



## COB-2021-1868

# PROBABILISTIC STUDIES OF THE COLLAPSE PRESSURE OF OVALIZED PIPELINES WITH CORROSION DEFECTS OBTAINED VIA SEMIEMPIRICAL METHODS AGAINST FEM

Vinícius W. S. Moura

Renato S. Motta

Dept. of Civil Engineering, LITPEG, CTG, UFPE

E-mail addresses: [vinicius.wendel@ufpe.br](mailto:vinicius.wendel@ufpe.br), [renatodesiqueira@gmail.com](mailto:renatodesiqueira@gmail.com)

**Abstract.** *The Finite Element Method (FEM) has been used in the literature as one of the most accurate approaches to quantify the remaining strength of the corroded pipes. The direct simulation of the physical phenomena, involved in the pipe failure, has helped to create, and validate several semiempirical equations used in the industry for the assessment of corroded pipelines. In this paper, results of the collapse pressure of a greater number of random generated corroded pipelines, subjected to external pressure, will be obtained using nonlinear FE analyses. The variables involved in each case are related to the pipe material properties, geometry of the pipe (including ovalization) and defect dimension. This system integrates several tools to automatically generate FE models, perform nonlinear analysis and to get the final (collapse) pressure. Two methods to generate the ovalized FE model will be tested. The results from four semiempirical equations for the collapse pressure of corroded pipeline (Bai and Hauch, DNV, Klever and Tamano, Netto) will be compared with results from the FE analyses. A probabilistic model of the error for each semiempirical method will be suggested for reliability and risk-based analysis applications.*

**Keywords:** *Corroded Pipelines, Ovalized Pipelines, Collapse Pressure Assessment, Automatic Finite Element Modelling, Semiempirical Methods*

## 1. INTRODUCTION

Corrosion is a chemical oxidation-reduction reaction that occurs in materials, usually metallics, is characterized by the transfer of electrons between the reaction agents. This degradation process on the surface of oil and gas pipelines, onshore and offshore systems, can be total or partial, single or multiple, presenting a reduction of pipelines thickness. Corrosion is one of the main causes of failure in production fields of oil and natural gas (Al-Moubaraki and Obot, 2021). In addition, corroded pipes in deep and ultra-deep waters must be resistant to external hydrostatic pressure (Fatt, 1999). The collapse pressure of the pipelines with corrosion defects can be obtained by the finite element method (FEM) due to non-linearity and complexity of the problem, but also by semiempirical methods and experimental.

Throughout the years, several studies and financial resources have been used to development of the oil and gas industry. At the same time, there were the improvements of the safety of these systems by means of rules and regulations to promote the prevention of accidents and failures risks, due to the major environmental, social, and economic damages (Oliveira et al, 2016). Likewise, the incorporation of probabilistic studies in the analysis of pipes failures has been used in the assessment of the collapse pressure, since some parameters of the problem as geometric and resistant properties of the pipes, dimensions of corrosion defects, and corrosion growth rate are approximations, with some degree of uncertainty. Each uncertainty is defined by a probability distribution function (pdf) based on observed and nominal values, and therefore, they are used to predict the probability of failure of corroded pipes along their useful life based on periodic inspections and maintenance plans.

Fatt (1999), in her study, presented a relation between corrosion, defined by the angular extent of corroded region and corrosion depth, and the collapse pressure. The proposed solutions are an extension of the Timoshenko and Gere (1961) equations for elastoplastic collapse of a cylindrical tube subjected to uniform external pressure. The study concluded that as the corrosion variables increase, the collapse pressure decreases in the same proportion. Oliveira et al (2016) analyzed the variation of the collapse pressure with the corrosion parameters from the perspective of reliability. A case study was proposed comparing four different defects and used a probabilistic model to predict the probability of failure of these pipes. It was concluded that deeper corrosion defects on the surface of the ducts have a higher probability of failure than the others.

Karadeniz (2001) studied the effects of ovalization on the stiffness matrix of offshore systems pipes with large diameter, subjected to uniform external water pressure. In the study is demonstrated an equation represented by harmonic functions to simplify ovalization, assuming variation only in the radial direction of the cross-section. Szary (2006) evaluated the resistance of corroded pipelines by the finite element method, at a certain point in the study, was analyzed

the collapse of intact pipes in which the ovalization was implemented. Szary concluded that ovalization has a significant influence on the collapse pressure results, presenting an even greater impact on the results in relation to surface corrosion shallow defects.

