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Reliability analysis of subsea pipelines under spatially varying ground motions by using subset simulation

Yuyin Li[a], Yahui Zhang[a,*], David Kennedy[b]

[a] State Key Laboratory of Structural Analysis for Industrial Equipment, Department of Engineering Mechanics, International Center for Computational Mechanics, Dalian University of Technology, Dalian 116023, PR China

[b] School of Engineering, Cardiff University, Cardiff CF24 3AA, Wales, UK

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ABSTRACT

A computational framework is presented to calculate the reliability of subsea pipelines subjected to a random earthquake. This framework takes full account of the physical features of pipelines and the earthquake, and also retains high computing precision and efficiency. The pipeline and the seabed are modelled as a Timoshenko beam and a Winkler foundation, respectively, while the unilateral contact effect between them is considered. The random earthquake is described by its power spectrum density function and its spatial variation is considered. After suitable discretizations in the spatial domain by the finite element method and the time domain by the Newmark integration method, the dynamic unilateral contact problem is derived as a linear complementarity problem (LCP). Subset Simulation (SS), which is an advanced Monte Carlo simulation approach, is used to estimate the reliability of pipelines. By means of numerical examples, the accuracy and robustness of SS are demonstrated by comparing with the direct Monte Carlo simulation (DMCS). Then a sensitivity analysis of the reliability and a failure analysis are performed to identify the influential system parameters. Finally, failure probabilities of subsea pipelines are assessed for three typical cases, namely, with and without the unilateral contact effect, with different grades of spatial variations and with different free spans. The influences of these effects or parameters on the reliability are discussed qualitatively.

1. Introduction

Subsea pipelines always rest freely on the seabed, rather than being buried or anchored. Due to the scouring or unevenness of the seabed, pipelines will not touch down uniformly along the length of the pipe, and free spanning inevitably occurs. Since subsea pipelines are generally important and costly facilities, their reliability has been a fundamental problem of interest throughout the world. In recent years, attention has mainly been focused on corrosion failure [1], vortex-induced vibration fatigue damage [2], on-bottom lateral instability [3] and so on. As an occasional random excitation, a strong earthquake poses a tremendous threat to the safety of pipelines, and hence the dynamic response and reliability of pipelines under an earthquake have also received great attention. However, the emphasis has been on buried pipelines, with much less research on unburied pipelines. The relevant standards, such as DNV-OS-F101 [4], do not provide design methods or guidelines for the earthquake reliability of unburied subsea pipelines. The failure of structures under an earthquake is a typical first-excursion problem. To assess the first-excursion reliability, the main difficulties arise from (1) the solution of random responses of structures under the earthquake and (2) the evaluation of the reliability by using the random responses obtained in (1).

In the solution of random responses, one of the most important problems is how to consider the relationship between pipelines and seabed as exactly as possible. In the literature on the dynamic analysis of unburied pipelines, pipelines are widely simplified as multi-supported beams or beams on an elastic foundation [5–8]. However, in reality unburied pipelines are constrained unilaterally by the seabed, which means that the reaction of the seabed can only be compressive, but not tensile. Hence, during the vibration of pipelines, particularly when the deformation takes place predominantly in the vertical plane, a separation of pipelines and the seabed will occur. Clearly, both the multi-supported beam model and the elastic foundation beam model will overestimate the constraint between pipelines and the seabed, and neither of these two models can take the separation of pipelines and the seabed into consideration. Therefore, a unilateral contact model is more appropriate to simulate the relationship between unburied pipelines and the seabed, and such models have been applied to various kinds of static and dynamic analysis of the subsea pipelines, such as the elastic and elasto-

* Corresponding author.
E-mail address: zhangyh@dlut.edu.cn (Y. Zhang).

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plastic analysis of subsea pipelines subjected to vertical static loads [9], stress analysis problems involving subsea pipelines freely resting upon irregular seabed profiles [10], optimal control of the dynamic response of subsea cables constrained by a frictionless rigid seabed [11] and so on. Nevertheless, due to the contact nonlinearity, obtaining the dynamic response of a unilateral contact system is a challenging task, and some classical methods of structural analysis, such as the analytical method used in [6] or the frequency-domain method used in [8], are no longer feasible. As a consequence, the unilateral model is not used frequently for the dynamic analysis of subsea pipelines under an earthquake, despite its good approximation to the relationship between subsea pipelines and the seabed. In general, the unilateral contact problem is dealt with by numerical methods, e.g., the combination of the finite element method and step-by-step integration method. In each time step, the nonlinear problem is solved by the Newton–Raphson method or a similar iterative method [10]. The unilateral contact problem can also be treated by deriving it as a linear complementary problem (LCP). There are many well-developed methods to solve the LCP and most of them have been included in commercial software, making it much more convenient to solve the unilateral contact method by the LCP method than Newton–Raphson methods.

