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Nonlinear stochastic seismic analysis of buried pipeline systems

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ABSTRACT

In this paper, a nonlinear stochastic seismic analysis program for buried pipeline systems is developed on the basis of a probability density evolution method (PDEM). A finite element model of buried pipeline systems subjected to seismic wave propagation is established. The pipelines in this model are simulated by 2D beam elements. The soil surrounding the pipelines is simulated by nonlinear distributed springs and linear distributed springs along the axial and horizontal directions, respectively. The joints between the segmented pipes are simulated by nonlinear concentrated springs. Thereafter, by considering the basic random variables of ground motion and soil, the PDEM is employed to capture the stochastic seismic responses of pipeline systems. Meanwhile, a physically based method is employed to simulate the random ground motion field for the area where the pipeline systems are located. Finally, a numerical example is investigated to validate the proposed program.

1. Introduction

Gas and water supply systems, which have pipelines that are mostly located underground, are important components of lifeline systems and play essential roles in sustaining modern cities. Historical data on strong earthquakes have demonstrated when such systems are interrupted, residential, commercial, and industrial activities are affected, huge economic losses are incurred, and secondary disasters (e.g., fires and epidemics) occur [1]. As the major components of pipeline systems, buried pipelines have been studied by many researchers. Since Newmark [2] first suggested that pipeline strain subjected to seismic wave propagation is as same as the soil strain around pipelines, many models have been presented to obtain the seismic response of pipelines, e.g., the elastic foundation beam model [3,4], shell model [5], and finite element model [6]. However, in these studies, only a single pipeline was considered and the interaction between different pipelines was not considered. Considering this interaction, some simple pipeline systems, such as a pipeline with branches and octothorpe-shaped pipeline system were studied [7–10].

Ground motions are usually modeled as a realization of a modulated non-stationary stochastic process [11] and many methods are used to produce stochastic ground motions. The classic method is an indirect two-step approach that first generates a stationary power spectrum through an iterative process and then adds some non-stationary attributes [12,13]. In 2012, Giaralis and Spanos [11] used a non-iterative "one-step" approach to derive stochastic processes that are compatible in the mean senses with a target response spectrum. In the same year, Vetter and Taflanidis [14] conducted a sensitivity analysis of stochastic ground motion models and identified the overall importance of uncertain model parameters. Actually, seismic ground motion records can usually be scaled based on earthquake intensity to analyze structures. However, the median nonlinear structural response may become biased [15] or cast doubts on the fragility estimates [16]. Given that ground motions are stochastic, the seismic responses of buried pipeline systems will also be stochastic. Deterministic analysis cannot capture the responses of actual pipeline systems precisely. Therefore, seismic stochastic response analyses should be conducted on buried pipeline systems to describe the seismic performance more precisely. In 1977, Shinozuka and Kawakami [17] carried out a stochastic seismic response analysis of buried pipelines for the first time and evaluated the statistics of the pipeline responses. Considering the randomness and spatial correlation of ground motions, Hindy and Novak [18] investigated the seismic responses of a buried pipeline in the axial and lateral directions when subjected to stochastic seismic excitations by using a classic random vibration method. After comparing the stochastic responses of a buried pipeline under seismic excitations with and without spatial variation, Zerva et al. [19] indicated that the seismic responses of pipelines are sensitive to the spatial correlation of ground motions. In addition to classical random vibration theory, the pseudo-excitation method [20] has also been

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applied to the stochastic seismic responses of buried pipelines. Maybe due to the complexity of pipeline systems and the difficulty of stochastic analysis, the studies mentioned above only consider a single pipeline and the stochastic responses are mainly characterized by second-order statistical quantities, such as mean, standard deviation and power spectral density.

In this paper, a new stochastic seismic response analysis theory called probability density evolution method (PDEM) [21] is introduced to capture the stochastic seismic response of buried pipeline systems. A nonlinear finite element model for buried pipeline systems subjected to seismic wave propagation is presented. The seismic responses of the systems can be obtained by using a ground motion field model. Thereafter, the basic theory of PDEM is outlined and a program is established to evaluate the probability density function (PDF) of the seismic responses of buried pipeline systems. Considering the basic random variables of the ground motion field, a numerical example and the typical probabilistic characteristics of the seismic responses of the systems are discussed.

2. Modeling for buried pipeline systems

The reasons for the failure of buried pipelines subjected to earthquakes can be classified into two types: permanent ground deformation (PGD) (e.g., surface faulting, landslides and soil liquefaction) and seismic wave propagation [4,22]. Although the damages caused by PGD are much more serious than those caused by seismic wave propagation, the latter causes more damages than the former because the affected area of PGD is much smaller. Therefore, only the effect of seismic wave propagation is considered in this paper.

The responses of buried pipeline systems are distinctly different from that of aboveground structures. For buried pipelines, inertia force is not the dominant factor during earthquakes [23]. Therefore, pipelines subjected to earthquakes are usually analyzed by using a quasi-static approach.

