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

Multi-level optimization of maintenance planning for corroded pipelines considering different corrosion growth models

Savanna C.M. D'Aguiar[1], Álamo D.S. Pessoa[1], Paulo F.S. Sousa[1], Silvana M.B.A. da Silva[1], Ramiro B. Wilmersdorf[2]

[1]*Dept. of Civil Engineering, Federal University of Pernambuco*
N/N Acadêmico Hélio Ramos st., 50740-530, Recife/Pernambuco, Brazil
savanna.cristina@ufpe.br, alamo.pessoa@ufpe.br, paulo.silvasousa@ufpe.br, silvana.bastos@ufpe.br
[2]*Dept. of Mechanical Engineering, Federal University of Pernambuco*
N/N Arquitetura av., 50740-550, Recife/Pernambuco, Brazil
ramiro.willmersdorf@ufpe.br

Abstract. Pipelines are safe and efficient elements used to transport oil & gas products, but over time their structural integrity can be compromised due to corrosion defects. In order to ensure the safety and efficiency of a pipeline, risk management through periodic inspections (and repairs when needed) is essential. In this work, the influence of different corrosion growth models - namely linear and power-law - on the estimated total costs (the sum of cost of inspections, failures and repairs) of inspection schedules is assessed; these schedules are, then, optimized for a given number of inspections, constrained to a predefined reliability threshold. Our findings reaffirm those of previous studies that show the linear model as being more conservative than the non-linear power-law one providing larger optimized total estimated costs.

Keywords: corroded pipelines, maintenance planning, multi-level optimization.

1 Introduction

Mahmoodian and Li [1] shows that around 60% of the world's fuel is still composed by petroleum and its derivatives, and pipelines are one of the safest ways of transporting these products [2]. In this context, Mahmoodian and Li [1] also showed that deterioration of the structural integrity of these pipes over time is a major concern in the petroleum industry, and several studies indicate that corrosion is a major reason for the structural problems in this infrastructure. The corrosion process usually grows over time, which reduces the pipe's resistance [3,4]. Therefore, keeping the pipeline in operation within safety conditions requires planning maintenance actions, such as inspections and repairs, during the pipe's lifecycle [5].

Defining this maintenance schedule is a main concern in the maintenance planning of corroded pipelines. In order to reduce the operational costs, recent literature is treating the scheduling of these maintenance actions as a cost-based optimization problem, in which these actions take place according to a schedule that minimizes the total expected costs, commonly known as the optimal schedule [6-9]. More recently, the literature introduced a reliability constraint in this action planning, treating this optimization as a constrained one [7]. Using reliability analysis is essential in this problem because it considers some of the most relevant uncertainties in the corroded pipelines problem, such as: the initiation and growth of the corrosion defects, the loads and also the pipeline's geometry and material parameters.

Sousa et al [8] applied an optimization methodology, previously proposed by Liu et al [10] combined with the methodology described by Mishra et al [7], in which the reliability constraint is considered. The multi-level strategy enables inspection schedule flexibility, resulting in lower total costs.

This paper uses a combination of methodologies discussed in the literature [3,7,8,10] - however considering different failure modes - and aims to evaluate the influence of two different growth models for the corrosion defect depth: one linear and one non-linear (power law function) in the problem of optimally planning interventions in corroded pipelines with different lifetimes.

2 Problem description

This paper follows the general methodology employed by Sousa et al. [8] regarding the optimization of total estimated cost (the summation of inspection, failure and repair costs), already taking in consideration the case where several modes of failure are considered, an improvement over that work. As for the corrosion defect's dimensions and corrosion growth rates, as well as the pipeline's shape and building material's properties, this work uses the same statistical parameters values as Bazán and Beck [11], who calibrated the corrosion models to actual data obtained from Caleyo et al. [12].

The pipeline in question started operations in 1981 and was inspected in 2002 and 2007 using magnetic flux leakage in-line-inspection. It is important to note that, just like Bazán and Beck [11], the corrosion defect is defined in our work by its longitudinal length, which remains constant, and depth, which varies over time; it is precisely the depth growth that will be studied regarding a linear model and a non-linear power-law model, also described in Bazán and Beck [11].

$$d(t) = d_0 + R_d\, t \tag{1}$$

$$d(t)= \kappa(t - t_0)^{\alpha} \tag{2}$$

where $d(t)$ is the defect depth over time, in mm; d_0 is the defect initial depth, in mm; R_d is the growth rate for depth, in mm/year; t_0 is the corrosion starting time, in year, κ and α are the proportionality and exponent factors. In this paper, t_0 = 2.88 years was adopted, according to [6,7,11]. The random distributions and the parameters used were the same adopted by Bazán and Beck [11].

