ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

OPTIMAL DESIGN AND INSPECTION PLANNING FOR ONSHORE PIPELINES SUBJECT TO CORROSION

Wellison José de Santana Gomes
André Teófilo Beck
Department of Structural Engineering, University of São Paulo, São Carlos, SP
gomes@gmail.com, atbeck@sc.usp.br

Abstract. *Corrosion is a random phenomenon which reduces the strength of pipeline systems over time. Continuous operation of such systems involves significant expenditures in inspection and maintenance. The cost-effective safety management of pipeline systems involves finding the appropriate amount of resources to allocate to initial design and to inspection and maintenance activities, in order to keep expected costs of failure (risk) under control. This article addresses the optimal inspection planning for onshore pipelines subject to external corrosion. The investigation combines a stochastic model of corrosion growth with limit state functions describing leak, burst or rupture of a pipeline segment containing corrosion defects. Uncertainties of inspection results are also taken into account. The objective function is obtained by adding initial costs, cost of inspections and the expected costs of repair and failure. The expected numbers of failures and repairs are evaluated by Monte Carlo simulation. Optimum inspection intervals are found for an example problem, and the sensitivities of these optima to assumed inspection and failure costs are investigated. It is shown that optimum results found herein are very sensitive to the assumed inspection and failure costs.*

Keywords: *corrosion, inspection, pipeline, optimization*

1. INTRODUCTION

Innumerous engineering systems are subject to strength degradation over time, due to random processes like fatigue, wear, and corrosion. The continuous operation of such systems involves large expenditures in inspection and maintenance activities, whose main purpose is to control risks. Quantifying risks, or expected costs of failure, allows the optimization of resources to be invested in inspection and maintenance activities. A practical case study is reported herein, addressing optimal design and inspection of a buried pipeline subject to external corrosion.

In this paper, a model for failure assessment of corroded pipelines is combined with a predictive pit growth model in order to solve a pipeline inspection optimization problem. The pipeline is subject to periodic inspections and possible repairs during each inspection. Risk optimization is a suitable tool to solve this problem. It addresses the objective of finding the best compromise between economy and safety. Specifically, risk optimization allows one to find the best inspection and maintenance policy, i.e., the optimum amount of resources to allocate to such activities.

The core of this paper is organized in four sections. The pipeline corrosion model is presented in Section 2. The formulation of the optimization problem in terms of expected cost of failure and repair is presented in Section 3. Results are presented and discussed in Section 5. The paper is finished with concluding remarks in Section 6.

2. PIPELINE CORROSION GROWTH MODEL

The corrosion defect is characterized by the maximum depth, d_{max}, and the defect length, L, in the longitudinal direction of the pipe. A predictive pit growth model developed by Caleyo et al. (2009) is used to describe the time evolution of d_{max}. This model is based on experimental data and takes into account the corrosion initiation time, t_0, and several properties of the soil that surrounds the pipe. For given values of the parameters k, α and t_0, the defect depth at time t is null if $t < t_0$, otherwise, it is given by:

$$d_{max}\left(t\right) = k\left(t - t_0\right)^{\alpha} \tag{1}$$

The parameters k and α are random variables, which can be derived from random variables describing soil properties (Caleyo et al., 2009). By adopting the general "All" soil category in (Caleyo et al., 2009), one million samples of the soil properties random variables are generated. Through maximum likelihood estimation, the probability distributions of k and α are obtained, as summarized in Table 1. The corrosion initiation time for this soil category is considered to be deterministic, and is also presented in Table 1.

The methodology adopted herein to evaluate the reliability of a pipeline segment containing corrosion defects was proposed by Zhou (2010). It consists of three different limit state equations, which are combined to define three different failure events: small leak, large leak, and rupture.

A small leak occurs when the defect penetrates the pipe wall. The limit state equation for this type of failure is a function of the maximum defect depth and the pipe wall thickness, *w*:

$$g_1(t) = 0.8 \cdot w - d_{\max}(t) \tag{2}$$

The limit state function for a so-called burst is given by:

$$g_2(t) = r_b(t) - p \tag{3}$$

where r_b is the burst pressure and p is the pipe internal pressure. The burst pressure is estimated using the PCORRC model (Leis & Stephens, 1997):

$$r_b(t) = X_M \cdot \frac{2 \cdot \sigma_u \cdot w}{D} \left[1 - \frac{d_{\max}(t)}{w} \cdot \left(1 - \exp\left(-\frac{0.157 \cdot L(t)}{\sqrt{0.5 \cdot D \cdot \left(w - d_{\max}(t) \right)}} \right) \right) \right] \tag{4}$$

where σ_u is the ultimate tensile strength of pipe material, D is the pipe diameter, L is the defect length in the pipe longitudinal direction, and X_M is a multiplicative model error factor. The input parameters required to assess the reliability are presented in Table 2. All values are obtained from (Zhou & Nessim, 2011), considering a Class 2 pipeline designed by the current pipeline standard in Canada (CSA, 2007), except the multiplicative model error, X_M, whose distribution is taken from (Zhou, 2010).

