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RISK QUANTIFICATION IN CORRODED OFFSHORE PIPELINES USING SEMI-EMPIRICAL METHODS AND FINITE ELEMENT MODELS

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Abstract. *The oil and gas sector is vital to the global industry by contributing to foreign exchange markets, job creation, and energy supply. Pipelines are the preferred method for transporting these resources due to their cost-effectiveness and security. However, pipeline corrosion poses a significant challenge, leading to environmental, economic, and social consequences if not addressed. This study aims to analyze the risk of corroded offshore pipelines using statistical concepts and reliability methods like FORM and Monte Carlo simulation. Computational simulations based on the finite element method and semi-empirical methods will quantify the failure pressure. The study follows DNV-RP-F101 (2015) recommendations for failure pressure semi-empirical quantification and uses axisymmetric elements for numerical modeling. DNV-RP-G101 (2017) recommendations guide the risk assessment, providing insights for pipeline integrity management and an efficient monitoring system. The study found that failure probabilities derived from Monte Carlo and FORM simulations using a semi-empirical approach were similar. Additionally, when only one variable was considered random, the failure pressures calculated using the finite element method closely matched those from the semi-empirical method. Furthermore, the research unveiled earlier average risk intervals (approximately 2 years) through Monte Carlo simulations and an axisymmetric numerical model, contrasting with the FORM method with DNV.*

Keywords: *risk, pipelines, reliability, FEM, offshore.*

1. INTRODUCTION

The oil and gas sector is a determining factor in the global industry and of vital importance to modern society (IBP, 2019). Based on studies conducted in recent decades regarding industrial applications, it has been confirmed that the use of pipelines is the most economical and safe way to transport fluids over long distances, despite the gradual deterioration that can lead to irreversible environmental, economic, and social impacts in the event of a rupture (ABYANI; BAHAARI, 2021).

Among the possible causes of pipeline wear, structural and mechanical problems, natural hazards, issues arising from third-party operations, system malfunction, and corrosion (EL-ABBASY et al., 2014) can be mentioned. Corrosion is a natural process that occurs due to the interaction between the pipeline materials and the environment, and it can happen on the internal or external walls (XIE; TIAN, 2018). Typically, pipeline surface defects have complex shapes and small sizes compared to the overall length. However, they can grow under the influence of the fluid, leading to perforation and, consequently, leakage or rupture if the internal pressure exceeds the allowable limit (ALJAROUDI et al., 2015; LARIN; BARKANOV; VODKA, 2016).

In this context, the probability of failure (or rupture) of a corroded pipeline is closely linked to its structural reliability, which is the ability of the structure to meet the specified requirements for which it was designed during its service life (ISO, 2015; SAGRILO, 1994; SAKAMOTO, 2016). Consequently, many studies have calculated this probability using methods that employ analytical equations, including Monte Carlo simulation and FORM (ABYANI et al., 2022; HEGGAB; EL NEMR; EL AGHOURY, 2023). Additionally, widely used practical manuals in the industry, such as DNV-RP-F101 (2015), estimate the burst pressure of corroded pipelines (ABYANI et al., 2022). However, these models are generally computationally simple to implement and yield conservative conclusions (MOTTA et al., 2017). As an alternative solution, the burst pressure (a variable in the failure function calculation) can also be quantified using Finite Element Methods (FEM) (ABYANI et al., 2022; ABYANI; BAHAARI, 2021; HEGGAB; EL NEMR; EL AGHOURY, 2023; SUN; CHENG, 2018), as several studies have demonstrated that, when an appropriate failure criterion is established, FEM accurately evaluates the failure pressure of corroded pipelines (SILVA; GUERREIRO; LOULA, 2007).

Once the failure pressure is quantified, it is possible to obtain the failure probability through structural reliability analysis, which allows determining the risks associated with the structure. According to Beck's definition (2012), risk can be defined as the product of the probability of an event and its consequences. Therefore, it is essential to perform a qualitative evaluation of the consequences to determine the severity level and then quantitatively measure the associated risk.

For measuring these risks, the company Det Norske Veritas - DNV has established practical recommendation manuals that will be followed in this study. Among them, the DNV-RP-G101 manual (2017) stands out, as it provides guidelines for fixed offshore structure projects, including information on performance evaluation, repair processes, updates, and the associated risks of structural failure.

