on experimental data. Paik and Kim [13] also proposed an advanced technique to develop time-dependent corrosion wastage model which was applied to oil well tube [14], offshore gas pipeline [15]. Caines et al. [16] also provided in-depth investigations on pitting corrosion literature reviews with modelling techniques on pitting corrosion rate. Recently, Kim et al. [17] proposed a refined technique by adopting a probabilistic approach which was applied to the empirical formulation of current offshore data.

The obtained corrosion models have been widely applied for the ultimate strength-based safety assessment of aged marine structures. A technical review of application studies on ultimate strength analysis of corroded structures has been conducted by Wang et al. [18]. In particular, many researchers have investigated on the degradation of ultimate strength behaviour of ships and offshore structures by considering the time-dependent corrosion damage such as container ship [19], oil tanker [20-23], bulk carrier [24] and fixed jacket platform [25].

Reliability Assessment

A pipeline system may be exposed to more than one type of failure; however, from the viewpoint of our study, we are concerned with system reliability only in the context of failure due to corrosion. Since the 1990s, researchers have been interested in using probabilistic approaches to assess the reliability of corroded pipelines [26-30]. However, these studies treated pipelines as a single unit and did not segregate the statistical responses of individual pipe segments. Rather, they integrated the existing failure pressure (PF), model. Rather, they integrated the strength/resistance (R) term of the existing failure pressure (PF) model with load (S) term, into a new limit state function (LSF) model. Therein, the equation used for *R* was mostly modified from PF models that originated from the NG-18 criterion. The NG-18 criterion is a surface flaw equation developed using a semi-empirical fracture mechanics by the NG-18 Line Pipe Research Committee of the American Gas Association (AGA). Note that all these studies used the same load term, namely the operational loading exerted by the transported hydrocarbon in the pipeline. Also, a few studies have reported on LSF development, a part of which covered the aspects of onshore and buried pipelines [31-39].

In the last few years, research focus has shifted to assessing the reliability of pipelines by treating them as a serial system with spatially correlated corrosion defects. De Leon and Macías were among the first to adopt this approach; however, their work simply assumed several degrees of spatial correlation (namely 0.0, 0.2, 0.4, 0.6, 0.8, and

1.0) for corrosion in certain sections of a pipeline [29]. Zhou later evaluated the time-dependent system reliability of a pipeline placed in series that contained multiple active corrosion defects, e.g. small leaks, large leaks, and ruptures [40]. Although it was investigated how the spatial variability of the pressure loading and pipe resistance associated with different defects impacts system reliability**,** the results suggested that the spatial variability of the pipe properties had a negligible impact on system reliability [40]. Later, Leira et al. studied and quantified system reliability about multiple components with arbitrary correlation levels and independent corrosion defects [41].

Their results showed that the failure probability decreased strongly as the degree of correlation increased; however, it remained unchanged at correlation degrees more than 0.2. Low values of the correlation coefficient of system-failure probability could be obtained simply by multiplying the failure probability for a single defect by the total number of defects. Simultaneously, Sahraoui et al. [42] developed a maintenance model for inspecting the optimisation of pipelines subjected to external corrosion and exposed to soil conditions, with special consideration given to the spatially varying corrosion rate. Monte Carlo simulations were used to evaluate the failure probability of the serial system**.**

Various attempts have been made to estimate the reliability of corroded pipelines by treating them either as a single unit or as multiple pipe segments; however, there have been fewer studies on the reliability of pipelines in series. The only work reported to date considered the influence of either different degrees of correlation or different combinations of corrosion defects. The definition of a serial system is somehow closely related to the degree of correlation. When this may be true, different representations of a serial system may also be considered, a part of which is presented in the present work.

METHODOLOGY

Corrosion Data

In this paper, corrosion is considered in an operational pipeline in Terengganu, which is located on the east coast of Peninsular Malaysia. The pipeline properties and corrosion information are given in Table 1.

Table 1. Pipeline properties and corrosion information.