The probability of failure at each point in time ($Pf(t)$), crucial to the reliability assessment, is evaluated considering the uncertainties of all variables related to each limit state function, which are: small leak, which occurs when the corrosion defect penetrates, or is close to penetrate, the pipeline wall; burst, which occurs whenever the internal operating pressure exceeds that which the pipeline is able to withstand (also called burst pressure); and rupture, which occurs when the corrosion defect is long enough to undergo unstable axial extension [5, 11]. The limit state equations are described below:

$$g_1(t) = 0.8 \times wt\ \ d_{max} \tag{3}$$

$$g_2(t) = r_b(t) - P_{int} \tag{4}$$

$$g_3(t) = r_{rp}(t) - P_{int} \tag{5}$$

In these equations, wt refers to the wall thickness; d_{max} to the defect depth; $r_b(t)$ to the burst pressure; and $r_{rp}(t)$ to the pressure needed for rupture to occur - once a burst has already taken place, as considered by Gomes et al. [6]. The internal pressure of the pipeline will be characterized by a discrete stochastic value of pulses representing annual (extreme) peaks of Borges internal pressure load process [11], unlike the constant deterministic internal pressure in Sousa et al. [8]. The calculation of the burst pressure of the pipe follows Bazán and Beck [11].

2.1 Optimization problem formulation

The optimization problem consists in, given a certain number of inspections, finding the inspection schedule which minimizes the total estimated costs during the pipeline's lifespan. Thus, the total estimated cost (sum of inspection, failure and repair costs) is the objective function to be minimized and the design variable $\boldsymbol{x}$ is a vector of inspection times. We have, then, the following:

$$\begin{array}{ll} \text{Minimize:} & C_{ET}(x) \\ \text{where:} & \boldsymbol{x}=[t_1, t_2, \ldots, t_n] \\ \text{subject to:} & P_{f,\,max} \le P_{f,\,target} \\ & t_1 < t_2 < \ldots\ t_n \end{array} \tag{6}$$

According to the literature [6-8], the total estimated cost (C_{ET}) is given by:

$$C_{ET}=C_{ref} + N_{insp} \times C_{insp} + EnR \times C_{rep} + EnF_{small\ leak} \times C_{small\ leak} + EnF_{burst} \times C_{burst} + EnF_{rupture} \times C_{rupture} \quad (7)$$

where C_{ref} is a reference cost, commonly equal to 1; N_{insp} is the number of inspections and C_{insp} is the cost of each inspection; EnR is the expected number of repairs and C_{rep} the cost of a repair; $EnF_{small\ leak}$ is the expected number of small leak failures and $C_{small\ leak}$ the cost of a small leak failure; the same applies for burst failures and any other failure one may consider in this kind of problem. The costs are defined by a multiplying factor f_i that increases or reduces the reference cost C_{ref}, as indicated in Equation 8.

$$C_i=f_i \times C_{ref} \quad (8)$$

with i = {*inspection*, *repair*, *small leak*, *burst*, *rupture*}. The multiplying factors are taken from Gomes [6].

Repairs take place on two specific occasions: 1) whenever a failure occurs or 2) when certain conditions are met at the time of an inspection, as exposed by Zhou and Nessim [14] and used by Liu [3], Gomes [6] and Sousa [8]. Those conditions are expressed in the equations below:

$$d(t) \geq 0.5 \times wt \quad (9)$$

$$1.39 \times P_{int} \geq r_b(t) \quad (10)$$

The peak value of total probability of failure over a life cycle $P_{f,max}$, described in Equation 11, is considered a non-linear constraint, since it must be less than or equal to the failure probability target.

$$P_{f,max}=max[P_f(t)] \quad (11)$$

Finally, the Interior-Point algorithm [15] is used to find the optimum solution. In order to efficiently determine an initial feasible point that leads to a good minimum, Latin Hypercube Sampling – LHS [16] was applied with a dimension of 30 times the number of inspections. The criterion for choosing the initial point is as follows: the one point with the lowest estimated total cost over the samples and whose failure probability is less than or equal to the target failure probability (thus, a viable point). However, if no viable point exists in the sample, that one with failure probability closest to the target failure probability is to be chosen.