Thus, the objective of this study is to perform a risk analysis of a corroded submarine pipeline based on the concepts of structural reliability. To achieve this, the failure pressure will be quantified, employing semi-empirical methods and numerical modeling using finite element analysis of the pipeline in question. The practical recommendations of the DNV-RP-G101 manual (2017) will be used for the quantitative and qualitative assessment of the risk associated with structural failure. Finally, a comparative analysis will be conducted between the results obtained from semi-empirical methods and FEM to observe their divergences and provide relevant recommendations regarding the practical needs and associated risks.

2. METHODOLOGICAL PROCEDURES

Both internal and external corrosion are destructive phenomena that can disrupt the continuous flow of services and cause severe damage to existing pipelines during their operational lifespan (ABYANI et al., 2022). The structure is susceptible to corrosion leaks in two cases: when there is equality between the depth of the defect and the wall thickness of the pipeline, or when rupture occurs, meaning that the internal pressure exceeds the maximum allowable limit at the corroded point (ALJAROUDI, 2014). The latter is considered the most critical type of leakage.

Determining this failure pressure is crucial for applying structural reliability methods, allowing the quantification and qualification of the risk associated with the possibility of rupture.

The risk associated with an event or activity can be calculated by multiplying the probability of the event occurring by the resulting consequences of that event. In risk analysis in engineering, the considered events are failures, as they do not fulfill the function for which the system was designed, failures to provide that function with the desired efficiency, or failures that lead to accidents (BECK, 2012).

Therefore, in this study, the statistical determination of failure probabilities for an offshore corroded pipeline is initially performed. Then, the resulting consequences of these failures are evaluated, considering the economic impacts. With this information, it is possible to establish corresponding risk levels and conduct the assessment. The following flowchart (Figure 1) graphically illustrates the adopted procedures.

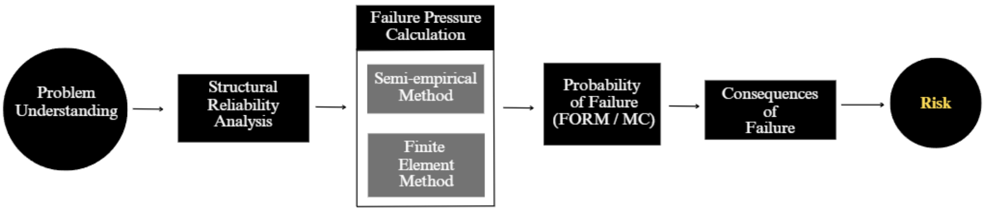

Figure 1. Flowchart of the adopted procedures.

According to Abyani (2020), the probability of failure is defined as the complement of the reliability function, which is the probability of a system remaining operational and within the specified performance limits.

Considering the function $g(U)$ (**U** is the vector of random variables), where the failure domain occurs when $g(U) < 0$, it is necessary to calculate the probability of this function assuming values in this domain to determine the probability of failure. Therefore, the failure function (Z) can be defined as:

$$g(U) = Z = R - S \tag{1}$$

where $\boldsymbol{R}$ is the random variable of resistance and $\boldsymbol{S}$ is the random variable of the system's demand.

This probabilistic analysis allows for the evaluation of risk and the implementation of appropriate measures to ensure the reliability and safety of the system in question.

2.1 Limit State Functions

This study considers two limit state functions for corroded offshore pipelines: leakage limit state function and rupture limit state function. The probability of failure due to rupture is defined as the probability of the pipeline's operating pressure exceeding the failure pressure (P_f). In the risk analysis of pipelines with corrosion defects, it is essential to determine the failure pressure as part of the failure function (Eq. 1) used in the reliability analysis. To achieve this, the semi-empirical method proposed in DNV-RP-F101 (2015) is employed for the calculation of the failure pressure (it is noteworthy that the equations proposed by DNV-RP-F101 (2015) refer to the BS-7910 (2005) standard).

There are three distinct categories of defects according to the practical manual: simple defects, interacting multiple defects, and complex-shaped defects. A simple defect is one that does not interact with adjacent defects and has its own failure pressure. The scope of this study is limited to the analysis of simple defects.

The choice of the DNV-RP-F101 (2015) method was based on its ability to provide more realistic results compared to other available methods, as mentioned by Vanhazebrouck (2008). The Matlab software (version 2022) was used in the process of applying the method proposed by DNV-RP-F101 (2015).

It is important to note that some simplifications are made regarding the geometry of the defects. The DNV manual approximates the irregularities of the actual defect using a rectangular defect, which is considered the most critical case. As a result, the failure pressure is underestimated, making the analysis more conservative in terms of safety, as observed by Silva (2016).

