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Multi-level optimization of maintenance plan for natural gas pipeline systems subject to external corrosion

Xiuquan Liu*, Jian Zheng, Jingjie Fu, Jingqi Ji, Guoming Chen

Centre for Offshore Engineering and Safety Technology, China University of Petroleum, Qingdao, Shandong 266580, China

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ABSTRACT

Failures of natural gas pipeline systems may result in severe consequences to social security and economic loss due to the combustibility of natural gas. Pipeline maintenance should be applied throughout the lifecycle to ensure that the pipeline system is managed safely and cost effectively. In this context, this study addresses optimal maintenance planning for natural gas pipeline systems subject to external metal-loss corrosion. The corrosion growth of natural gas pipeline systems is described as a Markov process. A multi-level strategy is proposed for the maintenance optimization of pipeline systems subject to external corrosion, which includes repaired Markov states (Level 1), maintenance time (Level 2), and maintenance number during the pipeline lifetime (Level 3). The multi-level optimization maintenance model is presented by synthetizing the corrosion Markov process and the multi-level maintenance strategy. The total cost of natural gas pipeline systems subject to external corrosion can be further decreased through the proposed multi-level optimization method compared with the adoption of traditional methods. Besides, genetic algorithm (GA) is also introduced for the multi-level optimization analysis of natural gas pipeline systems. A comprehensive optimization algorithm based on GA and the Markov process that can accurately and efficiently conduct multi-level optimal maintenance planning is proposed.

1. Introduction

Pipelines are vital infrastructure for transmitting large quantities of natural gas. Corrosion in natural gas pipelines is a serious problem in the petroleum industry today. Corrosion slowly but gradually reduces the resistance of mechanical components, leading to the increase in the likelihood of pipeline failure over time. Pipelines are susceptible to leakage and rupture due to corrosion. Previous reports have shown that corrosion constitutes the most important risk factors of pipelines, accounting for 36%. External corrosion has been identified as leading cause of the failure of pipelines worldwide (Achebe et al., 2012; CONCAWE, 2010; Palmer and King, 2008; Woodson, 1990). Pipeline failures due to corrosion can cause devastating accidents owing to the flammability of natural gas. In recent years, several accidents in natural gas pipelines have occurred and drawn significant public attention (Guo et al., 2016; Li et al., 2016; Lu et al., 2015). Thus, physical barriers such as anticorrosive coating and cathodic protection are often used in pipelines to reduce the probability of pipeline failure. However, the physical barriers cannot suppress corrosion growth completely. Pipeline integrity management such as pipeline inspection and maintenance should also be applied throughout a natural gas pipeline's lifecycle to ensure that it is managed safely and cost-effectively (DNV, 2015a, 2015b).

Pipeline integrity management is a continuous process of "knowledge and experience management." The four key steps in pipeline integrity management are hazard evaluation and risk assessment, development of an integrity management plan, implementation of the integrity management plan, and learning and improvement (DNV, 2008, 2015b). The development of an integrity management plan is a key problem. The pipeline integrity management plan often refers to the frequency and schedule of pipeline inspection and repair. Reliability- and risk-based inspections and maintenance are often adopted in pipeline integrity management, through which pipeline reliability and risk can be managed within acceptable limits (Khan and Haddara, 2003, Khan et al., 2006; Straub and Faber, 2005).

Researchers have conducted several studies on the reliability- and risk-based inspection of pipelines subject to corrosion. Teixeira et al. (2008) assessed the reliability of pipelines with corrosion defects subjected to internal pressure using the first-order reliability method. Sensitivity analysis was also performed for different levels of corrosion damage to determine the influence of various parameters on the probability of burst collapse of corroded and intact pipes. Ma et al.

* Corresponding author.
E-mail addresses: lxqmcae@163.com (X. Liu), zhj11041127@163.com (J. Zheng), fujingjie123@163.com (J. Fu), 1210457611@qq.com (J. Ji), offshore@126.com (G. Chen).

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(2011) discussed the development process of ASME B31G, which provided a fundamental method for assessing the remaining strength of corroded pipelines and presented a comparative analysis of ASME B31G, RSTRENG, and DNV RP-F101. Yang et al. (2017) developed a systematic corrosion failure model through Bow-Tie analysis and presented an approach for analyzing observed abnormal events to assess the condition of subsea pipelines using Bayesian network analysis. The pipelines can be inspected or repaired on the basis of the calculated reliability and risk. Hellevik et al. (1999) proposed a method for the cost-optimal reliability-based inspection and replacement planning of pipelines subject to CO_2 corrosion. Singh and Markeset (2009) proposed a method based on fuzzy logic framework for the establishment of a risk-based inspection program for oil and gas pipelines. Seo et al. (2015) presented the risk-based inspection of the probability of failure and the consequence of failure estimation of a time-variant corrosion model and burst strength for corroded oil pipelines. Gomes et al. (2013) and Gomes and Beck (2014) proposed a method for calculating sensitivities from sampling and the derivatives of optimal inspection objective functions. The proposed approach requires few samples to achieve the smooth convergence of total expected cost. Zhang and Zhou (2014) optimized the inspection intervals 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 the time-dependent growth of individual defects. However, these studies are specific to a single corrosion defect. System reliability, in the form of multiple corrosion defects in the same segment, as shown in Fig. 1, is likely to be relevant for the inspection and maintenance problem at hand (Gomes et al., 2013).

