XLIII CILAMCE
21-25, November, 2022
FOZ DO IGUAÇU - PR - BRAZIL

Risk analysis in corroded buried pipelines

Marilia G. A. de Arruda[1], Thiago V. S. Ferreira[1], Silvana M. B. Afonso[1] Juliana v. S. Torres[2]

[1]*Dept. of Civil Engineering, Universidade federal de Pernambuco*
Av. Acadêmico Hélio Ramos, S/N, Cidade Universitária, 50740-530, Pernambuco, Brazil
marilia.alvesarruda@ufpe.br, thiago.victorf@ufpe.br, silvana.bastos@ufpe.br
[2] *Technology core, Universidade federal de Pernambuco*
Centro Acadêmico do Agreste, BR104 Km59, Sítio Juriti, 55200-970, Pernambuco, Brazil
juliana.von@ufpe.br

Abstract. Transporting fluids such as oil and gas through corroded pipelines presents economic, human and environmental risks. This work aims to make a qualitative and quantitative analysis of these risks, based on DNV-RP-G101 (2010). To measure it, it is necessary to analyze the failure probability through structural reliability methods. Programming was made using MatLab software. For the use of the FORM and Pure Monte Carlo, statistical data of random variables such as thickness and diameter of the pipe, internal pressure and defect depth are used. The failure function is defined here by the difference between the failure pressure and the acting pressure in the pipeline. For this, the failure pressure is calculated applying the method proposed by the practical recommendation manual, the DNV-RP-F101 (2015). In possession of the failure probabilities, which are obtained in the reliability methods, it is made the risk analysis of the buried corroded pipelines. Therefore, it is possible to analyze and compare results obtained in this analysis, aiming a greater safety with less cost.

Keywords: Risk analysis, corroded buried pipelines, structural reliability.

1 Introduction

The use of pipelines to transport oil and gas has increased considerably in recent decades, mainly because it shows the safest and most economical means of transporting these substances. However, according to the environment where it is located and especially with the advanced age of the pipes, the ducts have failures due to corrosion, which is the second biggest cause of collapses, behind only failures caused by external factors, such as poor operation and falling objects (DILAY, 2001) [1]. According to Pinto [2], pipeline corrosion and external interference are the major causes of damage and failures in the transport of oil and gas.

Corrosion is a type of failure that varies with time, which starts on the external wall of the duct and gradually increases to the point that its wall has a significant loss, even causing a leak. But this is not the only and not the worst type of damage that can be caused by corrosion. As the dimensions of the defect increase, the integrity of the pipeline is affected, which may cause a sudden rupture of the pipeline.

In this way, we sought to analyze the risks of leakage in buried pipes subject to corrosion. For this, it is necessary to determine the values of probability of failure and consequences of failure, since the risk is obtained through the product between them. Failure probability data was obtained through the study of structural reliability, through the application of the FORM and Monte Carlo methods. However, to start such a study, it is necessary to know the failure pressure, which will be defined according to the equations proposed by the practical recommendation manual, the DNV-RP-F101 [3]. The second parameter of total importance for obtaining the risk is the consequence of failure, in which the costs caused by the leakage of pipelines, referring to the environment, the economy and human, the latter will be used only in qualitative analysis, beings were taken into account. For its determination, the practical manual DNV-RP-G101 [4] was used, which was also used to perform the qualitative and quantitative analysis of the cost of failure, that is, the risk.

The risk analysis in corroded buried pipelines was performed qualitatively, in terms of severity, and quantitatively, in order to determine the risk in monetary terms. In this way, based on a limit already pre-defined by the operating companies (ALJAROUDI, 2015) [5], to find the critical year for pipe failure when using the FORM method and the Monte Carlo simulation method, in order to compare them and know the degree of conservatism of each one.

2 Methodology

Corrosion varies according to time, where it starts on the external wall of the duct and gradually progresses until, at a certain point, it consumes the entire wall thickness, causing a leak. However, even before complete corrosion occurs, there is already a threat because, occasionally, due to the weakness of the material at the corroded point, a sudden rupture can occur. Thus, it is extremely important to analyze critical years and failure probabilities.

2.1 Structural reliability

Structural reliability (SAGRILO, 1994) [6] is an assessment of the safety of a system, that is, it estimates the probability of collapse in its useful life. Reliability is defined as a complement to the probability of failure, which are the chances of this system breaking down. As this probability of failure is very small for structures, it is common to use reliability to measure the level of safety.