Other study on the reliability analyses of collapse pressure of pipelines with corrosion defects, (Motta et al, 2021). The paper highlights how ovalization is one of the most important parameters in the structural analysis of the collapse pressure of pipelines. It is a complex nonlinear phenomenon that stands out for reducing the resistance of the ducts. The ovalization of pipes (or out-of-roundness) is an initial deformation in the cross section, can occur in all stages during the life of the structure: in production (construction), transportation, installation, and service, leading to a more elliptical geometry. It can be induced by loads as bending and external pressure. The main design codes (DNV-OS-F101, 2013), (ASME B31G, 2012) treat ovalization only as a deviation of the cross section of the pipes during the phases mentioned by (Motta et al, 2021): production (forming), transportation, installation, and service. However, it is necessary to analyze the ovalization in the design of deep and ultra-deep pipelines subjected to external hydrostatic pressure.

This work aims to assess the collapse pressure of oval pipes with corrosion defects obtained by four semiempirical methods proposed by (Bai and Bai, 2005), (DNV-OS-F101, 2013), (Klever and Tamano, 2006) and (Netto, 2010) using probability analyses of failure. The structural reliability analysis will be performed via First-order Reliability Method (FORM) and Monte Carlo Method (MC) to evaluate the combined effects of corrosion and out-of-roundness in the pipelines. The results from semiempirical methods are compared with the collapse pressure obtained by the FEM using a software of automatic generation of finite element MSC Patran and Ansys in the automatic analysis of nonlinear mesh containing the parameters of corrosion and ovalization. The ovalization factors analyzed by the FEM are based on the methods proposed by (Motta et al, 2021) and (Karadeniz, 2001) implemented in the algorithm. Finally, a probabilistic error model for each semiempirical method with respect to the FEM method is formulated to assess the performance of these methods and use in the context of reliability analysis.

## 2. FINITE ELEMENT METHOD

In this work, the FEM is applied using a software developed by PADMEC using Python language as main management, PCL (Patran Command Language) to the model generation and Ansys APDL to perform the nonlinear analysis. The input data of this tool are the properties of the pipeline, the corrosion defect and the loading, the output is the collapse pressure. The tool automatically generates a section of the pipeline in Patran and executes it in Ansys, then returns the failure pressure value, through an iterative process. Both software has graphics resources able to develop the physics of the nonlinear problem in several 3D elements in order to predict the behavior of the structure with corrosion defect. This work considers as a failure criterion when the incremental pressure is lower than 0.01 MPa and the iterative procedure is unable to converge. Due to the symmetry of the problem, the tool only models a quarter of the tube and corrosion defect, see in Figure 1

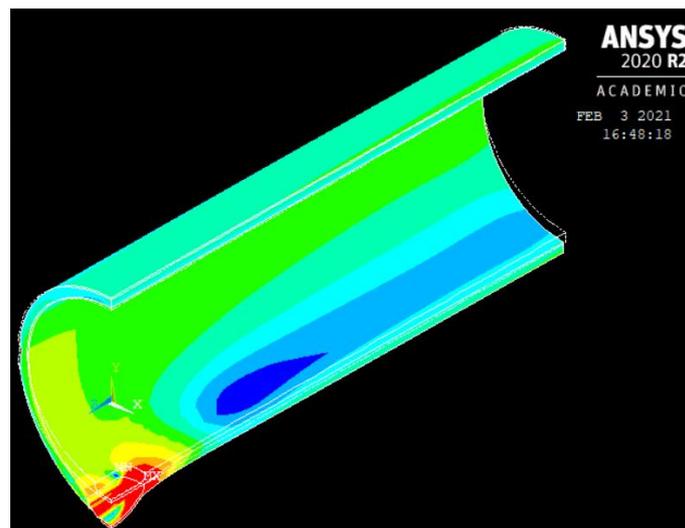


Figure 1. Ovalized pipeline and with corrosion defect in finite elements

### 2.1 Ovalization

This work considers the ovalization as an input data of the algorithm through the ovalization factor  $O$ , is defined in the Equation (1):

$$O = \frac{D_{max}-D_{min}}{\frac{D_{max}+D_{min}}{2}} = 2 \cdot \frac{D_{max}-D_{min}}{D_{max}+D_{min}}, \quad (1)$$