2.2 Reliability analysis

The reliability analysis is performed based on the calculation of the failure probability over the lifetime, considering the time interval *dt* equal to 0.125 years, a standard value in literature [4,6]. In the present paper, all reliability evaluations were performed by Monte Carlo simulation, also commonly used in the literature [5-9], using samples of size N = 1e6 in the optimization process; in the step of determining the starting point, samples of size N = 1*e*5 values were utilized.

3 Case study

The case study for the numerical evaluation of the proposed methodology is an example adapted from Bazan e Beck [11], with variables, distributions and statistics summarized in Table 1.

Table 1. Case study: variables, values and distributions

Variable	Unit	Mean	COV %	Distribution
Diameter (D)	mm	610	-	Deterministic
Wall thickness (t)	mm	9.52	0.015	Normal
Tensile strength (s_y)	MPa	496	0.03	Normal
Defect length (L)	m	90	-	Deterministic
Annual maximum internal pressure	MPa	7.056	0.05	Gumbel (maxima)

Source: adapted from Bazan e Beck [11].

To evaluate the influence of linear and non-linear models for the corrosion defect's depth growth, considering different failure modes simultaneously (small leak, burst and rupture), the total costs were calculated for the multilevel optimization of the maintenance planning.

In this optimization strategy, different stages are performed: (1) the optimal cost is obtained for different numbers of inspection and (2) the ideal maintenance plan corresponds to the one that minimizes the total expected costs and also obeys the maximum allowed failure probability. Figure 1a-b shows the optimal schedules' total cost and failure probability as a function of the number of inspections for linear and non-linear models, considering two exposure times (lifetime): 30 years and 100 years.

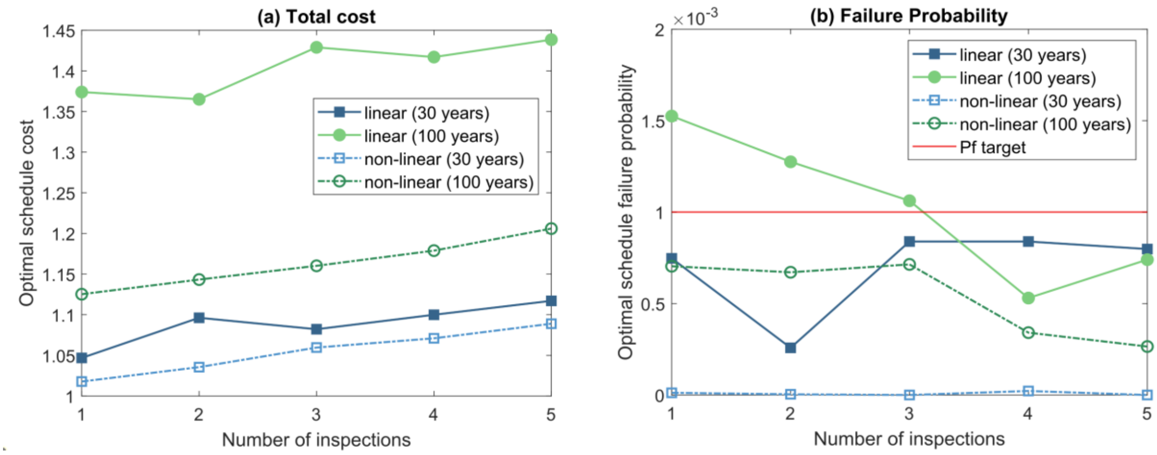

Figure 1. Optimal schedule total cost and failure probability for different corrosion growth models.

It can be seen (Figure 1a) that, as expected, the linear model for the corrosion defect's depth growth shows conservativeness when compared to a non-linear one. This characteristic is further enhanced with time, as it is clear that the difference among the two models is much larger for the longer 100 years lifetime than for the shorter 30 years one. As for the reliability constraint (Figure 1b), it appears that for the pipeline with a lifetime of 100 years the linear growth model only showed viable results after 4 inspections; also, again it is observed that the linear model presents more conservative results: at all numbers of inspection, its failure probability is greater than the one obtained by the non-linear model for the same lifetime.

Figure 2a-c presents the optimal scheduling costs broken down into inspection, repair and failure costs. From the detailed results it is possible to observe even more the differences of each model for the growth of the corrosion defect depth.

It is verified that the repair cost (Figure 2b), as the failure probability behavior, presents a larger value for the linear model when compared with solutions considering to the non-linear model. This behavior is similar to the total cost behavior (Figure 1a), since these differences seem proportional to the considered lifetime, representing a much larger gap for the 100 years scenario.

