Statistical analysis for reliability assessment of corroded structures: A pipeline case study

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ABSTRACT Corrosion defects are a major concern for pipeline operators, and in-line inspections (ILI) are essential to detect and identify such defects and to optimize maintenance actions to avoid costly losses. However, it is crucial to conduct statistical analysis to estimate and monitor the corrosion evolution over time and enhance the accuracy of pipeline reliability assessments. This paper presents a statistical study of corrosion defect parameters (length and depth) obtained from ILI. The study evaluates statistical moments, considers the Pearson correlation coefficient, and determines the probability of failure using the Monte Carlo method based on the burst criterion. Moreover, we examine the influence of the coefficient of variation of corrosion defects on the probability of bursting by analyzing the sensitivity of key design parameters, such as operating pressure and the depth-to-wall thickness ratio. The paper employs a real case study of a corroded gas pipeline in Algeria to illustrate these findings. The results of this study can provide crucial information to pipeline operators to make informed decisions regarding maintenance activities throughout the pipeline's operational life.

Keywords Reliability assessment, corroded pipeline, statistical analysis, dependencies, Monte-Carlo.

I. INTRODUCTION

Pipelines are a safe and cost-effective means of transporting hydrocarbons, such as oil, natural gas, over long distances. However, they are susceptible to environmental constraints, such as corrosion, which can lead to pipeline failure. Metal loss corrosion is a primary cause of underground pipelines failure during their operational lifetime. Corrosion can occur on both the inner and outer walls of a pipe, presenting a significant challenge for pipeline operators. In-line inspections (ILI) are essential for monitoring the progression of corrosion defects over time along the pipeline, allowing for optimization of maintenance plans to anticipate any potential loss of containment (LOC) and prevent it from occurring.

Underground pipeline failure occurs through the spread of corrosion over time, with a rate variation depending on the resistivity of the soil surrounding the pipeline. In the early stages, corrosion defects effect the pipe wall when the metal loss reaches 80% of the pipe wall thickness, causing a small leak; which is not authorized in the gas industry (Caleyo et al., 2002). The bursting occurs under the effect of the internal pressure at the location of the corrosion defects, and the rupture occurs when the through-wall defect, resulting from the burst undergoes unstable extension in the longitudinal direction.

Several studies in the past have focused on assessing the reliability of corroded pipelines based on multiple criteria and assumptions (Amaya-Gómez et al., 2019; Boufkhed et al., 2021; Zhou, 2010). Other studies have been oriented quantifying errors related to inspection tools to provide robust probabilistic models of corrosion growth and improve the accuracy of reliability assessments (Siraj, 2018; Stephens and Nessim, 2006). (Zhou and Zhang, 2016) have evaluated the impact of the model errors of burst capacity models on the reliability evaluation of corroded pipelines. The integrity assessment of corroded pipelines using dynamic segmentation and clustering has also considered (Amaya-Gómez et al. 2020). However, statistical analysis is not sufficiently investigated in past studies. For example, the investigation of the parametric estimation of corrosion defects, the effect of coefficients of variation and the correlation coefficient between defects. This analysis can enhance the accuracy of reliability assessments and ultimately optimize future maintenance actions.

In this study, a statistical analysis will be conducted on the data sample of the parameters of the corrosion defects (length, depth), obtained by the In-Line Inspection (ILI). The statistical moments will be analyzed to select a well-fitting distribution, and the correlation coefficient between the corrosion defects and their effect on the probability of failure will be estimated. Additionally, a sensitivity analysis to study the effects of the coefficient of variation of corrosion parameters, operating pressure, and depth-to-thickness ratio on the probability of failure.

II. RELIABILITY ANALYSIS

A. Limit state function

The pipeline is modeled as a series system containing of multiples corrosion defects. The failure of one segment will lead to the failure of the entire system. Corrosion that spread over time reduces the wall's resistance to the operating pressure.