The model is initially built cylindrical and is posteriorly ovalized through nodal coordinate transformation in Python. Two transformations equation is used, in which only the radius coordinate of the nodes is modified. Motta et al (2021) considers the ovalized geometry as an ellipse. Starting from the equation of the ellipse, in Eq. (2), where  $x_n$  and  $y_n$  are coordinates of the ellipse. The major and minor semi-axes,  $a$  and  $b$ , are defined, respectively in Eq. (3) and (4).

$$\frac{x_n^2}{a^2} + \frac{y_n^2}{b^2} = 1, \quad (2)$$

$$a = R_0 \cdot \left(1 + \frac{O}{2}\right), \quad (3)$$

$$b = R_0 \cdot \left(1 - \frac{O}{2}\right), \quad (4)$$

After mathematical/trigonometric manipulations and isolating the radius, so obtained the formulation presented in, Eq. (5), in which  $R_0$  is the circumference radius,  $R_n$  is the radius of each point of the ellipse and  $\theta$  is the angle of each node.

$$R_n = R_0 \cdot \frac{(1-O^2/4)}{\sqrt{(1-O/2)^2 + 2 \cdot O \cdot \sin^2(\theta)}} = R_0 \cdot \frac{a \cdot b}{\sqrt{b^2 + 2 \cdot (a-b) \cdot \sin^2(\theta)}}, \quad (5)$$

Karadeniz (2001) that by means of harmonic functions considers the ovalization varying only in the radial direction as well. In his equation the main values of displacement  $\delta$ , in the direction X and Y, are obtained through the ovalization factor, Eq. (6) and Eq. (7). According to Karadeniz the displacement  $w_n$ , from Equation (8), is assumed to be positive for the outward direction and the ovalization as symmetrical. Therefore, the negative sign in the Eq. (7) represents that for the Y axis direction is inward direction. However, Karadeniz's equation can get an enough approximate configuration of the pipe deformation, the physical point of view the problem, because it maintains the thickness of the pipeline constant in deformed condition, defined in the Eq. (9):

$$\delta_x = \frac{1}{2} \cdot (O \cdot R_0), \quad (6)$$

$$\delta_y = -\frac{1}{2} \cdot (O \cdot R_0), \quad (7)$$

$$w_n = \frac{1}{2} \cdot (\delta_x - \delta_y) \cdot \cos(2 \cdot \theta), \quad (8)$$

$$R_n = R_0 + w_n, \quad (9)$$

In which  $w_n$  is the total displacement of each node of the pipe,  $R_0$  is the circumference radius,  $R_n$  is the radius of each point of the ellipse and  $\theta$  is the angle of each node.

### 3. SEMI-EMPIRICAL ASSESSMENT OF THE COLLAPSE PRESSURE OF CORRODED PIPELINES

This paper adopts the semi-empirical models for obtaining the collapsed pressure of corroded pipelines by four studies (Bai and Bai, 2005), (DNV-OS-F101, 2013), (Klever and Tamano, 2006) and (Netto, 2010). The models used, in their calculation methods, parameters such as pipeline geometry, dimensions of corrosion defects, concept of ovalization, or out-of-roundness, external water pressure loading. The results obtained by these calculation models are compared against the result of the FEM.

#### 3.1 Bai and Bai

Bai and Bai (2005), in their book *Subsea Pipelines and Risers*, studied the importance of the buckling and collapse strength of metallic pipes for the design of pipelines, or other offshore structures. The authors cited the studies by Bai and Hauch (1998) that extended the solutions proposed by Timoshenko and Gere (1961) to assess the collapse pressure in a pipe with corrosion defects.

Considering an initial deviation of the shape of the tube from a perfect circular form, Timoshenko and Gere associated this imperfection with the action of uniform external pressure. The stresses perceived in the tube are defined by the initial

yielding condition, a sum of the stress induced by the uniform external pressure and the stress induced by the bending moment. Taking this bending moment as the maximum compressive moment in the region of extreme fibers, it is possible to calculate the uniform yielding pressure since the yield stress is known from the tube material.