Type:	API 5LX-65
Diameter:	28 in
Nominal wall thickness:	16.2 mm
Length:	128.9 km
Year of installation:	1999
Corrosion inspection year:	2007
Types of defect:	Internal and external corrosion
Number of defects:	861 defects (554 internal, 307 external)

The corrosion data were measured and recorded by a tool known as an intelligent pig (IP); they are presented according to the magnitude and location (orientation) of each defect. The defect magnitude is given by the depth of penetration (mm) or the amount of wall loss concerning pipeline wall thickness (%). Quite often, pipeline operators are more interested in the number of wall losses measured concerning the pipeline wall rather than the longitudinal or circumferential orientations. Thus, data on corrosion defects at depth *d* are generally given higher priority compared with the longitudinal length *l* or circumferential width *w*.

Effect of Pipeline Length

The procedure for analysing the effect of the length of a pipeline system was adapted from a reliability analysis applied to flood- and sea-defence structures and systems [1, 43]. The following assumptions were made.

i. The pipeline system with a total length *L* is divided into *n* sections, where *n* depends on the correlation distance, as shown in Figure 6.
ii. The failure mode (i.e., corrosion) contributes equally to the total failure probability of each pipeline section.
iii. The pipeline has a uniform cross-section along its length *L*.

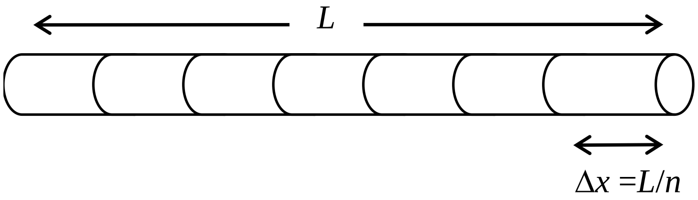

Figure 6. A pipeline of length *L* divided into *n* sections (not to scale).

As shown in Figure 6, a pipeline system with a uniform cross-section comprises *n* sections of a certain length. The strength/resistance *R* of every pipe section of a serial system can be described as a random variable. We assume that the strengths of two adjacent sections are correlated, with the degree of correlation depending on, among other factors, the distance Δ*x* between the two adjacent sections considered.

Statistically, the relationship between the correlation and distance can be described by a correlation function. A common form of an autocorrelation function ρ describing the strength parameter (*R*) at locations *x* and *x*+Δ*x* is described by Eq. (5).

$$\rho[R(x),R(x+\Delta x)]=e^{-\left(\frac{\Delta x}{d_{corr}}\right)^2} \tag{5}$$

where *x* is the characteristic under consideration, Δ*x* is the distance between two points (in time), which is known as the distance lag, d_{corr} is the correlation distance, sometimes referred to as the fluctuation scale.

In the context of this study, x is the corrosion depth d measured either in millimetres (mm) or as a percentage (%). From now on, we assume the development of corrosion in a particular pipeline section to be proportional to the corresponding pipeline strength; d_{corr} is defined as the distance over which the statistical properties of the reliability function are assumed to be completely correlated. Within a statistically homogeneous length of a pipeline, the number of pipeline sections is identified by setting the length of an individual section to d_{corr}. To continue the analysis, the reliability index β for section i (i = 1, 2,…n), where;

$$P(f_i)=\phi(-\beta) \tag{6}$$

is given by

$$\beta=\frac{\mu_R-\mu_S}{\sqrt{\sigma_R^2+\sigma_S^2}}=\frac{\mu_Z}{\sigma_Z} \tag{7}$$

where ϕ is the standard normal distribution; μ is the mean and σ is the standard deviation. The overall failure probability for a serial structure can be approximated by the Ditlevsen upper bound and is given by:

$$P(F)=\phi(-\beta)+(n-1)\left\{\phi(-\beta)+2\phi(-\beta)\phi\left(-\beta\frac{1-\varrho}{\sqrt{1-\varrho^2}}\right)\right\} \tag{8}$$

Because;

$$\mathrm{Max}_{j<i}P\big(f_i \text{ and } f_j\big)=P(f_i \text{ and } f_{i-1}),\rho=e^{-\left(\frac{\Delta x}{d_{corr}}\right)^2}\approx 1-\left(\frac{\Delta x}{d_{corr}}\right)^2 \text{ and } \rho^2\approx 1-2\left(\frac{\Delta x}{d_{corr}}\right)^2$$

