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Sensitivity analysis of site effects on response spectra of pipelines

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Abstract

In this paper, a numerical sensitivity analysis of the site effect on dynamic response of pipelines embedded in some idealised soil deposits resting on a halfspace covering a wide range of soil profiles encountered in practice and subjected to vertically propagating shear waves, is presented. The power spectrum of the lateral differential displacement between two distant points due to the site effect is formulated analytically by using an analytical amplification function of a viscoelastic inhomogenous soil profile overlying either a compliant halfspace or a bedrock, represented by a more realistic continuous model. Also, Kanai-Tajimi spectrum parameters are estimated and expressed analytically from the soil profile model. Finally, results in the form of stochastic response spectrum of pipelines, for different key soil and pipeline parameters, are given and discussed. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Pipelines; Response spectra; Spatial variability; Amplification function; Kanai-Tajimi spectrum; Site effects

1. Introduction

An important aspect of earthquake loads acting on extended structures such as pipelines, is the spatial variability of the seismic motion which can be affected significantly by the unpredictable path of seismic waves generated from an extended source (incoherence effect), the difference in the arrival times of waves at different ground distant points (wave passage) and the spatial variability of the local soil conditions (site response effect). Hence, a rigorous deterministic approach of the spatial character of the seismic input effects on pipelines gives imprecise results. So, a probabilistic method based on the random vibration theory has been developed for seismic analysis of pipelines subjected to incoherent seismic ground motion [1–4]. Most of these studies consider only the contributions of the wave passage and the incoherence effects and in consequence neglect the contributions of the site effects on the stochastic response of pipelines. The aim of this paper is to assess the contribution of the site effect on response spectrum of the lateral differential motion at joints (between the pipe segments of pipelines), for different key soil and pipeline parameters, which is of great importance in the earthquake resistant design of pipelines. In this case, one assumes that the spatial variability of the ground motion is the result of the variability of the local soil conditions. The discrete modified model of Nelson and Weidlinger [3,5] (in addition to the translational motions of the pipe segments, the rotations are also considered) representing two rigid pipe segments connected by a joint will be used in the present study to evaluate the lateral differential motion between the pipe segments. The soil–pipeline interaction is taken into account by the impedance functions. The power spectrum of the lateral differential displacement between two supports due to the site effect is expressed analytically using an analytical amplification function of a more realistic continuous viscoelastic inhomogenous soil profile overlying either a compliant halfspace or a bedrock. Finally, the response spectrum of pipelines are obtained for different key soil and pipeline parameters.

2. Description of the model

A buried discrete pipeline consists of a straight pipe segments connected by a joint [3] (Fig. 1). The two pipe segments are modelled as rigid bodies, interconnected by a joint spring k_p and a joint dashpot of damping c_p. The soil–pipeline interaction is generally represented by a soil spring k_g and a soil damping c_g, respectively, in the lateral direction. The pipe segments responses in the lateral direction are denoted by $y_1(t)$ and $y_2(t)$. The input motions at the supports are $y_{G_1}(t)$ and $y_{G_2}(t)$ and, $\theta_1(t)$ and $\theta_2(t)$ are the rotations of the pipe segments, m and l are the pipe segment lumped mass and the distance between the two centroids of the pipe segments, respectively.

Using the modified Nelson and Weidlinger discrete model and assuming the equality of the rotations of the two pipe segments [4], the equations of motion of the

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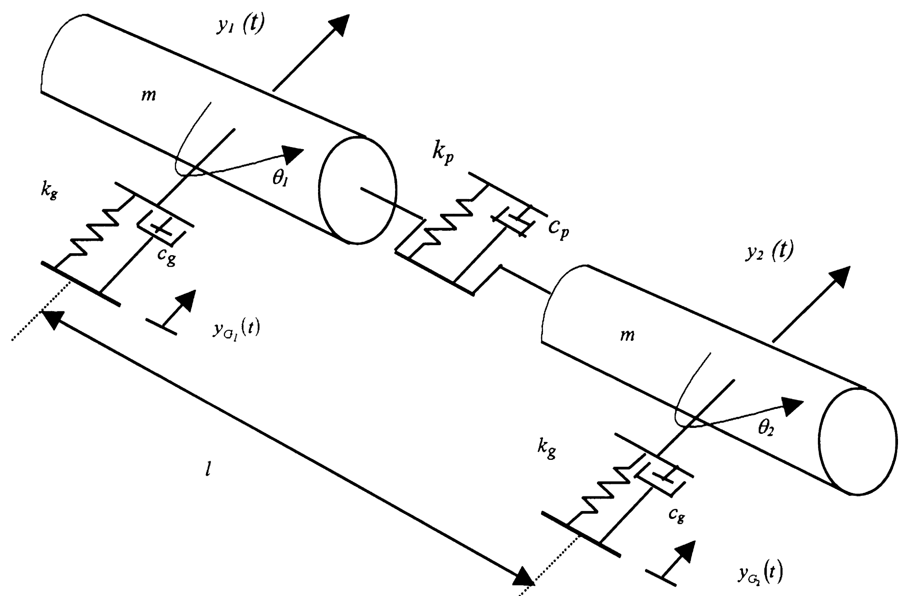

