Reliability Assessment of Pipelines with River-Bottom Corrosion Profile

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Abstract. The structural integrity assessment of pipelines can be performed through inspection, standards, and computer simulations. Although these methodologies are widely used, the data used for the evaluations have some uncertainties and these must be taken into account by the pipeline engineers. Based on inspection data, of the river-bottom corrosion profile, eleven specimens taken from a brazilian pipeline will be analysed. The present work will make a comparison between the use of different semi-empirical standards for the evaluation of structural integrity of corroded pipelines, using First Order Reliability Method (FORM) for reliability analysis. The problem of reliability analysis of corroded pipelines with idealized defects has been extensively addressed in the literature, but there are still few studies considering complex corrosion profiles. In this work, we will apply some semi-empirical equations found in international standards such as DNV RP F101, ASME B31G, modified ASME B31G, and RSTRENG Effective Area (river-bottom profile). The results of the probability of failure will be compared with each other, presenting the main conclusions in the use of each standard. To speed up the computation of failure pressures, parallel programming in GPU (Graphics Processing Units) is used.

Keywords: Corroded Pipeline, Reliability, Structural Integrity, GPU computing

1 Introduction

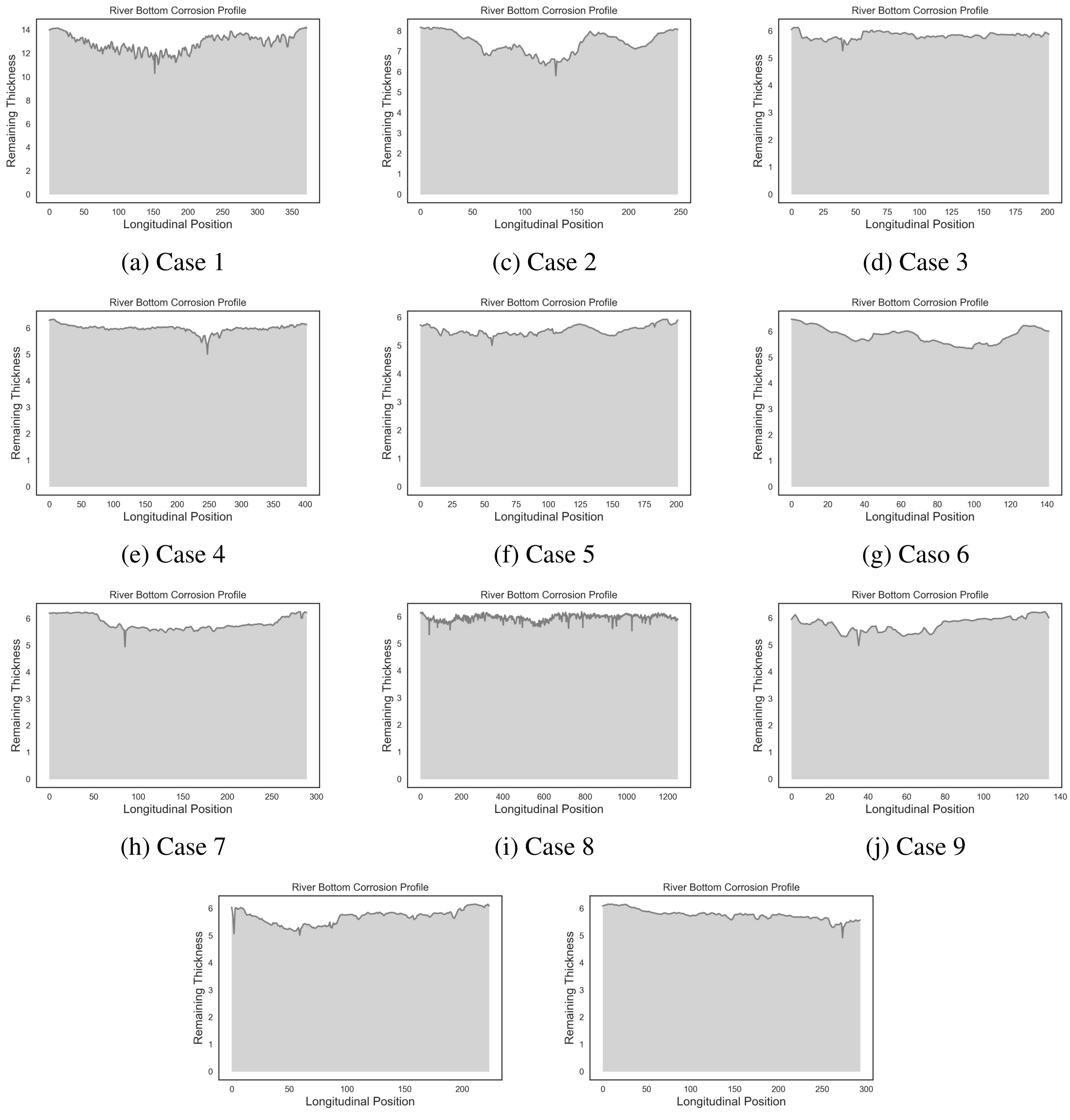
Assessment of corroded pipelines is a important task in oil and gas industry. Structural engineers are constantly challenged to estimate the lifetime of corroded pipelines and to define a maintenance schedule for them. In the pipeline integrity programs it is very important for operators to have information regarding corrosion activity. The ultrasonic technology inline inspection (UT-ILI) can provide data such as a river-bottom profile (rbp), that is a detailed two dimensional representation of the remaining wall thickness along the pipeline. These projections are formed by the minimum values across the circumferential width. With this data we can determine the shape of corrosion formed by circumferential peak depths and the total length of the defect.

