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An Analytical Model for Pipe-Soil-Tunneling Interaction

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Abstract

The underground space in urban areas is frequently congested with utilities, including pipelines and conduits that are affected by underground construction, e.g., tunneling. This paper develops a Winkler-based pipe-soil-tunneling interaction model for estimating pipe responses to tunneling-induced ground movement. Efforts are focused on different pipe-soil interaction in relative uplift and downward pipe movements. Governing equations are derived, and their closed-form solutions are provided. The closed-form solutions are then validated against finite element simulations. Finally, the effects of different pipe-soil interactions in relative uplift and downward pipe movements are explored. The effect of different pipe-soil interaction is shown to be significant, and it should be properly accounted for in the analysis.

Keywords: Pipe; Ground Movement; Uplift; Downward Movement; Tunnel

1. INTRODUCTION

The underground space in urban areas is frequently congested with utilities, including pipelines and conduits that are affected by underground construction, e.g., tunneling. Tunneling-induced ground movements cause pipeline deformation that may disrupt the conveyance of important services and resources (e.g., water, electric power, and telecommunications) and threaten the safety and security of urban inhabitants (e.g., flooding and leakage of combustible gas from ruptured or leaking mains). To evaluate the effects of tunneling-induced movements on underground utilities, it is necessary to account rationally for the interaction between pipeline and soil associated with tunneling-induced patterns of soil movement.

The pipe-soil-tunneling interaction has attracted increasing research attention recently. Attewell et al. (1986) proposed a Winkler-based model in which the soil subgrade modulus is used to account for soil-
pipe interaction in response to a Gaussian settlement profile. Wang et al. (2010) extended the Winkler-based model for a Gaussian settlement profile to one that can deal with an arbitrary ground settlement profile. Vorster et al. (2005) developed an elastic continuum method for evaluating the interaction between buried continuous pipelines and Green field settlement from tunneling and compared with the results of centrifuge experiments. Klar et al. (2005) further compared the elastic continuum method with the Winkler-based approach proposed by Attewell et al. (1986). Although these models are different in many aspects, they share one common assumption, e.g., the pipe-soil interaction is identical in relative uplift and downward pipe movements. However, it has been well recognized that soil resistance in uplift is different from that associated with downward movements, particularly for pipes buried at shallow depths (Trautmann et al. 1985, Committee on Gas and Liquid Fuel Lifelines 1984, Honegger and Nyman 2004).

This paper develops a Winkler-based model that accounts for different pipe-soil interaction in relative uplift and downward pipe movements. After this introduction, the previous work on Winkler-based pipe-soil-tunneling interaction model is briefly reviewed. Then, the different pipe-soil interactions in relative uplift and downward pipe movements are highlighted, and a Winkler-based model and its closed-form analytical solutions are developed to account for such difference. The closed-form solutions are validated against finite element simulation results. Finally, the effects of different pipe-soil interaction in relative uplift and downward pipe movements are explored.

2. WINKLER-BASED MODEL

Figure 1a shows a schematic view of pipe-soil-tunneling interaction model, in which a tunnel is excavated below an existing pipeline (Wang et al. 1010). The tunneling process deforms the soil
surrounding the existing pipeline, and through the soil, imposes an equivalent distributed load in the pipeline. As shown in Figure 1b, Winkler-based model (e.g., Attewell et al., 1986) considers the pipeline as an infinite Winkler beam that is supported by an elastic medium with a supporting force proportional to the deflection, \( v(x) \), of the pipe at the supporting point with a coordinate \( x \). The equivalent distributed load induced by tunneling is proportional to the Green field soil settlement \( S(x) \). The governing differential equation can be expressed as (Attewell et al., 1986):

\[
\frac{\partial^4 v(x)}{\partial x^4} + 4 \lambda^4 v(x) = 4 \lambda^4 S(x)
\]

