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Reliability-Based Maintenance Optimization Of Pipelines Considering Space-Variant Corrosion Rate

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ABSTRACT: The present work aims at developing a procedure for inspection optimization of pipelines subject to corrosion, including predictive degradation modelling, space-variant corrosion rate, time-dependent reliability assessment and inspection uncertainties. The space-variant corrosion is considered by the mean of Karhunen-Loève expansion in order to take account of soil aggressiveness regarding the variability of corrosion rate along the pipe length. The failure probability is evaluated by a series system combination, using Monte Carlo simulations. Then, the maintenance model is developed according to the inspection decision tree, where imperfect inspections are taken into account. Finally, the developed model is applied to gas pipeline under various corrosion rates, in order to show the effects of the main parameters of the system.

1. INTRODUCTION

Due to degradation, the pipelines undergo various maintenance operations, such as: regular inspections to assess degradation, repair actions to recover existing damage, overall repair to bring the structure close to its initial state, and finally complete replacement when the structure becomes technically inappropriate for operation. From the safety point of view, the optimal maintenance program should be defined on the basis of the minimum acceptable level of failure probability. From the cost-benefit point of view, the optimal maintenance planning should be defined on the basis of minimum expected cost (Laggoune et al., 2009).

As the real degradation state can only be known at the inspection time, the optimization of the intervals between inspections becomes a fundamental problem for maintenance quality and safe operation of pipelines. In practice, the inspection of existing pipelines cannot be perfect and their performance should be defined in terms of probability of good assessment and probability of wrong assessment (Straub and Faber, 2003; Rouhan and Schoefs, 2003). The application of Risk Based Inspection methods (RBI), on the basis of structural reliability analysis, failure consequence assessment and probabilistic modelling of inspection results, allows us to establish and to optimize the maintenance policies of aging installations by satisfying safety and availability requirements.

The present work aims at developing a procedure for inspection optimization of pipelines subject to corrosion, including predictive degradation modelling, space-variant corrosion rate, time-dependent reliability assessment, inspection uncertainties and expected cost minimization. The originality of this work lies in coupling space variability with inspection uncertainties, in order to allow for practical and accurate applications in the field of pipe engineering. First, the degradation model of pipelines under corrosion is described. The space-variant corrosion is considered through Karhunen-Loève expansion in order to take into account the variability of corrosion rate along the pipe length, depending on the soil aggressiveness. The failure probability is then evaluated by a series system combination, using Monte Carlo simulations. Then, the maintenance model is developed according to the decision tree, where imperfect inspections are taken into account. Finally, the developed model is applied to gas pipeline under various corrosion rates, and the effects of the main parameters of the probabilistic model are analyzed.

2. DEGRADATION MODEL

2.1. Pipeline corrosion

The corrosion distribution in pipes can be stochastically described by random fields over the material space. Although the corrosion geometry is usually described by either uniform corrosion or localized corrosion, most of corrosion problems encountered in the real world are a combination of these two forms. Consequently, the total corrosion depth at any location x and time T can be described by the sum of these two types of corrosion:

$$d_C(x,T) = d_{UC}(T) + d_{LC}(x,T) \qquad (1)$$

where $d_C(x,T)$ is the total corrosion depth at the location x and time T, $d_{UC}(T)$ is the depth of uniform corrosion and $d_{LC}(x,T)$ is the depth of localized corrosion defect. Figure 1 shows a longitudinally-oriented surface corrosion defect in the wall of a pressurized pipeline (Ahammed and Melchers, 1997). In this Figure, d is the pipe wall thickness, d_{UC} is the depth of uniform corrosion, d_{LC} is the depth of localized corrosion and l_{LC} is the length of the corroded region according to the longitudinal axis.

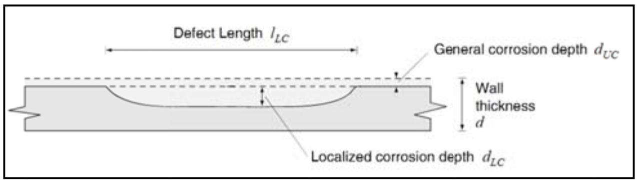

Figure 1. Idealized corrosion defect.