The extension proposed by Bai and Hauch is in the consideration of corrosion as one more imperfection in the solutions by Timoshenko and Gere, who already considered the initial ellipse (flattening or ovalization of the tube) as imperfection. Bai and Hauch accounts for the effects of corrosion by proposing to replace the pipe thickness  $t$  with the remaining wall thickness  $h$ , by Eq. (10), if the corrosion defect  $d$  is not too wide or deep.

$$h = t - d, \quad (10)$$

Based on the above, the problem's equilibrium equation is given by Eq. (11):

$$p_{iy}^2 - \left[ \frac{\sigma_y \cdot h}{R_0} + \left( 1 + 6 \cdot \frac{w_1}{h} \right) \cdot p_{el} \right] \cdot p_{iy} + \frac{\sigma_y \cdot h}{R_0} \cdot p_{el} = 0, \quad (11)$$

In which  $p_{iy}$  is the yielding uniform pressure in the extreme fibers,  $\sigma_y$  is the yield stress of the pipe material,  $R_0$  is the initial radius of the perfect circular section,  $w_1$  is the maximum initial deviation,  $p_{el}$  is the elastic collapse pressure, defined by Eq. (12):

$$p_{el}(t) = \frac{2 \cdot E \cdot \left( \frac{t}{D} \right)^3}{1 - \nu^2}, \quad (12)$$

In which  $E$  is the Young's Modulus,  $D$  is the nominal outsider diameter,  $\nu$  is the Poisson's ratio. In Eq. (11), the defect length and width are not explicitly reported in the assessment of the external pressure of collapse, an initial yielding condition, since the thickness of the pipe is reduced. According to (Teixeira et al, 2019), the estimative of this semi-empirical equation is acceptable in relation to the predictions obtained by the finite element method for not too wide or deep corrosion defects.

### 3.2 DNV-OS-F101

The DNV-OS-F101 standard also recommends in Section 5, Subsection D - Limit States, for the ultimate limit state the verification of the Local Buckling - external over pressure only, in which the external pressure at any point along the pipeline should fulfill the system collapse check, defined by Eq. (13):

$$p_e - p_{min} = \frac{p_c(t_1)}{\gamma_m \cdot \gamma_{SC}}, \quad (13)$$

In which  $p_e$  is the external pressure,  $p_{min}$  is the minimum internal pressure, this is normally taken as zero for as-laid pipeline,  $p_c$  is the characteristic collapse pressure, computed by Eq. (14),  $\gamma_m$  is the material resistance factor,  $\gamma_{SC}$  is the safety class resistance factor and  $t_1$  is the minimum wall thickness, the system collapse will occur at the weakest point in the pipeline. According to (Teixeira et al, 2019) although corrosion defects are not specifically accounted for the recommendation that collapse will take place at the damaged area, i.e., in the maximum corrosion depth  $d$ .

The characteristic resistance for external pressure (collapse) shall be computed solving Eq. (14):

$$(p_c(t) - p_{el}(t)) \cdot (p_c(t)^2 - p_p(t)^2) = p_c(t) \cdot p_{el}(t) \cdot p_p(t) \cdot O \cdot \frac{D}{t}, \quad (14)$$

In which:

$p_{el}(t)$  is given by Eq. (12).

$$p_p(t) = \sigma_y \cdot \alpha_{fab} \cdot \frac{2 \cdot t}{D}, \quad (15)$$

$O$  is given by Eq. (1).

$\alpha_{fab}$  is the fabrication factor,  $O$  is the ovality, should not be considered less than 0.5%.

### 3.3 Klever and Tamano

According to (Silva, 2018), the equation model for estimating the collapse pressure proposed by (Klever and Tamano, 2006) was intended to replace the equations recommended by (ISO/TR 10400, 2007). The authors presented the limitations of the current equations, the outdated statistical factors for today's tubes, the limitations of the experimental

tests to obtain the parameters of the equations, among others listed and defended by the authors. Also, according to Silva, the broad consensus made it possible to update the equations due to the reliable results that the semiempirical model produced.

The Klever and Tamano equation is like the equation proposed by Timoshenko and Gere for the design of tubes under uniform external pressure presented in subtitle 3.1 of this paper modifying only the imperfections inserted in the equation, given by Eq. (16):

$$p_{ult} = \frac{\{(pe_{ult} + po_{ult}) - [(pe_{ult} - po_{ult})^2 + 4 \cdot pe_{ult} \cdot po_{ult} \cdot Ht_{ult}]^{1/2}\}}{2 \cdot (1 - Ht_{ult})}, \quad (16)$$

