Monetary risk analysis of operating corroded offshore pipelines

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Abstract. The offshore oil and gas exploration activity involves a complexity high degree, being characterized by high extraction costs and being long distances from the coast, making the pipeline mode essential to guarantee the flow of production. However, one of the main mechanisms of pipeline degradation is corrosion, which results in compromising the pipeline integrity. Therefore, risk analysis is necessary to avoid the consequences of pipeline failure. Therefore, the objective of this study is to analyze the risks of operating corroded pipelines offshore and carry out a parametric study of the depth-to-thickness ratio of the corroded pipeline, assisting in the decision-making process. To this end, it will be important to predict the mechanical behavior of the pipeline, to reduce the failure probability and ensure continuity of operations. Therefore, a numerical example was carried out to verify the condition of use of the pipeline, using semi-empirical method and kriging model, obtaining effective answers to assist pipeline operators in decision-making.

Keywords: pipeline, offshore, risk, corrosion.

1 Introduction

According to Abyani and Bahaari [1], pipelines are the safest and most economical mode of transporting oil and natural gas from production sites to their markets and end users. However, corrosion is the main problem that compromises the structural safety of the pipeline, which can result in environmental, financial and human losses. Furthermore, damage to offshore pipelines is more challenging, as they are several kilometers offshore and several meters deep, making the process more time-consuming and expensive.

Therefore, it is important to predict the mechanical behavior of pipelines to reduce the failure probability, since the risk of leakage cannot be entirely eliminated. Calculating risk involves determining both the failure probability and the failure consequences. Keshtegar et al. [2] emphasized that assessing the failure probability allows for the evaluation of pipeline safety levels.

According to D'Aguiar et al. [3], reliability analysis is essential in this problem because it considers the most relevant uncertainties of the corroded pipeline problem, such as: the growth of corrosion defects, loads, geometry and parameters of the pipeline material.

Therefore, the objective of this study is to analyze the monetary risks of operating corroded pipelines offshore and carry out a parametric study of the ratio between the depth (d) and thickness (t) of the corrosion defect and how this can influence the risk outcome, given that, as it is a commodity, the company's competitive advantage is obtained through its ability to produce at the lowest cost and efficiently. And, faced with market pressure for Environmental, Social, Governance (ESG) practices, adequate risk management in operating corroded pipelines becomes a major priority for pipeline operating companies to ensure the safe operation of pipelines and increase their productivity and reduce your financial losses, according to Abyani and Bahaari [1].

2 Problem description

According to Mishra et al. [4] corrosion is a complex physical-chemical phenomenon, that is, it is a probabilistic problem, which is influenced by environmental conditions, as well as characteristics and compositions of materials, and can cause serious accidents due to the flammability of the transported material. Liu et al. [5] argued that pipeline integrity management is an ongoing process, which allows pipeline reliability and risk to be managed within acceptable limits. Furthermore, Amaya-Gómez et al. [6] highlighted that if failure distinction is extremely conservative, unnecessary interventions can be implemented, increasing maintenance and repair costs, compromising the profitability of pipeline operators. Therefore, it is extremely important to analyze risk to assist the decision-making process.

2.1 Limit state functions of the pipeline

According to Pourahmadi and Sayban [7], the failure function necessary to perform the reliability analysis can be defined based on the limit state function according to eq.(1), where $\mathrm{G}(\mathbf{X})$ is the performance function or limit state function; $\mathrm{R}(\mathbf{X})$ is the resistance to failure; $\mathrm{S}(\mathbf{X})$ is the load (request); and $\mathbf{X}$ is a vector of N random variables.

$$\mathrm{G}(\mathbf{X}) = \mathrm{R}(\mathbf{X}) - \mathrm{S}(\mathbf{X}) \tag{1}$$

Thus, $\mathrm{G}(\mathbf{X})\leq 0$ represents the failure region and $\mathrm{G}(\mathbf{X})>0$ corresponds to the safety region. Therefore, failure probability P_f associated with $\mathrm{G}(\mathbf{X})$ which can be expressed as $P_f = P[\mathrm{G}(\mathbf{X}) \leq 0\ ] = P[\mathrm{R}(\mathbf{X}) \leq \mathrm{S}(\mathbf{X})\ ]$, which can be estimated by solving eq. (2), Guillal et al.[8].

$$P_f = \int f_R(x) f_S(x)\, dx \tag{2}$$

Therefore, in this study $\mathrm{R}(\mathbf{X})$ is the pipeline rupture pressure and $\mathrm{S}(\mathbf{X})$ is the solicitation that corresponds to the difference between the internal and external pressure that an offshore pipeline is subjected .