Whereas, for a small,

$$\phi(u)=\frac{1}{2}+\frac{u}{\sqrt{2\pi}},\ P(F)=\Phi(-\beta)\left\{1+\frac{n-1}{d_{corr}}\frac{\beta\Delta x}{\sqrt{\pi}}\right\} \tag{9}$$

because $\Delta x=\frac{L}{n}$ and $\frac{n-1}{nd_{corr}}\frac{\beta L}{\sqrt{\pi}}\rightarrow\frac{\beta L}{d_{corr}\sqrt{\pi}}(\, n\rightarrow\infty)$

$$P_f=\Phi(-\beta)\left\{1+\frac{\beta}{\sqrt{\pi}}\frac{L}{d_{corr}}\right\} \tag{10}$$

which is independent of the number of sections n. Note that P_f has already been defined as the probability of failure. Also, the final computation of Eq. (10) relies on the predetermined value of d_{corr}; this will be explained further in the next section.

Correlation Distance, d_{corr}

Equation (10) can only be used successfully if the correct value of d_{corr} is chosen. This can be determined by satisfying both the left-hand side (LHS) and right-hand side (RHS) of Eq. (5). The LHS of Eq. (5) is shown in Eq. (11).

$$\rho[R(x),R(x+\Delta x)] \tag{11}$$

which corresponds to a standard autocorrelation function that can be computed using a commercial statistical programming language. Herein, the LHS term was evaluated using MATLAB. Meanwhile, the RHS term is shown in Eq. (12).

$$e^{-\left(\frac{\Delta x}{d_{corr}}\right)^2} \tag{12}$$

which can be calculated manually once d_{corr} is known. Brief guidelines on the procedure for obtaining d_{corr} using Eq. (5) are presented below. Recall that the parameter x is, in fact, the corrosion depth d measured in millimetres (mm) or as a percentage (%).

Solving the LHS term:

1. Identify the number of sections (n_1, n_2,… n_n) of the pipeline from which the size/distance Δx can be determined.
2. Compute the average corrosion depth at each section n_i, i.e., d_1, d_2,… d_n.
3. Evaluate the autocorrelation function for d_1, d_2,… d_n at each pipeline section using the standard statistical command in MATLAB.
4. Store the results for subsequent comparison.

Solving the RHS term:

1. Use step 1 to determine the values of n and Δx.
2. Assume an initial value for d_{corr}.
3. Calculate the RHS term manually and store the result.
4. Compare the result obtained from step 7 with the corresponding one from step 4.
5. Repeat steps 6–8 for another value of d_{corr} until the results from steps 4 and 7 agree sufficiently.

Basically, Eq. (5) is solved using trial and error for different values of d_{corr}. The best value of d_{corr} is the one that minimises the sum of the squares of the errors (SSE). If this task is conducted graphically, the graphs representing the LHS and RHS of Eq. (5) should approximate each other closely.

RESULTS AND DISCUSSION

It is noted earlier that computing P_f using in Eq. (10) relies on predetermining the value of d_{corr}. Thus, we begin this section by considering how to determine d_{corr} and then describe the method to use that value to compute P_f.

Determination of d_{corr}

We consider two different numbers of sections, namely n = 13 (scenario 1) and 128 (scenario 2), as given in Table 2. Fixing the number of sections then provides the corresponding value of Δx because $\Delta x = L/n$, where L is the pipeline length. A random trial value of d_{corr} was selected for each scenario (d_{corr} = 85 km and 65 km for scenario 1 and 2, respectively) and applied to Eq. (5). Following this, the LHS and RHS terms of Eq. (5) were calculated and plotted in a single graph. Because the process to visually compare the agreement between these two terms is complicated, we used SSE instead. As mentioned earlier, SSE measures the difference between the LHS and RHS terms and determines the potential source of error causing the difference. A small SSE is always preferable because in this case, the RHS and LHS of Eq. (5) are in better agreement. In this study, d_{corr} = 85 km gave a smaller SSE value of 0.034 as compared to 2.424 (d_{corr} = 65 km) and was used in the next step of the calculation.

Nevertheless, the SSE value obtained in scenario 2 was fairly acceptable. It would not be out of place to propose a certain range of values of the correlation distance d_{corr} for the pipeline structure, as was done for other structures, e.g., a flood-defence system [44]. Thus, given the characteristic similarities between a flood-defence system and the pipeline in question, we propose representing the latter with a d_{corr} of 65–85 km.

