Seismic Responses of Buried Segmented Pipelines to Spatially Varying Ground Motions Including Local Site Effect

Kaiming Bi[1], Hong Hao[2]

1. Corresponding Author. Lecturer, School of Civil and Resource Engineering, The University of Western Australia, WA.
   Email: kaiming.bi@uwa.edu.au

2. Professor, School of Civil and Resource Engineering, The University of Western Australia, WA.
   Email: hong.hao@uwa.edu.au

Abstract

Previous major earthquakes revealed that most damages of the buried segmented pipelines occur at the joints of the pipelines. It has been proven that the differential motions between the pipe segments are one of the primary reasons that results in the damage. This paper studies the combined influences of ground motion spatial variations and local soil conditions on the seismic responses of buried segmented pipelines. The heterogeneous soil deposits surrounding the pipelines are assumed resting on an elastic half-space (base rock). The spatially varying based rock motions are modelled by the filtered Tajimi-Kanai power spectral density function and an empirical coherency loss function. Local site amplification effect is derived based on the one-dimensional wave propagation theory by assuming the base rock motions consist of combined in-plane P and SV waves propagating into the site with an assumed incident angle. The differential axial displacement between the pipeline segments is stochastically formulated in the frequency domain. The influences of ground motion spatial variations and local soil conditions are investigated. Numerical results show that ground motion spatial variations and local soil conditions can significantly influence the differential displacements between the pipeline segments.

Key Words: buried segmented pipelines, seismic response, ground motion spatial variation, local site effect, stochastic method

1. INTRODUCTION

Buried pipelines were heavily damaged during previous major earthquakes. Based on the damage mechanism of buried pipelines, seismic impacts can be classified into being caused by permanent movements of ground (i.e., surface faulting, landsliding and soil liquefaction induced lateral spreading) or by transient seismic wave propagation (i.e. transient strain and curvature in the ground due to travelling wave effects) [1]. This paper studies the seismic responses of buried segmented pipelines due to seismic wave propagation effect.

Reconnaissance reports revealed that the joints are the most vulnerable parts of the segmented pipelines since large relative displacements usually occur between these segments, and these larger relative displacements in turn lead to the pull-out and shear crack damages at the joints. One of the main reasons that results in the large relative displacement is the ground motion spatial variations. The influence of spatially varying ground motions on the seismic responses of buried segmented pipelines have been studied by some researchers. Nelson and Weidlinger [2] considered the base motion at the left support as a given acceleration time history, whereas the input at the right support is the same acceleration time history but delayed by the travel time of the motion between the supports. In other words, only the ground motion wave passage effect was considered in the study. Zerva *et al*. [3] developed a model for the near source ground motions, in which, the excitation is modelled as a random process, the auto and cross power spectral density functions of accelerations at stations on the ground surface are estimated based on the data recorded at the SMART-1 array in Lotung, Taiwai. The developed model was then applied to stochastically investigate the differential displacements between different segments of buried pipelines [3-4]. However, it should be noted that the SMART-1 array is located at a relatively flat-lying alluvial site, therefore the influence of local soil conditions cannot be considered by using ground motion spatial variation model derived from the recorded spatial ground motions at the SMART-1 array.

Local soil site can filter the frequency contents and amplify the amplitudes of the coming seismic waves, which in turn further intensifies the ground motion spatial variations. Hadid and Afra [5] adopted the model proposed by Nelson and Weidlinger [2] and Zerva *et al*. [3-4], and carried out a sensitivity analysis of site effects on response spectra of pipelines. However, only the site amplification effect was considered in their study, the wave passage effect and coherency loss effect were neglected. Moreover, in their numerical model, the stiffness and damping of the soil springs at different supports of the segmented pipelines were assumed to be the same though the soil conditions surrounding the pipelines varied. This is obviously an unrealistic assumption since the stiffness and damping of the soil spring is undoubtedly related to the soil parameters. This assumption may lead to inaccurate predictions of pipeline responses.

Based on the discussion above, previous studies on the seismic responses of buried segmented pipelines either neglected ground motion spatial variations [5] or local site effect [2-4]. A comprehensive consideration of the combined ground motion spatial variations and local soil conditions on the seismic responses of buried segmented pipelines has not been reported. This paper directly relates the coefficients of the springs and dashpots with the surrounding soil properties and studies the combined ground motion spatial variations and local site effects on the seismic responses of buried segmented pipelines. The heterogeneous soil deposits surrounding the pipelines are assumed resting on an elastic half-space (base rock). The spatially varying based rock motions are modelled by the filtered Tajimi-Kanai power spectral density function and an empirical coherency loss function. Local site amplification effect is derived based on the one-dimensional wave propagation theory by assuming the base rock motions consist of combined in-plane P and SV waves propagating into the site with an assumed incident angle. The differential axial displacement between the pipe segments is stochastically formulated in the frequency domain. The influences of ground motion spatial variations and local soil conditions are investigated.

