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Application of subset simulation in reliability estimation of underground pipelines

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ABSTRACT

This paper presents a computational framework for implementing an advanced Monte Carlo simulation method, called Subset Simulation (SS) for time-dependent reliability prediction of underground flexible pipelines. The SS can provide better resolution for low failure probability level of rare failure events which are commonly encountered in pipeline engineering applications. Random samples of statistical variables are generated efficiently and used for computing probabilistic reliability model. It gains its efficiency by expressing a small probability event as a product of a sequence of intermediate events with larger conditional probabilities. The efficiency of SS has been demonstrated by numerical studies and attention in this work is devoted to scrutinise the robustness of the SS application in pipe reliability assessment and compared with direct Monte Carlo simulation (MCS) method. Reliability of a buried flexible steel pipe with time-dependent failure modes, namely, corrosion induced deflection, buckling, wall thrust and bending stress has been assessed in this study. The analysis indicates that corrosion induced excessive deflection is the most critical failure event whereas buckling is the least susceptible during the whole service life of the pipe. The study also shows that SS is robust method to estimate the reliability of buried pipelines and it is more efficient than MCS, especially in small failure probability prediction.

1. Introduction

Structural reliability algorithms have been received greater attention over the world, though prediction techniques of small failure probabilities are very few till now. In recent years, attention has been focused on reliability problems with complex system characteristics in high dimensions (i.e., with a large number of uncertain or random variables) [20]. Prediction of small failure probabilities is one of the most important and challenging computational problems in reliability engineering [33]. The probabilistic assessment of engineering systems may involve a significant number of uncertainties in their behaviour. To implement probabilistic assessment for an engineering system, main difficulties arise from (1) the relationship between the random variables, (2) too many random variables involved, (3) information about rare scenarios and (4) many interactive response variables in the description of performance criteria.

Like other engineering systems, reliability analysis of buried pipeline systems are characterised by a large number of degrees of freedom, time-varying and response dependent nonlinear behaviour. In the presence of uncertainty, the performance of an underground pipeline can be quantified in terms of 'performance margin' with respect to specified design objectives. In reliability engineering, 'performance margin' is denoted as reliability index, probability of failure, safety margin, etc. Failure events in pipe reliability analysis can be formulated as exceedance of a critical response variable over a specified threshold level. By predicting pipeline reliability, the safe service life can be estimated with a view to prevent unexpected failure of underground pipelines by prioritising maintenance based on failure severity and system reliability [28,14].

There is no general algorithm available to estimate the reliability of a buried pipeline system. The pipeline reliability is usually given by an integral over a high dimensional uncertain parameter space. Methods of reliability analysis such as first order reliability method (FORM), second-order reliability method (SORM), point estimate method (PEM), Monte Carlo simulation (MCS), gamma process, probability density evolution method (PDEM), etc. are available in literature [22,27,15,9,10]. In this context, a robust uncertainty propagation method whose applicability is insensitive to complexity nature of the problem is most desirable. Many methods are inefficient when there are a large number of random variables and/or failure probabilities are small. Moreover, some methods need a large number of samples which is time-consuming.

Advanced Monte Carlo methods, often called 'variance reduction techniques' have been developed over the years. In this respect, a promising and robust approach is Subset Simulation

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(SS) which is originally developed to solve the multidimensional problems of engineering structural reliability analysis [3,5]. A structural system fails when the applied load or stress level exceeds the capacity or resistance. SS is well suited for quantitative analysis of functional failure systems, where the failures are specified in terms of one or more safety variables, e.g., temperatures, pressures, flow rates, etc. In the SS approach, the functional failure probability is expressed as a product of conditional probabilities of adaptive chosen intermediate events. The problem of evaluating small probabilities of functional failures is thus tackled by performing a sequence of simulations of more frequent events in their conditional probability spaces; then the necessary conditional samples are generated through successive Markov Chain Monte Carlo (MCMC) simulations in a way to gradually populate the intermediate conditional regions until the final functional failure region is reached [31].

Many researchers, such as Au and Beck [3], Au et al. [5], Ching et al. [8], Song et al. [23] and Zhao et al. [32] have used SS in reliability analysis of engineering structures, such as bridges and buildings. However, according to authors' knowledge, no such work has been found in the literature on time-dependent reliability analysis of buried pipeline systems. This paper focuses on application of SS for computing time-dependent reliability of flexible buried metal pipelines. Failure probabilities for corrosion induced multi-failure events, namely deflection, buckling, wall thrust and bending have been predicted in this study. Firstly, the SS is applied for estimating the failure probabilities for each failure case individually and then due to multi-failure modes, an upper and lower bounds of failure probabilities are predicted as a series system. Besides that, coefficients of variation (COVs) and a sensitivity analysis of pipe failure due to corrosion induced deflection, as an example of failure event, have also been assessed to illustrate the robustness and effectiveness of SS method. The application of SS method is verified with respect to the standard MCS.