(1)

where \( \lambda = \sqrt{K/4E_p I_p} \), \( E_p \) is Young’s modulus of the pipe, \( I_p \) is the moment of inertia of the pipe, and \( K \) is the subgrade modulus that represents the pipe-soil interaction. In other words, the pipe-soil-tunneling interaction is modeled as a Winkler beam subjected to a distributed load equal to \( KS(x) \). On the other hand, an arbitrary settlement profile, \( S(x) \), can be represented mathematically by an n-order polynomial series, i.e., \( S(x) = \sum \alpha_i x^i \), where \( \alpha_i \) are constants in the polynomial series. When the arbitrary settlement profile \( S(x) \) is imposed on pipeline, the Winkler model can be divided into three regions, as shown in Figure 1b. The corresponding governing equations for these three regions are given as,

\[
\frac{\partial^4 v}{\partial x^4} + 4 \lambda^4 v = 0 \quad -\infty < x \leq a \text{ or } b \leq x < +\infty \quad \text{(Regions I or III)}
\]

\[
\frac{\partial^4 v}{\partial x^4} + 4 \lambda^4 v = 4 \lambda^4 S(x) \quad a \leq x \leq b \quad \text{(Region II)}
\]

(2)

General solutions for Equation (2) are given as following (Hetényi 1946),

\[
v = e^{\lambda x} \left( C_{11} \cos \lambda x + C_{12} \sin \lambda x \right) + e^{-\lambda x} \left( C_{13} \cos \lambda x + C_{14} \sin \lambda x \right) \quad -\infty < x \leq a
\]

\[
v = e^{\lambda x} \left( C_{21} \cos \lambda x + C_{22} \sin \lambda x \right) + e^{-\lambda x} \left( C_{23} \cos \lambda x + C_{24} \sin \lambda x \right) + v_n^* \quad a \leq x \leq b
\]

\[
v = e^{\lambda x} \left( C_{31} \cos \lambda x + C_{32} \sin \lambda x \right) + e^{-\lambda x} \left( C_{33} \cos \lambda x + C_{34} \sin \lambda x \right) \quad b \leq x < +\infty
\]

(3)

where \( C_{ij} \), \( i, j = 1, 2, 3, 4 \) are integration constants, and \( v_n^* \) is a particular solution for \( S(x) \). \( v_n^* \) is an n-order polynomial series and is obtained using the method of undetermined coefficients (Wang et al. 2010). There are twelve integration constants in Equation (3), \( C_{ij} \), and they can be interpreted from corresponding boundary conditions. Detailed equations and their implementation in Matlab (Mathworks Inc 2007) are referred to Wang et al. (2010).

3. DIFFERENT PIPE-SOIL INTERACTION IN RELATIVE UPLIFT AND DOWNWARD PIPE MOVEMENTS

It has been well recognized that soil resistance in uplift is different from that associated with downward movements, particularly for pipes buried at shallow depths typical of most utilities (Trautmann et al. 1985, Committee on Gas and Liquid Fuel Lifelines 1984, Honegger and Nyman 2004). Generally speaking, the soil subgrade modulus (\( K_u \)) in relative pipe uplift is smaller than the soil subgrade modulus (\( K_d \)) in relative pipe downward movement, as shown in Figure 2. The \( K_u \) and \( K_d \) can be estimated...
following the ASCE “Guidelines for the Seismic Design of Oil and Gas Pipeline Systems” (Committee on Gas and Liquid Fuel Lifelines 1984). Bearing capacity equations for foundations are used to estimate \( K_d \) in relative pipe downward movement. In contrast, the \( K_u \) values are obtained from a design chart that was developed from experiment results. Consider, for example, a steel pipe, with an outer diameter = 610mm, wall thickness = 9.5mm and \( E_p = 200 \)GPa, buried in dense sand with a buried depth of 0.9m, unit weight of 20kN/m\(^3\) and friction angle of 40°. The \( K_u \) and \( K_d \) are estimated as 2318kN/m\(^2\) and 21293kN/m\(^2\), respectively. It is evident that the \( K_d \) is about one order of magnitude larger than the \( K_u \).

Note that the pipe deflections resulted from tunneling-induced ground movements contain both uplift and downward movements. Figure 3 illustrates a typical profile of tunneling-induced ground settlement and corresponding absolute pipe deflections and pipe-soil relative displacements. Generally speaking, based on pipe-soil relative displacement, the pipe can be divided into five zones with relative uplift in Zones I, III, and V and relative downward movements in Zones II and IV. Note that although the absolute pipe deflections in Zone III are downward, the pipe-soil relative displacements are uplift as the absolute pipe downward movements are smaller than the ground settlements. Therefore, an uplift soil subgrade modulus (i.e., \( K_u \)) should be used for Zones I, III, and V, as opposed to Zones II and IV, where a downward soil subgrade modulus (i.e., \( K_d \)) should be applied.