2. STRUCTURAL RESPONSE EQUATION FORMULATION

Figure 1 shows the discrete model for differential axial motion across the joint. The two pipeline segments are assumed to behave as rigid bodies, and interconnected by a spring with stiffness k_{pA} and a dashpot with damping c_{pA}. Pipe-soil interactions are represented by springs and dashpots, with k_{g1A} and c_{g1A} for the left segment and k_{g2A} and c_{g2A} for the right segment, respectively. The lengths and masses of the pipeline segments are *l* and *m* respectively, the separation distance between the two centroids of the segments is thus also *l*. The axial displacements of the two pipes are $x_1(t)$ and $x_2(t)$, whereas $x_{g1}(t)$ and $x_{g2}(t)$ are the axial ground excitations at the two supports. This model is revised from a previous study [5] in which the coefficients of the soil-pipe interactions are assumed to be the same for the two supports (i.e., $k_{g1A} = k_{g2A}$ and $c_{g1A} = c_{g2A}$) though different soils surrounding the pipelines are assumed. In the present study, the coefficients of the soil springs directly relate to the surrounding soil properties, with $k_{g1A} = 2G_{s1}$ and $k_{g2A} = 2G_{s2}$ [4], where G_{s1} and G_{s2} are the shear moduli of the surrounding soils.

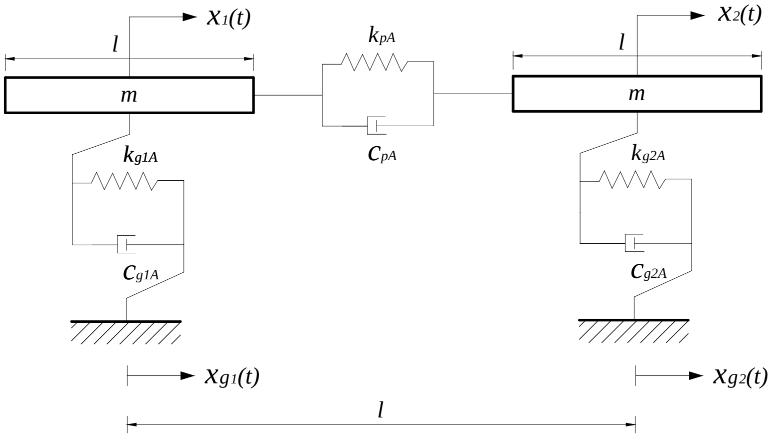

Figure 1. Discrete model for differential axial motion across the joint (not to scale)

With the numerical model shown in Figure 1, the equilibrium equation of the system can be written as

$$[M]_A\{\ddot{x}\} + [C]_A\{\dot{x}\} + [K]_A\{x\} = [K_{sb}]_A\{x_g\} + [C_{sb}]_A\{\dot{x}_g\} \quad (1)$$

Eqn 1 can be decoupled into its modal vibration equation as

$$\ddot{q}_{kA} + 2\xi_{kA}\omega_{kA}\dot{q}_{kA} + \omega_{kA}^2 q_{kA} = \frac{[\varphi_k^T]_A[K_{sb}]_A}{[\varphi_k^T]_A[M]_A[\varphi_k]_A}\{x_g\} + \frac{[\varphi_k^T]_A[C_{sb}]_A}{[\varphi_k^T]_A[M]_A[\varphi_k]_A}\{\dot{x}_g\} \quad (2)$$

where $[\varphi_k]_A$ is the *k*th vibration mode shape of the system, q_k is the *k*th modal response, ω_{kA} and ξ_{kA} are the corresponding circular frequency and viscous damping ratio, respectively.