The limit state function is defined as the difference between the pressure resistances P_b, and operating pressure P_o. Mathematically, it can be expressed as follows:

$$G(X) = P_b - P_o \tag{1}$$

Where $G(X)$ represents the limit state (or performance) function; $G(X) \geq 0$ represents safety state, and $G(X) \leq 0$ is the failure state (i.e., burst). The probability of failure is given by:

$$P_f = P\left[G(X) \leq 0\right] = \int_{g(x)\leq 0} f(X)dx \tag{2}$$

Where $f(X)$ is the joint probability density function that depends on the random variables that are involved in the limit state function -i.e., vector X . In our study, it represents the geometry of corrosion defects (i.e., depth, length, and width), pipe yield or tensile strength, operating pressure, geometric dimensions of the pipe. The computational complexity of equation (2) depends on the number of random variables and the form of limit state function. To solve this problem, we can used approximation methods such as, first and second-order reliability methods (FORM and SORM), which are based on the search for the design point, which represents the shortest distance from the origin in the normed space. Alternatively, we can use simulation methods such as the Monte Carlo method.

Several models have been proposed in the literature to evaluate the burst pressure, such as the one by Amaya-Gómez et al. (2019). For our study, the burst capacity model reported by Netto et al. (2005) is selected in this study. This widely used model only requires geometric information about the corrosion defects (depth and length), and depends on the pipe's geometry and mechanical properties (e.g., yield strength).

$$P_b(T) = \frac{(1.1\sigma_y)2t}{D}\left[1 - 0.9435\left(\frac{d(T)}{t}\right)^{1.6}\left(\frac{L(T)}{D}\right)^{0.4}\right] \tag{3}$$

Where σ_y is the yield strength, D is the diameter, t the wall thickness, d , L , is the depth, and length of corrosion defects, respectively (Figure 1).

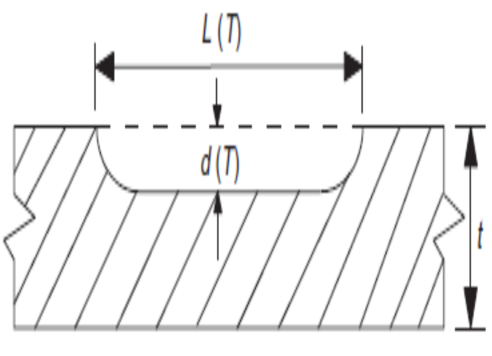

FIGURE 1. **Schematic illustration of the geometry of a typical corrosion defect**

B. Corrosion growth model

The model-localized corrosion reported by Ahammed and Melchers (1996), is chosen in this study. Indeed, it is well known that the underground pipelines are more subject to localized corrosion than the other forms of corrosion. In the other hand, the pipeline reliability is more sensitive to the localized corrosion than the uniform one, which tends to underestimate the failure probability. This model is described by the following equations:

$$d(T) = d_0 + V_r\left(T - T_0\right) \quad (4)$$

$$L\left(T\right) = l_0 + V_a\left(T - T_0\right) \quad (5)$$

Where d_0 and l_0 represent the initial depth and length of the corrosion defect respectively, detected during the last time inspection T_0, the V_r, V_a are radial and axial corrosion growth rate, respectively; they are given by:

$$V_r = \frac{\Delta d}{\Delta T} \qquad V_a = \frac{\Delta l}{\Delta T} \quad (6)$$

The linear growth of the corrosion can be considered as a realistic assumption because the inspection interval is enough large to guarantee that the growth leads to a steady state rate (Ahammed and Melchers, 1996; Caleyo et al., 2002). In our study, the inspected interval is 9 years, as indicated in the inspection reports.