4. CLOSED-FORM SOLUTION WITH DIFFERENT PIPE-SOIL INTERACTION

Figure 4a shows the pipe-soil relative displacement when the pipe is subject to a Gaussian settlement profile approximated by a polynomial function. Because the Gaussian profile is symmetric, the pipe response is also symmetric. Therefore, analysis for only half of the pipe is needed. Figure 4a shows that the left half of the pipe can be divided into three parts (i.e., Parts I, II, and III) with different pipe-soil relative movements (i.e., \( K_d \) and \( K_u \)) by Points A, B, and O. To account for different \( K_d \) or \( K_u \) in different parts of pipe with finite length (Parts II and III) or semi-infinite length (Part I), the principle of superposition is used, together with solutions for pipe under arbitrary settlement profile (Wang et al. 2010) and concentrated load and moment (Hetenyi 1946). For Winkler beam on elastic foundation media, the response of finite or semi-infinite beam can be obtained by superimposition of the response of infinite beam under the same loading conditions with the response of infinite beam under appropriate end-conditioning forces (i.e., concentrated load \( P \) and/or moment \( M \)) at the ends to fulfill the boundary (or end) conditions. Figure 4b shows the Winkler models for Parts I, II, and III under equivalent distributed loads from tunneling-induced ground movements and their associated end-conditioning forces, respectively. There are totally ten end-conditioning forces (i.e., \( P_k \) and \( M_k \) for \( k = 1, 2, 3, 4, \) and 5, as shown in Figure 4b) for Parts I, II, and III. The corresponding deflections (i.e., \( v \)), slopes (i.e., \( \theta = v' \)), section moments (i.e., \( M = -E_p I_p v'' \)), and shearing forces (i.e., \( Q = -E_p I_p v''' \)) of infinite beam under concentrated load and moment can be obtained from Hetenyi (1946). Note that each Part shown in Figure 4b is only subject to a portion of the Gaussian settlement profile. Therefore, the closed-form solution for arbitrary settlement profile developed by Wang et al. (2010) and reviewed briefly in the previous section is readily applicable when estimating the response of infinite pipe under a portion of the Gaussian settlement profile. The boundary conditions that Parts I, II, and III have to satisfy include the continuity conditions at Point A and B and the symmetric conditions at Point O. Detailed equations and solutions are given in the following subsection.
4.1. Governing Equations

To facilitate derivation of the governing equations for Parts I, II, and III, a series of notations are defined. The responses of an infinite pipe to an arbitrary settlement profile \( S(x) \) are denoted as pipe deflection \( v^j_S \), slope \( \theta^j_S \), moment \( M^j_S \), and shearing force \( q^j_S \). The subscript “\( S \)” represents that the pipe responses are caused by settlement profile \( S(x) \) and are obtained from the closed-form solution developed by Wang et al. (2010). The superscript “\( \lambda \)” can be either “\( \lambda_u \)” or “\( \lambda_d \)” representing pipe-soil relative uplift (i.e., \( K_u \)) or downward (i.e., \( K_d \)) movements, respectively. Similarly, the responses of an infinite pipe to end-conditioning forces \( P_k \) and \( M_k \) are denoted as \( v^j_k \), \( \theta^j_k \), \( M^j_k \), \( Q^j_k \), \( Q^j_{kP} \), and \( Q^j_{kM} \). The subscript “\( P_k \)” and “\( M_k \)” represents that the pipe responses are caused by end-conditioning forces \( P_k \) or \( M_k \).

There are three sets of equations for Parts I, II, and III, respectively. For Part I \((-\infty < x \leq x_A)\),

\[
v_I = v^j_S + v^j_{P_1} + v^j_{M_1}; \quad \theta_I = \theta^j_S + \theta^j_{P_1} + \theta^j_{M_1}; \quad M_I = M^j_S + M^j_{P_1} + M^j_{M_1}; \quad Q_I = Q^j_S + Q^j_{P_1} + Q^j_{M_1} \quad (4)
\]