The structural reliability analysis is based on the existence of a failure function g($\mathbf{V}$) which represents the limit state, with V being the random variables (VANHAZEBROUCK, 2008) [7]. The limit state function must be defined at the limit where g($\mathbf{V}$) is equal to zero, that is, when it is on the verge of breaking. Generally speaking, this boundary will separate the risk zones (failure domain) where g($\mathbf{V}$)<0 and safe locations where g($\mathbf{V}$)>0, as shown in figure 1 below. When the function g($\mathbf{V}$)=0 means that the pipeline is on the verge of failure.

Thus, it is necessary to define the failure probability, that is, the probability that the failure function presents values within the failure domain (g($\mathbf{V}$)<0). So, the failure function is defined as follows:

$$g(\boldsymbol{V}) = Z = R - S. \tag{1}$$

where R is the resistance and S represents the solicitation. To determine the resistance of the pipeline, it is necessary to define the failure pressure.

2.2 Failure pressure

The pressure acting on the pipeline that causes it to rupture is called the failure pressure. To perform the risk analysis in pipelines with corrosion defects, it is initially necessary to define the failure pressure, to compose the failure function that will be applied in the reliability analysis. For this, the semi-empirical method of DNV RP-F101 [3] is used, a practical recommendation for the evaluation of corroded pipelines based on laboratory experiments using the finite element method developed by the Norwegian organization Det Norske Veritas. The choice of the DNV RP-F101 method was defined because it presents more realistic results among the methods studied by the adopted reference. (VANHAZEBRUCK, 2008) [7].

Corrosion defects are irregularly shaped, much like a parabola. The standard approximates these irregularities by a rectangular defect, which is the most critical case. In this way, the failure pressure is underestimated, making the analysis situation in favor of safety (SILVA, 2016) [8].

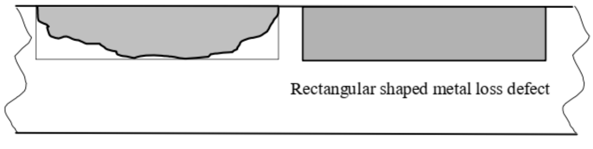

Figure 1. Approximation of the irregular defect

Thus, we can define the failure pressure as:

$$P_f = \frac{\sigma_u 2t}{D-t} * \left[\frac{1-\frac{d}{t}}{1-\frac{d}{t}.M^{-1}}\right]. \quad (2)$$

Where $\boldsymbol{\sigma_u}$ is the ultimate limit state stress of the material, *t* is the duct thickness, D is the duct diameter, d is the corrosion depth and M is the Folias factor.

In order to study the failure function, in addition to knowing the resistance of the pipeline, it is necessary to analyze the stresses in the pipeline. The requesting load is composed of the internal pressure of the fluid and the loads that act externally (ASTM A796/A796M-21) [9]. The internal pressure is a design data defined for the service limit state or to satisfy the need for fluid distribution according to the design desired. This value varies from project to project.

The external pressure for buried ducts is composed of the ground load above the duct (EL), the live loads (LL) and the impact loads (IL). Loads are applied as a fluid pressure acting on the surroundings of the duct (ASTM A796/A796M-21) [9]. These loads act as longitudinal compressive stresses. Soil load is determined by the soil column above the duct and the soil weight. As it is buried, the boundary condition of the duct is considered a restricted situation (AFONSO et al., 2020) [10], with no bending moment involved, only the external pressure, which is the weight of the soil column above the duct acting as external load.

2.3 Probability of failure

The probability of failure (***Pof***) is fundamental to analyze the safety of structures. There are some known methods to calculate it, among them the analytical method FORM (First Order Reliability Method) and methods based on Monte Carlo simulation. According to DNV-RP-F101 (2015) [3], a failure probability to be considered normal is in the range of 10^{-4} for the ultimate limit state of the material.

According to Sagrilo (1994) [6], in the FORM (first order reliability method) the variables that have statistical information are transformed into independent standard normal variables and the failure function is written in the space of reduced variables with zero mean and standard deviation. unitary.