With the stiffness proportional damping, the *k*th modal response in the frequency domain can be obtained from Eqn 2 as

$$\bar{q}_{kA}(i\omega) = H_{kA}(i\omega)\left[\frac{[\varphi_k^T]_A[K_{sb}]_A}{[\varphi_k^T]_A[M]_A[\varphi_k]_A}\{\bar{x}_g(i\omega)\} + \frac{[\varphi_k^T]_A[C_{sb}]_A}{[\varphi_k^T]_A[M]_A[\varphi_k]_A}\{\bar{\dot{x}}_g(i\omega)\}\right] =$$
$$H_{kA}(i\omega)\left[\frac{[1+2i\omega\,\xi_{kA}/\omega_{kA}][\varphi_k^T]_A[K_{sb}]_A}{[\varphi_k^T]_A[M]_A[\varphi_k]_A}\right]\{\bar{x}_g(i\omega)\} = H_{kA}(i\omega)\sum_{j=1}^{r}\psi_{kjA}\,\bar{x}_{gj}(i\omega) \quad (3)$$

in which *r* is the total number of supports, and

$$H_{kA} = \frac{1}{-\omega^2 + \omega_{kA}^2 + 2i\xi_{kA}\omega_{kA}} \quad (4)$$

is the *k*th modal frequency response function,

$$\psi_{kjA} = \frac{[1+2i\omega\,\xi_{kA}/\omega_{kA}][\varphi_k^T]_A[K_{sb}^j]_A}{[\varphi_k^T]_A[M]_A[\varphi_k]_A} \quad (5)$$

is the participation coefficient for the *k*th mode corresponding to a movement at support *j*, $[K_{sb}^j]_A$ is a vector in the stiffness matrix $[K_{sb}]_A$ corresponding to support *j*.

The structural response of the *i*th degree of freedom is

$$x_i(t) = \sum_{k=1}^{n}\varphi_{kA}^i\, q_{kA}(t) \quad (6)$$

where *n* is the number of modes considered in the calculation, and φ_{kA}^i is the *k*th mode shape value corresponding to the *i*th degree of freedom.

For the system shown in Figure 1, the differential axial displacement between the two pipeline segments is

$$\Delta x = x_1 - x_2 = \sum_{k=1}^{n}(\varphi_{kA}^1 - \varphi_{kA}^2)\, q_{kA} \quad (7)$$

The power spectral density function of Δx then can be derived as

$$S_{\Delta x} = \frac{1}{\omega^4}\left[|P_1|^2 S_{x_{g1}} + |P_2|^2 S_{x_{g2}} + 2\text{Re}\left(P_1 P_2^* S_{x_{g1g2}}\right)\right] \tag{8}$$

where

$$P_1(i\omega) = \sum_{k=1}^{n}[\varphi_{kA}^1 - \varphi_{kA}^2]\, H_{kA}(i\omega)\psi_{k1A}$$
$$P_2(i\omega) = \sum_{k=1}^{n}[\varphi_{kA}^1 - \varphi_{kA}^2]\, H_{kA}(i\omega)\psi_{k2A} \tag{9}$$

$S_{x_{g1}}$ and $S_{x_{g2}}$ are the auto spectral density functions of the axial ground motions at the two supports, $S_{x_{g1g2}}$ is the axial ground motion cross power spectral density function between the two supports. The formulation of them will be discussed in Section 3. 'Re' denotes the real part of a complex quantity and '*' represents complex conjugate. The mean peak response of the differential displacement can be obtained by using the standard random vibration method [6] once the corresponding power spectral density function is formulated.

3. SPATIALLY VARYING GROUND MOTION

According to Eqn 8, the power spectral density functions of differential displacements in the axial direction can be formulated when the corresponding auto and cross power spectral density functions of the ground motions are known. For a single soil layer resting on an elastic half space, the spatially varying surface motions can be formulated based on the combined one-dimensional wave propagation theory and spectral representation method [7], which is briefly introduced in this section.

Figure 2 shows a single soil layer resting on an elastic half space (base rock). The shear modulus, density, depth, damping ratio and Poisson's ratio for the soil layer are G_s, ρ_s, h_s, ξ_s and υ_s, respectively. The corresponding values on the base rock are G_R, ρ_R, ξ_R and υ_R. The base rock motions are assumed consisting of combined in-plane P and SV waves propagating into the site with an assumed incident angle α.