For Part II \((x_A \leq x \leq x_B)\),

\[
v_{II} = v^j_{S_H} + v^j_{P_2} + v^j_{M_2} + v^j_{P_3} + v^j_{M_3}; \quad \theta_{II} = \theta^j_{S_H} + \theta^j_{P_2} + \theta^j_{P_3} + \theta^j_{M_2} + \theta^j_{M_3}; \quad M_{II} = M^j_{S_H} + M^j_{P_2} + M^j_{M_2} + M^j_{P_3} + M^j_{M_3}; \quad Q_{II} = Q^j_{S_H} + Q^j_{P_2} + Q^j_{P_3} + Q^j_{M_2} + Q^j_{M_3} \quad (5)
\]
For Part III \((x_B \leq x \leq 0)\),

\[
v_{III} = v_0^{\lambda_i} + v_4^{\lambda_i} + v_5^{\lambda_i} + v_6^{\lambda_i} + v_7^{\lambda_i}; \quad \theta_{III} = \theta_0^{\lambda_i} + \theta_4^{\lambda_i} + \theta_5^{\lambda_i} + \theta_6^{\lambda_i} + \theta_7^{\lambda_i};
\]

\[
M_{III} = M_0^{\lambda_i} + M_4^{\lambda_i} + M_5^{\lambda_i} + M_6^{\lambda_i} + M_7^{\lambda_i}; \quad Q_{III} = Q_0^{\lambda_i} + Q_4^{\lambda_i} + Q_5^{\lambda_i} + Q_6^{\lambda_i} + Q_7^{\lambda_i}.
\]  

(6)

Substituting the infinite pipe responses \(v_j^{\lambda_i}, v_j^{\lambda_i}, \theta_j^{\lambda_i}, \theta_j^{\lambda_i}, M_j^{\lambda_i}, M_j^{\lambda_i}, Q_j^{\lambda_i}\), and \(Q_j^{\lambda_i}\) (for \(j = u\) or \(d\) and \(k = 1, 2, 3, 4,\) and \(5\)) from Hetenyi (1946) into Equation groups 4-6 leads to the following

\[
v_j = v_0^{\lambda_i} - \frac{P_j^{\lambda_i}}{2K_u} A_{j,x} + \frac{M_j^{\lambda_i} A_j^{\lambda_i}}{K_u} B_{j,x} + \frac{M_j^{\lambda_i} A_j^{\lambda_i}}{K_u} B_{j,x}; \quad \theta_j = \theta_0^{\lambda_i} - \frac{P_j^{\lambda_i}}{2K_u} A_{j,x} + \frac{M_j^{\lambda_i} A_j^{\lambda_i}}{K_u} B_{j,x};
\]

\[
M_j = M_0^{\lambda_i} - \frac{P_j^{\lambda_i}}{4K_u} C_{j,x} + \frac{M_j^{\lambda_i} A_j^{\lambda_i}}{K_u} C_{j,x} + \frac{M_j^{\lambda_i} A_j^{\lambda_i}}{K_u} C_{j,x};
\]

\[
Q_j = Q_0^{\lambda_i} - \frac{P_j^{\lambda_i}}{2D_{j,x}} + \frac{M_j^{\lambda_i} A_{j,x}}{2D_{j,x}} - \frac{M_j^{\lambda_i} A_{j,x}}{2D_{j,x}}.
\]  

(7)

For Part II \((x_A \leq x \leq x_B)\),

\[
v_{II} = v_0^{\lambda_i} - \frac{P_j^{\lambda_i}}{2K_u} A_{j,x} + \frac{M_j^{\lambda_i} A_j^{\lambda_i}}{2K_u} B_{j,x} + \frac{M_j^{\lambda_i} A_j^{\lambda_i}}{2K_u} B_{j,x}; \quad \theta_{II} = \theta_0^{\lambda_i} - \frac{P_j^{\lambda_i}}{2K_u} A_{j,x} + \frac{M_j^{\lambda_i} A_j^{\lambda_i}}{2K_u} B_{j,x};
\]

\[
M_{II} = M_0^{\lambda_i} + \frac{P_j^{\lambda_i}}{4K_u} C_{j,x} + \frac{M_j^{\lambda_i} A_j^{\lambda_i}}{2K_u} C_{j,x} + \frac{M_j^{\lambda_i} A_j^{\lambda_i}}{2K_u} C_{j,x};
\]

\[
Q_{II} = Q_0^{\lambda_i} - \frac{P_j^{\lambda_i}}{2D_{j,x}} + \frac{M_j^{\lambda_i} A_{j,x}}{2D_{j,x}} - \frac{M_j^{\lambda_i} A_{j,x}}{2D_{j,x}}.
\]  

(8)