When evaluating the limit state of the material, the circumferential stress equals the rupture stress, and the acting pressure becomes the failure pressure (P_f). Knowing that the Folias dilation factor (F) is defined through Eq. (2), the failure pressure is quantified using Eq. (3) (taken from the DNV_RP-F101, 2015).

$$F = \sqrt{(1 + 0{,}31\frac{L^2}{D.t})} \tag{2}$$

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

where $\boldsymbol{D}$ is the pipe external diameter, $\boldsymbol{\sigma_u}$ is the ultimate material stress, $\boldsymbol{t}$ is the pipe wall thickness, $\boldsymbol{L}$ is the pipe defect length, and $\boldsymbol{d}$ is the defect depth. However, it is noteworthy that in the case of small leaks, the pipeline does not experience plastic collapse at the point of failure causing a rupture. Therefore, Eq. (3) is not applicable for the limit state function related to leakage.

According to DNV-RP-F101(2015), the depth that characterizes failure is equivalent to 85% of the pipeline wall thickness. Therefore, values below this target depth should be disregarded for the analysis of critical corrosion depth (d_c).

In this study, pipelines with corrosion depths exceeding 85% of the wall thickness will be considered at higher risk of failure. To monitor the growth of this defect, the product of the annual radial growth rate (d_A) and the time interval (T) will be added to the initial depth (d_0) for each new interval, as described in Eq. (4) (ALJAROUDI, 2014).

$$d(T) = d_0 + d_A * T \tag{4}$$

Thus, the failure function (Z) for the case is defined as follows:

$$Z = d_c - d(T) \tag{5}$$

2.2 Monte Carlo and First Order Reliability Method (FORM)

The goal of Monte Carlo simulations for system reliability analysis is to determine how many times a random point falls within the failure region, considering all the simulations performed. Simply put, this method allows testing a wide range of different random variables to obtain more accurate results of the failure probability. The failure probability in the Monte Carlo method is calculated by taking the ratio of the number of simulations that fall within the failure domain to the total number of simulations, as shown in Eq. (6). The indicator function (I) takes a unit value when $g(\boldsymbol{U}) \leq 0$, and a null value otherwise (ABYANI & BAHAARI, 2020).

$$Prob_f = \frac{1}{n} \Sigma_{i=1}^{n} I \{g(U) \leq 0\} \tag{6}$$

where $\boldsymbol{Prob_f}$ represents the failure probability and $\boldsymbol{n}$ is the total number of samples.

In FORM (First-Order Reliability Method), statistical variables are transformed into independent standard normal variables, with the failure function expressed in the reduced variable space, which has a mean of zero and a standard deviation of one (SAGRILO, 1994). The main idea of the FORM method is that in the reduced space of independent standard normal variables and for a linear failure function, reliability can be easily determined by the shorter distance of the function to the origin ($\boldsymbol{\beta}$) (SAGRILO, 1994).

Each iteration includes the calculation of the standard deviation and the mean of the equivalent normal distribution, the reliability index, and the new point in the original space to be used in the next iteration (TORRES, 2009).

The random variables $\boldsymbol{U}$, which may be dependent on each other or not, are transformed into independent variables $\boldsymbol{V}$ with a standard normal distribution. The failure function $g(\boldsymbol{U})$ is rewritten as $g(\boldsymbol{V})$, using the transformed variables. Then, the failure surface $g(\boldsymbol{V})$= 0.0 is approximated by a linear hyperplane at the point that has the shortest distance to the origin, called $\boldsymbol{V^*}$. This point is considered the design point in the reduced variable space.

The calculation of the failure probability using the FORM method is an approximation (BECK, 2012). This approximation can result in either a conservative estimate (favoring safety) or a non-conservative estimate (against safety), depending on the shape of the function $g(\boldsymbol{V})$ in the reduced space. Figure 2 illustrates an equivalent linear approximation of the failure function $g(\boldsymbol{V})$, around the design point, for both a concave (non-conservative) curve and a convex curve (conservative). In this figure, $\boldsymbol{\beta}$ is the reliability index, which is represented by the shorter distance to the design point (SAGRILO, 1994).

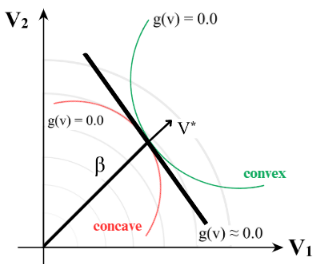

Figure 2. Approximation of the FORM method for concave and convex surfaces.

In this process (reliability analyses), it is important to determine the target failure probability for a design. In the case of offshore pipelines, the DNV-RP-F101 (2015), in the normal safety class, recommends a target failure probability of 10^{-4}. If the calculated failure probability during operation exceeds the target failure probability, it means that the pipeline is not safe for operation.