Table 2. Two scenarios for computing the correlation distance d_{corr}.

Scenario	Number of sections, n	Δx (km)	SSE	Correlation distance d_{corr} (km)
1	13	10	0.034	85
2	128	1	2.424	65

While assuming and choosing the correct d_{corr} value for the candidate pipeline API 5LX-65, it was interesting to notice the effect of the number of sections on the autocorrelation functions. Figure 8 and 10 provide a better view on this aspect. Selecting fewer sections (scenario 1) led to a relatively consistent pattern. This was because the defects had been grouped at reasonable intervals (Δx), for which the corresponding mean values were within a relatively small range of 1.0–1.6 mm, as shown in Figure 7. This promoted fairly smooth autocorrelation functions, as can be seen in Figure 8. In contrast, having a large number of sections (scenario 2) tended to depict the actual corrosion distribution along the whole length of the pipeline. As such, any significant or insignificant (i.e., extremum) defect characteristics were taken into account, preventing them from simply being ignored (i.e., through averaging). The mean values computed in scenario 2 shown in Figure 9 seem to fall within 0-2.6 mm, which is a wider range than that obtained in scenario 1; moreover, the corresponding autocorrelation functions result in fluctuating and “peaky” trends illustrated in Figure 10.

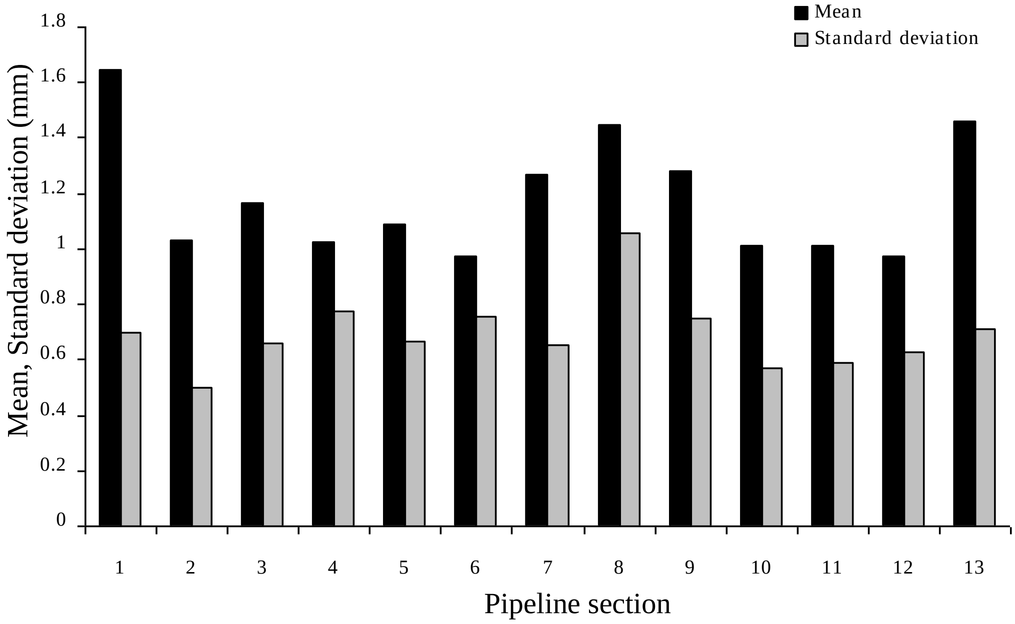

Figure 6. Mean and standard deviation for the pipeline divided into 13 sections.