Here the assessment methods used to predict the burst pressure of corroded pipeline are the B31G [1], 085dL method or modified B31G [2], DNV RP-F101 [3] and RSTRENG Effective Area (EA)[4]. The first three consider the corrosion profile as an idealized geometry considering only the minimum defect thickness, the last ones considers a complex corrosion profile in the river bottom shape.

2 River Bottom Profiles

In this work, eleven real river bottom profiles obtained through ILI inspection are used for reliability analysis. Figure 1 shows the representation of the remaining thickness as a function of the longitudinal length of all profiles used.

The external diameter (D) for all pipes is $609.16mm$, the yield stress σ_y is $365.2MPa$, the ultimate stress σ_u is $468.6MPa$ and the thicknesses ranges from $6.39mm$ to $14.56mm$.



(a) Case 1 (c) Case 2 (d) Case 3

(e) Case 4 (f) Case 5 (g) Caso 6

(h) Case 7 (i) Case 8 (j) Case 9

(k) Case 10 (l) Case 11

Figure 1. *River-bottom* profiles used in this work.

3 GPU Computing

Semi-empirical assessment methods, like RSTRENG Effective Area, are computationally expensive. The computational complexity is $\mathcal{O}(N^2)$. In the cases analysed in this work, the number of the thickness measurements reaches the order of 10^3 and the reliability assessment can take weeks to be concluded. To speed up and to make feasible the reliability analysis of the pipe with corrosion river bottom profiles, the calculations are done using parallel processing using CUDA (Compute Unified Device Architecture).

CUDA is a parallel computing platform and programming model developed by NVIDIA for general computing on its GPUs (graphics processing units). To write a code in CUDA is necessary to configure global memory accesses, cache, number, and thread layout.

To enable the parallel computing, all code is written in a vectorized form. The vectorized code enables several burst pressures to be calculated in the same iteration. In this implementation, for each iteration, one million of parameters set necessary to calculate the burst pressure (D_e, t, A_{ef}, A_0, L_{ef}) are pre-processed and sent to GPU to compute the pressure (P_f).

To enable using CUDA distributed computing the computer cluster of the PADMEC research group was used . The SGI ICE X system has 17 nodes with a total of 544 CPUs and 34 GPUs. The nodes are interconnected through a high-performance infiniband network. The GPU model is the NVIDIA Tesla M2075, which has 448 cores and 6 GB of ram. Figure 2 shows a image of a GPU of the same model.