2.1.1. 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 (Kucera and Mattsson, 1987; Ahammed and Melchers, 1997). The general form of the corrosion power law is written as:

$$d_{UC}(T) = \kappa_{UC}\, T^n \qquad (2)$$

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) to field corrosion data (Kucera and Mattsson, 1987; Amirat, Chateauneuf and Chaoui, 2006). For atmospheric conditions, 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 (Kucera and Mattsson, 1987).

2.1.2. Localized corrosion

In the past decades, extensive researches have been performed on localized corrosion, in order to derive empirical models for different environmental conditions.

In order to account for random distribution of localized corrosion defects over the pipe surface, the pipeline is considered as a system of segments in series. Each segment presents a number of localized corrosion defects, as shown in Figure 2. As corrosion is induced by external environment (i.e. soil composition for underground pipes), the spatial correlation should be considered to compute the system reliability.

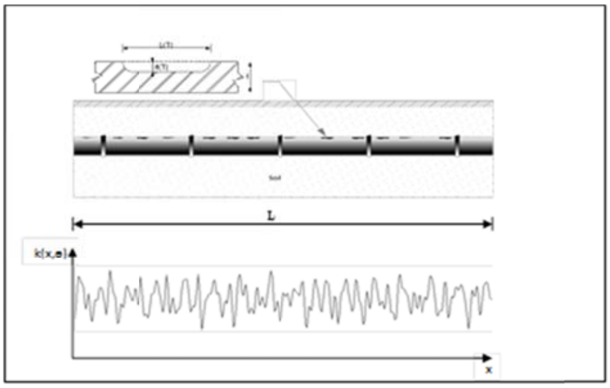

Figure 2. Pipeline segments and localized corrosion profile.

The empirical equations for time-dependent corrosion usually considered in the literature (e.g. Ahammed, 1998; Qian, Niffenegger and Li, 2011) are extended herein to include the space-variant field as following:

$$d_{LC}(x,T) = k(x,\theta)\ T^n \tag{3.a}$$

$$l_{LC}(x,T) = \gamma\ k(x,\theta)\ T^n \tag{3.b}$$

where $d_{LC}(x,T)$ and $l_{LC}(x,T)$ are respectively the localized corrosion depth and length, $k(x,\theta)$ defines the corrosion rate, according to soil aggressiveness, x is the longitudinal pipe coordinate, θ is the stochastic set, and γ is the ratio between the length and the depth of localized corrosion.

3. PIPELINE RELIABILITY

3.1. Stochastic corrosion field

An appropriate representation of the stochastic corrosion field can be performed by the mean of Karhunen-Loève expansion (Ghanem and Spanos, 1991). In this expansion, the stochastic field is given by the sum of a finite number of independent standard gaussian variables ξ_i:

$$k(x,\theta) = \bar{k}(x) + \sum_{i=1}^{M} \sqrt{\lambda_i}\,\varphi_i(x)\,\xi_i(\theta) \tag{4}$$

In this expression, the space-variant effects are defined by introducing the eigen modes of the covariance kernel, where λ_i are the eigen values and φ_i are appropriate orthogonal functions. In our case, the autocorrelation function is assumed to exponential, allowing us to consider Hermite orthogonal functions for stochastic field expansion. Moreover, the stochastic field is considered as stationary within the same type of soil.

3.2. Failure probability

The failure of pipes is identified by using a semi-empirical model based on fracture mechanics to determine the pressure at which the vessel fails as a function of the size and the geometry of the corrosion defect. This approach has been developed in the early seventies (e.g. see Maxey et al. (1972) and Kiefener et al. (1973)), and still remain the most widely applied approach. It is furthermore used in several standards, such as the B31G (ASME-B31G, 1991, 1995). A review of the approach and different modifications are given by Ahammed and Melchers (1996).