2.3 Finite Element Method

The Finite Element Method (FEM) allows for the discretization of the problem's geometry into finite elements for the numerical solution of equations. This enables obtaining approximate, yet viable, results for complex problems that cannot be solved analytically. The process involves discretizing the geometry into finite elements, defining boundary conditions and material properties, formulating the governing equations of the problem, and numerically solving these equations using solution methods such as the Gauss-Seidel method or the Jacobi method (SORIANO, 2009). This work utilizes the ANSYS 2020 R1 software to solve the mesh generated by the preprocessor Patran 2012.

2.4 Risk Analysis and Inspection

The risk management approach is based on following a previously structured process and utilizing the available knowledge in the best possible way to assess, mitigate (to an acceptable level), and monitor risks (ISO 2000).

During the inspection process, the analysis of consequences and the probability of failure is performed separately. The results are then combined to determine the involved risk. It is important to note that this assessment can be performed separately to address three fundamental aspects: safety (involving potential personal injuries), environment (focusing on environmental damage), and economic, considering potential financial losses (DNV, 2017). The scope of this work is limited to the analysis of the risk associated with monetary losses over the years.

According to DNV-RP-G101 (2017), risk assessment can be carried out using qualitative or quantitative methods. In practice, most risk-based inspections use a combination of both methods, thus being called a semi-quantitative method.

Furthermore, quantitative values can be expressed and presented in a qualitative manner for the sake of simplification, by assigning ranges to the probability and consequence of failure, and by determining risk values for risk classifications.

The failure consequences (C_{of}) that comprise the economic costs (C_{eco}) resulting from these consequences are based in the sum of three pillars: the financial losses attributable to the lost production cost (C_{pd}); the inspection cost (IC); and the maintenance costs (Mc) (Aljaroudi et al., 2015).

The value of deferred production is calculated using the production per hour multiplied by the number of hours at the reduced production rate (Eq. 7).

$$C_{pd} = Q_d \cdot (T_{pd} + T_{lp}) \cdot C_p \tag{7}$$

where $\boldsymbol{Q_d}$ is the deferred production (barrels/h), $\boldsymbol{T_{pd}}$ is the lost deferred production time due to pipeline shutdown for repair (in hours), $\boldsymbol{T_{lp}}$ is the deferred production time, which is the sum of the period in which production was lost due to the leakage (in hours), and $\boldsymbol{C_p}$ is the cost per barrel of oil ($).

The quantity of leaked products (Q_d) can be calculated using Eq. (8), where $\boldsymbol{D}$ is the diameter of the defect at the start of the leakage, $\boldsymbol{C_a}$ is the discharge coefficient - assumed as 0.61 for liquids in DNV-RP-G101 (2017), $\boldsymbol{\rho}$ is the density of the liquid in kg/m^3, $\boldsymbol{P_0}$ is the operating pressure of the pipeline segment (MPa), and $\boldsymbol{P_s}$ is the external pressure surrounding the leakage point.

$$Q_d = 3600 \cdot \frac{\pi D^2}{4} \cdot C_a \sqrt{2\rho(P_0 - P_s)} \tag{8}$$

This study assumes that the damaged pipeline is immediately replaced, and a fixed rate is used to calculate the inspection cost. Additionally, interest rates and inflation are used to calculate future costs.

Therefore, the total cost of economic consequences (C_{eco_t}) of failure in year $\boldsymbol{T}$ will be determined by the following equation.

$$C_{eco_t} = C_{eco} \cdot \left(\frac{1+i}{1+I}\right)^T \; where \; C_{eco} = C_{pd} + IC + Mc \tag{9}$$

In this equation, $\boldsymbol{i}$ is the nominal interest rate (13.75% per year), and $\boldsymbol{I}$ is the inflation rate (5.32% per year) (G1, 2023).

The risk associated with a failure is estimated as the product of the probability of failure and the consequence of failure (BECK, 2012). The growth of both occurs due to the advancement of the corrosive process over the years, expressed by annual rates of radial and longitudinal corrosion for the depth of corrosion and the length of corrosion, respectively (ALJAROUDI, 2014).

When qualitative or semi-quantitative methods are used, a decision matrix should be applied. The risk matrix shows three risk levels identified by colors: green represents low risk, where the risk is considered acceptable, and measures should be implemented to keep it within this region. Moving on to yellow, which denotes medium risk, the risk is still acceptable, but actions need to be taken to assess the extent of degradation. Finally, red indicates high risk, at which point the risk is deemed unacceptable. In this case, immediate action becomes imperative to reduce the probability, consequence, or both aspects of the risk, ensuring it falls within the acceptable region (DNV-RP-G101, 2017).