The earthquake excitation model is another key point in the process of the solution of random responses of subsea pipelines. Due to the natural random factors of the soil, the motion of the seabed is more likely to exhibit strong randomness during an earthquake, as are the responses of structures. Hence it is more rational to study the responses of structures subjected to an earthquake from the point of view of the random vibration. On the other hand, variations can be found during earthquake wave propagation along the length of long-span structures, such as subsea pipelines, which result in differences in the amplitude and phase of ground motions at the supports of the structures. This phenomenon is termed as spatially varying ground motions [13]. Many random vibration methods have been developed for the analysis of multi-span structures subjected to spatially varying ground motions [14–16]. However, these methods are no longer feasible after taking the contact of pipelines and the seabed into consideration, for two reasons. Firstly, these methods are based on the power spectrum density or response spectrum, which are essentially frequency-domain methods, and thus cannot be used to treat the contact problem because of the nonlinearity. Secondly, the response of a nonlinear system is always non-Gaussian even if the input is a Gaussian random process, and these methods can only provide the first- and second-order statistical moments of the response, which are insufficient to describe totally the statistical properties of the non-Gaussian response. In the circumstances, the Monte Carlo simulation (MCS) method, which is suitable for both linear and nonlinear random vibration analysis, seems to be the best and only choice, despite its relatively large computational requirements [17].

After obtaining the random response of subsea pipelines, the problem which follows is how to estimate the reliability of subsea pipelines through this random response. Due to the complex nature of the first-excursion failure and the unilateral contact problem, the limit state function of subsea pipelines is extremely complicated and has no explicit expression, while extreme values of the random response are not Gaussian distributed. Therefore, popular methods of reliability analysis such as the first order reliability method (FORM) [18], second order reliability method (SORM) [19], point estimate method (PEM) [20], etc. are unable to predict accurately the reliability of subsea pipelines under an earthquake. The MCS is one of most well-known methods for reliability analysis because it is independent of the complexity and dimension of the problem. However, the number of samples required by the MCS is proportional to the reciprocal of the failure probability. Hence, when the failure probability is very small, e.g., of order 10^{-3}, this method will suffer from inefficiency due to its demand for a large number of samples. In order to reduce the computational cost of the MCS, an advanced MCS called Importance Sampling (IS) was developed [21,22]. The IS requires prior knowledge of the system in the failure region, so it works well when applied to a linear and low-dimensional problem, whose failure region is quite simple. However, the failure region geometry of subsea pipelines under an earthquake is complicated and prior knowledge of the random responses is unavailable, hence the IS is not suitable for the problem considered in this paper. In order to carry out reliability analysis with small failure probabilities, Au et al. [23,24] developed another advanced MCS named Subset Simulation (SS). The basic idea of SS is to express a small failure probability event as a product of a series of intermediate events with larger conditional probabilities. Through setting these intermediate events properly, the conditional probabilities can be large enough to be estimated with a small number of samples. SS is a robust and efficient method and has been used for predicting small failure probabilities in engineering fields, such as the time-dependent reliability of underground flexible pipelines [25], the probabilistic dynamic behaviour of mistuned bladed disc systems [26], radioactive waste repository performance assessment [27], the stochastic dynamic stiffness of foundations for large offshore wind turbines [28] and so on. A general form of SS is presented in [29] is mainly, with application to a seismic risk problem involving dynamic analysis.

As mentioned above, reliability analysis of subsea pipelines subjected to random earthquakes faces two difficulties: the solution of random responses and estimation of reliability, and these are the focus of this paper. Regarding random response solutions, mathematical models with reasonable simplifications and assumptions are firstly estimated for pipelines, seabed and ground motions, and then a corresponding solution strategy is given based on LCP. Regarding reliability estimation, SS is introduced to increase the computational efficiency for the predictions of first-excursion failure probabilities of pipelines. This paper therefore provides a practical computational framework for the reliability analysis of subsea pipelines subjected to random earthquakes. The work is structured as follows. In Section 2, the mathematical formulation of a subsea pipeline under a random earthquake is given. In Section 3, by combining the finite element method and Newmark integration method, a solution strategy is obtained by deriving the unilateral contact problem as a LCP. In Section 4 the fundamental concept and implementation procedures of SS are briefly presented. Section 5 gives some numerical examples. The feasibility of SS is verified with respect to direct MCS, and the contribution of some random parameters to the failure of pipelines is addressed through a sensitivity analysis. Then, influences of the unilateral contact effect, the spatial variation and the free span on the reliability of pipelines are investigated. Finally, conclusions are given in Section 6.

2. Problem formulations

2.1. Governing equations of the pipeline

A schematic of a subsea pipeline and the seabed is shown in Fig. 1(a). There is a free span in the middle of the pipeline due to the scouring or unevenness of the seabed. The length of the pipeline is denoted by L_0, while the location and length of the free span are denoted by L_1 and L_2, respectively. Because of the complex formation mechanism and the lack of practical measured data of the free span, the seabed profile $w_g^{(0)}$ is approximated with the following function

$$w_g^{(0)} = \begin{cases} 0 & 0 \le x < L_1 - L_2/2 \\ \frac{h_{\text{free}}}{2}\left[1 - \cos\frac{2\pi(x - L_1 + L_2/2)}{L_2}\right] & L_1 - L_2/2 \le x < L_1 + L_2/2 \\ 0 & L_1 + L_2/2 \le x \le L_0 \end{cases} \quad (1)$$

where h_{free} is the maximum depth of the free span.

The pipeline is modelled based on the Timoshenko beam theory and hydrodynamic forces of the internal oil and the surrounding seawater are considered. The seabed is simplified as a Winkler foundation. In the coordinates shown in Fig. 1(b), the governing equations for the vibration