By considering uniform and localized corrosion, the expression of the pipe capacity at a given cross-section can be written as (Ahammed, 1998):

$$P_r(x,T) = 2(f_y + 68.95)\frac{d(T)}{D}\left[\frac{1-\dfrac{d_{LC}(x,T)}{d(T)}}{1-\dfrac{d_{LC}(x,T)}{M\cdot d(T)}}\right] \tag{5}$$

where D is the pipe diameter, f_y is the yield stress, $d(T)$ is the wall thickness at time T, given by $d(T) = d - d_{UC}(T)$, and M is the Folias factor, as given in the work of Ahammed and Melchers (1996).

The limit state function $G(x_i)$ considered for reliability analysis is defined by the safety margin, given by the difference between the pipe resistance $P_r(x,T)$ and the applied pressure P_a (Amirat, Chateauneuf and Chaoui, 2006; Khelif, Chateauneuf and Chaoui, 2007), For any cross-section at location x, the associated limit state function $G(x,T)$ is:

$$G(x,T) = P_r(x,T) - P_a \tag{6}$$

The failure probability of the pipeline can be evaluated by performing Monte-Carlo simulations (Ditlevsen and Madsen, 1996). The system reliability can be evaluated as the union of the limit state events at various cross-sections x_i along the pipe. The system failure probability can be expressed as:

$$P_f(T) = P\left[\bigcup_{x=x_i} G(x,T) \le 0\right] \tag{7}$$

4. COST MODEL

The optimization of inspection plan is based on the minimization of the expected total cost, which is given by the expected costs related to each branch of the decision tree in Figure 3, over a given time span (Goyet et al., 1994; Goyet, Straub and Faber, 2002).

$$\min E[C_T] = \min \sum C_i P_i \tag{8}$$

where $E[C_T]$ is the mathematical expectation of the total cost C_T , P_i is the probability of occurrence of the i-th scenario and C_i is the total cost of the i-th scenario. The expected total cost $E[C_T]$ is decomposed as following:

$$E[C_T] = E[C_{IN}] + E[C_R] + E[C_F] \tag{9}$$

where $E[C_{IN}]$ is the expected inspection cost, $E[C_R]$ is the expected repair cost, and $E[C_F]$ is the expected failure cost. Referring to Figure 3, these expected costs can be easily calculated.

- Expected failure cost:

$$E[C_F] = C_F P_F(T_1) + (1 - P_F(T_1)) \sum_{j=1}^{6} C_F P_{Fj.1.Act} P(S_j)$$

- Expected repair costs:

$$E[C_R] = C_R(1 - P_F(T_1))[P(S_3) + P(S_4)]$$

- Expected inspection costs:

$$E[C_{IN}] = (1 - P_F(T_1))\left[C_i + \sum_{j=1}^{6} C_i(1 - P_{Fj.1.Act}) P(S_j)\right]$$

where C_F and C_i are respectively the failure and inspection costs, C_R is the repair cost, $P_F(T_1)$ is the failure probability at the inspection time T_1, and $P_{Fj.1.Act}$ is the updated failure probability after inspection at time T_1 for the j-th scenario.