Pipeline systems often contain numerous external corrosion defects, as shown in Fig. 1. Any pipeline corrosion defect can lead to small leak, burst, and unstable rupture of the pipeline system. The probability of pipeline failure due to each defect is calculated individually according to the limit state functions of pipelines. For an entire pipeline system, the pipeline system model is regarded as a chain of series-connected defects in classical approach. In this case, the reliability of the pipeline system is the product of the reliability of each defect. In this scheme, the reliability index of such a system is lower than the reliability index of its defects. In addition, as the number of defects increases, the system reliability decreases drastically. It is practically impossible to create a high reliability system. Markov processes are often used to describe the pipeline degradation/growth of many corrosion defects. Adopting such processes considers the collective behavior of the set of actively growing defects in the pipeline as a distributed system and eliminates the restrictions of the classical approach (Gong and Zhou, 2017; Timashev and Bushinskaya, 2016; Zhou, 2010). Thus, Timashev et al. (2008) and Timashev and Bushinskaya (2010) presented a Markov model of the corrosion growth of pipe wall defects and its implementation for assessing the conditional probability of pipeline failure and optimizing pipeline repair and maintenance. However, the existing optimal maintenance model can determine the fixed maintenance time intervals, which is not a multi-level maintenance optimization. Multi-level maintenance refers to the repaired Markov states of each maintenance (Level 1), the optimal time of each maintenance that is not at a fixed interval (Level 2), and the maintenance number of natural gas pipeline systems during their lifetime (Level 3). Compared with the maintenance strategy with fixed maintenance time intervals, the total cost of natural gas pipeline systems may be lowered on the basis of the multi-level optimization maintenance strategy.

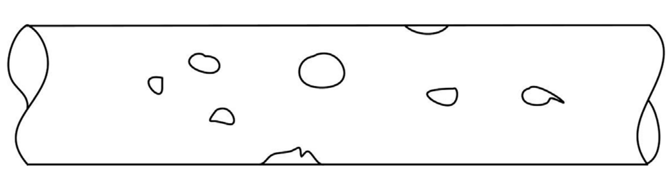

Fig. 1. Multiple corrosion defects.

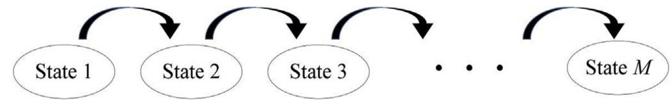

Fig. 2. Markov chain.

The remainder of this paper is organized as follows. Section 2 discusses the Markov process and the limit state function of a corroded pipeline system. Section 3 introduces the multi-level optimization model of maintenance. Section 4 describes the optimization process based on genetic algorithm (GA). Section 5 presents a numerical example. Section 6 concludes the paper.

2. Corrosion degradation model

2.1. Markov process of corrosion

A Markov process is selected to describe the pipeline corrosion growth of a set of defects because of its advantage in treating simultaneously growing defects as a distributed system. The Markov model of corrosion growth of pipeline wall is based on a continuous-time, discrete state pure birth homogenous Markov process, as shown in Fig. 2. The corrosion growth rate is treated implicitly as a constant in the Markov model. The thickness of the pipeline system wall is divided into M non-overlapping intervals I_i ($i = 1, 2, \ldots, M$). Each non-overlapping interval represents a Markov state. The thickness of the pipeline system wall decreases when the corrosion depth increases. The Markov state of the pipeline thickness will transition from the i-th to the $(i+1)$-th state, and the future Markov state only depends on the present Markov state.

The key problem of the Markov process is determining the intensity of the probability transition from the i-th to the $(i+1)$-th state. The probability of the pipeline thickness in every state at any time can then be determined through a series of Markov analyses and defined as follows (Timashev and Bushinskaya, 2016):

$$\begin{cases} \frac{dP_1(t)}{dt} = -\lambda_1 P_1(t) \\ \frac{dP_i(t)}{dt} = \lambda_{i-1}P_{i-1}(t) - \lambda_i P_i(t), \quad i = 2, \ldots, M \end{cases}, \tag{1}$$

where $P_i(t)$ is the probability that the thickness of the pipeline system wall is in the i-th state at time t, and λ_i is the intensity of probability transition from the i-th to the $(i+1)$-th state.

An initial Markov state and a Markov state at any time should be provided to solve first-order differential equations, as shown in Eq. (1). The depths of corrosion defects at time $t = 0$ can be spread assessed through pipeline inspections and assume that the initial depths of corrosion defects or the wall thickness of the pipeline system are all in the first Markov state. The initial Markov state can be expressed as follows:

$$\begin{cases} P_1(0) = 1 \\ P_i(0) = 0, \quad i = 2,3, \ldots, M \end{cases}. \tag{2}$$

In addition, the Markov state at any time can also be determined via pipeline inspections. Assuming that the defect depths are already distributed over all intervals at time t_1 and the probabilities of defects $P_i(t_1)$ in each interval are known, then the initial Markov state and the Markov state at time t_1 are substituted into Eq. (1). The unknown intensities of probability transition λ_i can be calculated according to the following equations:

$$\begin{cases} \lambda_1 = -\frac{\ln[P_1(t_1)/p_1^*]}{t_1} \\ P_i(t_1) = \sum_{j=1}^{i} \mu_{ij} \exp(-\lambda_j t_1), \quad i = 2,3, \ldots, M \end{cases}, \tag{3}$$

where