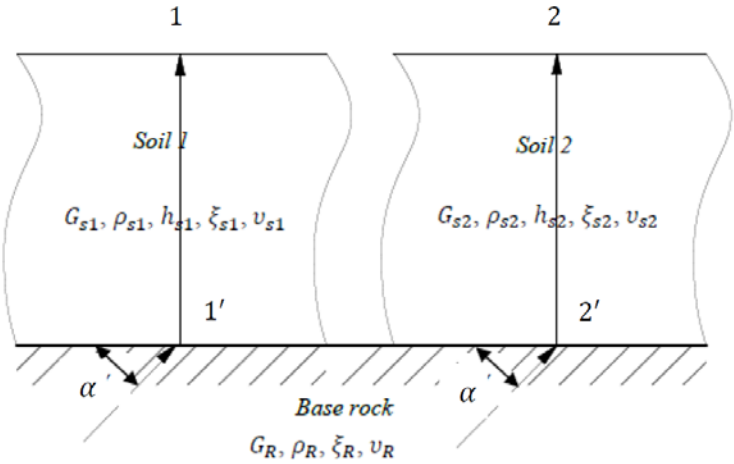

Figure 2. A single soil layer resting on an elastic half space

The motion on the base rock (Points 1' and 2' in Figure 2) is assumed to have the same intensity and frequency contents, and is modelled by a filtered Tajimi-Kanai power spectral density function $S_g(\omega)$ [8]. The incoherency and wave passage effects of the motions on the base rock are represented by an empirical coherency loss function $\gamma_{1'2'}(i\omega)$ [9]. The one-dimensional (1D) wave propagation theory proposed by Wolf [10] is adopted in the present study to consider the influence of local soil conditions. In this theory, the seismic waves propagate with an incident angle α in the base rock and then propagate vertically into the soil layer as shown in Figure 2.

After obtaining the ground motions on the base rock and the transfer functions of local soil sites, the spatially varying axial motions on the ground surface then can be formulated as

$$S_{x_{g1}} = |H_{sA1}(i\omega)|^2 S_g(\omega)$$
$$S_{x_{g2}} = |H_{sA2}(i\omega)|^2 S_g(\omega) \quad (10)$$
$$S_{x_{g1g2}} = H_{sA1}(i\omega) H_{sA2}^*(i\omega) S_g(\omega) \gamma_{1'2'}(i\omega)$$

Where H_{sA1} and H_{sA2} are the transfer functions of sites 1 and 2 respectively.

4. NUMERICAL RESULTS

Two segmented steel pipelines connected by a joint are selected as an example. The mass density of the pipe=7800kg/m^3, length *l*=100m, inner diameter=0.6m and outer diameter=0.61m. The segmented pipeline is buried in a heterogeneous soil layer resting on an elastic half space as shown in Figure 2. The properties of soil 1 are $G_{s1} = 40MPa$, $\rho_{s1} = 1600kg/m^3$, $h_{s1} = 50m$, $\xi_{s1} = 5\%$ and $\upsilon_{s1} = 0.4$, and those for the base rock are $G_R = 1800\ MPa$, $\rho_R = 2500kg/m^3$, $\xi_R = 5\%$ and $\upsilon_R = 0.33$, respectively. To study the influence of different soil conditions, the properties of soil 2 vary in the present study. In particular, the shear modulus of soil 2 varies from 20 to 160MPa, while other parameters are the same as soil 1. Another factor, which significantly influences the structural response, is the stiffness of the joint. For simplicity, following two parameters are defined:

$$\chi = \frac{k_{g2A}}{k_{g1A}} = \frac{k_{g2L}}{k_{g1L}}, \quad \eta = \frac{k_{pA}}{k_{g1A}} = \frac{k_{pL}}{k_{g1L}} \quad (11)$$

These two parameters describe the relation between the stiffness of the supporting soils and that between the joint and the soil.

To investigate the influence of ground motion spatial variations, highly, intermediately and weakly correlated ground motions are investigated. For comparison purpose, uniform excitations are also considered. To preclude the influences of other parameters, the incident angle is assumed to be $\alpha = 45°$ and the stiffness ratio between the joint and soil 1 is $\eta = 0.2$. Figure 3 shows the shows the different coherency loss functions.

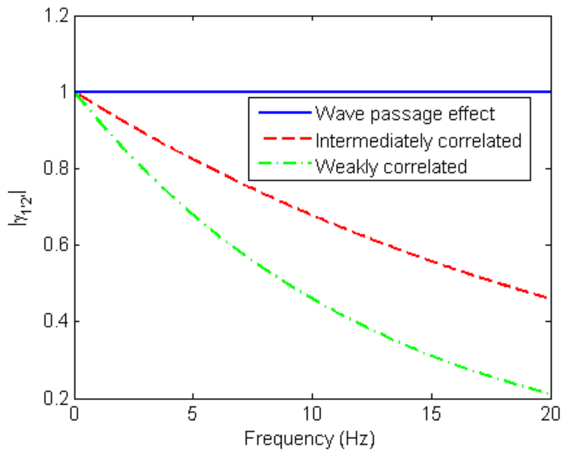

Figure 3. Different coherency loss functions

The effect of ground motion spatial variations on the differential axial displacement across the joint is shown in Figure 4. The corresponding standard deviations, which are not shown here, are rather small as compared to the mean peak responses. Therefore, only the mean peak responses are presented and discussed hereafter.