An example of a decision matrix (risk matrix) that depends on the probability and consequences of failure can be referred to in Table 1, taken from DNV-RP-G101 (2017).

Table 1. Decision matrix based on probability and consequence of failure (adapted from DNV-RP-G101:2017).

P_{of} Ranking	*Annual failure probability*		A	B	C	D	E
	Quantitative	Qualitative					
5	> 10^{-2}	Failure expected					
4	10^{-3} to 10^{-2}	High					
3	10^{-4} to 10^{-3}	Medium					
2	10^{-5} to 10^{-4}	Low					
1	< 10^{-5}	Negligible					
CoF Type	Business		No downtime or asset damage	< $ 10.000 damage or downtime < one shift	< 100.000 damage or downtime < 4 shifts	< $ 1.000.000 damage or downtime < one month	< $10.000.000 damage or downtime one year
CoF Ranking			A	B	C	D	E

2.5 Case Study

The objective is to determine the remaining service life of the pipeline before a failure occurs and the monetary risk associated with each year, based on the calculated consequences and probability of failure.

A pipeline with an initial corrosion depth of 4.6 mm and a length of 200 mm was considered for the case study. Other relevant information about the pipeline is presented in Table 2. For the semi-empirical quantitative analysis using the equations from DNV-RP-F101(2015), all these variables will be treated as random variables. However, in the numerical analysis using finite element method (which will be used to compose the failure function for reliability analysis through Monte Carlo simulation), except for the internal pressure, all the other variables will be treated as deterministic values for subsequent comparative analysis.

Like the work conducted by Aljaroudi (2015), it is assumed that it will take 4 (four) working days to identify or have a high certainty of a leak or rupture in the pipeline. Additionally, it is estimated that 7 (seven) working days will be required to restore the damaged pipelines.

It is assumed that the corrosion depth and length rates are 0.2 mm/year and 20 mm/year (Table 2), respectively, and follow a normal distribution. The simulation was conducted using Monte Carlo Simulation $1\text{x}10^6$ times for each time interval, and the FORM algorithm. All implementation was done in the MATLAB environment. This program contains the programming for calling the finite element analysis using Patran and ANSYS, as well as for the reliability and risk analysis. The input data for this work was extracted from the study conducted by Aljaroudi *et al*. (2014).

Table 2. Input values of the random variables in the analyzed pipeline model.

Variable	Unit	Mean	Std. dvn.	Distribution
Internal Pressure, P_o	*MPa*	6.7	0.7	Normal Distribution
Pipe Diameter, D	*mm*	600	18	Normal Distribution
Pipe Wall Thickness, t	*mm*	14	0.07	Normal Distribution
Pipe Yield Strength, σ_y	*MPa*	423	28	Log Normal Distribution
Pipe Ultimate Tensile Strength, σ_u	*MPa*	550	36	Normal Distribution
Initial Corrosion Depth, d_0	*mm*	4.6	1.1	Normal Distribution
Initial Corrosion Length, L_0	*mm*	200	4	Normal Distribution
Corrosion Depth Rate, d_{rate}	*mm/year*	0.2	0.04	Normal Distribution
Corrosion Length Rate, L_{rate}	*mm/year*	20	4	Normal Distribution

3. RESULTS AND DISCUSSION

3.1 Analysis using semi-empirical method

In the calculation of the failure probability due to rupture, considering all the input parameters (Table 2) as random variables and using Eq. (3) for calculating the failure pressure, simulations were performed with 10^6 samples (generated by the '*random*' command in MATLAB, following the pre-established distribution from Table 2) using the Monte Carlo method for each half-year interval (6 months).

Subsequently, the reliability analysis was conducted using the FORM algorithm considering the same variables for comparative effect. Each analysis was terminated when the absolute value of the failure function was less than 10^{-6}, establishing a stopping criterion. The comparison of failure probabilities obtained by the Monte Carlo and FORM methods, using Eq. (3) as the rupture pressure value, for a 20-year time interval (where year 0 represents the defect with the initial parameters from Table 2), can be observed in Figure 3(a).

