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Stochastic seismic response analysis of buried onshore and offshore pipelines

Kaiming Bi[a,*], Hong Hao[a], Chao Li[b], Hongnan Li[b]

[a] Centre for Infrastructure Monitoring and Protection, School of Civil and Mechanical Engineering, Curtin University, Kent Street, Bentley WA 6102, Australia

[b] Faculty of Infrastructural Engineering, Dalian University of Technology, Dalian 116024, China

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ABSTRACT

Previous studies on the seismic responses of offshore pipelines are not only very limited but also usually use earthquake ground motions recorded at the onshore sites as the inputs in the analyses due to the lack of seafloor earthquake recordings and the difficulty to predict seafloor seismic motions. This application may lead to erroneous predictions of offshore pipeline seismic responses, since it has been revealed that the existence of the seawater can significantly suppress the seafloor vertical motions near the *P*-wave resonant frequencies of the seawater layer. Moreover, the seawater layer can indirectly influence the seafloor motions by changing the water saturation and pore pressure of subsea soil layers, which in turn may obviously affect the propagation of seismic *P*-wave at the offshore site and therefore the pipeline seismic responses. This paper investigates the stochastic seismic responses of buried onshore and offshore pipelines. The direct and indirect influences of seawater layer on the seafloor seismic motions are explicitly considered by using the recently derived theoretical local site transfer functions. The mean peak seismic responses of buried onshore and offshore pipelines in the axial and lateral directions are stochastically formulated in the frequency domain. The differences between the onshore and offshore pipeline seismic responses are emphasized and the influences of seawater depth and water saturation level of the subsea site on the offshore pipeline responses are discussed.

1. Introduction

Previous studies on the seismic responses of buried pipelines subjected to seismic wave propagation effect mainly focused on the onshore pipelines, investigations on the seismic responses of offshore pipelines are surprisingly rare. To the best knowledge of the authors, only [1–4] investigated the seismic responses of offshore pipelines. Due to the lack of seafloor earthquake recordings and the difficulty to predict seafloor seismic motions, onshore motions were used as inputs in all these studies [1–4]. This may lead to erroneous predictions of offshore pipeline seismic responses, since previous studies (e.g. [5,6]) revealed that the existence of seawater can significantly suppress the seafloor vertical motions near the *P*-wave resonant frequencies of the seawater layer. Moreover, the seawater layer can indirectly influence the seafloor motions by changing the water saturation and pore pressure of subsea soil layers, which in turn can significantly affect the propagation of seismic *P*-wave at the offshore site. However, the direct and indirect influences of seawater layer on the seismic responses of buried offshore pipelines have not been reported yet.

Recently, Li et al. [7,8] theoretically derived an offshore site transfer function based on the fundamental hydrodynamic equations and one-dimensional wave propagation theory. The direct and indirect influences of seawater layer on the offshore site transfer function can be conveniently considered by using this model. The seismic responses of offshore pipelines subjected to earthquake loadings therefore can be more realistically simulated. This paper carries out stochastic analysis on the seismic responses of buried onshore and offshore pipelines subjected to spatially varying earthquake loadings. The differences between the onshore and offshore pipeline seismic responses are compared and the influence of seawater layer on the seismic responses of buried offshore pipeline is discussed.

2. Structural responses

Fig. 1 shows a pipeline buried in a typical onshore site (Fig. 1(a)) and an offshore (Fig. 1(b)) site. The meanings of different parameters in the figure can be found in [7,8]. Previous studies revealed that the effect of cross-correlations between ground motions in different directions are insignificant, the seismic responses of the pipeline in the axial (X direction) and transverse directions (Y and Z directions) therefore

* Corresponding author.
E-mail address: kaiming.bi@curtin.edu.au (K. Bi).

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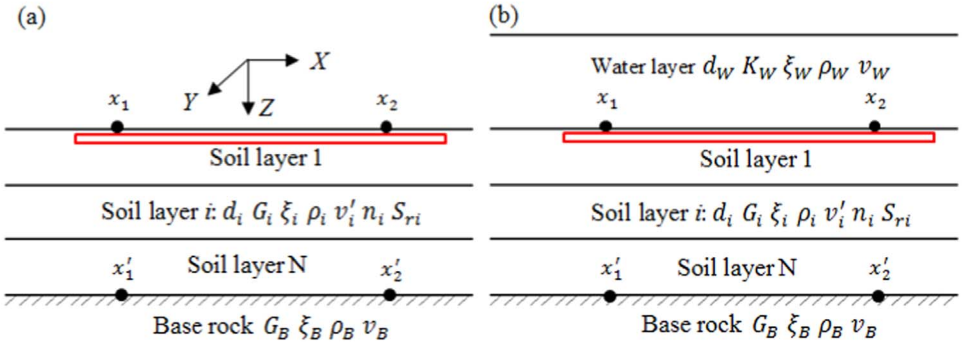

Fig. 1. A pipeline buried in a typical layered (a) onshore site and (b) offshore site.

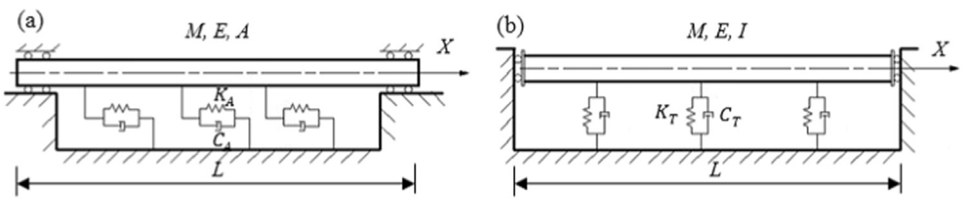

Fig. 2. Structural model of a buried pipeline under (a) axial seismic motion and (b) transverse seismic motion.

can be formulated independently [9].