A buried pipeline can usually be idealized as a beam on elastic foundation (BEF) (Fig. 1) and its seismic responses can be obtained through the quasi-static approach. For the pipeline in Fig. 1, the axial and lateral motion equations can be described as follows:

$$EA\frac{\partial^2 u(x,t)}{\partial x^2} - k_A u(x,t) = -k_A u_g(x,t) \tag{1}$$

$$EI\frac{\partial^4 v(x,t)}{\partial x^4} + k_L v(x,t) = k_L v_g(x,t) \tag{2}$$

where EA and EI are the axial and bending stiffness of the pipeline, respectively; k_A and k_L are the spring stiffness per unit length of the soil surrounding the pipeline along the axial and lateral directions, respectively; $u(x,t)$ and $v(x,t)$ are the axial and lateral displacements of the pipeline, respectively; $u_g(x,t)$ and $v_g(x,t)$ are the axial and lateral displacements of ground motion, respectively.

When the BEF model is adopted, the pipeline itself is simulated as a beam. Thus, when the pipeline is discretized as many elements, the element stiffness matrix of a buried pipeline element can be described as follows:

$$[K_P] = \begin{bmatrix} \frac{EA}{L} & 0 & 0 & -\frac{EA}{L} & 0 & 0 \\ & \frac{12EI}{L^3} & \frac{6EI}{L^2} & 0 & -\frac{12EI}{L^3} & \frac{6EI}{L^2} \\ & & \frac{4EI}{L} & 0 & -\frac{6EI}{L^2} & \frac{2EI}{L} \\ & \text{Symmetric} & & \frac{EA}{L} & 0 & 0 \\ & & & & \frac{12EI}{L^3} & \frac{6EI}{L^2} \\ & & & & & \frac{4EI}{L} \end{bmatrix} \tag{3}$$

where L is the length of element.

When the pipe–soil interaction is simulated as the axial spring and lateral spring, the corresponding stiffness matrix can be written as follows [24]:

$$[K_S] = \begin{bmatrix} \frac{1}{3}\alpha & 0 & 0 & \frac{1}{6}\alpha & 0 & 0 \\ & \frac{13}{35}\beta & \frac{11}{210}L\beta & 0 & \frac{9}{70}\beta & -\frac{13}{420}L\beta \\ & & \frac{1}{105}L^2\beta & 0 & \frac{13}{420}L\beta & -\frac{1}{140}L^2\beta \\ & \text{Symmetric} & & \frac{1}{3}\alpha & 0 & 0 \\ & & & & \frac{13}{35}\beta & -\frac{11}{210}L\beta \\ & & & & & \frac{1}{105}L^2\beta \end{bmatrix} \tag{4}$$

where $\alpha = k_A L$; $\beta = k_L L$.

The axial interaction between the pipeline and soil occurs when the buried pipelines are subjected to seismic wave propagation. This axial interaction is usually simulated by an axial spring in Fig. 1 and can be described by a relationship between the slippage and shear stress at the pipe–soil contact surface. According to the literature [25], a constitutive relationship curve for this interaction can be empirically described by a hyperbola function (Fig. 2). The corresponding equation can be written as follows:

$$\tau = \frac{\Delta u}{a + b\cdot\Delta u} \tag{5}$$

where τ and Δu represent the shear stress and slippage at the pipe–soil contact surface, respectively; a and b are constants whose physical interpretations are given as follows:

$$a = 1/\left(\frac{\tau}{\Delta u}\right)_{\Delta u \to 0} = 1/\bar{k}_0 \tag{6}$$

$$b = \left(\frac{1}{\tau}\right)_{\Delta u \to \infty} = \frac{1}{\tau_{ult}} \tag{7}$$

where $\bar{k}_0$ is the initial stiffness and τ_{ult} is the shear strength at the pipe–soil contact surface (Fig. 2).

When Eq. (5) is used to describe the axial springs between the pipeline and soil, the axial secant spring stiffness can be written as

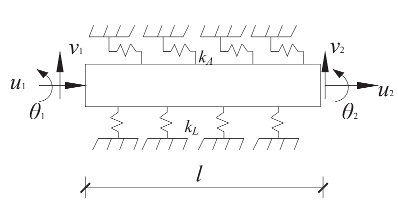

Fig. 1. Modeling pipeline as beam on elastic foundation.

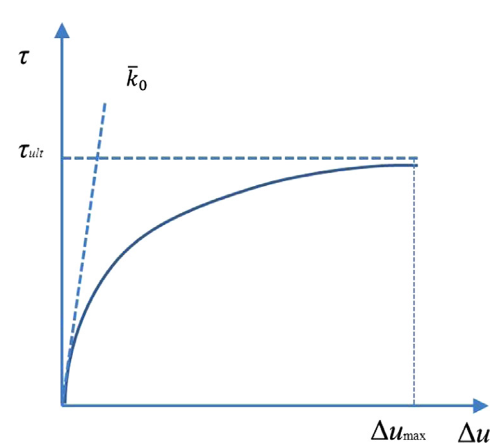

Fig. 2. The relationship between shear stress and slippage at pipe–soil contact surface.