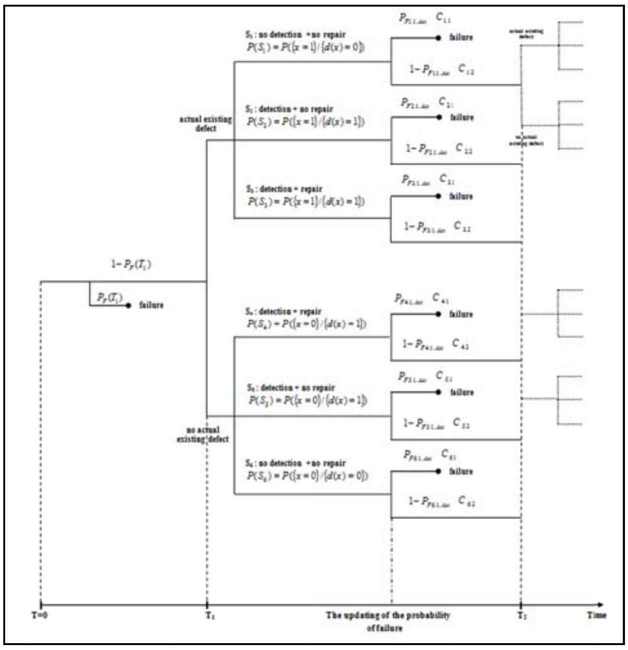

Figure 3. Inspection decision tree.

5. APPLICATION TO CORRODED PIPE

The above model is now applied to steel pipe of grade X52, with diameter D and wall thickness t, and subjected to internal pressure p. This pipe is designed for a service life of 50 years. The probabilistic data are provided in Table 1, where all variables are lognormally distributed.

Table 1. Statistical moments of random variables.

Variable	Mean	St. Dev.
Diameter D (mm)	600	18
Wall thickness d (mm)	10	0.5
Yield stress f_y (MPa)	423	28.3
Internal pressure P_a (MPa)	5	0.5
Length-to-depth ratio of localized corrosion γ	10	2
Uniform corrosion rate κ_{UC}	0.02	0.005
Average Localized corrosion rate κ_{LC}	0.164	0.028
Corrosion parameter n	0.780	-

5.1. Pipeline reliability

In the numerical application, we consider a length of 200 km for the underground pipeline. Figure 4 compares the time-variant failure probability considering space variability (i.e. stochastic field with correlation length lc = 20m) with the case without space variability (i.e. $lc = \infty$). It can be seen that considering the stochastic field reduces the dispersion of the lifetime distribution, leading to a reliability increase in the first part of the lifetime (i.e. before 35 years herein) and a reliability decrease in the second part of the lifetime. It can be concluded that neglecting the spatial variability leads to pessimistic estimation of the lifetime, and consequently to lowering the operating conditions or to early replacement of the pipeline.

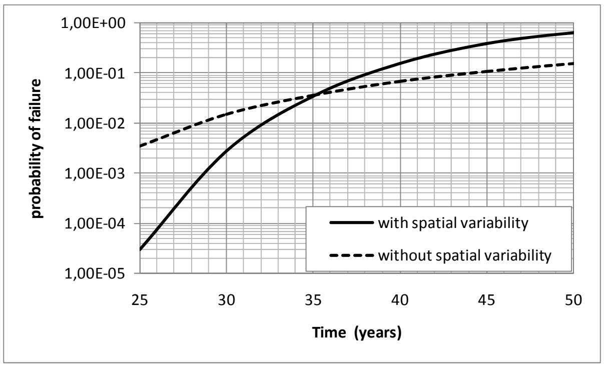

Figure 4. Effect of spatial variability on the pipe failure probability.

5.2. Optimal inspection interval

To determine the maintenance policy, it is necessary to specify the costs related to failure, inspection and repair, as well as the minimum detectable defect $d_{\min}$ and the defect size at conventional failure d_{cr} ; these parameters are given in Table 2. The critical defect size d_{cr} corresponds to the failure probability of 10^{-2}.

Table 2. Cost data and maintenance thresholds.

Item	Value
Failure cost C_F	230 000 €
Inspection cost C_i	3 500 €
Repair cost C_R	10 400 €
Detection threshold $d_{\min}$	1.5 mm
Size of critical defect d_{cr}	2.8 mm

5.3. Optimal time between inspections

Figure 5 depicts various expected costs (failure $E[C_F]$, inspection $E[C_{IN}]$ and repair $E[C_R]$) in terms of time interval between inspections. Naturally, by increasing the time between inspections, the inspection and repair costs decrease, while the failure cost increase. The optimal time interval between inspections is obtained at 34 years.