In which:

$$pe_{ult} = \frac{ke_{ult} \cdot 2 \cdot E}{[(1 - \nu^2) \cdot (\frac{D}{t}) \cdot (\frac{D}{t} - 1)^2]}, \quad (17)$$

$$po_{ult} = ko_{ult} \cdot 2 \cdot \sigma_y \cdot \left(\frac{t}{D}\right) \cdot \left[1 + \left(\frac{t}{2 \cdot D}\right)\right], \quad (18)$$

$$Ht_{ult} = 0.127 \cdot O + 0.0039 \cdot \Xi_{ec} - 0.440 \cdot \left(\frac{rs}{\sigma_y}\right) + h_n, \quad (19)$$

where  $pe_{ult}$  is the ultimate (collapse) elastic pressure,  $po_{ult}$  is the yield pressure,  $ke_{ult}$  and  $ko_{ult}$  is the calibration factors for each level of steel and fabrication method,  $Ht_{ult}$  is the decrement function described by Eq. (19) in which  $O$  is the initial ovalization of the tube by Eq. (1),  $\Xi_{ec}$  is the eccentricity, a measure of the thickness variation,  $rs$  is the residual stress and  $h_n$  is a rounding factor related to tensile test curve of low yield steel qualities according (Brechan et al, 2020).

### 3.4 Netto

Netto (2010) proposed a method for to estimate of the collapse pressure of corroded pipes based on a combination of small-scale experimental program and nonlinear numerical analyses accounting for different material and defect geometries. The idea of his work was to establish a simple procedure that could enable the surveyor to instantly evaluate the detrimental effect of a single, narrow, and long defect, considered to be the most common type of defect encountered in the field. Netto reassessed your model with a set experimental recently published, and a good correlation was found, proving the reliability of the proposed equation for evaluating the detrimental effect of corrosion defects on the collapse resistance of pipes ( $\bar{P}_{COR}$ ).

Based on the above experimental and numerical data was adjusted to an augmented equation using the least square fit method according the Netto's equation by Eq. (20):

$$\frac{\bar{P}_{COR}}{\bar{P}_{CO}} = \left[ \frac{1 - \frac{d}{t}}{1 - \frac{d}{t} \cdot \left(1 - \left(\frac{c}{\pi \cdot D}\right)^{0.4} \cdot \left(\frac{l}{10 \cdot D}\right)^{0.4}\right)} \right]^{2.675}, \quad (20)$$

According to Motta et al (2021), the Equation (20) is a reduction factor of the collapse of pipes due to corrosion defects, in which  $c$  is the defect width,  $l$  is the defect length and  $\bar{P}_{CO}$  is a collapse pressure of intact pipe can be calculated for the Eq. (14), i.e., DNV formulation.

The equation was calibrated for a combination of geometrics parameters, as follows:

- Shallow defects. A defect is considered shallow when:

$$\left(0.1 \leq \frac{d}{t} \leq 0.2, \frac{c}{\pi \cdot D} \leq 0.1\right), \quad (21)$$

- Moderately deep defects. A defect is considered moderately deep when:

$$\left(0.2 \leq \frac{d}{t} \leq 0.4, \frac{c}{\pi \cdot D} \leq 0.1\right), \quad (22)$$

For this range, if

$$\left(\frac{c}{\pi \cdot D} \geq 0.15 - 0.25 \cdot \frac{d}{t} \text{ then } \frac{c}{\pi \cdot D} = 0.15 - 0.25 \cdot \frac{d}{t}\right), \quad (23)$$

- Deep and narrow defects. A defect is considered deep and narrow when:

$$\left(0.4 \leq \frac{d}{t} \leq 0.6, \frac{c}{\pi \cdot D} \leq 0.2 - 0.25 \cdot \frac{d}{t}\right), \quad (24)$$

In this range, if

$$\left(\frac{c}{\pi \cdot D} \geq 0.1 - 0.125 \cdot \frac{d}{t} \text{ then } \frac{c}{\pi \cdot D} = 0.1 - 0.125 \cdot \frac{d}{t}\right), \quad (25)$$

In all cases,  $l/D$  shall be fixed as 10. If  $l/D > 10$ , since the collapse pressure for all defects tend asymptotically to lower bounds according Netto (2010).