C. Variables dependencies

Pipeline reliability is influenced by the physical dependencies between the parameters considered in the model. These physical dependencies will be represented herein by the correlation coefficient (ρ), which is given by:

$$\rho = \frac{n\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{\sqrt{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2} \cdot \sqrt{n\sum_{i=1}^{n} y_i^2 - \left(\sum_{i=1}^{n} y_i\right)^2}} \quad (7)$$

In this study, the correlation coefficient evaluates the dependence between the corrosion parameters (length and depth) and their impact on the pipeline reliability (i.e.; probability of failure and reliability index). We use the Pearson function in MATLAB to calculate the correlation coefficient.

III. NUMERICAL APPLICATION

The case study concerns an API 5L X60 steel pipeline located in Algeria. The pipeline is 48 km long, has a diameter of 1067mm, a nominal wall thickness of 12.7mm, and maximum operating pressure (MOP) of 7MPa. The pipeline is divided into segments, with an average length of 11.7m, and it crosses various geographical areas.

An in-line inspection tool using MFL technology was used collect corrosion defects along the pipeline. This tool can detect, locate, and size corrosion defects. According to the analysis of results reported by MFL, the majority of corrosion defects are located on the outer wall of the pipe due to deterioration of the coating layer and cathodic protection system. The inspection tools provide information on the geometry of corrosion defects, including length, width, and depth.

We carried out a Statistical analysis on the pipeline's characteristics, such as operating pressure, wall thickness, yield strength, and tensile strength, as well as the geometry of the corrosion defects, including length and depth. These characteristics are considered random variables and are characterized by their mean and coefficient of variation, as shown in Table 1. **It should be noted that the corrosion evolution rates (axial and radial) have been derived from the literature. The selection of these parameters considers the pipeline's geometry, the steel of the pipeline, and the initial corrosion defects.**

TABLE 1. Probabilistic characteristics of random variables for the pipeline X60 in the reliability analysis

Parameters	Unit	Distribution	Mean value	Coefficients of variation (CoV)	Source
Wall thickness (t)	mm	Normal	12.7	0.05	-
Diameter (D)	mm	Deterministic	1067	-	-
Internal pressure (P)	Mpa	Normal	4.85	0.79	-
Material yield stress σ_y	Mpa	Lognormal	476	0.07	(Seghier et al., 2018)
Ult. tensile strength σ_u	Mpa	Lognormal	576	0.08	
V_r	mm/y	Normal	0.26	0.05	(Xie and Tian, 2018)
V_a	mm/y	Lognormal	10	0.1	

We determined the probability densities from a statistical analysis on a data sample (Figures 3 and 4). We also conducted a study to determine the most suitable distribution function using the maximum likelihood estimation (MLE) method. This study and the figures above demonstrate that the generalized extreme value (GEV) distribution fits better for the corrosion data, which was validated using a Kolmogorov-Smirnov test. We also evaluated the statistical moments of the random variables of these parameters, which are presented in Table (2).

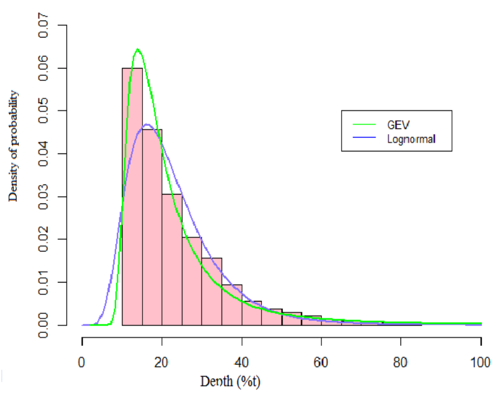

FIGURE 2. Probability density function of the corrosion depth (%t)