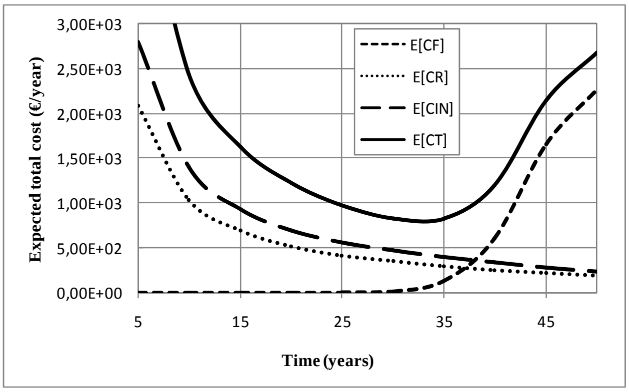

Figure 5. Expected costs in terms of inspection time.

5.4. Inspection quality

In order to allow for clear understanding of the contribution of cost components, Figure 7 plots the cost evolutions with time, for the case of perfect inspections. As can be observed, the variation of the expected total cost increases rapidly around the optimum value of 30 years, due to high increase of failure cost.

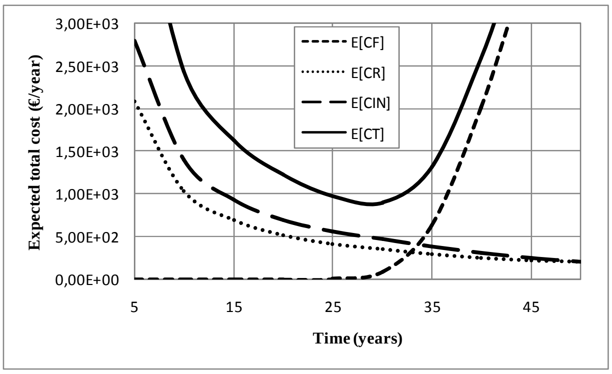

Figure 6. Expected costs as a function of perfect inspection time.

The inspection quality is now considered in terms of cost and detection level. Four detection precisions are considered: low $d_{\min} = 2.0\,mm$, medium $d_{\min} = 1.5\,mm$, high $d_{\min} = 1.0\,mm$, perfect $d_{\min} = 0.0\,mm$. For a given inspection cost, a better precision leads to a reduction of the time interval between inspections. For three inspection costs (i.e. initial, ten times less and ten times more), Figure 7 shows that the expected total cost increases with the detection quality. It can be observed that the curves resulting from low qualities are more scattered. This can be explained by the lack of precision leading to high overall uncertainties.

