

Failure Probability Assessment for Pipelines under the Corrosion Effect

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Abstract In this work, a numerical method was developed, by a reliability mechanical coupling, in order to define the reliability index and probability of failure evolutions for pipelines under corrosion effect. The chosen model, takes into account uniform and localized corrosion. Thus, the hardness and tensile tests were worked out to characterize the mechanical properties of pipelines material. Once the model was defined, a simulation was carried out by the software Phemica. The importance factors were also estimated. A methodology has been presented for the reliability analysis of pipelines subjected to localized corrosion. The variables influencing the reliability are treated as random variables and represented by suitable statistical distributions. An approximate limit state function was developed. Advanced first-order second moment reliability theory was employed for the estimation of the probability of pipeline failure by Phimeca software logiciel. From a numerical investigation, it was found that both defect depth and fluid pressure have significant influences on pipeline reliability.

Keywords: reliability index, corrosion, pipelines, probability of failure, Folias factor

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1. Introduction

The exploit of pipelines is, to some level, the most efficient way to convey hydrocarbons. In Algeria, there are 11000 kilometers of gas and oil pipelines. Pipeline managers need assessments of integrity and safety in order to make appropriate decisions regarding the allocation of funds for maintenance and operation. Limited resources require rational and sound criteria for realistic assessment directed towards their best utilization. Over time, this assessment is resorting more to the use of structural reliability techniques [1,2,3,4].

During service, the remaining strength of pipelines depends on number of factors, including the operational conditions, and defects introduced by construction, third-party damage, corrosion and ground movement, etc. In particular, corrosion and ground movement constitute two important causes resulting in pipeline failure [5,6,7,8]. Corrosion is of concern because any loss of the pipe all thickness means a reduction of pipeline structural intensity and hence an increase in the risk of failure, while the ground movement produces a longitudinal load on the pipe, creating stress/strain to threaten the pipeline safety. Thus, a synergistic effect of corrosion and the soil-induced strain on the pipeline integrity should be considered in strain-based design of pipelines. Reliability methods are a powerful and useful tool when assessing defects in pipelines. The basis for a probabilistic assessment is the distributions of all variables, including load (internal pressure), material strength and the sizing accuracy of the

inspection tool. There are many studies and papers on reliability based assessments of corroded pipelines, such as a computer program based on the FORM/SORM [9] procedure was developed to calculate failure probabilities when a crack-like defect size is obtained from nondestructive testing. Reliability analysis can be used for the assessment of pipeline safety. It can be used also as a rational and consistent tool for assessment of pipeline integrity when this is measured in terms of containment. The analysis can also be used to assess the effect of the various random parameters on the estimate of pipeline safety. This could help pipeline operators make proper decisions about maintenance, repair and replacement programs. The present analysis is confined to strength assessment of pressurized pipelines subject to transport hydrocarbons under high pressure. It is assumed that these flaws mainly interrupt the load carrying capacity of pipelines in direct proportion to their depths.

2. Corrosion Model

The geometry of corrosion is usually described by uniform corrosion or located corrosion, the majority of problems of corrosion affecting the structures are a combination of these two forms. The distribution of corrosion in pipes can be stochastically described by the space random fields. Consequently all the depth of corrosion at any place x and time t can be described by the sum of these two types of corrosion:

$$d_C(x,t) = d_U(t) + d_{LC}(x,t) \quad (1)$$

where $d_C(x,t)$ is the total corrosion depth at the location x and time t , $d_{LC}(x,t)$ is the depth of the localized corrosion defect and $d_U(t)$ is the depth of the uniform corrosion. Figure 1 shows a longitudinally-oriented surface corrosion defect in the wall of a pressurized

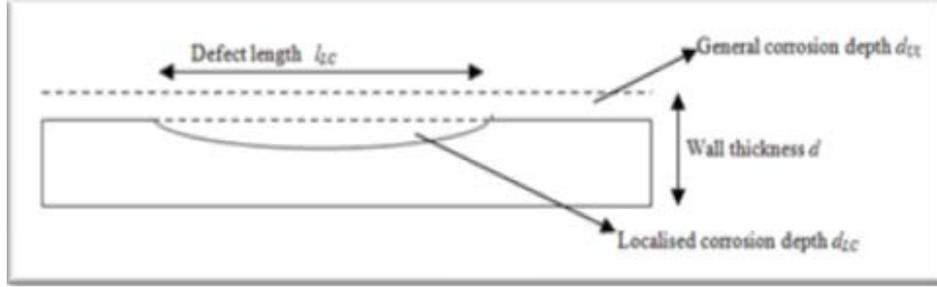


Figure 1. Idealized corrosion defect

2.1. Uniform Corrosion

A practical engineering way to account for uniform corrosion is to use a power law to model the loss of wall thickness with the exposure time [8,11]. The general form of the corrosion power law is written as:

$$d_{UC}(t) = \kappa_{UC} t^n \quad (2)$$

where $d_{UC}(t)$ is the thickness of the corroded layer, t is the elapsed time (i.e. age of the pipe) and κ_{UC} and n are the corrosion constants, to be evaluated by fitting Eq. (2) from field corrosion data [5- 6]. For atmospheric pressure, the mean and standard deviation are, respectively, 0.066 and 0.037 for the multiplier κ_{UC} , and 0.53 and 0.14 for the power n [11].

2.2. Localized Corrosion

In the past decades, extensive researches have been performed on localized corrosion, in order to derive empirical models for different environmental conditions. The mostly used empirical equations for the time-dependent corrosion depth $d_{LC}(t)$ and length $l_{LC}(t)$ take the form [6,9]:

$$d_{LC}(t) = (\kappa_{UC} + \alpha_{LC} \Delta\kappa_{LC}) t^n \quad (3)$$

$$l_{LC}(t) = \gamma_{LC} (\kappa_{UC} + \alpha_{LC} \Delta\kappa_{LC}) t^n \quad (4)$$

where $d_{LC}(t)$ and $l_{LC}(t)$ are respectively the localized corrosion depth and length, $\Delta\kappa_{LC}$ is the specific rate of localized corrosion, α_{LC} is the localized corrosion fraction and γ_{LC} is the length-to-depth ratio of localized corrosion.

2.3. Failure Pressure

The defects form a region of stress concentration, thus interrupting the normal hoop force trajectories along its length, depth and compelling the interrupted tensile hoop force to be redistributed around it, like is showing in Figure 1. The primary failure mechanism is generally considered to be the extension of the defect through the remaining portion of the pipe wall. At failure, the pipe

pipeline. In this figure, d is the pipe wall thickness, d_{LC} is the depth of localized corrosion, d_{UC} is the depth of uniform corrosion and l_{LC} is the length of the corroded region projected on the longitudinal axis.

wall is severed and the failure occurs either by leak or by rupture. The type of failure is dependent on the size of the resulting through-wall defect; attention is confined herein only to the failure event, not to the type of failure.

An expression largely used in order to estimate the constraint of failure given in the following form:

$$P_r = 2S_f \frac{(d - d_{UC})}{D} \frac{1 - \frac{d_{LC}}{d - d_{UC}}}{1 - \frac{d_{LC}}{(d - d_{UC})M}} \quad (5)$$

where D is the pipe diameter, S_f is the flow stress, defined by multiplying the yield stress by a factor m_f : $S_f = m_f f_y$. Ahammed and Melchers [7] proposed to model m_f by a lognormal distribution with mean value equal to 1.1 and coefficient of variation of 0.05.

2.4. Folias Factor

A comparative study of Folias factors was developed in literature [12], where the correlation between the Folias factor M and $L^2/(Dt)$ is plotted which is given in Figure 2. M1, M2, M3 and M4 represent the expressions of Folias factor in NG-18, B31G and PCORRC respectively. The K in the Figure 2 represents the value of $L^2/(Dt)$. It can be seen from Figure 2 that the Folias factor in the B31G is larger than that in the NG-18 in spite of their same form about corroded pipe assessment criterion. The form of PCORRC is different than NG-18 and B31G its Folias factor cannot be directly compared to these two [12].

