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The effects of spatial variability of the aggressiveness of soil on system reliability of corroding underground pipelines

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ABSTRACT

In this paper, a probabilistic methodology is presented for assessing the time-variant reliability of corroded underground pipelines subjected to space-variant soil aggressiveness. The Karhunen-Loève expansion is used to model the spatial variability of soil as a correlated stochastic field. The pipeline is considered as a series system for which the component and system failure probabilities are computed by Monte Carlo simulations. The probabilistic model provides a realistic time and space modelling of stochastic variations, leading to appropriate estimation of the lifetime distribution. The numerical analyses allow us to investigate the impact of various parameters on the reliability of underground pipelines, such as the soil aggressiveness, the pipe design variables, the soil correlation length and the pipeline length. The results show that neglecting the effect of spatial variability leads to pessimistic estimation of the residual lifetime and can lead to condemn prematurely the structure.

1. Introduction

The role of pipelines is mandatory in oil and gas industries, as they help in sustainable development by ensuring the functions of product generation, transmission and distribution [1]. Pipelines are most often made of steel pipes, assembled by welding linear segments. Despite its high interest in piping industry, the steel has the disadvantage of being affected by corrosion, especially when buried in the soil [2,3]. In addition, the soil properties vary along the pipeline, which may cross desert sand, wetlands, agricultural areas and mountains. There variations will have direct impact on the lifetime of the pipeline, and directly affecting the product conveying reliability.

Aging underground oil and gas pipelines can suffer from several localized forms of corrosion despite the significant development in cathodic protection techniques, as well as internal and external coating methods [4]. In many cases, an extremely fast corrosion can be observed in highly aggressive soils. Knowing that the soil is a complex amalgam [2] of solids, liquids and gases, the interaction between the pipe steel and the soil constitutive materials still represents an active research field. In the past years, various corrosion studies have been performed on buried pipelines in order to assess their remaining capacity [5–12].

The reliability analysis allows us to understand how the uncertainties are propagating within the structural system, and hence provides the necessary information for inspection planning [13]. In the large majority of researches in the literature, the corrosion models of underground steel pipes [2,14–16] do not take into account the spatial variability of corrosion and the large heterogeneity of the segment exposure. In fact, these models lead to penalizing estimations of the residual lifetime, as they tend to condemn prematurely the structure. Nonetheless, only few studies can be noticed about the correlation between various defects in probabilistic analysis of pipelines [17–19], and the enhancement of the existing models still needs further developments.

The spatial variability can be explained by various factors related to physical and chemical heterogeneity of the soil, such as water content, resistivity, pH, redox potential, composition and concentration of chemical species. These factors generally change with the topographic profile that characterizes pipeline configurations, even for the same type of soil [3]. Therefore, the estimation and the

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evaluation of the material losses caused by corrosion of buried pipes is complex and the methods applied for their assessment should consider the aforementioned factors. As these variabilities are random by nature and the corrosion phenomena are complex, the predictive models are affected by large amount of uncertainties. It is therefore mandatory to develop stochastic methodologies in order to assess properly the strength and the lifetime of corroded underground pipelines.

In the general framework, the reliability assessment of corroded pipeline should take into account various types of corrosion, as well as other uncertainties related to material and loading conditions. The stochastic modelling of pipelines should be able to take into account the real complexity of the system, namely the spatial variability along the pipeline [20] and the stochastic nature of localized corrosion [21,22]. Theses phenomena can be represented by either continuous or discontinuous stochastic fields. The discretization of the correlated pit depth can be considered as a countable set [23] which varies with the pipe length, making localized corrosion a good candidate for Karhunen-Loève expansion [24,25]. As a matter of fact, the methods for random field discretization are mainly classified into three groups: point discretization methods, average discretization methods and series expansion methods [26]. The advantages and disadvantages of each of these methods are widely discussed in Refs. [26,27]. The efficiency of a random-field discretization method is characterized by its ability to accurately represent the original random field with the lowest number of random variables (i.e. its capability of representing continuous field by few discrete variables). The series expansion discretization methods have shown to be more efficient for discretizing the random field than the other two groups (point discretization methods and average discretization methods). Among the available methods approximating the autocorrelated random fields by a finite sum of weighted random variables, the Karhunen–Loève (KL) expansion has shown to give the best accuracy (i.e. lowest mean square error) with respect to the number of random variables [25]. This is the reason why it received intensive attention in the literature [28].