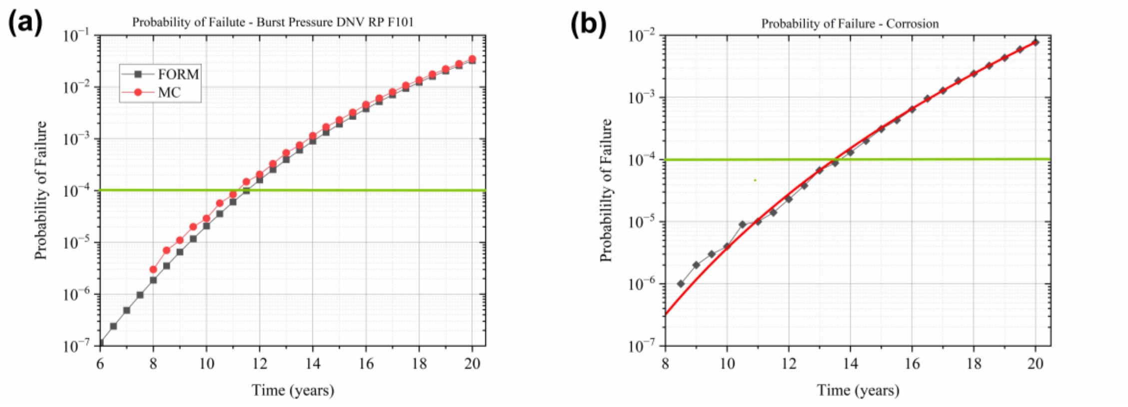

Figure 3. Probability of failure due to: (a) rupture and (b)leakage, over a 20-year period.

From Figure 3(a), it can be observed that the failure probability results calculated by both methods, using the semi-empirical equations from DNV, are practically similar. However, it can be noted that the results obtained by the Monte Carlo method are slightly more conservative, since it achieves the target failure probability earlier than the FORM method. It can be concluded that the target failure probability (10^{-4}) was achieved by both methods (FORM and Monte Carlo) between the 11th and 12th year in case of rupture (Figure 3.a.), and after 13º year in case of leakage (Figure 3.b).

Based on these results, it is evident that the pipeline operates for a longer period, before reaching the limit of the safe range. Leakage failure usually occurs due to gradual wear over time, while rupture failure is a sudden event. The failure mechanisms associated with leakage are slower and more progressive, taking more time to reach a critical level of deterioration (the defect thickness becomes equal to the pipe thickness), as it can be observed in Figure 3(b). On the other hand, rupture failure can occur abruptly when loading conditions exceed the material capacity. This accounts for the difference in elapsed time to reach the target probability of failure, in the two limit state functions.

3.2 Analysis through finite element models

The data from Table 2 were selected as deterministic variables to model an axisymmetric case, to verify the rupture pressure value obtained through FEM at the initial time $T = 0$. Figure 4 displays the distribution of von Mises stresses at the loading step that reached the rupture pressure.

It is observed that the calculated rupture pressure value using FEM is 22.62 MPa (Figure 4), for the initial time instant. Using Eq. (3) to calculate the failure pressure (semi-empirical model) for the same time instant, a value of 22.30 MPa is obtained. Based on this, a new analysis was conducted using the Monte Carlo method. In this analysis, a 20-year interval was considered with a total of 10^6 samples. The random variable used was the internal pressure, while all other input parameters (except for the internal pressure) in Table 2, were treated as deterministic variables.

The values obtained for failure pressure using Eq. (3) and FEM (for the axisymmetric case) remained close. Furthermore, even with the generation of new random samples from a normal distribution for internal pressure, it was noted that the failure probability values resulting from the failure function fed with the pressure values from the axisymmetric model, remained close to the failure probability results obtained from the semi-empirical models. However, it is expected that as the study progresses, new analyses can be performed considering all variables as random (such as material properties pipeline and defect geometric dimensions) and not just the internal pressure, using the FORM method. It is expected to provide a less conservative result for the failure pressure calculated, through the Finite Element Method (FEM).

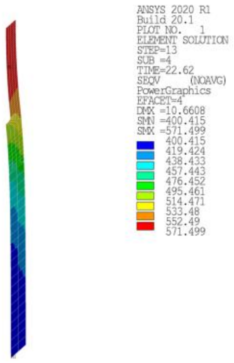

Figure 4. Distribution of von Mises stresses (SEQV) at the loading step that reached the rupture pressure.

3.3 Risk Analysis

Here, the risk analysis is based on the principle of calculating the total economic cost. In this context, the total economic cost is defined as the sum of expenses related to maintenance, inspection, and production (Eq. 9). To achieve this, the first step involved identifying the increase in fluid flow over the years, with the growth of the defect width.