For Part III \((x_B \leq x \leq 0)\),

\[
v_{III} = v_0^{\lambda_i} - \frac{P_j^{\lambda_i}}{2K_u} A_{j,x} + \frac{M_j^{\lambda_i} A_j^{\lambda_i}}{2K_u} B_{j,x} + \frac{M_j^{\lambda_i} A_j^{\lambda_i}}{2K_u} B_{j,x}; \quad \theta_{III} = \theta_0^{\lambda_i} - \frac{P_j^{\lambda_i}}{2K_u} A_{j,x} + \frac{M_j^{\lambda_i} A_j^{\lambda_i}}{2K_u} B_{j,x};
\]

\[
M_{III} = M_0^{\lambda_i} - \frac{P_j^{\lambda_i}}{4K_u} C_{j,x} + \frac{M_j^{\lambda_i} A_j^{\lambda_i}}{2K_u} C_{j,x} + \frac{M_j^{\lambda_i} A_j^{\lambda_i}}{2K_u} C_{j,x};
\]

\[
Q_{III} = Q_0^{\lambda_i} - \frac{P_j^{\lambda_i}}{2D_{j,x}} + \frac{M_j^{\lambda_i} A_{j,x}}{2D_{j,x}} - \frac{M_j^{\lambda_i} A_{j,x}}{2D_{j,x}}.
\]  

(9)

where \(A_j^{\lambda_i} = e^{-\lambda_j x} \left( \cos \lambda_j x + \sin \lambda_j x \right) \), \(B_j^{\lambda_i} = e^{-\lambda_j x} \sin \lambda_j x \), \(C_j^{\lambda_i} = e^{-\lambda_j x} \left( \cos \lambda_j x - \sin \lambda_j x \right) \), and \(D_j^{\lambda_i} = e^{-\lambda_j x} \). Note that the unknowns in Equation groups 7-9 include ten end-conditioning forces (i.e., \(P_j, P_2, P_2, P_4, P_5, M_1, M_2, M_3, M_4,\) and \(M_5\)) and \(x_A\) and \(x_B\).

The boundary conditions that the aforementioned equation groups have to satisfy include symmetric conditions at Point O (i.e., \(\theta_{OIII} = 0\) and \(Q_{OIII} = 0\)) and continuity conditions at Points A and B. At Point A (i.e., \(x = x_A\)), the pipe deflections, slopes, section moments, and shearing forces calculated from the solutions for Part I must equal to those calculated from the solutions for Part II (i.e., \(v_{AI} = v_{AII}, \theta_{AI} = \theta_{AII}, M_{AI} = M_{AII},\) and \(Q_{AI} = Q_{AII}\)). Similarly, four equations at Point B (i.e., \(v_{BII} = v_{BIII}, \theta_{BII} = \theta_{BIII}, M_{BII} = M_{BIII},\) and \(Q_{BII} = Q_{BIII}\)) can be established. Therefore, for given Points A and B
There are totally ten independent equations for ten unknowns (i.e., \(P_1, P_2, P_3, P_4, P_5, M_1, M_2, M_3, M_4, \text{ and } M_5\)). Then, the ten unknowns can be obtained by solving these ten equations, and the pipe deflections are determined accordingly.

Note that the locations of Points A and B are unknown (i.e., \(x_A\) and \(x_B\) are unknown), but Points A and B share a common feature that the direction of pipe-soil relative movement changes and the pipe-soil relative movements are zero at these locations. Therefore, the pipe deflections (i.e., \(v_A\) and \(v_B\)) at Points A and B equal to the ground settlement at these locations. To estimate the correct locations of Points A and B, an iterative procedure is used in this work. Firstly, a set of initial \(x_A\) and \(x_B\) values are proposed, and they are used to calculate the ten end-conditioning forces and resulting pipe deflections. The pipe deflections are compared with the ground settlement profile to determine the locations of zero pipe-soil relative movement, and hence obtaining an updated set of \(x_A\) and \(x_B\) values. Then, the updated set of \(x_A\) and \(x_B\) values is compared with the previous set of \(x_A\) and \(x_B\) values. If the difference between the previous and updated sets of values is smaller than a predefined tolerance value, the updated set of \(x_A\) and \(x_B\) values is used as the correct coordinates of the Points A and B. Otherwise, the updated set of \(x_A\) and \(x_B\) values is used to recalculate the ten end-conditioning forces and resulting pipe deflections. The iteration procedure continues until the difference between the previous and updated sets of values is smaller than the predefined tolerance value. The equations and solution described above are implemented in Matlab.