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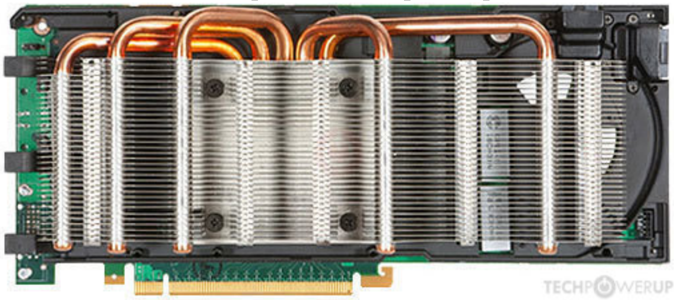

Figure 2. NVIDIA Tesla M2075

4 Semi-empirical assessment methods

To estimate the failure pressures in corroded pipelines, different assessment methods are used. The methods used are ASME B31G method, the DNV RP-F101 method for single defect, B31G RSTRENG 0.85dL, and the RSTRENG Effective area (EA) method. Table 1 shows the failure pressure equations according to the different standards considered here. Some standards use the yield strength (σ_y), others uses the ultimate tensile strength (σ_u). ASME, B31G and RSTRENG uses the maximum depth (d) of the corrosion area projected onto the pipe longitudinal plane. Effective Area method use possible combinations of contiguous defect areas, and choose the minimum calculated pressure as the one that represents the bursting pressure of the pipe.

Table 1. Formulas for computation of failure pressure.

Method	P_f	Length limit	M
B31G	$P_f = 1.1\sigma_y \left(\frac{2t}{D_e}\right)\left[\frac{\left(1-\frac{2d}{3t}\right)}{\left(1-\frac{2d}{3tM}\right)}\right]$	$L \leq \sqrt{20D_e t}$	$M = \sqrt{1+0.8\left(\frac{L^2}{D_e t}\right)}$
	$P_f = 1.1\sigma_y \left(\frac{2t}{D_e}\right)\left(1-\frac{d}{t}\right)$	$L > \sqrt{20D_e t}$	$M = \infty$
DNV (Single)	$P = \frac{2t\sigma_u}{(D_e-t)}\frac{\left(1-\frac{d}{t}\right)}{\left(1-\frac{d}{tM}\right)}$	–	$M = \sqrt{1+0.31\left(\frac{L}{\sqrt{D_e t}}\right)^2}$
0.85dL	$P_f = (\sigma_y + 68.95MPa)\left(\frac{2t}{D_e}\right)\left[\frac{\left(1-0.85\frac{d}{t}\right)}{\left(1-0.85\frac{d}{tM}\right)}\right]$	$L \leq \sqrt{50D_e t}$	$M = \sqrt{1+0.6275\left(\frac{L^2}{D_e t}\right)-0.003375\left(\frac{L^4}{D_e^2 t^2}\right)}$
		$L > \sqrt{50D_e t}$	$M = 0.032\left(\frac{L^2}{D_e t}\right)+3.3$
Effective Area	$P_f = (\sigma_y + 68.95MPa)\left(\frac{2t}{D_e}\right)\left[\frac{\left(1-\frac{A_{ef}}{A_0}\right)}{\left(1-\frac{A_{ef}}{A_0 M}\right)}\right]$	$L_{ef} \leq \sqrt{50D_e t}$	$M = \sqrt{1+0.6275\left(\frac{L_{ef}^2}{D_e t}\right)-0.003375\left(\frac{L_{ef}^4}{D_e^2 t^2}\right)}$
		$L_{ef} > \sqrt{50D_e t}$	$M = 0.032\left(\frac{L_{ef}^2}{D_e t}\right)+3.3$

5 Reliability Analysis

The Reliability Analysis aims to obtain the probability of failure of an undesirable event. The problem is defined by a failure (limit state) function and the random variables.

The failure function considered here is the pipe burst, and its limit state function (G) is shown in eq. (1).

$$G(D, t, d, L, \sigma_y, \sigma_u, P_{int}) = P_f - P_{int} \tag{1}$$

where P_{int}, P_d and S can be computed by eq. (2), eq. (3) and eq. (4), respectively.

$$P_{int} = 1.05 \times P_d \tag{2}$$

$$P_d = (2 \times S \times t)/D \tag{3}$$

$$S = 0.72 \times E \times SMYS \tag{4}$$

where P_f, P_d , t, d, L, σ_y, σ_u, S, D, E and SMYS are respectively the pressure obtained by semi-empirical methods, design pressure, wall thickness, maximum defect depth, defect length, yield stress, ultimate stress, allowable stress, external diameter, weld joint factor and specified minimum yield strength of the pipe.

In the present work, P_d, t, d, L,D, σ_y, σ_u are random variables. Table 2 shows the type of distribution, the mean and the coefficient of variation (CoV) of each random variable. These data was obtained from DNV [3].

