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Optimal Inspection of Onshore Pipelines Subject to External Corrosion

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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.

1. Introduction

In this paper, a model for failure assessment of corroded pipelines (Zhou, 2010) is combined with a predictive pit growth model (Caleyo et al., 2009) in order to solve a pipeline inspection optimization problem. The pipeline is subject to periodic inspections and possible repairs during each inspection. Risk optimization (Beck and Gomes, 2012; Beck et al., 2012) 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, followed by the formulation of the optimization problem in terms of expected cost of failure and repair in Section 3. Thereafter, a probabilistic analysis using Monte Carlo sampling is carried out in Section 4. The results are presented and discussed in Section 5. Section 6 finishes the paper with concluding remarks.

2. Pipeline Corrosion Model

2.1 Models of corrosion growth

The corrosion defect is characterized by the maximum depth, d_{max}, and the defect length, L, in the longitudinal direction of the pipe, as shown in Figure 1.

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:

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

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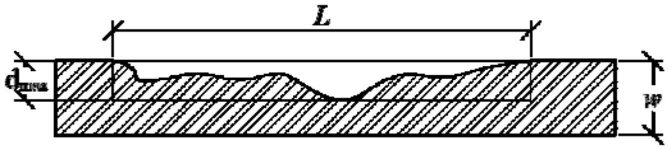

Figure 1: Dimensions of a corrosion defect.

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.

To describe the growth in the defect length, a linear model similar to the one employed by Zhou & Nessim (2011) is adopted. In this case, the defect length is assumed to grow with constant rate, but the rate is a lognormal random variable. In Zhou & Nessim (2011), the defect length has an initial mean value 30.0mm and a growth rate with lognormal distribution, mean 1.0 mm/y and standard deviation 0.5mm/year, leading to an average defect length equal to 80.0 mm in 50 y. To include the initiation time in this model, the initial defect length was considered null, at t_0, and the parameters of the rate distribution were adjusted in order to achieve the same average defect length after 50 y as the original linear model. The parameter values are shown in Table 1.

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

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	$t_0 = 2.88\ years$

2.2 Limit state functions for corroded pipelines

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:

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

The limit state function for a so-called burst, which will be related to large leaks and ruptures shortly, is given by:

$$g_2(t) = r_b(t) - p \quad (3)$$

where r_b is the burst pressure and p is the pipe internal pressure. The burst pressure is a function of material and geometry properties of the pipe, as well as the defect geometry. In this study it is estimated using the so-called PCORRC model developed by Leis & Stephens (1997), through the following expression:

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

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 burst of a pipeline containing a corrosion defect can be followed by instable rupture in the longitudinal direction. The limit state function for this failure mode is:

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

where r_{rp} is the rupture pressure for a pipe containing a through-the-wall defect. The rupture pressure can be calculated by a model developed by Kiefner et al. (1973), which takes into account the flow stress, σ_f:

$$r_{rp}(t) = \frac{2 \cdot w \cdot \sigma_f}{M(t) \cdot D} \tag{6}$$

where the Folias factor, M, is approximated by the expression

$$M(t) = \begin{cases} \sqrt{1 + 0.6275 \cdot \dfrac{L(t)^2}{D \cdot w} - 0.003375 \cdot \left(\dfrac{L(t)^2}{D \cdot w}\right)^2}, & \text{if } \dfrac{L^2}{D \cdot w} \le 50 \\ 0.032 \cdot \dfrac{L(t)^2}{D \cdot w} + 3.293, & \text{otherwise.} \end{cases} \tag{7}$$

and the flow stress, σ_f, is defined as $0.9 \cdot \sigma_u$. A burst occurs when the pipe wall undergoes plastic collapse due to internal pressure at the defect location, before the defect penetrates the pipe wall. It is this situation that is classified as either a rupture or large leak. In particular, a rupture occurs when the through-wall defect resulting from a burst is long enough to undergo unstable axial extension, while a large leak is defined as a burst without unstable axial extension of the resulting through-wall defect. In summary, letting negative realizations of a limit state function denote failure, a small leak takes place when $g_1 \le 0$ and $g_2 \le 0$, a large leak takes place when $g_1 > 0$, $g_2 \le 0$, and $g_3 > 0$, and a rupture takes place when $g_1 > 0$, $g_2 \le 0$, and $g_3 \le 0$.

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 Z662-07, except the multiplicative model error, X_M, whose distribution is taken from Zhou (2010).

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:

$$C_i = f_i \cdot C_{ref}, \qquad i = \{\text{small leak, burst, inspection, repair}\}. \tag{8}$$

Following an inspection, if a defect is located, it can be repaired or not. The repair criteria adopted in Zhou & Nessim (2011) are considered herein, i.e., a defect is repaired immediately after an inspection if it meets any of the following criteria:

$$d_{\max}(t) \geq 0.5 \cdot w \tag{9}$$

$$p \geq r_b(t) \cdot \tag{10}$$

Eq. (10) corresponds to an estimated repair factor (ERF) of 1.39, which is the safety factor adopted in design. After a segment is repaired, a new corrosion defect starts again at the corrosion initiation time, t_0.