#### 4. RELIABILITY ANALYSIS OF CORRODED PIPELINES

The four previous semi-empirical equations mentioned and two reliability methods, MC (Monte Carlo) and FORM (First-Order Reliability Method), are used to obtain probability of failure estimations of corroded pipes subjected to external hydrostatic pressure. The reliability analysis of the pipes can be used as a consistent tool for the assessment of safety and integrity of corroded pipelines, Motta et al (2021). The limit state function, or failure function  $G(\mathbf{X})$ , in which  $\mathbf{X}$  is the vector of random variables, is defined as:

$$G(\mathbf{X}) = P_{COR}(\mathbf{X}) - P_{Ext}, \quad (26)$$

in which  $P_{COR}(\mathbf{X})$  is the collapse pressure of the pipe, that in this work is calculated using the equations for a given vector of random variables,  $P_{Ext}$  is the external hydrostatic pressure. The failure occurs when the function  $G(\mathbf{X})$  is equal to or less than zero.

The MC method is a statistical evaluation that consists of generating random samples to obtain numerical results. According to Motta et al (2021), the MC method has advantages, which is that the order of the probability of failure error, can be estimate and adjusted with sample size. But also, a great disadvantage for small  $P_f$  values, is that the sample size increases for greater accuracy. The Equation (27) defines the probability of failure approximation computed via MC, it is calculated by ratio of the number (sum) of the failures by the sample size:

$$P_f = P(G(\mathbf{X}) < 0) = \frac{N(G(\mathbf{X}) < 0)}{N_T}, \quad (27)$$

The FORM is a reliability analysis method that consists of transforming a vector of random variables into a vector of standard normal random variables. According to Motta et al (2021), the FORM approximates the limit state by a linear function through standard normal distribution, i.e., zero mean and unitary standard deviation, in the MMP (most probable failure point). The vector of random variables is inserted in a standard reduced space, and the probability of failure is approximated by the cumulative distribution function of the standard normal distribution, or  $\Phi(-\beta)$ , where  $\beta$  is the reliability index, is the distance from the origin of the reduced space to the failure region. The higher the value of  $\beta$ , the greater the safety or the less the  $P_f$ .

In this article, the procedure is elaborated in the Matlab computer program.

##### 4.1 Validation

Table 1 presents the main random variables and properties of the pipeline used here, taken from Teixeira et al (2019), that will be used to validate our tool.

Table 1. Pipe random variables and properties

Order	Random variable	pdf	Mean	Standard deviation
1	d (mm)	Normal	2.2	0.3902
2	l (mm)	Normal	168.0	9.505
3	c (mm)	Normal	91.0	10.0
4	D (mm)	Normal	304.8	0.3048
5	t (mm)	Normal	20.1	0.201
6	$\sigma_y$ (mm)	Lognormal	348.0	27.84
7	$O$	Normal	4.9E-4	0.49E-4
8	$p_{ext}$ (MPa)	Gumbel	26.6	0.7980
9	$Xc_{(d/t)}$	Normal	var	var
-	E (GPa)	Deterministic	200.0	
-	$\nu$	Deterministic	0.32	

The  $P_f$  for ovalized and corroded pipelines subjected to external hydrostatic pressure is obtained by semiempirical methods using FORM and MC using a Matlab computational tool, then it is validated by the work of Teixeira et al (2019). All parameters of pipes, dimensions and resistant properties, defect, and the ovalization and of the external loading, i.e., input values of the models are listed in Table 1. These parameters are defined by a pdf (probability distribution function) that describes the behavior of this random variable.

A sample of size  $G(d, l, c, D, t, \sigma_y, O, p_{ext}, X_{C(d/t)})$  was generated, and a MC analysis was performed. Figure 2 shows the Correlation Coefficients of each random variable with the failure function of the Netto's model in which the parameter 9 means the uncertainty factor of the semi-empirical models for the ratio between the maximum corrosion depth and the average thickness of the intact pipeline wall. Figure 2 shows the yield stress has the greatest importance for this example of corroded pipes, the variables that represent corrosion defects have an inversely proportional correlation with reliability. Thus, these results in have a physical meaning for the problem, the increase in the dimensions of corrosion defects implies a higher  $P_f$ . The ovalization of the pipes negatively affects the reliability of the problem, i.e., the  $P_f$  increases and consequently the collapse pressure decreases.