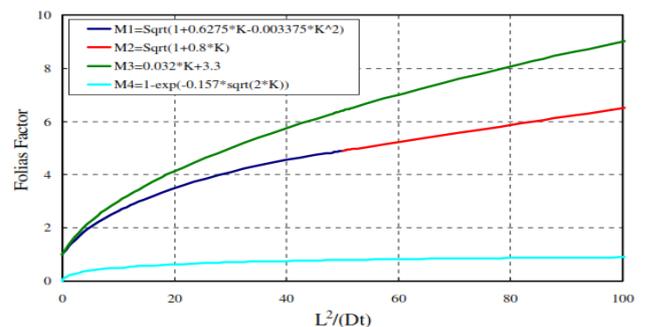


Figure 2. Comparison of Folias factor at different assessment procedure

The Folias factor M (also known as bulging factor) is a semi-empirical factor that covers the fracture mechanics aspects; it is given by [7]:

$$M = \begin{cases} \sqrt{1 + 0.6275 \frac{l_{LC}^2}{D(d-d_{UC})} - 0.003375 \frac{l_{LC}^4}{D^2(d-d_{UC})^2}}, & \frac{l_{LC}^2}{D(d-d_{UC})} \leq 50 \\ 0.0032 \frac{l_{LC}^2}{D(d-d_{UC})} + 3.3, & \frac{l_{LC}^2}{D(d-d_{UC})} > 50 \end{cases} \quad (6)$$

$$M = 0.0032 \frac{l_{LC}^2}{D(d-d_{UC})} + 3.3, \quad \frac{l_{LC}^2}{D(d-d_{UC})} > 50 \quad (7)$$

3. Reliability Analysis

The concept of reliability being posed, a criterion of failure is defined using a function known as a performance (or limit state), noted G , and which depends on the random variables of the model. The analysis of reliability enables us to know the criticality of failures which can arrive at structures (pipeline), as well as the economic impact of these failures, and hence provides mandatory information for inspection planning. So, it is necessary to define a limit state function.

The reliability R of a structure is conventionally defined in the following way [3,4]:

$$R = 1 - P_f \quad (8)$$

Where the probability of failure P_f corresponds to the probability of occurrence of the event $G(\{X\}) < 0$

$$P_f(t) = P[G(X_i, t) \leq 0] = \int_{G(X_i, t) \leq 0} f_{X_i}(x_i, t) dx_i \quad (9)$$

The limit state function $G(x_i)$ corresponds to the security border, which is conventionally defined by the difference between the pipe pressure resistance P_r and the applied pressure P :

$$G(x_i) = P_r - P \quad (10)$$

where x_i are the realizations of the random variables of the pipe X_i . This margin is defined such that $G(x_i) > 0$ indicates safety and $G(x_i) \leq 0$ corresponds to conventional failure. So, by replacing P_r by P' we obtained:

$$G(x_i, t) = 2m_f f_y \frac{(d-d_{UC}(t))}{D} \frac{1 - \frac{d_{LC}(t)}{d-d_{UC}(t)}}{1 - \frac{d_{LC}(t)}{(d-d_{UC}(t))M(t)}} - P_a \quad (11)$$

$$P_f(t) = P[G(X_i, t) \leq 0] = \int_{G(X_i, t) \leq 0} f_{X_i}(x_i, t) dx_i \quad (12)$$

where $P[]$ is the probability operator and $f_{X_i}(x_i, t)$ is the joint probability density function of the random variables at time t . As the limit state function is nonlinear in terms of the input random variables, iterative algorithms [12] are conveniently applied in order to

reduce the computation time. In the present work, the First Order Reliability Method, known as FORM [12], is applied to compute the reliability index β , which is defined as the minimum distance between the median point and the failure domain in the standard Gaussian space. This index is evaluated by solving iteratively the constrained optimization problem:

$$\beta(t) = \text{minimize} \sqrt{\sum_i [T_i(x_j)]^2} \quad \text{subject to } G(x_j, t) \leq 0 \quad (13)$$

where $T_i(x_j)$ is the probabilistic transformation of the model variables to standard Gaussian variables. The solution of this optimization problem can be obtained by optimization or reliability algorithms [11,12,13]. The failure probability can thus be evaluated by the first order approximation:

$$P_f(t) = P[G(X_i, t) \leq 0] = \Phi(-\beta(t)) \quad (14)$$

where $\Phi()$ is the cumulative Gaussian probability function.

4. Pipeline Reliability Assessment

To evaluate reliability or probability of failure, we are applied to use a software simulation (Phémica). A summary of the input data used in the probabilistic corrosion assessment is given in Table 1 and more details on the input assumptions are given below. Also, the acceptable defect size can be estimated based on the acceptable failure probability. In order to illustrate the above concepts, a pipeline with known corrosion defects was analyzed. This reflects the situation where defect dimensions are known from measurements by 'intelligent' tools. The random variables considered in this study are presented in Table 2 along with the typical statistical values and distribution functions for the variables.