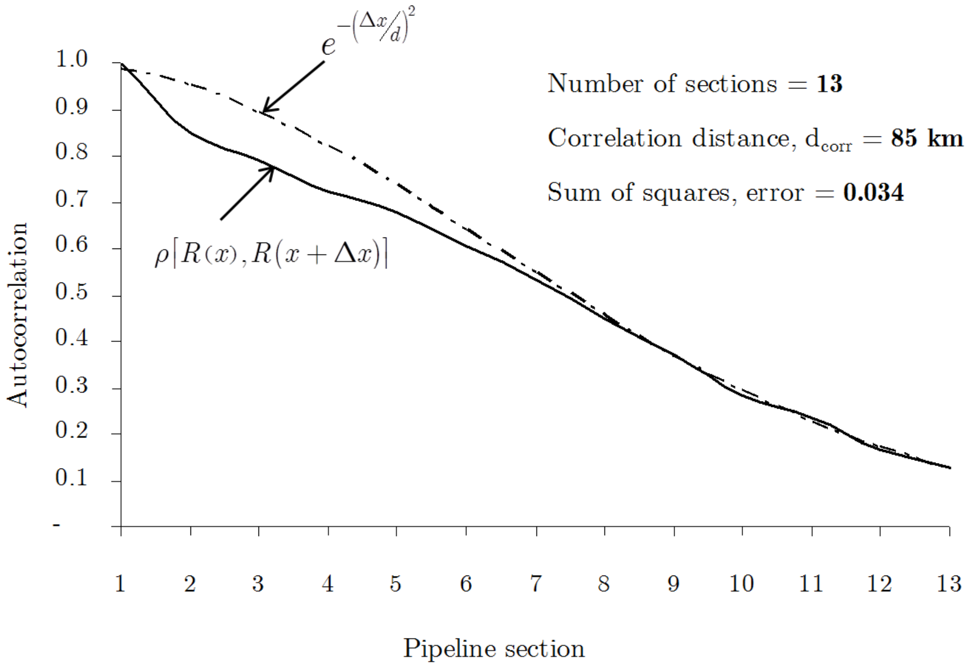

Figure 7. Autocorrelation functions for the pipeline divided into 13 sections.

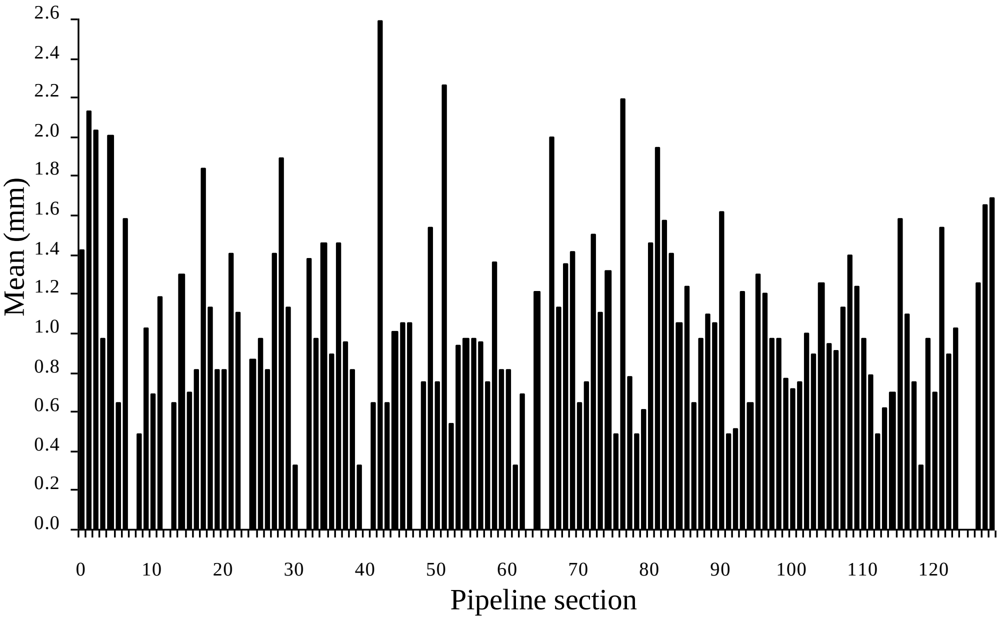

Figure 8. Mean for the pipeline divided into 128 sections.