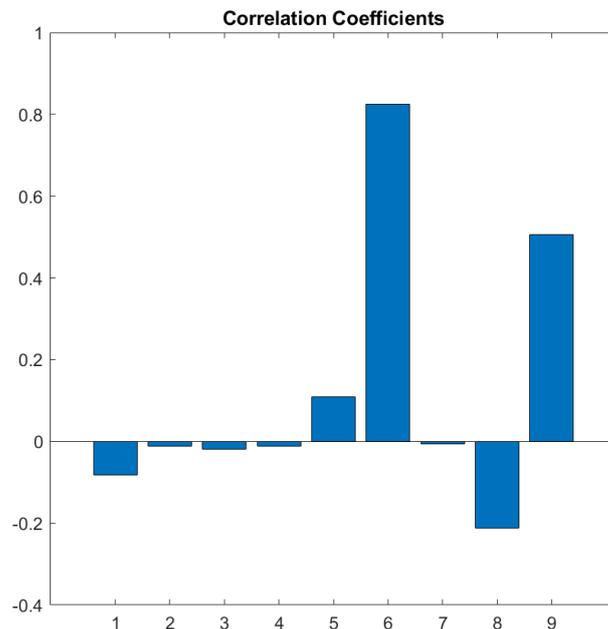


Figure 2. Correlation Coefficients, specially Netto's model.

The results of the probability of failure and the reliability index for each model are shown in Table 2. The sample size for the Monte Carlo method in the reliability assessment is 1,000,000. According to Teixeira et al (2019) it is observed, by the results of Table 2, a trend in reliability index values for the Netto, Klever and Tamano, and DNV methods. The Bai and Bai method, as expected, is conservative as it proposes to reduce the thickness of the entire tube (cylinder) for the remaining wall according to Teixeira et al (2019) and by Timoshenko and Gere (1961).

Table 2. Results of the reliability analysis evaluation

Models	MC (N = 1.0000E+6)		FORM		Teixeira et al			
	$P_f$	$\beta$	$P_f$	$\beta$	MC (N = 1.0000E+6)		FORM	
					$P_f$	$\beta$	$P_f$	$\beta$
Netto	3.4000E-5	3.9832	3.0870E-5	4.0061	6.1500E-8	5.2900	7.0400E-8	5.2600
DNV	2.8000E-5	4.0291	3.1474E-5	4.0015	4.8400E-7	4.9000	5.2900E-7	4.8800
Klever and Tamano	0	$\infty$	2.8548E-9	5.8250	8.9600E-8	5.2200	9.6700E-8	5.2100
Bai and Bai <sup>(1)</sup>	4.1000E-3	2.6430	4.2000E-3	2.6377	-	-	-	-

<sup>(1)</sup> no results to compare.

## 4.2 Results

Table 3 presents the values of the collapse pressure between the semi-empirical methods and the FEM for the input data in table 1. In the generation of the FEM mesh, the Karadeniz ovalization factor is considered.

Table 3. Results of the collapse pressures between method semi-empirical and FEM.

Method	Collapse Pressure (MPa)
Netto	38.78
DNV	45.31
Klever and Tamano	53.42
FEM ( <i>O – Karadeniz</i> )	55.21

## 5. CONCLUSIONS

This work has used a computational tool to evaluate corroded and ovalized pipelines subjected to external hydrostatic pressure by reliability analysis through semiempirical methods proposed by authors and studies. The results of the reliability analysis are validated by Teixeira et al (2019) studies and compared with the FEM presenting a good comparison, only the Bai and Bai method presents conservative results in relation to the others due to the initial conditions imposed by the study methodology.

The results confirm that the ovalization of the pipes as also corrosion defects negatively affect the reliability of the problem, i.e., the  $P_f$  increases and consequently the collapse pressure decreases according to Motta et al (2021) concluded in his study. The analysis of the Correlation Coefficients confirms that the yield stress is the most important variable in the assessment of the problem according to Teixeira et al (2019) studies. Demonstrating the importance of using reliability analysis for pipeline evaluation according to its main variables and uncertainties.

Furthermore, the combined effects of ovalization and corrosion defect contribute to the decrease in the resistant pressure of the pipelines, which in turn needs to be greater than the external hydrostatic pressure, as shown in the results of this work. Table 3 presents a negative correlation between the external hydrostatic pressure and the collapse pressure, so the subsea production of oil and natural gas must consider pipelines that serve these loads.

## 6. ACKNOWLEDGEMENTS

The authors would like to thank LITPEG (UFPE) for the infrastructure. Also, the authors wish to thank incentive programs and resources for the financial support of various research projects developed in this area by the PADMEC Research Group.