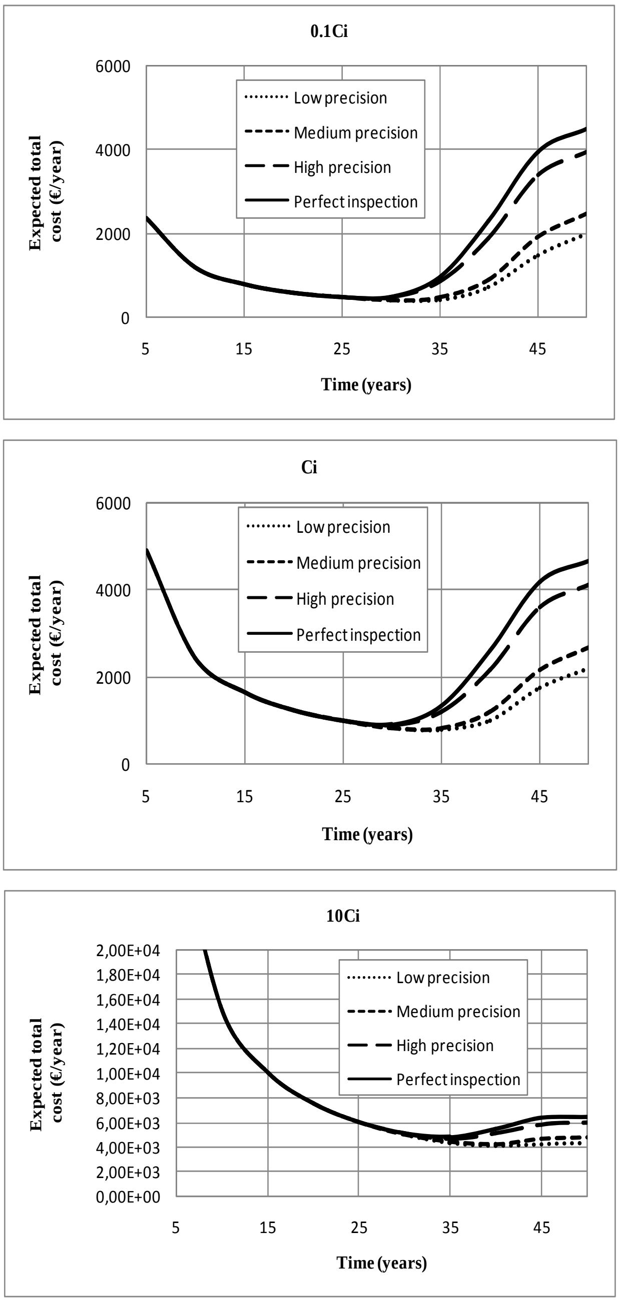

Figure 7. Influence of the quality of detection of the expected total cos.

5.5. Influence of corrosion rates

In order to analyze the influence of corrosion rate on the optimal interval between inspections, three corrosion rates are considered: low, moderate and high, according to the parameters indicated in table 3.

Table 3. Uniform and localized Corrosion rates.

Uniform corrosion rate κ_{UC}	Mean	St. Dev.
Low	0.14	0.014
Moderate	0.37	0.037
High	0.62	0.062
Localized corrosion rate κ_{LC}	Mean	St. Dev.
Low	0.14	0.028
Moderate	0.37	0.074
High	0.62	0.124

The expected total cost is depicted in Figure 8 for the three corrosion rates. As expected, the optimal inspection time is strongly dependent on the corrosion rate, as it highly decreases with the environment aggressiveness. In case of high corrosion rate, the optimal interval is about 10 years and 34 years in the case of a moderately aggressive (Table 4). The optimal time is beyond the service life when the corrosion rate is low, and no inspection should be scheduled during the design lifetime.

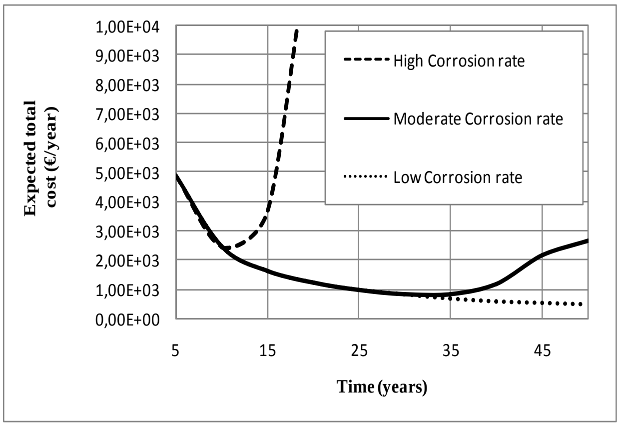

Fig. 8. Expected total costs for various corrosion rates

Table 4. Inspection times and total cost for different corrosion rates.

Corrosion rate	Optimal inspection interval	Minimum expected cost
Low	-	-
Moderate	34 yr	822.6 €/yr
High	10 yr	2445 €/yr

6. CONCLUSION

This work presents a complete approach for inspection-repair planning of corroded pipelines allowing the consideration of space variability and inspection uncertainties. The proposed procedure allows us to compare various strategies, by comparing the effectiveness of inspection techniques. The formulation of the expected cost in different situations provides a decision-making tool for optimal scheduling of inspections according to corrosion rates. The numerical application shows the coherence of the proposed model as well as its capacity to take account for practical inspection planning.

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