Table 1. Input variables used for the probability analysis

Variables	Probability distribution function type	Mean value	Standard Deviation
Operation pressure (MPa)	Normal	60	2
Yield strength (MPa)	Normal	302,7	24
Tensile strength (MPa)	Normal	470,5	30
Defect depth (mm)	Normal	10.0	1.0
Defect length (mm)	Normal	250	20.0
Nominal wall thickness (mm)	-	12.8	-
Outside diameter (mm)	-	192.7	-

Table 2. Data for an example pipeline reliability analysis

Symbol	Description	Distribution	Mean value	Coefficient of variation
d	Defect depth	Normal	3,5 mm	0,1
D	Pipe diameter	Normal	192,7 mm	-
L	Defect length	Normal	250 mm	0,05
m_f	Multiplying factor	Log normal	1.1	0,05
P	Failure pressure	Normal	60 Mpa	0,054
S_y	Material yield stress	Log normal	302,7 Mpa	0,056
T	Pipe wall thickness	Log normal	12,8 mm	-

4.1. Experimental Study

The workshop TSS (seamless tube), which was conducted the study, carried out a number of quality tests

on its production. In the case of tubes for transport of hydrocarbons, the objective it was obtaining the resistance $R_{p0,5}$ (strain conventional), R_m (maximum strength).



Figure 4. view of the machine Zwick / Roell

A elongation and hardness HRC, during tensile, elongation and hardness tests. The machine used for these tests is a tensile testing machine Zwick / Roell equipped with a sensor and hydraulic jaws-loaded from the specimen through maintaining heels together at both ends (Figure 4).

Tensile test: The test specimens used, according to the U.S. standard API. The goal is to determine the maximum strength and strain conventional, and we obtained the following results: $R_{p0,5} = 302.7$ MPa and $R_m = 470.5$ MPa.

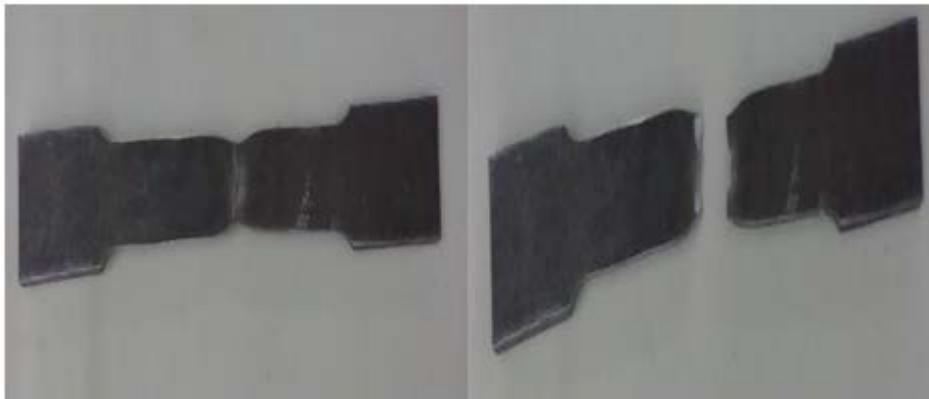


Figure 5. Tensile specimen

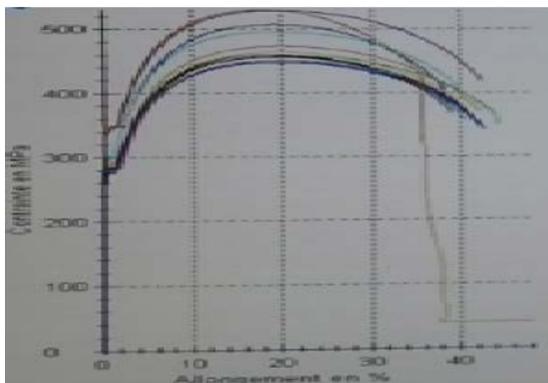


Figure 6. strain conventional curve of X52

4.2. Experimental Results

The reliability index calculation was carried out using Monte Carlo simulation which is integrate on PHEMECA data [12], and 10^6 simulation times is applied. The

calculation results are shown in the Figure 7, the figure show a rather fast reduction in the index of reliability opposite the lifespan of pipeline, influenced by the various constraints which the structure undergoes.