2.2 Failure Analysis Methods

According to Adumene et al. [9] Several failure analysis methods have been developed to evaluate plastic collapse. However, DNV-RP-F101 [10] is a validated method and according to Lee et al. [11] is the most used in the O&G industry, allowing the evaluation of simple corrosion defects under combined internal pressure and longitudinal compressive stress. Not being applied to pipelines with a class higher than X80, Stress Corrosion Cracking (SCC) and where a fracture is expected to occur (Amaya-Gómez et al. [6]). Furthermore, DNV-RP-F101[10] is not applicable to corrosion defects with depths exceeding 85% of the wall thickness. Therefore, from eq. (3) the rupture pressure P_b is calculated, where the Folias factor M is given by eq. (4).

$$P_b = \frac{\sigma_u\, 2t}{D-t}\left(\frac{1-\left(\frac{d}{t}\right)}{1-\left(\frac{d}{t}\right)M^{-1}}\right) \tag{3}$$

$$\mathrm{M} = \sqrt{\left(1 + 0{,}31\frac{L^2}{D.t}\right)} \tag{4}$$

Where D is the pipe external diameter, σ_u is the ultimate material stress, t is the pipe wall thickness, L is the pipe defect length, and d is the defect depth.

2.3 First-Order Reliability Method

By analyzing structural reliability, it is possible to obtain the probability of failure of the corroded pipeline. Thus, reliability methods are divided into analytical and simulation methods. The analytical methods are based on an approximation of the limit state surface in the standard domain to obtain the closest point on the surface to the origin of space, as an example the first/second order reliability method (FORM/SORM) stands out. Simulation methods are based on repeated sampling algorithms, the most popular of which is the Monte Carlo simulation (MCS) method (Guillal et al. [8]). And according to Chakraborty and Tesfamariam [12], despite being considered the simplest approach to evaluating pipeline reliability, if the probability of failure is small, the Monte Carlo convergence rate is very slow.

To this end, the use of the First-Order Reliability Method (FORM) stands out in this study, as it has been used successfully in several structural engineering problems, as argued Lee and Kim [13]; and because it seeks to approximate the failure surface to the limit state of a linearized surface to obtain the probability of failure, it provides accurate results and is very computationally efficient, they added Bonstrom and Corotis [14].

Furthermore, from DNV-RP-G101 [15], it was adopted in this study that the target failure probability to satisfy the safety level is 10^{-4} for offshore corroded pipelines, which corresponds to the ultimate limit state situation.

2.4 Kriging Model

In recent years, metamodels have been used for reliability analysis, since a surrogate model uses a limited number of design points and can represent a viable alternative to complex models that require a large computational effort. Examples of metamodels include polynomial response surface, sparse polynomial chaos expansion, support vector machine, neural networks and Kriging [16].

Among the metamodels, Kriging is the most widely used for reliability analysis, due to its interpolation capacity and the ability to provide a measure of local uncertainty in the model's prediction [17], in addition to its high computational efficiency [18]. For this work, the kriging surface presented by Torres et al. [19] was used.

2.5 Risk Analysis

According to Aljaroudi et al. [20] and Silva et al. [21] to carry out the risk assessment it is necessary to consider the consequences caused by the failure in addition to the probability of failure. A consequence of the failure is the leakage rate defined by DNV-RP-G101 [15], which can be obtained according to eq. (5), where D is the diameter of the defect at the start of the leakage, C_a is the discharge coefficient - assumed as 0.61 for liquids in DNV-RP-G101 [15], ρ is the density of the liquid in kg/m^3, P_0 is the operating pressure of the pipeline segment (MPa), and P_s is the external pressure surrounding the leakage point.

$$Q_h = 3600 \cdot \frac{\pi D^2}{4} \cdot C_a \sqrt{2\rho(P_0 - P_s)} \quad (5)$$

From the leakage rate, the cost of environmental consequences can be calculated, as presented by Kontovas et al. [22] in eq. (6), where C_{Env} is the cost of environmental consequences (in dollar); Q_h is the spill rate (barrels/hour); and T_{LP} is the period of time in which production was lost due to the spill (hours).