2.1. Axial response

Fig. 2(a) shows the structural model of a buried pipeline under axial seismic motion. The considered length of the pipeline is L. Neglecting the internal damping of the pipe, the equation of motion can be written as [9]:

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

where M is the mass per unit length of the pipe, C_A and K_A are the damping and stiffness in the axial direction provided by the surrounding soil, E and A are the Young's modulus and cross sectional area of the pipe. $u(x,\,t)$ is the total displacement of the pipe in the axial direction and $u_g(x,\,t)$ is the axial seismic excitation.

After some lengthy but straightforward derivations, the power spectral density (PSD) function of the axial displacement can be formulated as

$$S_u(x,\,\omega)=\frac{1}{M^2}\left[\frac{C_A^2}{\omega^2}+\frac{K_A^4}{\omega^4}\right]\sum_{m=1}^{N}\sum_{n=1}^{N}\frac{\phi_m(x)\phi_n(x)}{L_mL_n}H_{0m}^*(i\omega)H_{0n}(i\omega)\times S_{g,X}(\omega)\int_0^L\int_0^L H_{x1,X}^*(i\omega)H_{x2,X}(i\omega)\phi_m(x_1)\phi_n(x_2)\gamma_{x_1'x_2'}(i\omega)dx_1dx_2 \tag{2}$$

where $\phi_m(x)=\cos\frac{(m-1)\pi x}{L}$ is the mth vibration mode of the pipeline, $L_m=\int_0^L\phi_m^2(x)dx=\begin{cases}L & \text{when} m=1\\ L/2 & \text{when} m\neq 1\end{cases}$, $H_{0m}(i\omega)=1/(\omega_m^2-\omega^2+2i\xi_m\omega_m)$ is the frequency response function for mode m, $S_{g,X}$ is the PSD function of base rock motion, $H_{x1,X}$ and $H_{x2,X}$ are the transfer functions at sites x_1 and x_2 respectively, * denotes complex conjugate and $\gamma_{x_1'x_2'}$ is the coherency loss function between motions at locations x_1' and x_2' on the base rock. The site transfer functions can be derived based on the one-dimensional wave propagation theory [10] (for the onshore site) and the theoretical method proposed by Li et al. [7,8] (for the offshore site). Detailed steps for deriving Eq. (2) can be found in [9]. It can be seen that if local site amplification effect is not considered, i.e. $H_{x1,X}^*(i\omega)=H_{x2,X}(i\omega)=1$, Eq. (2) becomes the same as those obtained in [9]. In other words, the previous derivations in [9] are a special case of the current study.

Previous studies (e.g. [9]) revealed that the displacement of buried pipeline is dominated by the rigid body motion of the pipe, the stress developed in the pipeline is therefore of more interest in engineering practice. Based on Eq. (2), the PSD of the axial stress can be formulated and it can be expressed as

$$S_{\sigma A}(x,\,\omega)=\frac{E^2\pi^2}{M^2L^2}\left[\frac{C_A^2}{\omega^2}+\frac{K_A^4}{\omega^4}\right]\sum_{m=1}^{N}\sum_{n=1}^{N}(m-1)(n-1)\frac{\phi_m'(x)\phi_n'(x)}{L_mL_n}H_{0m}^*(i\omega)H_{0n}(i\omega)\times S_{g,X}(\omega)\int_0^L\int_0^L H_{x1,X}^*(i\omega)H_{x2,X}(i\omega)\phi_m(x_1)\phi_n(x_2)\gamma_{x_1'x_2'}(i\omega)dx_1dx_2 \tag{3}$$

2.2. Lateral responses

Seismic responses of the buried pipeline in the lateral directions (transverse horizontal and vertical directions) can be formulated by following the same procedure as presented in Section 2.1. Fig. 2(b) shows the structural model of the pipeline under transverse seismic motion $v_g(x,\,t)$, which excites in the Y direction as shown in Fig. 1. The equation of motion can be expressed as [9].

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

where C_T and K_T are the damping and stiffness in the Y direction provided by the surrounding soil, I is the moment of inertia of the pipe cross section and $v(x,\,t)$ is the total pipe displacement.

Follow the same steps as presented in [9], the PSD for the bending stress induced by transverse earthquake $v_g(x,\,t)$ is

$$S_{\sigma Bv}(x,\,\omega)=\frac{E^2R^2\pi^4}{M^2L^4}\left[\frac{C_T^2}{\omega^2}+\frac{K_T^4}{\omega^4}\right]\sum_{m=1}^{N}\sum_{n=1}^{N}(m-1)^2(n-1)^2\frac{\phi_m(x)\phi_n(x)}{L_mL_n}H_{0m}^*(i\omega)H_{0n}(i\omega)\times S_{g,Y}(\omega)\int_0^L\int_0^L H_{x1,Y}^*(i\omega)H_{x2,Y}(i\omega)\phi_m(x_1)\phi_n(x_2)\gamma_{x_1'x_2'}(i\omega)dx_1dx_2 \tag{5}$$

Similarly, the PSD function of the bending stress induced by the vertical earthquake loading $w_g(x,\,t)$ can be formulated by replacing the base rock motion $(S_{g,Y}(\omega))$ and site transfer functions