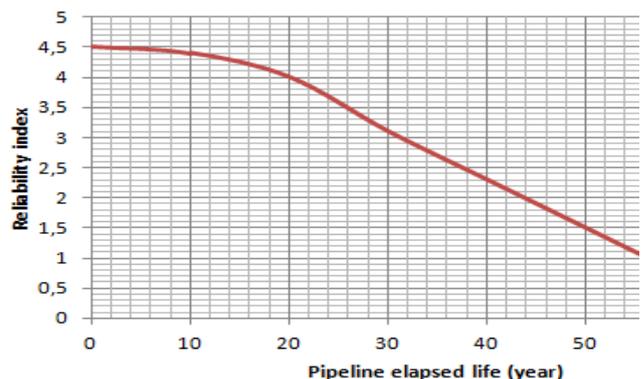


Figure 7. Evolution of reliability index

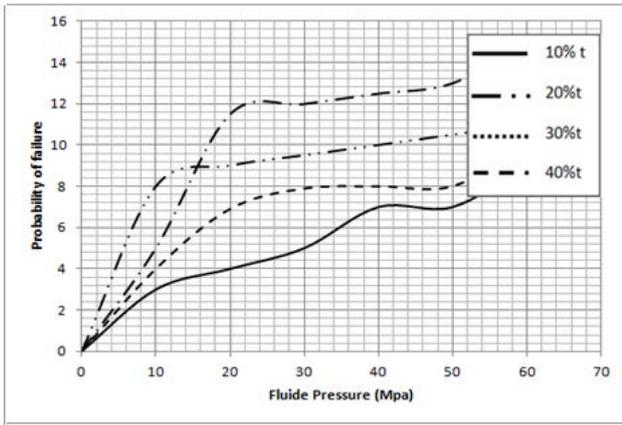


Figure 8. Probability of failure vs fluid pressure for different defect depth

Figure 8 shows the probability variation of failure depending on the defect depth generated by the corrosion phenomenon for four cases, and we see that there is a proportional relationship between the probability of failure and defect depth. In addition when the defect depth is important, we can see an important increase of the probability of failure. So the defect depth affects aggressively the structure studied.

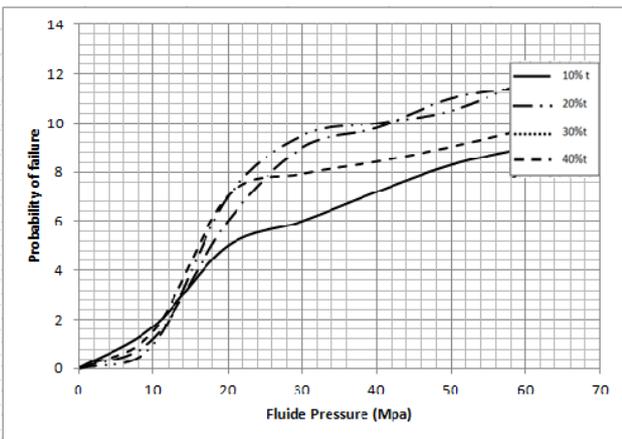


Figure 9. Probability of failure vs fluid pressure for different defect length

In this figure we show a second case, by the change in the probability of failure as a function of the defect length is presented. And we can conclude that here also the variation has a proportional relationship with the defect length caused by corrosion. Four cases were taken, we can notice that whenever we increase the defect length can be seen a significant increase in the probability of failure.