Table 1 - Input parameters for the maximum defect depth and defect length models.

Model	Variable	Probability distribution	Parameters
Maximum defect depth	k	T-location scale	Location $\mu = 0.168$
			Scale $\sigma = 0.063$
			Shape $\nu = 4.780$
	α	Inverse Gaussian	Mean $\mu = 0.762$
			shape $\lambda = 27.016$
Defect length	Defect length growth rate	Lognormal	Mean $\mu = 1.698\, mm/year$
			C.O.V. = 0.5
Both	t_0	Deterministic	$t_0 = 2.88\ years$

Table 2 - Basic pipeline attributes and model error distribution.

Variable	Mean	C.O.V.	Distribution type
Diameter (D)	508 mm	-	Deterministic
Internal pressure (p)	9.653 MPa	-	Deterministic
Wall thickness (w)	7.05 mm	1.5%	Normal
Tensile strength (σ_u)	615.9 MPa	3.0%	Normal
Model error for burst pressure (X_M)	0.97	10.5%	Lognormal

3. FORMULATION OF OPTIMIZATION PROBLEM

In this paper the optimal schedule is the one that leads to the minimum total expected cost. In other words, the total expected cost is the objective function of the optimization problem. To formulate the total expected cost, a reference cost, $C_{ref,}$ is adopted. This cost represents the cost to produce and install one unit length of pipe, and can be replaced by the actual cost of a real pipe if a measure of the real objective function is required. However, in the numerical examples herein, a unitary reference cost is considered and all the other costs are defined as functions of C_{ref}. Multiplicative factors are used to obtain the relative costs for small leak, burst, inspection and repair:

ISSN 2176-5480

$$C_i = f_i \cdot C_{ref}, \quad i = \{\text{small leak, burst, inspection, repair}\}. \tag{5}$$

Inspection, repair and failure costs are determined based on the unit costs presented by Zhou & Nessim (2011). For the case of burst failure, it is observed that, by considering different scenarios, with different numbers of injuries, fatalities, defects per kilometer and other factors, the failure cost can vary between about 25 and 200 times C_{ref}. These costs reflect pipelines passing through areas of different population density. The cost of a small leak is assumed to be solely the cost of excavating and repairing the pipeline at the location of the leak, which leads to a cost equal to about 0.243 times C_{ref}. The same cost is assumed as the cost for repair. The cost of inspection is found to be about $0.01778 \cdot C_{ref}$. In the above cost scenarios, eventual costs associated with downtime are not considered. For a fixed lifetime, T, and time between inspections, t_{insp}, the number of inspections is given by the largest integer obtained from the ratio T / t_{insp}. Finally, the total expected cost, C_{ET}, is equal to the sum of the initial cost, which is equal to the reference cost, C_{ref}, the cost of inspections, and all the expected costs of repair and failure:

$$C_{ET} = C_{ref} + N_{insp} \cdot C_{insp} + EnR \cdot C_{rep} + EnF(1) \cdot C_{small} + \left(EnF(2) + EnF(3)\right) \cdot C_{burst} \tag{6}$$

where EnR is the expected number of repairs and EnF is a vector containing the expected number of failures for each failure event, *i.e.*, for each leak, burst and rupture. For a given time between inspections, t_{insp}, evaluation of the expected number of repairs and failures is a highly complex and computationally expensive task when calculating the total expected cost. The evaluation of these expected values is addressed next.

The expected number of repairs and failures are calculated by Monte Carlo sampling. Each sample is defined by one realization of each random variable at the initial time, as well as the evolution of the corrosion process over the lifetime T, with time steps dt. In the present paper, the number of time history points, is 400, which together with a design life of T=50 years leads to dt=0.125 years.

Following an inspection, if a defect is located, it can be repaired or not. A defect is repaired immediately after an inspection if it meets any of the following criteria:

$$d_{\max}(t) \geq 0.5 \cdot w \quad \text{or} \quad p \geq r_b(t) \cdot \tag{7}$$

After a segment is repaired, a new corrosion defect starts again at the corrosion initiation time, t_0. For each pipe history sample, once and if a failure occurs, the respective indicator function for number of failures is increased by one and the pipe segment is repaired. When a defect is repaired, as result of an inspection or following failure, the indicator function for the number of repairs is increased by one. After a repair, a new corrosion initiation time, t_0, is applied and new realizations of k, α, and the defect length growth rate are sampled in order to describe the time evolution of the corrosion after the repair. The computations are performed at the discrete time points mentioned above. It is important to observe that, as the pipeline needs to be kept in service, if a failure occurs the pipe segment is replaced and the simulation proceeds until the end of the lifetime, T=50 years. Thus, the expected number of failures is computed by statistical analysis, instead of the more common probability of failure, computed by reliability analysis.