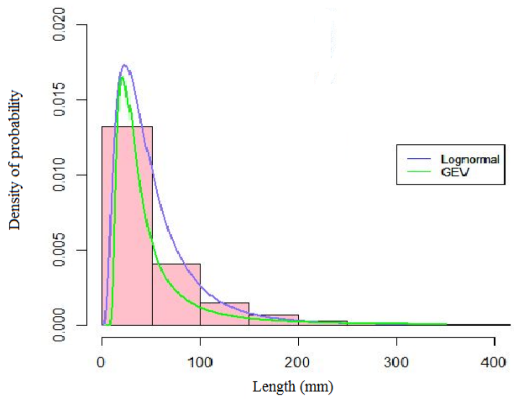

FIGURE 3. **Probability density function of the corrosion length (mm)**

TABLE 2. **Statistical analysis for geometry defects of corrosion**

Parameter	**Distribution**	**Parameter GEV**	**Mean**	**Coefficient of variation (Cov)**
Depth (mm)	GEV	$K = 0.417$ $\sigma_{GEV} = 6.171$ $\mu_{GEV} = 16.066$	3.05	0.087
Length (mm)	GEV	$K = 0.64$ $\sigma_{GEV} = 16.93$ $\mu_{GEV} = 28.60$	37.12	0.74

The correlation matrix between the corrosion parameters (depth and length) was estimated using the coefficient of Pearson and given as follows:

$$\rho_{d,L} = \begin{pmatrix} 1 & 0.4 \\ 0.4 & 1 \end{pmatrix} \tag{8}$$

In this study, the performance function given in equation (1) was generated by 10^5 Monte Carlo Simulation (MCS) method, for two case: one where the random variables are considered independent and another where the variables are mutually dependent. The results are shown in Figure (5). Based on the results presented in Figure 5, we found that the probability of pipeline failure is close to zero for the first 10 years of service. However, it increases and eventually reaches a state of bursting or failure after 40 years of service. Additionally, we observed that the probability of failure is less significant in the case of dependent corrosion defects, compared to independent corrosion defects.

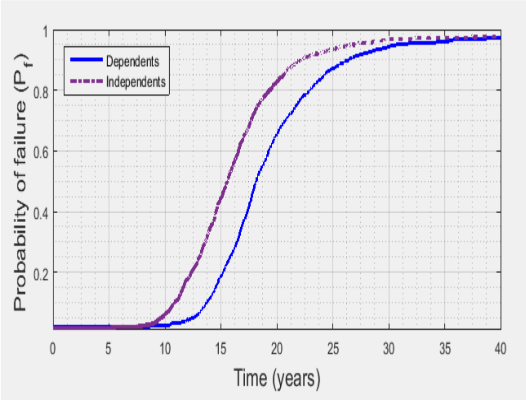

FIGURE 4. Probability of failure of the pipeline for two case, r.v independents and dependents

We also analyzed of the effect the coefficients of variation of corrosion defects (depth and length) on the probability of pipeline failure, which are presented in Figures 6 and 7. Figure 6 shown that the probability of failure is sensitive to the coefficient of variation of the depth of corrosion. For example, in 30 years, when the coefficient of variation is high, the probability of failure decreases, whereas it becomes more significant when the coefficient of variation is low.

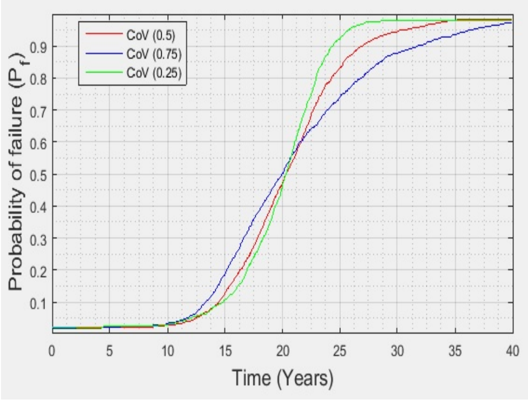

FIGURE 5. Probability of failure as function of CoV of the depth of corrosion

On the other hand, Figure 7 shown the variation of the probability of failure as a function of the coefficient of variation of the corrosion length. It should be noted that the variation of the COV of the defect length has less influence than in the previous case. Based on the previous results, it can be concluded that the COV of the depth has a greater impact on the pipeline's reliability than the defect length.