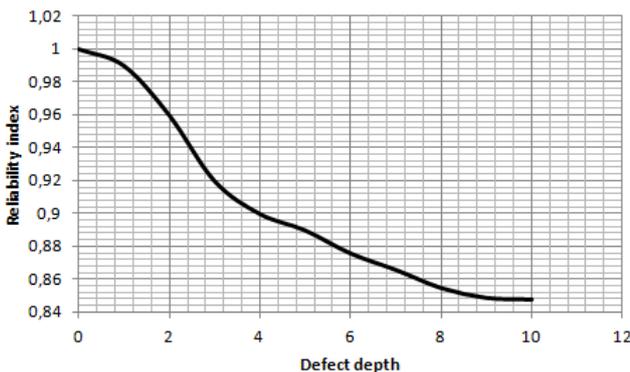


Figure 10. Reliability index vs defect length

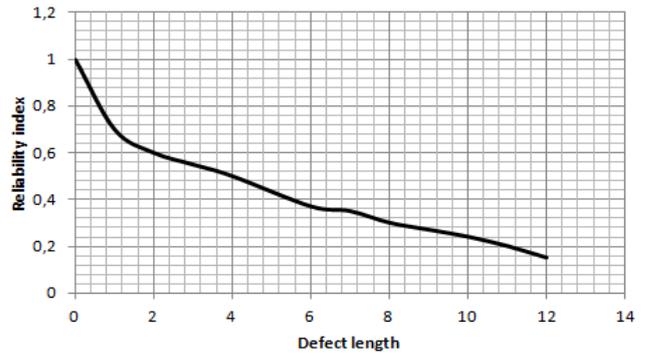


Figure 11. Reliability index vs defect depth

The two curves showed in Figure 10 and Figure 11 show the variation in the reliability index as a function of both defect depth and defect length variation. Where we can say that there is a clear decrease in the reliability index when the defect becomes more important.

5. Assessment Reliability Index with Different Folias Factor

In this section of work, we determined the reliability index using different Folias factor which are given respectively by, NG-18, B31G and PCORRC. The found result is shown in the following curve. The curve show a difference between three reliability indexes, where we can see a better result of the one who has a relationship with B31G.

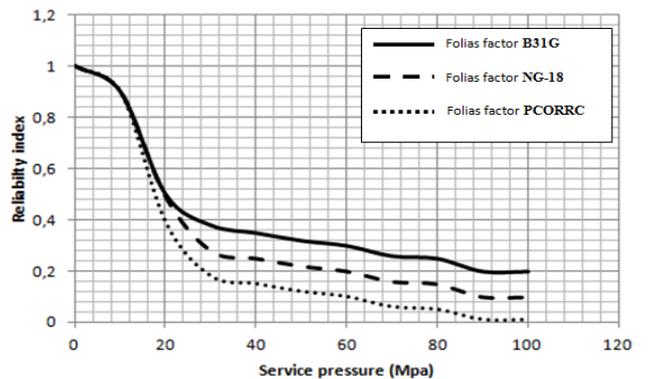


Figure 12. Reliability index vs service pressure (for different Folias factor)

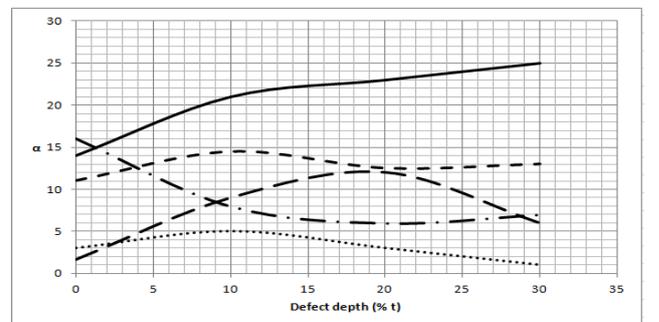


Figure 13. Sensitivity factors VS depth of corrosion

The above figure shows the variation of sensitivity factors according to the corrosion depth. The idea is to divide the corrosion depth at different percentages thickness of pipe, after that we see sensitivity factors

evolution. The found result gives a domination of two essential factors, the operating pressure and the maximum strength of material, considering the influence of corrosion weakens this resistance and increases the impact of the operating pressure which generates a significant constraint more in the internal month of the pipe walls.

6. Conclusion

This study was conducted for a goal to predict and evaluate the parameters of pipeline safety, which undergo to corrosion phenomenon, which is considered as a major problem that affects the tubes intended for the carriage of hydrocarbons. The probability of failure and reliability index, were calculated using probabilistic models based on the reliability-mechanical coupling. A comparative study of the evolution of the reliability index based on various Folias factors was also made, which aims to choose the best result, where we found a better evolution of reliability that takes into account the Folias factor given by B31G.

A methodology has been presented for the reliability analysis of pipelines subjected to localized corrosion. The variables influencing the reliability are treated as random variables and represented by suitable statistical distributions. An approximate limit state function was developed. Advanced first-order second moment reliability theory was employed for the estimation of the probability of pipeline failure by Phimeca software. From a numerical investigation, it was found that both defect depth and fluid pressure have significant influences on pipeline reliability.

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