## 7. REFERENCES

- Al-Moubaraki, A.H., Obot, I.B., 2021. "Top of the line corrosion: causes, mechanisms, and mitigation using corrosion inhibitors". *Arabian Journal of Chemistry*, Vol. 14, Issue 5, pp. 103116. <https://doi.org/10.1016/j.arabjc.2021.103116>.
- ASME B31G, 2012. "An American National Standard ASME B31G-2012: Manual for Determining the Remaining Strength of Corroded Pipelines – Supplement to ASME B31 Code for Pressure Piping". *The American Society of Mechanical Engineers*, New York, USA.
- Bai, Y., Bai, Q., 2005. *Subsea Pipelines and Risers*. Elsevier Ltd., Oxford.
- Bai, Y., Hauch, S., 1998. "Analytical collapse of corroded pipes". Paper presented at *The Eighth International Offshore and Polar Engineering Conference*. Vol. 2, pp. 182-188. Montreal, Canada.
- Brechan, B., Teigland, A., Dale, S., Sangesland, S., Kornberg, E., 2020. "Collapse prediction of pipe subjected to combined loads". *Journal of Petroleum Science and Engineering*, Vol. 191. <https://doi.org/10.1016/j.petrol.2020.107158>.
- DNV OS F101, 2013. "Offshore Standard DNV-OS-F101: Submarine Pipeline Systems". *Det Norske Veritas*, Oslo, Norway.
- Fatt, M.S.H., 1999. "Elastic-plastic collapse of non-uniform cylindrical shells subjected to uniform external pressure". *Thin-Walled Structures*, Vol. 35, Issue 2, pp. 117-137. [https://doi.org/10.1016/S0263-8231\(99\)00021-X](https://doi.org/10.1016/S0263-8231(99)00021-X).
- ISO/TR 10400, 2007. "Petroleum and Natural Gas Industries – equations and calculations for the properties of casing, tubing, drill pipe and line pipe used as casing or tubing". *International Organization for Standardization*, Geneva, Switzerland.
- Karadeniz, H., 2001. "A Method for including ovalization effects of tubular member on cross-section properties." Paper presented at the *The Eleventh International Offshore and Polar Engineering Conference, June 2001*. Stavanger, Norway.
- Klever, F.J., Tamano, T., 2006. "A New OCTG Strength Equation for Collapse Under Combined Loads." *SPE Drilling & Completion*, Vol. 21, Issue 3, pp. 164-179. <https://doi.org/10.2118/90904-PA>.
- Motta, R.S., Leal, C.F., Ferreira, A.D., Afonso, S.M.B., Lyra, P.R.M., Willmersdorf, R.B., 2021. "Reliability analysis of ovalized deep-water pipelines with corrosion defects". *Marine Structures*, Vol. 77. <https://doi.org/10.1016/j.marstruc.2021.102969>.

- Netto, T.A., 2010. “A simple procedure for the prediction of the collapse pressure of pipelines with narrow and long corrosion defects — Correlation with new experimental data”. *Applied Ocean Research*, Vol. 32, Issue 1, pp. 132-134. <https://doi.org/10.1016/j.apor.2009.12.007>.
- Oliveira, N., Bisaggio, H., and Netto, T., 2016. “Probabilistic analysis of the collapse pressure of corroded pipelines”. In *Proceedings of the ASME 2016 35th International Conference on Ocean, Offshore and Arctic Engineering in Busan, South Korea, June 19-24, 2016*. Pipelines, Risers and Subsea Systems. Vol. 5. <https://doi.org/10.1115/OMAE2016-54299>.
- Silva, E.F.P. da, 2018. *Numerical-experimental study of the collapse of tubes of coated and production under axial tension and external pressure* (in Portuguese). Master’s Thesis, Program of Ocean Engineering, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil.
- Szary, T., 2006. *The finite element method analysis for assessing the remaining strength of corroded oil field casing and tubing*. Doctoral Dissertation. Freiberg University of Mining and Technology, Freiberg, Germany.
- Teixeira, A.P., Palencia, O.G., Soares, C.G., 2019. “Reliability analysis of pipelines with local corrosion defects under external pressure.” *Journal of Offshore Mechanics and Arctic Engineering*. Vol. 141. <https://doi.org/10.1115/1.4042384>
- Timoshenko, S.P., Gere, J.M., 1961. *Theory of elastic stability*. McGraw-Hill Publishing Company, New York.

## 8. RESPONSIBILITY NOTICE

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