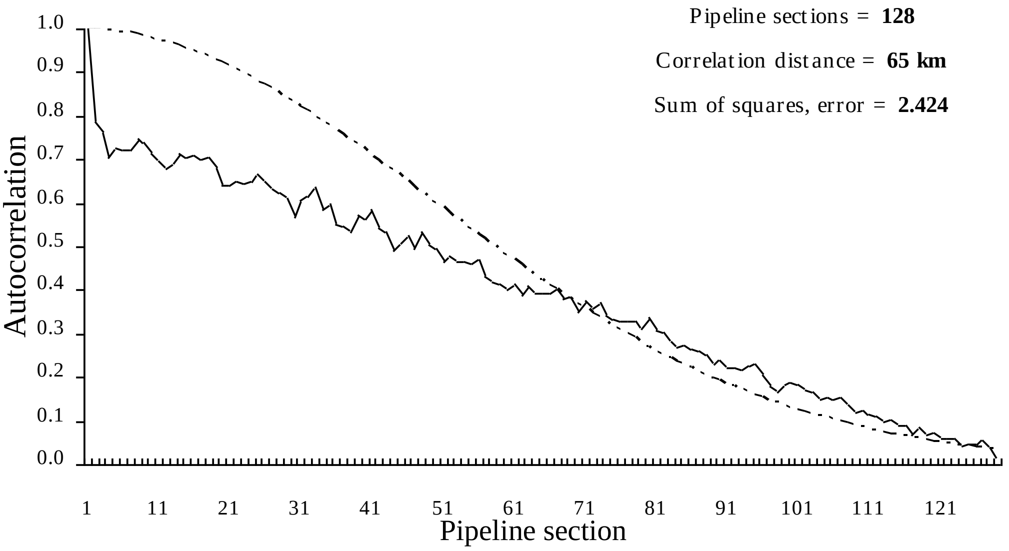

Figure 9. Autocorrelation functions for the pipeline divided into 128 sections.

Determination of Failure Probability, P_f

For the sake of illustration, we assumed a correlation distance d_{corr} = 85 km for the remaining analysis described in this section. This value was then applied to Eq. (10) to complete the analysis of length effects. Different loading values (i.e., operating pressures) were applied to the equation, which produced different P_f values, as shown in Figure 11.

For comparison, we used a different reliability model called the “dimensionless limit state function” [45]. This is given by Eq. (13) and is computed in the absence of sectional length effects, as plotted in Figure 11.

$$Z=\underbrace{\left[\left(\frac{t}{D}\right)^{0.8442}\left(\frac{d}{t}\right)^{-0.0545}\left(\frac{l}{w}\right)^{-0.0104}\right]}_{\text{Resistance}}-\underbrace{\frac{P_o}{SMTS}}_{\text{Load}} \tag{13}$$

Where P_o is the operating pressure, SMTS is the specified minimum tensile strength, t is the pipeline wall thickness, D is the diameter, d is the corrosion depth, l is the longitudinal corrosion length and; w is the circumferential corrosion width.

It is worth noting here that a typical limit-state function, given by Eq. (13), comprises two important terms: resistance and load. When generated and evaluated statistically, these terms represent the remaining strength of the corroded pipeline through the value previously defined as P_f. We recommend that the interested readers refer to the original paper by Mustaffa et al. for further details on the development of Eq. (13) [45]. Here, we are content to show in Figure 12 the sensitivity of each parameter used in Eq. (13). This implies that D and t are the most important variables in the reliability model given by Eq. (13), followed by SMTS of the pipeline material. The negative sensitivity of P_o implies that the structure is prone to failure under high loads. Through these findings, the effect of each parameter was later presented through the final values of P_f obtained under different dimensionless loading conditions ($P_o/SMTS$), as shown in Figure 11.