4.2. Illustrative Example

Consider, for example, the steel pipe and ground condition described in Section 3 interacting with a Gaussian ground settlement profile

\[ S(x) = S_{\text{max}} \exp \left[ -\frac{1}{2} \left( \frac{x}{i} \right)^2 \right] = S_{\text{max}} \sum_{m=0}^{\infty} \frac{(-1)^{m+2}}{2^m \cdot i^{2m} \cdot m!} x^{2m} \]

where \(i = 2m\) and \(S_{\text{max}} = 0.1m\). Figure 5a shows the pipe deflections obtained from the closed-form solutions together with the ground settlement profile. As the ground settlement profile is symmetric, the pipe deflections are also symmetric. At the center of settlement trough, the maximum pipe deflection is about 40 mm, which is smaller than the maximum ground settlement (i.e., 100mm). This results in a relative uplift pipe movement at the center of settlement trough, as opposed to the relative downward pipe movements at \(x = \pm 5m\), where the pipe deflection is larger than the ground settlement. Figure 5b shows the pipe section moments obtained from the closed-form solutions. The pipe section moments are also symmetric, and the maximum section moment of about 620 kN*m occurs at the center of settlement trough.

5. VALIDATION AGAINST FINITE ELEMENT MODELS

The proposed closed-form solutions for pipe-soil-tunneling interaction are validated against finite element models (FEM) using the software package ABAQUS (ABAQUS 2006). Continuous pipe segments and pipe-soil interaction are simulated explicitly in the ABAQUS finite element models. Beam elements with pipe cross section are used to simulate pipe segments, and the pipe-soil interaction is modeled by pipe-soil interaction (PSI) elements in ABAQUS. The PSI element in ABAQUS is formulated in accordance with the ASCE “Guidelines for the Seismic Design of Oil and Gas Pipeline Systems” (Committee on Gas and Liquid Fuel Lifelines, 1984) and is consistent.
with estimate of $K_u$ and $K_d$ for relative uplift and downward pipe movements in the closed-form solutions. The tunneling-induced ground displacements are imposed on the PSI elements as distributed displacement boundary conditions. Figure 5 also includes the FEM results, and it is evident that the FEM results (i.e., both pipe deflections and section moments) are virtually identical to those from closed-form solutions.

6. EFFECTS OF DIFFERENT PIPE-SOIL INTERACTIONS

The effects of different pipe-soil interactions in relative uplift and downward pipe movements are then explored. Figure 6 compares the results in Figure 5 (i.e., with different pipe-soil interactions) with those from two sets of analyses that do not consider different pipe-soil interactions (i.e., only one subgrade modulus $K$ is considered, and $K = K_d = 21293 \text{kN/m}^2$ or $K = K_u = 2318 \text{kN/m}^2$). It is obvious that their maximum pipe deflections and moments differ significantly. When $K = K_d = 21293 \text{kN/m}^2$, the maximum pipe deflections and moments are almost twice larger than those with different pipe-soil interaction (i.e.,
use both $K_d = 21293 \text{kN/m}^2$ and $K_u = 2318 \text{kN/m}^2$). It is interesting to note that, even when $K = K_u = 2318 \text{kN/m}^2$, the corresponding maximum pipe deflection is larger than that with different pipe-soil interaction. The effect of different pipe-soil interaction is significant, and it should be properly accounted for in the analysis.

7. CONCLUSIONS

This paper developed a Winkler-based pipe-soil-tunneling interaction model for estimating pipe responses to tunneling-induced ground movement. Efforts have been focused on different pipe-soil interaction in relative uplift and downward pipe movements. According to direction of pipe-soil relative displacement, the pipes are divided into several segments, and different soil subgrade modulus for uplift or downward movements are adopted accordingly. The response of these several segments of pipes are obtained by superposition of the response of infinite pipe under the same loading conditions with the response of infinite beam under appropriate end-conditioning forces (i.e., concentrated load $P$ and/or moment $M$) at the ends to fulfill the boundary conditions, such as continuity conditions. Governing equations and their closed-form solutions were derived. The closed-form solution results are shown to be in good agreement with the finite element simulations results. Then, the effects of different pipe-soil interactions in relative uplift and downward movements are explored. The effect of different pipe-soil interaction is shown to be significant, and it should be properly accounted for in the analysis.

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REFERENCES