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Cost-based optimal maintenance decisions for corroding natural gas pipelines based on stochastic degradation models

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ABSTRACT

This paper investigates the optimal inspection interval for newly-built onshore underground natural gas pipelines with respect to external metal-loss corrosion by considering the generation of corrosion defects over time and time-dependent growth of individual defects. The non-homogeneous Poisson process is used to model the generation of new defects and the homogeneous gamma process is used to model the growth of individual defects. A realistic maintenance strategy that is consistent with the industry practice and accounts for the probability of detection (PoD) and sizing errors of the inspection tool is incorporated in the investigation. Both the direct and indirect costs of failure are considered. A simulation-based approach is developed to numerically evaluate the expected cost rate at a given inspection interval. The minimum expected cost rule is employed to determine the optimal inspection interval. An example gas pipeline is used to examine the impact of the cost of failure, PoD, the excavation and repair criteria, the growth rate of the defect depth, the instantaneous generation rate of the generation model and defect generation model on the optimal inspection interval through parametric analyses. The results of the investigation will assist engineers in making the optimal maintenance decision for corroding natural gas pipelines and facilitate the reliability-based corrosion management.

1. Introduction

Metal-loss corrosion is a major threat to the structural integrity of underground oil and gas pipelines world-wide [1]. Periodic inspection and maintenance, as a key component of the pipeline corrosion management program [2], is an effective means to reduce the probability of failure and maintain safe operation of the pipeline system. Determination of the optimal inspection/maintenance interval is of great importance for the pipeline operators: a too short inspection interval will result in unnecessary inspections and mitigation actions, which can be costly, whereas a too long inspection interval could lead to critical defects not mitigated in a timely manner and failures due to such defects, which can have serious safety and economic implications.

It is a challenging task to determine the optimal inspection interval in that various uncertainties are involved in the decision-making. First, the inline inspection (ILI) tools, e.g. the magnetic flux leakage (MFL) tool, are associated with certain measurement errors. Second, the deterioration or degradation of the pipe resistance due to corrosion is also uncertain and time-varying because the growth of individual corrosion defect as well as the total number of defects are uncertain and vary with time. Third, the pipe geometry, material properties and internal pressure are also uncertain in reality. Finally, the capacity model for the corroded pipeline is imperfect and therefore involves the model uncertainty. The above-mentioned uncertainties need to be incorporated in the determination of the optimal inspection interval.

The selection of optimal maintenance schedules for corroding pipelines has been investigated using the reliability-based criteria [3–5]. Provan and Rodriguez [3] developed a Markov process-based model for the growth of corrosion defects in the context of determining the optimal inspection time. They considered the imperfection of inspection tools in detecting the defect, i.e. the probability of detection (PoD), but ignored the imperfection of inspection tools in sizing the defect, i.e. the measurement errors. Morrison and Worthingham [4] employed the same corrosion growth model to determine the optimal inspection time but ignored both PoD and measurement errors associated with the inspection tools. Hong [5] investigated the optimal inspection and maintenance schedule for corroding pipelines based on the reliability constraint. The Markov process was employed to model the growth of corrosion defects; the PoD and measurement errors associated with the inspection tool were incorporated in the failure probability

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evaluation, and the Poisson process was used to model the generation of new defects.

The investigations of condition-based maintenance optimization for degrading piping systems using the cost-based criterion have been reported in a few recent studies [6,7]. Cheng and Pandey [6] investigated the optimal inspection interval for a single-component degrading system using analytical methodologies, where the degradation of the system was modeled as a homogeneous gamma process and the optimal inspection internal was selected based on the minimum expected cost rule. Perfect inspection was implicitly assumed in their study. Gomes et al. [7] used a simulation-based approach to investigate the optimal inspection interval for buried pressurized pipelines subjected to external corrosion based on the minimum expected cost rule. A single pipeline joint that contains at most one corrosion defect at a given time was considered in the analysis, which is somewhat unrealistic. A time-independent power-law model that incorporates uncertain power law parameters but a deterministic corrosion initiation time was assumed to characterize the growth of the defect depth. Although PoD of the inspection tool was incorporated in the analysis, the measurement errors of the tool were ignored. The generation of new corrosion defects was also ignored.

In this paper, we use the Monte Carlo simulation to investigate the optimal maintenance decision for newly-built onshore underground natural gas pipelines with respect to external metal-loss corrosion by considering the generation of corrosion defects over time and time-dependent growth of individual defects. To this end, the non-homogeneous Poisson process is used to model the generation of new defects, and the homogeneous gamma process is used to model the growth of the defects. The minimum expected cost rule is used to select the optimal inspection interval. Both the PoD and measurement errors of the inspection tool are considered in the optimization. The investigation considers a realistic maintenance strategy and realistic costs of maintenance and failure that are consistent with the industry practice but have not been well accounted for in the literature. In particular, the excavation and repair actions are pipe joint-based as opposed to defect-based; that is, all the defects on an excavated pipe joint are mitigated by the repair actions. The failure event is defined as burst of the corroded pipeline under internal pressure, and the time-dependent probability of failure is evaluated by employing the limit state function for burst as opposed to the hazard function associated with the time-to-failure [8]. The cost of failure includes both the direct and indirect costs, the latter of which is incorporated through the parametric analysis.