Table 2. Distributions and moments for each variable.

Variables	Distributions	Mean	CoV
P_{int}	Gumbel	1.05xPd	3.0%
D	Normal	Nominal	3.0%
t	Normal	Nominal	3.0%
d	Normal	Measured value	CoV(d)
σ_y	Lognormal	$1.08 \times SMYS$	4.0% or 8.0%
σ_u	Normal	$1.09 \times SMTS$	3.0% or 6.0%
L	Normal	Measured value	5%

The coefficient of variation of the maximum defect depth was calculated taking into account the type of PIG (Pipeline Inspection Gauge) used in the inspection (UT – ultrasonic technology) and the calculation of the standard deviation follows eq. (5).

$$StD[d/t] = (\sqrt{2} \times acc\_abs)/(t \times \phi^{-1}(0.5 + conf/2)) \tag{5}$$

Where, acc_abs is the absolute depth accuracy, ϕ^{-1} is the inverse of the cumulative distribution function of a standard normal variable and $conf$ is the confidence level. In this paper acc_abs and $conf$ are 0.25 e 0.9 respectively, obtained from DNV [3]. At each iteration of FORM the thicknesses in the defect region of the river-bottom profile are perturbed uniformly, i.e, all points in the bottom of the defect move together, maintaining the geometry of the defect.

5.1 FORM

FORM approximates the problem around the most probable failure point (MPP) with an equivalent basic problem by transforming the original random variable space (U) into a standard reduced space (V), using the Nataf transformation (T) [5]. A graphical interpretation of the method is shown in Figure 3. The MPP (V^*) is the shortest distance point from the limit state ($G(U) = 0$) to the origin in the standard space (V). The minimum distance $\beta = |V^*|$ is called the reliability index. The standard reduced space is a space of equivalent standard normal distribution of uncorrelated random variables, i.e. $f_V(V)$ is the standard normal distribution (zero mean and unity standard deviation). In the standard space the limit state is linearly approximated around the MPP [5, 6].

In the standard space P_f is approximated by $\Phi(-\beta)$, where Φ is the cumulative distribution function of the standard normal distribution. The opposite procedure could be used to approximate the reliability index from the P_f value (obtained via Monte Carlo [7], for instance). To find the MPP any optimization method can be applied. In this work, the iterative algorithm called HL-RF from Hasofer and Lind [8], Rackwitz and Flessler [9], is used. The gradient of G with respect to the random variables in the standard space (∇G) is used in the optimization process

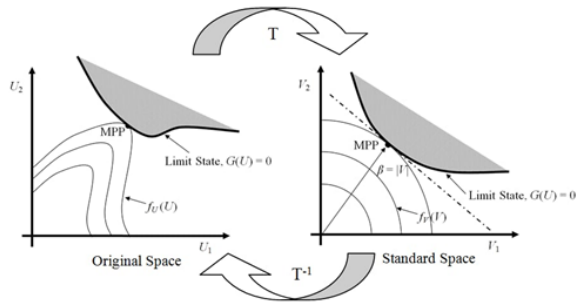

Figure 3. Graphical interpretation of the FORM procedure.

to find the MPP. The MPP, (V^*) can be obtained as $V^* = \beta\alpha$, in which α is the unitary vector of the gradient ∇G, that can also be used to evaluate the importance of each random variable in the problem.

The FORM method has demonstrated to be very computationally efficient when compared to other approaches such as the sampling-based schemes. But it can provide inaccurate results in problems with non-Normal random variables and highly non-linear limit state functions Lopez and Beck [10], Torii et al. [11]. Besides that, problems with discontinuity may lead to convergence problems resulting in increased computation cost and/or inaccurate results.

6 Results

A reliability analysis, using FORM, of all the eleven real profiles was performed. The burst pressure was computed using the ASME B31G, the DNV RP-F101 for single, B31G RSTRENG 0.85dL, and the RSTRENG Effective Area semi-empirical methods. Table 3 shows the full numerical results to the failure probability with five decimal places.