The growth of the leakage rate in kg/h and barrels/h over the years, considering an external pressure of 5 MPa (the oil pipeline is at approximately 500 meters of depth), can be observed in Figure 5(a) and Figure 5(b) respectively.

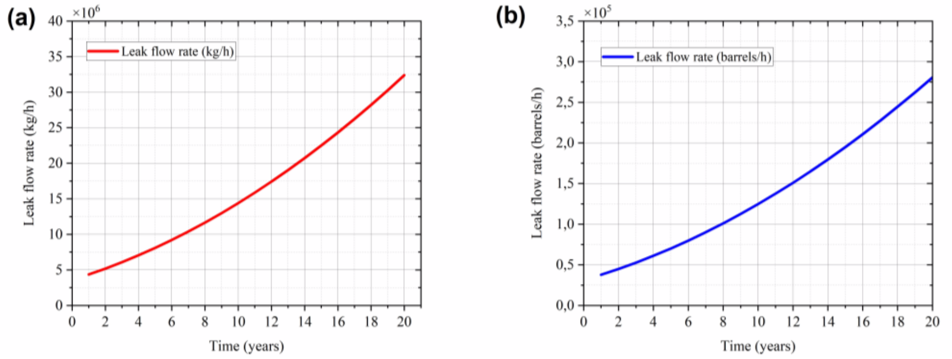

Figure 5. Leak flow rate: (a) in kg/h and (b) barrels/h.

As specified in section 2.5, considering the price of a barrel of oil at $74.89 (OILPRICE, 2023) and 11 (eleven) business days until the identification and necessary repair of the pipeline, the cost of approximately $ 745.988.068 dollars per hour of expended production (Eq. 7) was found under the initial condition of the pipeline (T = 0, L = 200mm).

Adding the cost of unplanned maintenance (Mc) and inspection (IC) (assessed at $115,000 by Aljaroudi, 2015) to the expended production cost, the new C_{eco} (Eq. 9) becomes $746,103,068 dollars per hour.

In Figure 6, the values of C_{eco_t} over the course of 20 years are presented, considering the Brazilian inflation rate of 5.32% per year and an interest rate of 13.75% per year (G1, 2023).

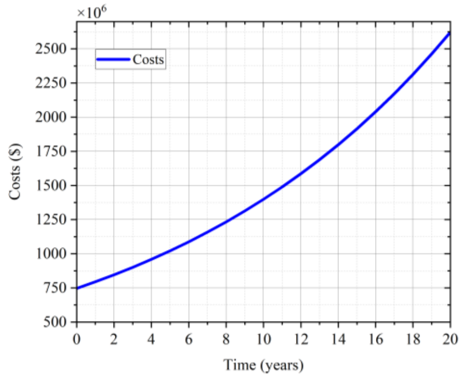

Figure 6. Cost associated with the expended flow rate over the years.

Therefore, the risk was calculated and compared by taking the product of economic failure consequences and the probability of failure ($Prob_f$) derived from the FORM (using DNV to determine P_f) and Monte Carlo (using FEM methods to determine P_f), for the same year. The results are presented in Figure 7 (a). As observed, the economic risk associated increases significantly with the increase in failure probability (Figure 7(a)). The exponential growth curve reinforces the idea that as time goes by, the process becomes more costly. Figure 7 (b) is a zoomed-in section of Figure 7(a) focusing on years 9 to 12 (which are the years that have failure probabilities closest to the target failure probability, according to Figures 3(a) and 3(b)).