$$C_{Env} = 51432[0.001(Q_h \times T_{LP})]^{0,728} \quad (6)$$

The cost of lost production, C_{LP}, can be obtained from the eq. (7), according to the work of Aljaroudi [23], where C_{oil} is the price of oil ($86,97 per Barrel, [24]); and Q_{LP} is the quantity of lost production in (barrels/hour).

$$C_{LP} = Q_{LP} \times C_{oil} \times T_{LP} \quad (7)$$

To calculate deferred production (in dollar), C_{DP}, eq. (8), developed by Aljaroudi [23], can be used, where Q_{DP} is the quantity of deferred production in (barrels/hour); and T_{DP} is the time of the deferred production from the start of the shutdown until the completion of the repair (hours).

$$C_{DP} = Q_{DP} \times C_{oil} \times T_{DP} \quad (8)$$

The repair cost (in dollar), C_{Repair}, was defined by DNV-RP-G101 [15] based on eq. (9), where C_{UM} is the cost of unplanned inspection (in dollar) and C_{UI} is the cost of unplanned maintenance (in dollar).

$$C_{Repair} = C_{UM} + C_{UI} \quad (9)$$

The economic cost that may be incurred as a result of the consequences of the failure can be calculated using eq. (10), as defined by Kontovas et al. [22]:

$$C_{Eco} = LPC + C_{DP} + C_{Repair} \quad (10)$$

According to Aljaroudi [23], the failure cost in year T must be estimated through the future value of the total cost considering interest rates and inflation, according to eq. (8). In this equation, i is the nominal interest rate (10,5% per year [25]), and I is the inflation rate (3,93% per year [26]).

$$C_T(T) = [C_{Eco}(T) + C_{Env}(T)\,]\left(\frac{1+i}{1+I}\right)^T \quad (11)$$

Thus, to calculate the values of the consequences of failure, data from the research work to Aljaroudi [23], were used. And, according to Mehrafrooz et al. [27], the risk is obtained from the product between the failure probability and its consequences.

3 Case study

The pipeline offshore analyzed is made of X52 steel, operating in salt water and is subject to internal and external pressure, with a single defect, whose corrosion is uniform. It was considered that the last inspection of the pipeline was carried out 10 years ago and it was assumed that the growth of the corrosion defect is linear. The input data for this work adapted from the study by Ahammed [28]. The parameters were considered as random variables, where the statistical values of each variable are presented, as shown in Tab. 1.

Table 1. Parameters of Analyzed Pipeline

Parameters	Symbol	Mean	Cov	Distribution
Internal Pressure (MPa)	IP	8,5	0,1	Normal
External Pressure (MPa)	EP	0,6	-	Normal
Pipe Diameter (mm)	D	600	0,03	Normal
Pipe Wall Thickness (mm)	t	20	0,05	Normal
Pipe Yield Strength (MPa)	σ_y	423	0,067	Lognormal
Pipe Ultimate Tensile Strength (MPa)	σ_u	709,46	0,03	Lognormal
Initial Corrosion Depth (mm)	d_0	3	0,1	Normal
Initial Corrosion Length (mm)	L_0	200	0,05	Normal
Corrosion Depth Rate (mm/year)	d_{rate}	0,1	0,2	Normal
Corrosion Length Rate (mm/year)	L_{rate}	0,1	0,2	Normal

To calculate the probability of failure, the FORM method was implemented in Matlab (2016a), where only three random variables were considered (depth, thickness and internal pressure), due to the influence that these variables exert on the reliability of the pipeline, for more details see the study by Guillal et al. [8] and Abyani and Bahaari [1]. From the analysis of Fig. 1 it is possible to identify that from the 41rd year onwards, the pipeline exceeds the recommendation of the DNV-RP-G101 [15]. Therefore, it can be said that the remaining useful life of the in-service pipeline is 27 years ($T - T_0$), where $T = 37$ years and $T_0 = 10$ years. However, it can be observed that through the Kriging model it only reaches this probability in 41 years, that is, the useful life of the pipeline in service is 31 years.