4. NUMERICAL RESULTS

Figure 1 presents objective function values for different values of t_{insp}, for $C_{insp}=0.0177 \cdot C_{ref}$ and $C_{burst}=25 \cdot C_{ref}$. For small values of t_{insp} the number of inspections is very high, therefore, the cost of inspections, which tends to infinity when t_{insp} tends to zero, dominates the total expected cost. As the inspection interval increases, the expected number of failure increases, leading to a higher influence of the cost of failure over C_{ET}. However, for each number of inspections the objective function assumes a convex shape, *i.e.*, there is a minimum for each number of inspections, and this behaviour is more pronounced for smaller numbers of inspections, for example in the case where just one inspection takes place, N_{insp}=1 and $T/2 \leq t_{insp} \leq T$. Inside each valley, the minimum is defined by the combination of expected number of repairs and expected number of failures which leads to the lowest total expected cost.

It is noted that, in spite of using a continuous design variable, t_{insp}, the number of inspections in T is discrete, which leads to oscillations and considerable discontinuities in the total expected cost function. Moreover, the cost of repair itself introduces considerable discontinuities in the total expected cost. In principle, these discontinuities make the use of gradient-based optimization methods unfeasible, unless mitigating strategies are employed.

Since the problem addressed here has one design variable, the optimal inspection interval can be found directly by means of an exhaustive search, which consists of evaluating the objective function for all possible values of the design variable and selecting the optimum among these values. For this purpose, total expected costs are evaluated 1000 times within the interval [0.75; 40] years and the computed value of t_{insp} leading to the minimum C_{ET} is chosen as the optimal

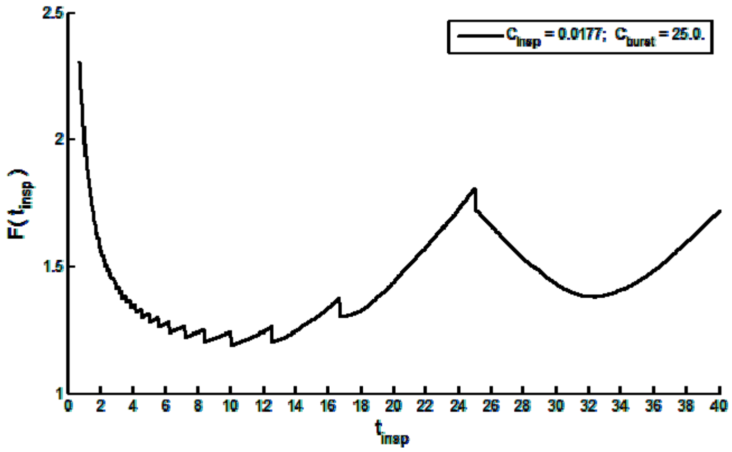

Figure 1 - Objective function values for different times between inspections, reference cost configuration.

one. It is also noted that a multi-start gradient-based approach could also be employed, especially for problems with a higher number of design variables.

5. CONCLUDING REMARKS

In this paper, optimal inspection intervals were obtained for a buried pipeline subject to external corrosion. This was accomplished by solving a risk optimization problem, where not only inspection and maintenance costs are considered, but also the expected costs of failure. It is claimed herein that such an optimization problem cannot be solved without including the expected costs of failure. Specific results for the case-study presented herein showed an optimum inspection interval of around ten years. Clearly, these results are valid for scheduling the first inspection, since in practice the second inspection would be scheduled considering the corrosion rates measured via the first inspection. In a companion paper, it is shown how the results presented herein are sensitive to the choices of failure and inspection costs made herein.

6. ACKNOWLEDGEMENTS

The authors kindly acknowledge financial support of this research project by the agencies CNPq (Na-tional Council for Research and Development) and FAPESP (São Paulo State Foundation for Research).

7. REFERENCES

Zhou W. System reliability of corroding pipelines. Int. J. of Pressure Vessels and Piping. 2010; 87:587-595.

Caleyo F, Velázquez JC Valor A, Hallen JM. Markov chain modelling of pitting corrosion in underground pipelines. Corrosion Science 2009; 51(9):2197–2207.

Beck AT & Gomes WJS. A comparison of deterministic, reliability-based and risk-based structural optimization under uncertainty. Probabilistic Engineering Mechanics 2012; 28: 18-29.

Beck At, Gomes WJS & Bazan FAV. On the robustness of structural risk optimization with respect to epistemic uncertainties. International Journal for Uncertainty Quantification 2012; 2(1): 1-20.

Zhou W, Nessim, MA. Optimal Design of Onshore Natural Gas Pipelines. Journal of Pressure Vessel Technology 2011; 133.

Leis BN, Stephens DR. An alternative approach to assess the integrity of corroded line pipe – part II: alternative criterion. Proc.of the 7th International Offshore and Polar Engineering Conference 1997; 635-640.

Canadian Standard Association. Oil and Gas Pipeline Systems. Z662-07, 2007.

8. RESPONSIBILITY NOTICE

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