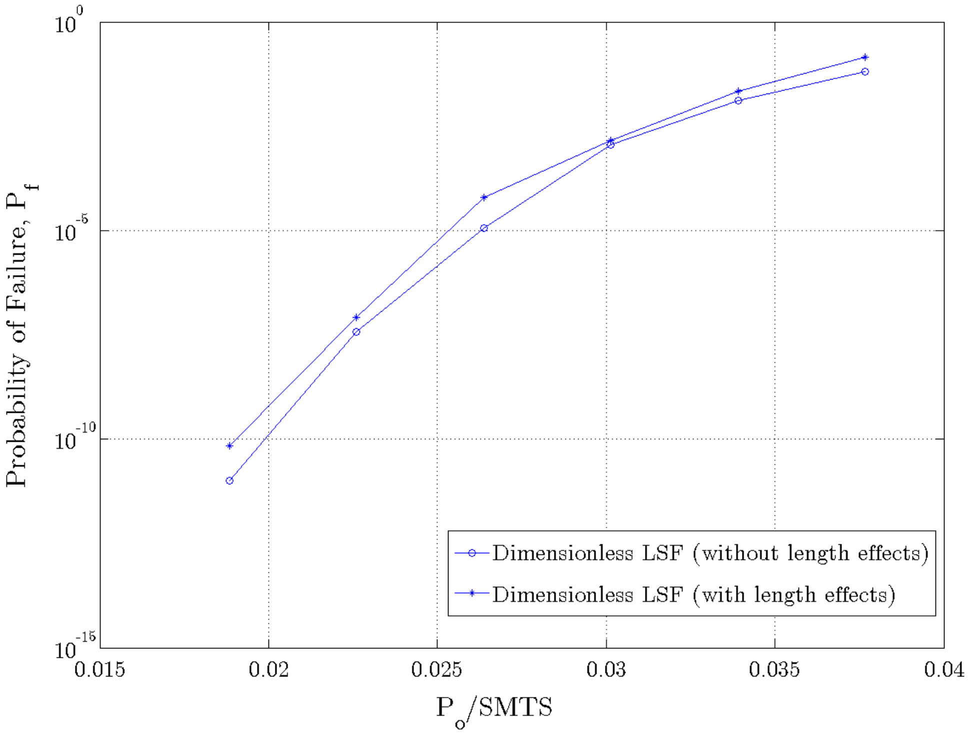

Figure 11. Failure probability P_f determined for the API 5LX-65 pipeline with Eq. (10) and without Eq. (13) length effects.

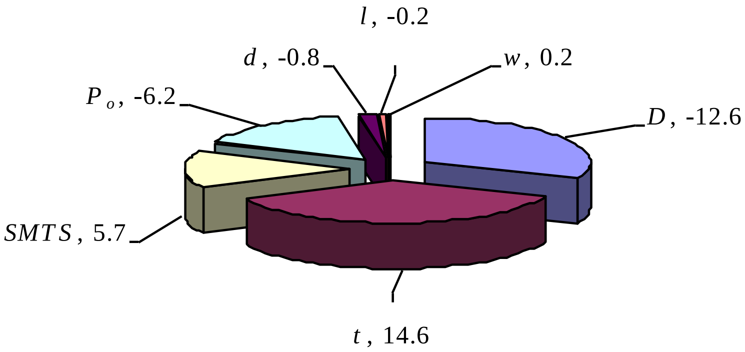

Figure 12. Degree of sensitivity of the parameters.

Figure 11 shows that the pipeline reliability model that considers the influence of length effects in Eq. (10) produces a higher probability of failure than the one that excludes these effects as in Eq. (13). Despite the close agreement between the two models, it is important to note that we expect a higher reliability value when the strengths of two adjacent sections of a corroded pipeline are assumed to be correlated. This is true for any structure operated serially because failure in one section might lead to failures in the adjacent sections. Hence, relying solely on the governing parameters affecting corrosion in a pipeline as given in Eq. (13) is not entirely correct when estimating the reliability of the structure. Instead, a proper reliability estimation using the model proposed in Eq. (10) is necessary for better prevention of failure due to leaks.

CONCLUSION

The outcomes of this research are useful in that they provide pipeline operators with different options for managing their corroded pipelines. Tackling the problem by dividing the pipeline into sections may be economical and practical if the threat is considered to be moderate. However, if reliability along the entire length of the pipeline becomes a major concern, our findings suggest performing analysis while considering length effects. This method seems to represent a worse scenario (i.e., higher P_f) when compared with the one that excludes length effects.

A cluster of interacting defects may pose a greater risk of pipeline failure. This is because corrosions in different segments of a pipeline placed in series are considered to be correlated; this can be described probabilistically using an autocorrelation function. Determining the value of d_{corr} enables a pipeline to be analysed in sections for which the statistical properties of the reliability function are correlated. Depending on their concerns and limitations (e.g., budget, manpower, and resources), pipeline operators may apply one of the proposed approaches to determine the reliability of the pipeline structure.

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