2. Formulation for pipe failure

A system failure occurs when a system does not meet its requirement. The number of potential failure modes is very high for buried pipe structures. This is true in spite of the simplifications imposed by assumptions such as having a finite number of failure elements at given points of the structure and only considering the proportional loadings. It is, therefore, important to have a method by which the most critical failure modes can be identified. When the residual ultimate strength of a buried pipeline is exceeded, breakage becomes imminent and the overall reliability of the pipe is reduced. The critical failure modes are those contributing significantly to the reliability of the system at the chosen level. The failure criteria adopted here are due to loss of structural strength of pipelines by corrosion through reduction of the pipe wall thickness which then lead to pipe failure by excessive deflection, buckling, wall thrust and bending.

2.1. Corrosion of metal pipes

Buried pipes are made of plastic, concrete or metal, e.g. steel, galvanised steel, ductile iron, cast iron or copper. Plastic pipes tend to be resistant to corrosion. Damage in concrete pipes can be attributed to biogenous sulphuric acid attack [29,2]. On the other hand, metal pipes are susceptible to corrosion. Metal pipe corrosion pit is a continuous and variable process. Under certain environmental conditions, metal pipes can become corroded based on the properties of the pipe, soil, liquid properties and stray electric currents. The corrosion pit depth can be modelled with respect to time as shown in Eq. (1) [1,18].

The corrosion pit depth,

$$D_T = kT^n \tag{1}$$

where D_T is pit depth and T is exposure time. The parameters k and n are corrosion empirical constants and depend on pipe materials and surrounding environments.

For a plain pipe, due to reduction of wall thickness given by Eq. (1), the moment of inertia of pipe wall per unit length, I and the cross-sectional area of pipe wall per unit length, A_s can be defined as below [30,24].

$$\text{Moment of inertia,} \quad I = (t - D_T)^3/12 \tag{2}$$

$$\text{Cross}-\text{sectional area,} \quad A_s = t - D_T \tag{3}$$

where t is the thickness of the pipe wall. The pipe is assumed as a thin-walled pipe with $D/t > 10$ where D is mean diameter. The corrosion empirical constants (k and n) and pipe wall thickness (t) are considered as random variables.

2.2. Pipe failure criteria

In this paper, the chosen dominating failure criteria of flexible pipes are characterised by corrosion induced deflection, buckling, wall thrust and bending stress.

2.2.1. Deflection

The performance of flexible pipes in its ability to support load is typically assessed by measuring the deflection from its initial shape. Deflection is quantified in terms of the ratio of the horizontal (or vertical) increased diameter to the original pipe diameter. The critical or allowable deflection for flexible pipe, Δy_{cr} is normally determined as 5–7% of inside diameter of pipe [12]. The actual deflection, Δ_y can be calculated as shown in Eq. (4) (BS EN 1295:1, 1997; [7,30]). $Z(X) = \Delta y_{cr} - \Delta_y = 0$ is the limit state function for this failure mode where $Z(X) < 0$ represents failure state and $Z(X) > 0$ indicates a safe state.

$$\Delta_y = \frac{K_b(D_L W_c + P_s)D}{\left((8EI/D^3) + 0.061E'\right)} \tag{4}$$

where K_b is deflection coefficient, D_L is deflection lag factor, D is mean diameter$=D_i+2c$ where D_i is inside diameter and c is distance from inside diameter to neutral axis, E is modulus of elasticity of pipe material and E' is modulus of soil reaction $= k'E_s(1-\nu_s)/(1+\nu_s)(1-2\nu_s)$ where E_s is modulus of soil and k' is a numerical value depends on poison's ratio, ν_s [21].

The loads acting on the pipe are governed by the term $D_L W_c + P_s$ where W_c is soil load and P_s is live load. Soil load can be calculated by multiplying unit weight of soil (γ_s) by the height of soil on the top of pipe invert (H) [19].

2.2.2. Buckling pressure

Buckling is a premature failure in which the pipe is not able to maintain its initial circular shape and the structure becomes unstable at a stress level that is well below the yield strength of the structural material [22]. The actual buckling pressure should be less than the critical buckling pressure for the safety of structure. The actual buckling pressure, p and the critical buckling pressure, p_{cr} can be calculated as shown in Eqs. (5) and (6), respectively [6]. $Z(X) = p_{cr} - p = 0$ is the limit state function for this failure mode where $Z(X) < 0$ represents failure state and $Z(X) > 0$ indicates a safe state.

$$p = R_w \gamma_s + \gamma_w H_w + P_s \tag{5}$$

$$p_{cr} = \sqrt{\left(32 R_w B' E_s \frac{EI}{D^3}\right)} \tag{6}$$