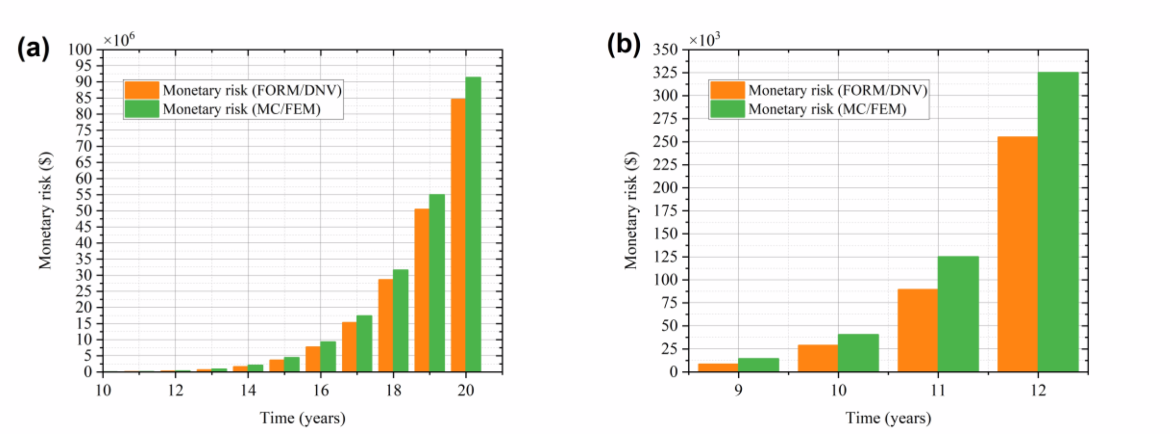

Figure 7. Monetary risk calculated based on the probability of failure using semi-empirical (DNV, 2015) and finite element methods: (a) results without graphical zoom and (b) results with graphical zoom.

Based on the monetary risk data and failure probability over the years, Table 1 was used to conduct a qualitative analysis of this information. Table 3 specifies the years and the associated risk, based on the data from Table 1 and the failure probability obtained through FORM (using DNV) and Monte Carlo (using FEM methods).

Table 3. Annual Qualitative Risk Analysis for the FORM (DNV) and Monte Carlo (FEM) methods over the years.

Method	Years															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
FORM (DNV)	A1	A1	A1	A1	A1	A1	A1	B1	B1	C2	C2	D3	D3	E4	E4	E4
MC (FEM)	A1	A1	A1	A1	A1	A1	A1	B1	C2	C2	D3	D3	D3	E4	E4	E4

When comparing the results obtained from both methods (Table 3), that are directly associated with the calculation of failure probability, it was observed that the Monte Carlo method with failure pressure calculated using the axisymmetric model in FEM, is more cautious regarding the range of economic risk (medium risk, according to Table 1, occurring in 9^{th} and 10^{th} years). This implies that the time interval during, which the pipeline is subject to medium risk, occurs earlier compared to the FORM method with failure pressure calculated using DNV. Thus, due to the higher probability of failure obtained from MC method, the results from the product of cost and probability of failure for those years became larger.

However, since only one random variable (internal pressure) was used, while all other input parameters (Table 2) were treated as deterministic variables, it may have caused the risk estimation to be as cautious as the Monte Carlo method (applying the axisymmetric numerical model). This is because both semi-empirical methods generally produce more conservative results than numerical models in FEM, as previously pointed out by Motta (2017). Thus, it is expected that the time interval of average risk obtained through numerical modeling will occur after the time interval presented by the other two methods, considering the randomness of other involved variables in numerical simulations.

4. CONCLUSION

In summary, this study aimed to comprehensively analyze the risks associated with a corrosion-affected offshore pipeline, employing both quantitative and qualitative methods. To achieve this, we employed a semi-empirical approach, as outlined in the DNV-RP-F101 (2015) standard, along with finite element analysis to calculate the failure pressure. Reliability analysis was conducted using Monte Carlo and FORM simulations, while the DNV-RP-G101 (2017) guidelines were utilized to assess and quantify the associated risks, resulting in the acquisition of valuable data.

Our findings revealed that the failure probabilities, as calculated by the Monte Carlo and FORM methods, using the equations from DNV-RP-F101 (2015), exhibit a remarkable convergence. However, the Monte Carlo method tends to adopt a more conservative stance under these circumstances, reaching the target probability a little earlier than the FORM method.

An important distinction emerged in the failure mechanisms – gradual failure due to defect depth versus sudden rupture failure caused by exceeding material capacity. This dichotomy significantly impacts the time required to achieve the target failure probability (approximately 2 years), especially in cases of defect depth-induced leakage, resulting in an extended lifespan.

The reliability analysis, conducted through Monte Carlo simulations with only the operating pressure as a random variable, along with the failure pressure calculated via the finite element method and semi-empirical equations (DNV-RP-F101, 2015), consistently produced similar failure probabilities.

Additionally, the study identified economic risks associated with monetary losses over time. Notably, the Monte Carlo simulations coupled with the axisymmetric numerical model demonstrated an earlier occurrence of average risk intervals (approximately 2 years) compared to the FORM method coupled with DNV (as depicted in Table 3). It is worth highlighting that this paper is part of an ongoing research endeavor by the author, aimed at expanding the range of random variables and investigating the behavior of risk analysis as these variables are added.

In conclusion, this risk analysis approach, rooted in structural reliability, provides valuable insights into the safety and economic risks associated with corroded submarine pipelines. Employing a strategy centered on risk-based inspection (RBI) can greatly enhance effective management of potential issues, mitigating the potential for catastrophic failures and safeguarding the interests of both human safety and the environment within the oil and gas industry.

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6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.