The remainder of the paper is organized as follows. Section 2 presents the degradation models including the generation of new defect and the growth of the defect depth; Section 3 describes the uncertainties associated with ILI tools; the limit state function for burst, mitigation criteria, maintenance policy and the procedures to evaluate the expected cost rate are presented in Section 4; Section 5 presents a numerical example and parametric analysis results followed by the conclusions in Section 6.

2. Degradation models

2.1. Generation of new defect

Consider a reference joint of a newly-built pipeline (a typical pipe joint is approximately 12 m long). The non-homogeneous Poisson process (NHPP) was adopted to model the generation of new defects on the reference joint based on the consideration that the corrosion defects are not necessarily generated uniformly in time with a constant rate [9]. The total number of defects, $N(t)$, generated within a time interval $[0, t]$ (e.g. $t = 0$ denotes the time of installation of the pipeline) over the pipe joint follows a Poisson distribution with a probability mass function, $f_P(N(t)|\Lambda(t))$, defined as [10]:

$$f_P(N(t)|\Lambda(t)) = \frac{(\Lambda(t))^{N(t)} e^{-\Lambda(t)}}{N(t)!} \quad (t > 0) \tag{1}$$

where $\Lambda(t)$ denotes the expected number of defects generated over the time interval $[0, t]$, and $\Lambda(t) = \int_0^t \lambda(\tau) d\tau$. $\lambda(\tau)$ is the assumed intensity function (or the instantaneous generation rate) corresponding to the reference pipe joint. For example, it can be assumed that $\lambda(\tau) = \lambda_0 \tau^b$, where λ_0 and b are positive quantities that can be determined based on the inspection data and/or expert judgement. Note that Eq. (1) is simplified to a homogeneous Poisson process (HPP) if b is equal to zero, i.e. the intensity function is constant and independent of time. Three NHPP examples corresponding to $\lambda_0 = 1$, 2 and 4 are illustrated in Fig. 1, where the exponent b is assumed to equal one, i.e. $\Lambda(\tau) = \lambda_0 \tau^2/2$. Results associated with each of the examples include the expected value, 2.5- and 97.5-percentile values as well as one realization of the NHPP.

Consider that n defects have been generated on the reference pipe joint up to time T. The initiation times of the n defects are denoted by $T_1, T_2, \ldots,$ and T_n ($T_1 \leqslant T_2 \leqslant \cdots \leqslant T_n \leqslant T$), respectively. The joint probability density function (PDF) of ($T_1, T_2, \ldots, T_n$) conditional on $N(T) = n$ can be expressed as [10,11]:

$$f_{T_1,\ldots,T_n|N(t)}(t_1,\ldots,t_n|n) = \frac{n!\prod_{i=1}^{n}\lambda(t_i)}{[\Lambda(t)]^n} \quad (0 < t_1 < t_2 < \cdots < t_n \leqslant T) \tag{2}$$

For the homogeneous Poisson process (i.e. $b = 0$ in the intensity function), Eq. (2) becomes $n!/t^n$ [10]. This indicates that the joint PDF of the initiation times for HPP conditional on $N(T) = n$ is the same as the joint PDF of the order statistics of samples of (U_1, $U_2, \ldots, U_n$), where $U_1, U_2, \ldots, U_n$ are n independent and identically distributed (iid) random variables that are uniformly distributed over $[0, T]$. This conclusion for HPP can be generalized to NHPP; that is, U_i ($i = 1, 2, \ldots, n$) are independent and identically distributed random variables with the distribution [10,12]

$$P(U_i \leqslant t) = \frac{\Lambda(t)}{\Lambda(T)} \quad (0 \leqslant t \leqslant T) \tag{3}$$

2.2. Growth of defect

In this study, the growth of defect depth (i.e. in the through pipe wall thickness direction) was modeled by the homogeneous gamma process. The distribution of the depth of the ith defect at

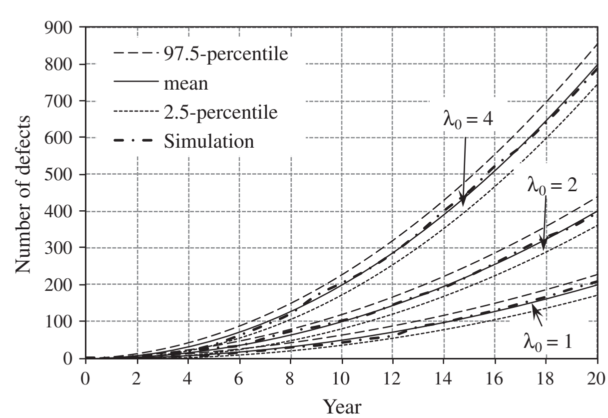

Fig. 1. Illustration of the NHPP.