According to Vanhazebrouck (2008) [7], Monte Carlo simulation is a technique in which a pre-defined number of simulations is performed in order to obtain points that simulate random variables in the standard normal space. In the context of reliability analysis, the purpose is to know the number of times that randomly generated points are within the failure region, among all the simulations performed. More simply, this method allows testing with a large number of different random variables to more accurately provide the results of the probability of failure.

2.4 Consequences of failure

The consequences of pipeline failure encompass both environmental and socioeconomic consequences, given in monetary value. In the case of more than one failure event, the risk will be the sum of the individual risks associated with the failure probabilities and consequences for each event. To measure it, the practical recommendation DNV-RP-G101(2010) [4] is used.

These types of consequences must be taken into account in order to carry out a qualitative and quantitative risk analysis. It is recommended that these analyzes be done individually according to the type of consequence. Three types of consequences can be cited: human, environmental and economic. The total consequences of failure (***Cof***) cover all types of consequences mentioned above. In this way, all the consequences are summed up. According to Beck (2012) [11], human consequences can be calculated based on GDP.

2.5 Risk analysis

Risk is the product of the probability of failure and the consequence of failure.:

$$Risco(T) = P_{of}(T) * C_{of}(T). \quad (3)$$

To determine the critical years of failure risk, it is necessary to know the probabilities and consequences of failure. The variation in the probability of failure and the consequences of failure is due to the growth of corrosion over the years. An annual radial and longitudinal corrosion rate are applied to the corrosion depth and corrosion length, respectively. The critical year in terms of corrosion depth failure risk is precisely the year in which, applying the annual rate of radial corrosion, the defect depth exceeds the limit given by DNV-RP-F101 (2015) [3]. Thus, indicating the need for a repair.

Another parameter that presents a critical year in terms of the probability of failure of the pipeline, in which it has a maximum allowed value of 10^{-4} for pipelines that do not present a high frequency of human activities, for the definition in the normal safety class (DNV -RP-F101,2015) [3].

The risk estimate can be presented as a risk matrix, depending on the probability of failure and the types of failure consequences (DNV-RP-G101, 2010) [4]. This matrix is a way of relating quantitative values to qualitative degrees. Table 1 is an example of a matrix given by DNV-RP-G101 [4], in which the failure consequence parameters are shown horizontally and the failure probability parameters vertically.

PoF Ranking	PoF Description	A	B	C	D	E
5	(1) In a small population, one or more failures can be expected annually. (2) Failure has occurred several times a year in the location.	YELLOW	RED	RED	RED	RED
4	(1) In a large population, one or more failures can be expected annually. (2) Failure has occurred several times a year in operating company.	YELLOW	YELLOW	RED	RED	RED
3	(1) Several failures may occur during the life of the installation for a system comprising a small number of components. (2) Failure has occurred in the operating company.	GREEN	YELLOW	YELLOW	RED	RED
2	(1) Several failures may occur during the life of the installation for a system comprising a large number of components. (2) Failure has occurred in industry.	GREEN	GREEN	YELLOW	YELLOW	RED
1	(1) Several failures may occur during the life of the installation for a system comprising a large number of components. (2) Failure has occurred in industry.	GREEN	GREEN	GREEN	YELLOW	YELLOW
CoF Types	Safety	No Injury	Minor Injury Absence < 2 days	Major Injury Absence > 2 days	Single Fatality	Multiple Fatalities
	Envirnoment	No pollution	Minor local effect. Can be cleaned up easily.	Significant local effect. Will take more than 1 man week to remove.	Pollution has significant effect upon the surrounding ecosystem (e.g. population of birds or fish).	Pollution that can cause massive and irreparable damage to ecosystem.
	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

Table 1. Example of a risk matrix

3 Results

The parameters studied of the pipe and the defects geometry is described in Tab. 2.

Variável		Média	Cov	Und
Pressão Interna	P0	7,7	0,07	Mpa
Diamentro do Duto	D	400	0,003	mm
Espessura da parede do duto	t	10	0,005	mm
Resistencia de escoamente do duto	σy	420	0,07	MPa
Resistencia à tração do duto	σu	520	0,065	MPa
Profundidade inicial do defeito	do	3	0,24	mm
Comprimento inicial do defeito	Lo	800	0,2	mm
Taxa de profundidade de corrosão	d rate	0,2	0,02	mm/ano
Taxa de comprimento de corrosão	L rate	20	0,2	mm/ano

Table 2. Parameters of the duct

According to the FORM and Monte Carlo results, it is observed that the Monte Carlo failure probabilities are slightly higher (≅ 25%) than those obtained by FORM. This means that for this analysis, Monte Carlo was more conservative, tending towards security.