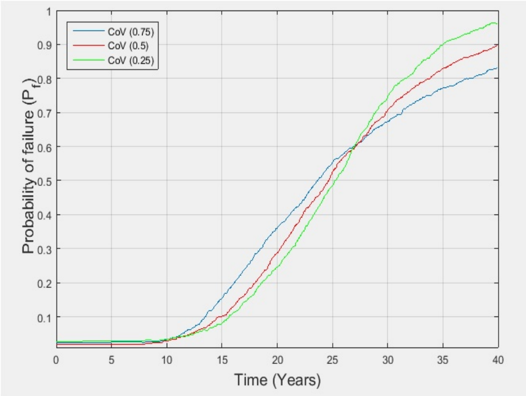

FIGURE 6. Probability of failure as function of CoV of the length of corrosion

Furthermore, the effect of different operating pressure levels on the reliability of the pipeline was also analyzed, and the results are presented in Figure 8. As depicted in this figure, it can be observed that the fluctuation in operational pressure has a notable impact on the safety of the pipeline. Additionally, as the operating pressure increases, the probability of failure also increases. In addition, the probability of failure varies with the variation of the depth/thickness ratio as shown in Figure 9. The study of the importance factors allowed us to estimate the importance of the parameters on the reliability of the pipeline. As well affirmed in this analysis, the parameters affecting pipeline safety are depth, thickness, and operating pressure. The pipeline operators must monitor these last parameters during their operational life, in order to maintain a targeted level of reliability. It is to note that these general conclusions remain valid for all underground pipelines subjected to corrosion.

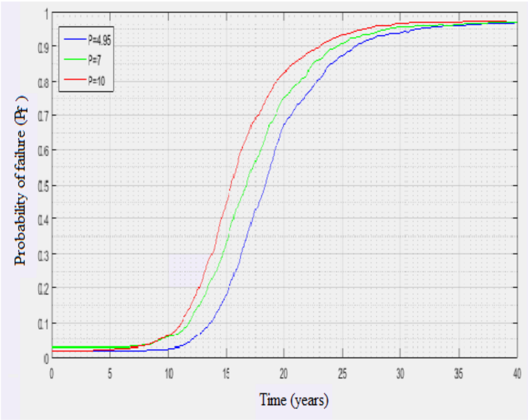

FIGURE 7. Probability of failure as function of variation on operating pressure

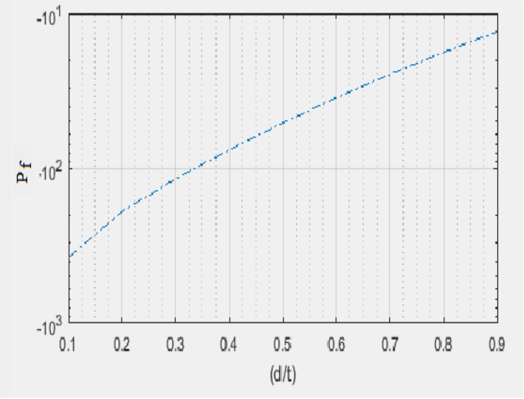

FIGURE 8. **Probability of failure as function of the depth/thickness ratio**

CONCLUSION

In this paper, a statistical study was carried out on a pressurized gas pipeline containing multiple corrosion defects. Based on inspection reports (ILI), statistical moments of the corrosion defects were evaluated, and the GEV distribution was found as the best fit for the corrosion defects (depth and length). The MCS method was applied to evaluate the probability of pipeline failure, considering independent and mutually dependent random variables. It has been observed that the correlation between corrosion parameters can significantly affect the reliability of the pipeline. Investigation of the coefficient of variation effects of corrosion defects on the probability of burst suggests that the coefficient of variation of defect depth has a remarkable effect on pipeline reliability in comparison with the variation of the defect length. In addition , a sensitivity analysis show that the operating pressure and the ratio of the depth/thickness significantly affect the reliability of the structure. The results of this study can provide valuable information for pipeline operators to make informed decisions about maintenance actions during the operational life of the pipeline.

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