As shown in Figure 4, with an assumption of uniform excitation, the differential axial displacement between the pipeline segments is relatively small when the soil conditions surrounding the two pipelines are similar, and is zero when $\chi = 1$. This is because the vibration modes of the two segments are exactly the same and the two segments will vibrate in phase in this case. Therefore, there is no relative displacement between them. Spatially varying ground motions can significantly influence the differential axial displacement between the segments, especially when the soil conditions at the two sites are similar. Contrast to the uniform excitation, the minimum relative displacement does not exactly occur at $\chi = 1$, but slightly smaller than unity at $\chi = 0.9$ owing to the coupling of the joint [11]. The ground motion spatial variation effect is most significant when χ is close to unity, and weakly correlated ground motions cause larger relative displacement than highly correlated ground motions. When soil 2 is much stiffer than soil 1, e.g., when $\chi > 2$, the influence of soil conditions on the differential axial displacement is relatively small since the value is almost a constant as shown in Figure 4. This is because the total response of the structure can be divided into dynamic response and quasi-static response. When soil 2 is stiff enough, the response of the right segment (surrounded by soil 2) is mainly determined by the quasi-static response and the quasi-static response is independent of the structural frequency and is only related to the ground displacement [12]. Figure 5 shows the mean peak ground displacement of soil 2 with respect to χ. As shown, the ground displacement is almost a constant when $\chi > 2$, which in turn results in the constant relative axial displacement between the two segments in Figure 4.

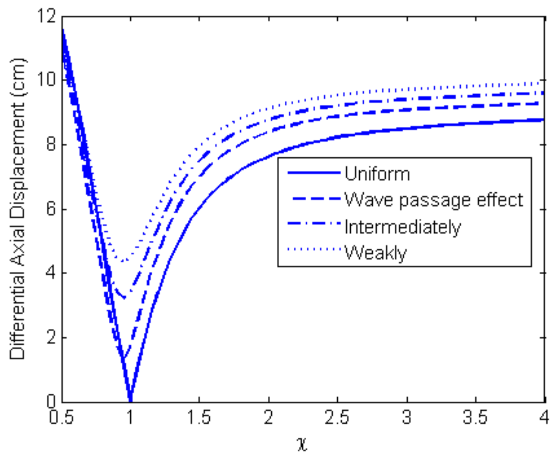

Figure 4. Influence of ground motion spatial variations on the differential axial displacement across the joint

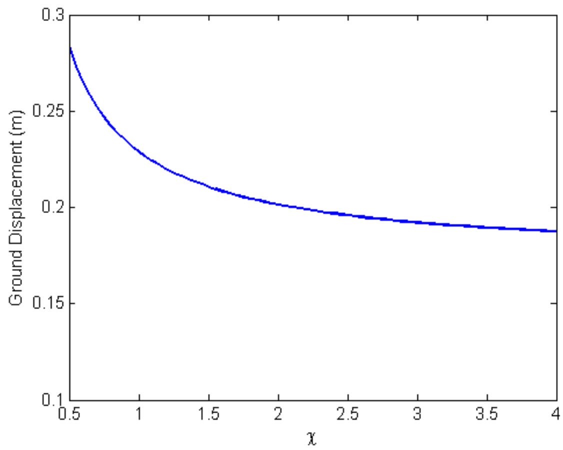

Figure 5. Mean peak ground displacement of site 2

5. CONCLUSIONS

Earthquake induced pipeline damages were observed in many previous major earthquakes. For buried segmented pipelines, the joint is the most vulnerable part since large relative displacements between the pipeline segments usually result in the pull-out and shear crack damage of the joint. This paper studies the differential axial and lateral displacements between segmented pipelines buried in a heterogeneous soil site resting on an elastic half space. Compared with previous studies, the combined influences of ground motion spatial variations and local soil conditions are considered, and the soil-pipe interaction coefficients are directly related to the supporting soils. This paper is thus believed more realistically modelled the seismic responses of buried segmented pipelines. Based on numerical results it is shown that ground motion spatial variations can significantly influence the differential displacement between the pipeline segments especially when the soil conditions surrounding the two pipelines are close to each other. Uniform excitation usually underestimates the differential displacements and weakly correlated ground motions generally lead to the largest structural responses.

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