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}. The same cost range is assumed for failure by rupture. 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 cost of inspection is found to be about $0.0177 \cdot C_{ref}$. Values of all multiplicative cost factors are given in Table 3. In the above cost scenarios, eventual costs associated with downtime are considered to be outside the scope of this study.

Table 3: Multiplicative factor to calculate costs.

Factor	Value(s)
f_{insp}	0.01778
f_{rep}	0.243
f_{small}	0.243
f_{burst}	25

Imprecision of the inspection equipment is also considered. The probability of detection curve (POD) follows the curve considered in Zhou & Nessim (2011). However, it is assumed that if a defect is detected then a perfect measure of its depth and length is obtained. The POD is of the following exponential form:

$$POD = 1 - e^{-q \cdot d_{\max}} \tag{11}$$

where q=3.262. 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:

$$C_{ET} = C_{ref} + N_{insp} \cdot C_{insp} + EnR \cdot C_{rep} + EnF(1) \cdot C_{small} + \left(EnF(2) + EnF(3)\right) \cdot C_{burst} \tag{12}$$

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 in the next section.

4. Probabilistic Analysis

4.1 Computation of expected numbers of repairs and failures

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 y leads to dt=0.125 y.

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. At the resolution employed herein, dt=0.125 y, and for near-critical defects, failure and repair following an inspection could occur simultaneously during the same dt. In order to avoid such non-physical behavior, linear approximations are employed to decide which events occur first. In particular, for a given time t_1 and for each limit state function g_i, with i=1,2,3, a linear approximation is considered by using two limit state values $g_i(t_1)$ and $g_i(t_1+dt)$. Hence, it can be determined whether a failure occurs within the interval $[t_1,t_1+dt]$, and subsequently the exact time of failure t^i_f.

If a defect is detected in an inspection, linear approximations are also applied to evaluate the repair criteria given by Equations (9) and (10), using values of d_{max} and r_b at the time of inspection.

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 y. Thus, the expected number of failures is computed by statistical analysis, instead of the more common probability of failure, computed by reliability analysis. This expectation-oriented approach is adopted here because it is expected numbers that are required in the objective function of the decision problem, as described earlier.

4.2 Reliability Updating

In a probabilistic analysis where all possible outcomes of a future inspection are accounted for, the knowledge that a future inspection event will take place does not actually provide new information. Instead, the theorem of total probability is invoked to integrate over all possible outcomes of the inspection, *i.e.*, no detection or detection of a certain defect. In contrast, the reliability/probabilistic updating in this paper is done automatically, by direct simulation, since each pipe history sample includes replacement of failed segments and/or possible repair following an inspection.

5. Numerical Results

Figure 2 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 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.

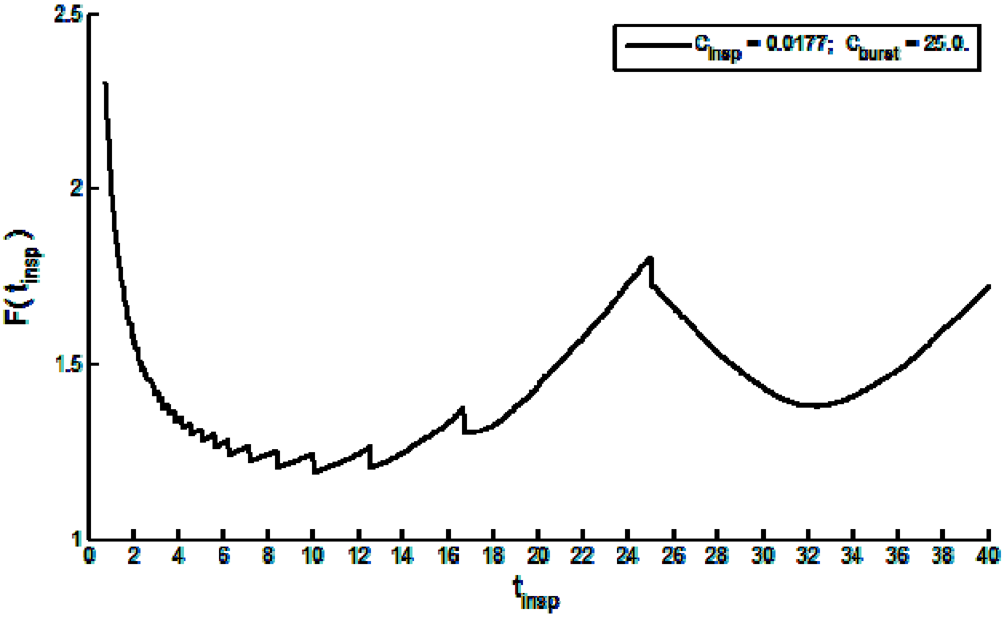

Figure 2: Objective function values for different times between inspections, reference cost configuration.

6. 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.

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