The failure cost (Figure 2c), however, shows a particularly singular behavior for the '100 years – Linear' scenario: a sharp decreasing trend when more inspections are performed. This, together with the behavior of the repair cost, indicates that, although more failures are happening, directly impacting the repair cost (Figure 2b), the cost associated with failures are lower, pointing to a prevalence of small leaks with considerable reduction of burst and ruptures (expensive failures).

Inspection costs grow linearly for each scenario discussed here, as it is a deterministic value and is just the sum of the cost referring to the number of inspections. It is important to note that the magnitude of repair and failure costs is greater than the cost of inspections when considering the 100 years lifetime, which directly reflects on the behavior of the total cost, shown in Figure 1a.

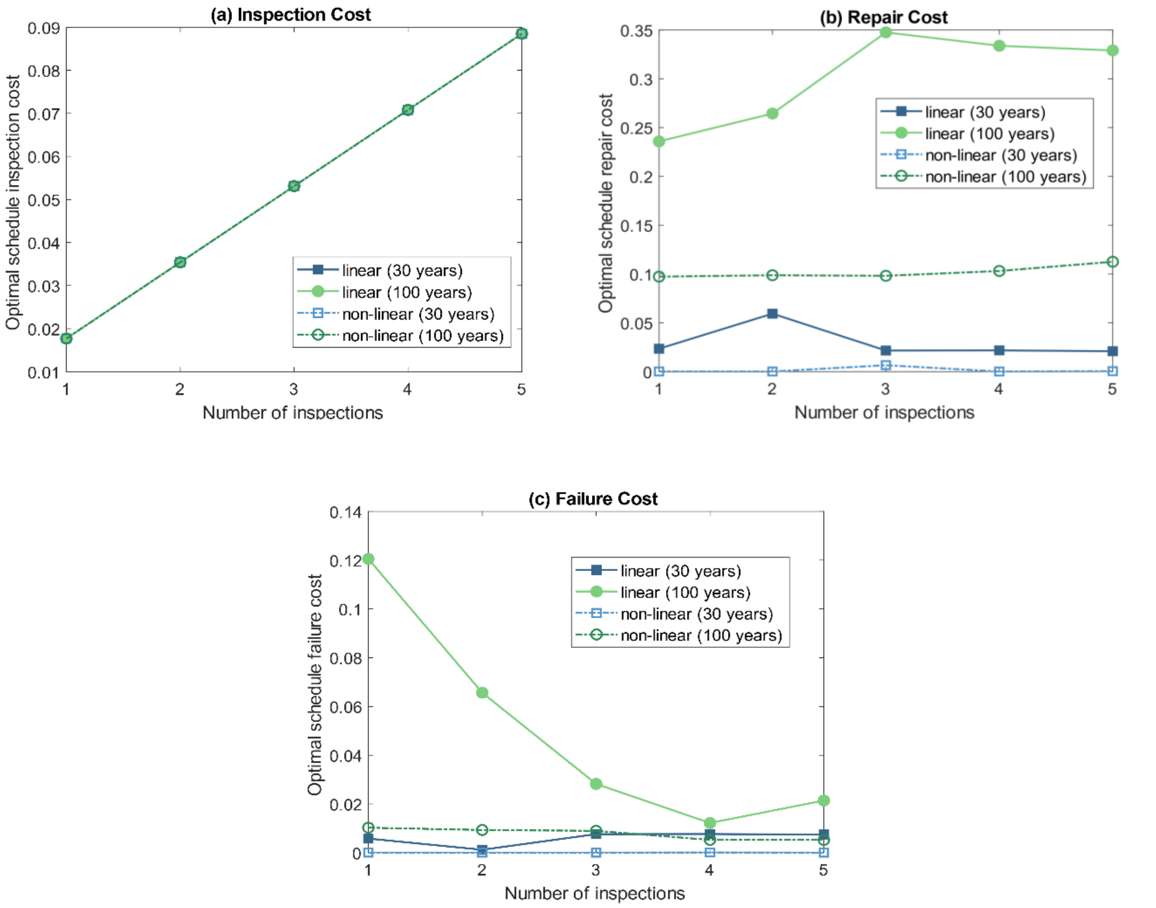

Figure 2. Detailed optimal schedule costs for different corrosion growth models.

4 Final remarks

This paper evaluated the influence of the defect depth growth model - linear and non-linear (power model) - on the optimal schedules for cost minimization (inspection, failure and repair costs) during the pipeline's lifespan and on its probability of failure. A multilevel optimization was performed, constrained to a certain failure probability threshold. Different failure modes were considered (small leak, burst and rupture). A stochastic model was adopted for the internal pressure acting on the pipeline.