In the present work, a probabilistic method is developed to evaluate the reliability of pipelines by taking into account the aging induced by space-variant corrosion. The performed analyses are focused on the spatial variability of soil aggressiveness, by studying the influence of the correlation length on the system failure probability. The originality of the developed model is to handle both space variability for corrosion rate induced by soil aggressiveness, and time variability for the remaining wall thickness by cumulated corrosion. This space-time coupling of variabilities leads to realistic modelling of underground pipeline degradation. Another interesting feature of the model lies in the stochastic dependence between pipe corrosion and soil properties.

The methodology considers the pipeline as a system of segments in series. Each segment presents a number of localized corrosion defects in such a way that failure of any single segment induces the failure of the whole system. First, the probabilistic model of corroded pipeline is described. The space-variant corrosion is considered through Karhunen-Loève expansion in order to take into account the variability of corrosion level according to soil aggressiveness. The failure probabilities of the pipeline and its components are then evaluated as a series system, using Monte Carlo simulations. Finally, the numerical examples are provided to illustrate the proposed method, where the effects of the main parameters of the probabilistic model are analyzed.

2. System definition

The pipeline is considered as a system of segments of pipes forming a series system; i.e. the failure of one segment leads to the failure of the whole system. Knowing that localized corrosion defects are randomly distribution over the pipe surface, each segment presents a number of localized corrosion defects, as shown in Fig. 1. The pipe corrosion is induced by the external environment (i.e. soil composition in the case of underground pipes), which is continuously varying along the pipe length. The size of corrosion defects, and their number per unit area, will therefore depend on the spatial correlation of the soil aggressiveness. This information has to be considered to assess the system integrity. The failure mode corresponds to the capacity of the corroded pipeline under the applied internal pressure. By considering the system uncertainties and variations, the reliability analysis aims at computing the failure

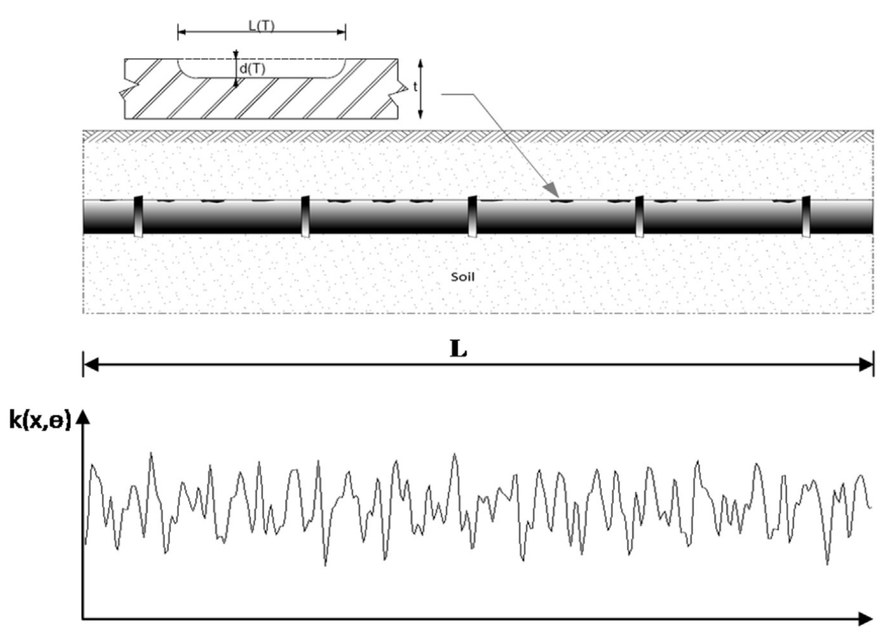

Fig. 1. Pipeline segments and localized corrosion profile.