Fig. 1. Idealised structural model for discrete buried pipeline.

system in the lateral direction can be written in matrix form by [4]

$$\boldsymbol{M}\ddot{\boldsymbol{Y}} + \boldsymbol{C}\dot{\boldsymbol{Y}} + \boldsymbol{K}\boldsymbol{Y} = \boldsymbol{F}(t) \tag{1}$$

$$\boldsymbol{M} = \begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ -m/6 & m/6 & m/6 \end{bmatrix}, \boldsymbol{C} = \begin{bmatrix} c_g & 0 & c_p \\ 0 & c_g & -c_p \\ 0 & 0 & c_p \end{bmatrix},$$

$$\boldsymbol{K} = \begin{bmatrix} k_g & 0 & k_p \\ 0 & k_g & -k_p \\ 0 & 0 & k_p \end{bmatrix}, \boldsymbol{Y} = \begin{Bmatrix} y_1(t) \\ y_2(t) \\ \Delta y(t) \end{Bmatrix},$$

$$\boldsymbol{F}(t) = \begin{Bmatrix} c_g \dot{y}_{G_1}(t) + k_g y_{G_1}(t) \\ c_g \dot{y}_{G_2}(t) + k_g y_{G_2}(t) \\ 0 \end{Bmatrix}$$

and $\Delta y(t) = y_1(t) - y_2(t) + l\theta(t)$ is the differential lateral displacement between the two pipe segments.

The natural frequencies of the system are

$$\omega_{1,2}^2 = \frac{(8k_p + k_g) \pm \sqrt{64k_p^2 - 8k_p k_g + k_g^2}}{2m} \quad \text{and} \quad \omega_3^2 = \frac{k_g}{m} \tag{2}$$

The corresponding modal shapes are

$$\{\Phi_{1,2}\} = \begin{Bmatrix} 1 \\ -1 \\ \phi_{1,2} \end{Bmatrix}, \qquad \{\Phi_3\} = \begin{Bmatrix} 1 \\ 1 \\ 0 \end{Bmatrix} \tag{3}$$

with

$$\phi_{1,2} = \frac{(8k_p - k_g) \pm \sqrt{64k_p^2 - 8k_p k_g + k_g^2}}{2k_p} \tag{4}$$

We can note that the third mode is the rigid body motion. If the damping is assumed to be proportional, Eq. (1) yields the following uncoupled equations

$$\ddot{z}_n + 2\zeta_n \omega_n \dot{z}_n + \omega_n^2 z_n = \frac{F_n(t)}{M_n}, \qquad n = 1, 2, 3 \tag{5}$$

where ζ_n is the modal damping

$$M_{1,2} = m\left(2 - \tfrac{1}{3}\phi_{1,2} + \tfrac{1}{6}\phi_{1,2}^2\right),\ M_3 = 2m,$$

$$c_g = 2\xi_3 \omega_3 m,\ k_g = \omega_3^2 m,$$

$$F_1 = F_2 = c_g(\dot{y}_{G_1} - \dot{y}_{G_2}) + k_g(y_{G_1} - y_{G_2}) \text{ and}$$

$$F_3 = c_g(\dot{y}_{G_1} + \dot{y}_{G_2}) + k_g(y_{G_1} + y_{G_2}).$$

The differential lateral displacement between the two pipe segments is expressed in terms of the generalised displacement as

$$\Delta y(t) = \phi_1 z_1(t) + \phi_2 z_2(t) \tag{6}$$

After some straightforward mathematical manipulations related to the random vibration theory, the power spectral density of the differential lateral displacement for the pipes