The main conclusions of this study were:

- The combining the proposed methodologies was possible, and it also suggests that using the two different growth models lead to different costs and conclusions;
- Despite the set of results being based on defect depth's growth rate parameters obtained from limited corrosion data, the nonlinear model represents the physics of the problem much better when compared to the linear model [11], and, as shown in this work, the selection of this depth growth model directly affects maintenance costs, especially when the pipelines have a longer lifetime. In this way, the present work's results reinforce the importance of calibrating models to accurately predict the growth rates of defects [11] in order to have, in practice, increasingly economical and safe solutions.

Acknowledgements. The financial support for this research, provided by FACEPE, Grant Program IBPG-1295-3.01/20, IBPG-1303-3.01/20, IBPG-0959-3.01/17, is acknowledged, as well as CAPES and CNPq for the financial support of various research projects developed in this area by the PADMEC Research Group.

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] M. Mahmoodian, C.Q. Li. Failure assessment and safe life prediction of corroded oil and gas pipelines. *Journal of Petroleum Science and Engineering*, vol. 151, pp. 434-438, 2017.
[2] B. Keshtegar, M.E.A.B. Seghier. Modified response surface method basis harmony search to predict the burst pressure of corroded pipelines. *Engineering Failure Analysis*, vol. 89, pp.177-199, 2018.
[3] X. Liu, J. Zheng, J. Fu, Z. Nie and G. Chen. Optimal inspection planning of corroded pipelines using BN and GA. *Journal of Petroleum Science and Engineering*, vol. 163, pp. 546-555, 2018.
[4] K.F. Tee, K. Pesinis. Reliability prediction for corroding natural gas pipelines. *Tunnelling and Underground Space Technology*, vol. 65, pp. 91–105, 2017
[5] W.J.S. Gomes, A.T. Beck. Optimal inspection and design of onshore pipelines under external corrosion process. *Structural Safety*, vol. 47, Pages 48-58, 2014.
[6] W.J.S. Gomes, A.T. Beck and T. Haukaas. Optimal inspection planning for onshore pipelines subject to external corrosion. *Reliability Engineering and System Safety*, vol. 118, pp. 18–27, 2013.
[7] M. Mishra, V. Keshavarzzadeh, A. Noshadravan. Reliability-based lifecycle management for corroding pipelines. *Structural Safety*, vol. 76, pp.1-14, 2019.
[8] P.F.S. Sousa, S.M.B. Afonso, R.B. Willmersdorf. Multi-level strategy in optimal maintenance planning for corroded pipelines. *Rio Oil & Gas Expo and Conference*, 2020.
[9] P.F.S. Sousa, S.M.B. Afonso, R.B. Willmersdorf. Reliability-based preventive maintenance planning for corroded pipelines using a RBF surrogate model. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 43-521, 2021.
[10] X. Liu, J. Zheng, J. Fu; J. Ji.; G. Chen. Multi-level optimization of maintenance plan for natural gas pipeline systems subject to external corrosion. *Journal of Natural Gas Science and Engineering*, v. 50, p. 64-73, 2018.
[11] F.A.V. Bazán and A.T. Beck. Stochastic process corrosion growth models for pipeline reliability. *Corrosion Science*, vol. 74, pp. 50-58, 2013.
[12] F. Caleyo, J.C. Velázquez, A. Valor, J.M. Hallen. Markov chain modelling of pitting corrosion in underground pipelines, *Corrosion Sciences*, vol. 51, pp.2197–2207, 2009
[13] R. Amaya-Gómez, M. Sánchez-Silva, E.Bastidas-Arteaga, F. Schoefs, F.Muñoz. Reliability assessments of corroded pipelines based on internal pressure – A review, *Engineering Failure Analysis*, Vol. 98, pp. 190-214, 2019
[14] W. Zhou, M.A. Nessim. Optimal design of onshore natural gas pipelines. *Journal of Pressure Vessel Technology*, vol. 133-3. 11 pages, 2011
[15] I. I. DIKIN. Iterative solution of problems of linear and quadratic programming. **In:** *Doklady Akademii Nauk*. Russian Academy of Sciences, 1967. p. 747-748.
[16] M.D. MCKAY., R.J. BECKMAN, W.J. CONOVER. A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code. *Technometrics*, vol. 21, n. 2, pp. 239-245, 1979.