The estimated risk can be defined as the estimated financial loss, that is, the expected cost. In this way, several operating companies deem it necessary to have this prior knowledge in order to minimize costs in the long run. Such companies set a risk target value; in this case it was $10,000. Thus, the critical year was found for both structural reliability methods as shown in Figure 2.

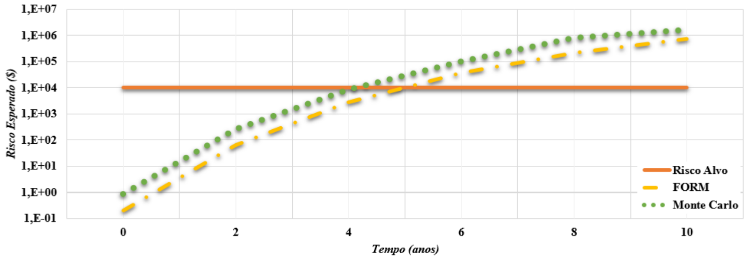

Figure 2. Results of the comparison between methods.

From Fig. 2 it is possible to identify the equivalent critical years for each of the reliability analysis methods, with FORM represented by the dashed line, Monte Carlo by the dotted line and the solid line representing the target risk. Thus, similarly to what happened in the failure probability, when applying the Monte Carlo method, a more conservative behavior is observed in relation to the FORM, with the 4th and 5th year as critical years referring to the estimated risk, respectively.

4 Conclusions

This work shows, throughout its development, to survey the risks and obtain the critical years of failure for a buried pipeline subject to corrosion through different methods of structural reliability analysis, and for this work FORM and Monte Carlo were used.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] DILAY, J. Pipeline Safety: Technology and Communication. Opening Plenary Lecture, Banff, Pipeline Workshop, Calgary; 2001.
[2] PINTO, Olivier Stephane Xavier. Avaliação numérico-experimental de métodos analíticos para cálculo da pressão de ruptura de dutos corroídos. 2007. 103 f. Dissertação (Mestrado) - Curso de Engenharia Oceânica, Universidade Federal do Rio de Janeiro, Rio de Janeiro, 2007. Cap. 1.
[3] DNV, "DNV Recommended Practice – DNV-RP-F101 – Corroded Pipelines", Det Norske Veritas, Norway, 2015.
[4] DNV "DNV-RP-G101. (2010). Risk based inspection of offshore topsides static mechanical equipment". Oslo, Norway: Det Norske Veritas.
[5] ALJAROUDI, A., THODI, P., AKINTURK, A., KHAN, F., & PAULIN, M. (2014a). Application of probabilistic methods for predicting the remaining life of offshore pipelines. Proceedings of the 10th International Pipeline Conference, IPC2014, Setembro 29 –Outubro 3, 2014, Calgary, Alberta, Canada.
[6] SAGRILO, L. V. S., Análise de Confiabilidade Estrutural Utilizando os Métodos Analíticos FORM e SORM, Tese de Doutorado, Programa de Engenharia Civil, COPPE/UFRJ, 1994.
[7] VANHAZEBROUCK, V. M., Análise de dutos corroídos por meio de método de confiabilidade estrutural. 2008. Dissertação (Mestrado) - Pontifícia Universidade Católica do Paraná, Curitiba, 2008, 139 p.
[8] SILVA, E. S., Análise da Integridade Estrutural de Dutos com Defeitos de Corrosão Interagentes Através de Modelagem Multifísica. 2016. Dissertação (Mestrado) – Universidade Federal de Pernambuco, Recife, 2016, 102 p.
[9] AMERICAN SOCIETY FOR TESTING AND MATERIAL. ASTM A796/A796M-21: Standard test method of water vapor transmission of materials. Philadelphia, 2021.
[10] AFONSO, S. M. B. et al. Desenvolvimento de metodologia para a avaliação de integridade estrutural de dutos terrestres e submarinos. Recife, 2020.
[11] BECK, A. T., Curso de Confiabilidade Estrutural. São Paulo. 2012.