Table 3. Failure probability

Cases	Effective Area	B31G RSTRENG	B31G	DNV RP F101
Case 1	1.28318e-06	2.74548e-01	3.79238e-01	1.81546e-04
Case 2	1.28641e-06	2.65671e-01	3.89764e-01	2.11500e-04
Case 3	1.28353e-06	2.59789e-02	1.42444e-02	1.20877e-07
Case 4	1.29789e-06	1.20248e-01	1.20248e-01	3.95859e-05
Case 5	1.28444e-06	9.39659e-02	3.47166e-03	4.17040e-06
Case 6	1.28513e-06	2.85055e-02	7.90312e-04	9.98542e-08
Case 7	1.28351e-06	1.29464e-01	1.26543e-01	1.86274e-05
Case 8	1.28199e-06	1.35035e-02	1.35035e-02	1.72136e-06
Case 9	1.28538e-06	7.49107e-02	2.67977e-03	1.22836e-06
Case 10	1.28567e-06	9.10865e-02	9.72665e-02	4.36756e-06
Case 11	1.33821e-06	1.25978e-01	1.19336e-01	1.74516e-05

The Fig. 4 shows the failure probability computed for all cases.

The results from the Effective Area method and DNV F101 presented in Fig. 4 are very close for this scale, Fig. 5 shows the detailed results of these two methods.

The results are in the same order of magnitude because the DNV F101 method uses ultimate stress ($\sigma_u = 468.6MPa$) and Effective Area uses yield stress ($\sigma_y = 365.2MPa$). For comparison using the same material

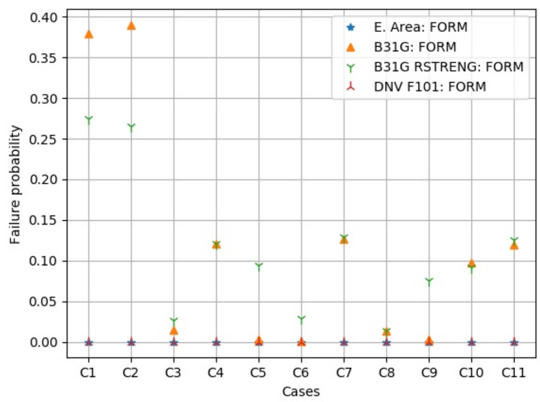

Figure 4. Failure Probability.

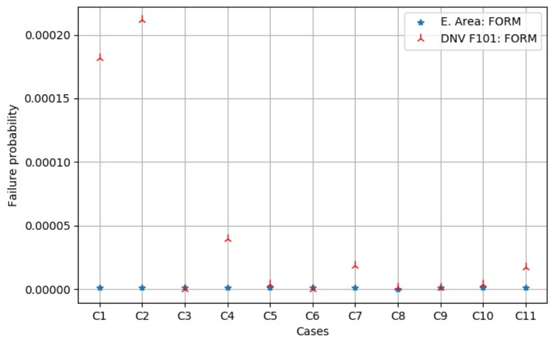

Figure 5. Details of the probability of failure for the Effective Area and DNV methods.

properties, the failure probability was computed with the effective area method using the ultimate stress (σ_u). The results are show in Table 4.

Table 4. Failure probability for Effective Area using σ_u

Cases	Effective Area (σ_u)
Case 1	2.146404e-13
Case 2	2.150869e-13
Case 3	2.145035e-13
Case 4	1.068035e-11
Case 5	2.146700e-13
Case 6	2.147460e-13
Case 7	2.145664e-13
Case 8	2.145027e-13
Case 9	2.148887e-13
Case 10	1.074696e-11
Case 11	2.132390e-13

7 Conclusions

This work evaluated the probability of failure of corroded pipelines considering both idealized defects and river bottom profile defects. Prediction of failure pressure was performed using semi-empirical methods (ASME B31G, DNV RP-F101, B31G RSTRENG 0.85dL, and RSTRENG Effective Area).

The results show that, for the studied cases, the use of complex corrosion profiles is a better option to predict the failure probability in pipelines. Considering all uncertainties included in the system is fundamental to define the correct pressure that the pipe should be operating.

Failure probability results to the DNVF101 and Effective Area method are close because the DNV method uses ultimate stress (468.6 MPa) to predict the burst pressure while Effective Area uses yield stress (365.2 MPa) in calculations. If we consider the ultimate stress in the Effective Area method the order of magnitude of failure probability is less than 10^{-11}.

The reliability analysis from corroded pipelines using river bottom profiles can be very useful for the oil & gas industry and the result can be less conservative when confronted with the one computed with idealized corrosion profiles. This can save money by increasing the time between corrective maintenance and can be used to optimize the maintenance schedules.

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