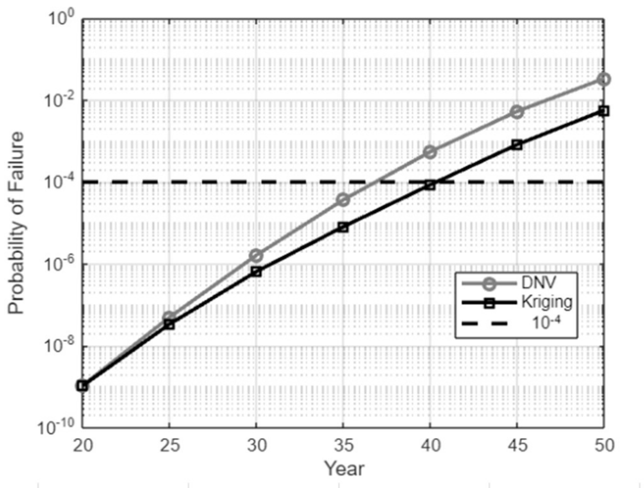

Figure 1. Probability of Failure Across Years

Therefore, even if the pipeline does not fail, after this period its use is no longer safe, but for pipeline operators to make structured decisions, the monetary risk is calculated to avoid an inefficient allocation of resources with maintenance and repairs, making it more expensive operation, since, Calixto [29] argued that competition in the O&G sector occurs through the ability to produce at a lower cost, through operational efficiencies, it is very important to guarantee the flow of production. Therefore, it was defined that the maximum risk that the operating company can accept is $200.000,00.

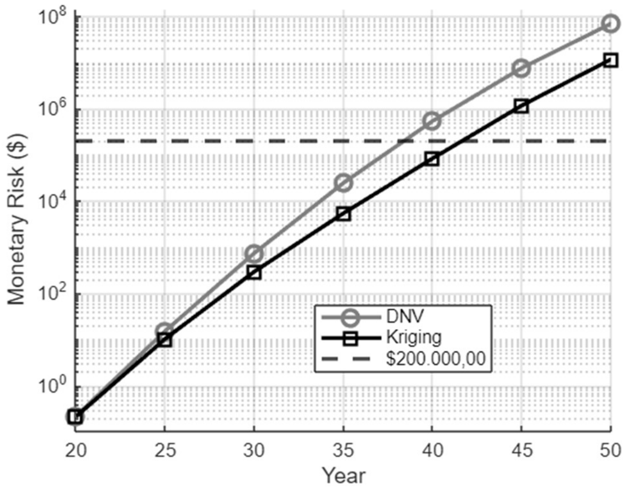

Figure 2. Monetary Risk Over Time

Thus, from the analysis of Fig. 2 it can be identified that in the 37rd year, the risk obtained from DNV-RP-F101[10] is $90.405,08, that is, the pipeline can continue operating, as it does not approach the maximum risk allowed by the organization $200.000,00 dollars. However, from the 39th year onwards, corrosion defects as they can compromise the organization's resources if the failure occurs. In addition, using the kriging method starting from year 42, more rigorous monitoring of the defect is crucial to ensure that the risk remains within the acceptable limit.

However, it can be identified from the parametric study it is highlighted that as the defect becomes deeper, the DNV-RP-F101[10] result becomes more conservative, greatly increasing the value of the monetary risk, that is, this can make the operation more expensive, resulting in repairs pipelines more frequently, as can be seen in the Tab.2.

Table 2. Parametric Study

Year	d/t	Risk-DNV	Risk-Kriging
20	0,4	$ 0,22	$ 0,215
25	0,45	$ 15,37	$ 10,41
30	0,50	$ 752,26	$ 298,32
35	0,55	$ 24.976,75	$ 5.493,20
40	0,6	$ 547.979,05	$ 84.985,55

4 Final remarks

In the O&G sector, the company's competitive advantage is obtained through its ability to produce at the lowest cost and efficiency. Associated with this, ESG practices are important elements that increasingly arouse the interest of investors.

In this context, the complexity of exploring O&G at sea stands out, the impact of a spill can reach large proportions, compromising safety, generating environmental contamination and damaging the company's image.

Therefore, seeking to remain competitive in the market and guarantee a good reputation in society, in addition to carrying out reliability analysis, it is essential to analyze the risk of operating corroded submarine pipelines, to guarantee the flow of production and avoid additional operational costs by carrying out repairs or unnecessary substitutions.

Finally, it is highlighted that DNV-RP-F101[10], despite being widely used, is suitable for superficial defects, but as the depth of the defect increases, the conservatism of the standard generates a higher risk value, making the operation more expensive. Thus, one can consider the use of more sophisticated methods, such as the Finite Element Method.

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