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Effect of a forced harmonic vibration pile to its adjacent pile in layered elastic soil with double-shear model

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ABSTRACT

A new model named double-shear model based on Pasternak foundation and Timoshenko beam theory is developed to evaluate the effect of a forced harmonic vibration pile to its adjacent pile in multilayered soil medium. The double-shear model takes into account the shear deformation and the rotational inertia of piles as well as the shear deformation of soil. The piles are simulated as Timoshenko beams, which are embedded in a layered Pasternak foundation. The differential equation of transverse vibration for a pile is solved by the initial parameter method. The dynamic interaction factors for the layered soil medium are obtained by the transfer matrix method. The formulation and the implementation have been verified by means of several examples. The individual shear effects of soil and piles on the interaction factors are evaluated through a parametric study. Compared to Winkler model with Euler beam, the present model gives much better results for the dynamic interaction of piles embedded in stiff soil with small slenderness ratios. Finally, the effect of a forced long pile to a short pile embedded in multilayered soil medium is studied in detail.

1. Introduction

Piles as deep foundations have been commonly used to support engineering structures in the form of closely spaced group. In addition to the loads transmitting from the pile cap, each pile in the group would experience additional loads arising from the interference of adjacent piles. For statically loaded piles, Poulos [1] introduced the concept of 'interaction factor' which is the ratio of displacement of an unloaded pile to that of a loaded pile due to soil deformation. In practice, piles of different lengths can be used to improve the foundation performance and provide a more economical solution. Attention has been paid to the interaction factors for long–short piles [2–4]. Wong and Poulos [2] developed an approximate solution for the settlement interaction factor between two piles of different diameters or lengths in homogeneous medium by the boundary element method. It was extended later by Zhang and Zhang [3] to a layered soil medium through the shear displacement method. Liang et al. [4] adopted an integral equation method with a fictitious pile model to analyze the piled raft foundation supported by piles of unequal lengths.

The aforementioned static interaction factors are not applicable to the dynamic analysis of piles, except perhaps at very low frequencies of oscillation. Kaynia and Kausel [5] extended the interaction factor of identical piles to the dynamic analysis by the boundary integral techniques. Various methods, such as the experimental methods [6,7], the numerical methods [8–14] and the analytical methods [15–20] have been developed to study the pile-to-pile interaction under dynamic excitation. Using the analytical method, Dobry and Gazetas [16] developed a wave model to study the pile–soil–pile dynamic interaction. Makris and Gazetas [17] accounted for the pile-to-pile interaction factors based on a simplified model, in which the pile is simulated as a Bernoulli–Euler beam on a Winkler foundation. In addition to the simplicity, the results from their method were in reasonable agreement with those rigorous solutions [5]. Due to the clear physical concept and the low computational complexity, Makris and Gazetas's method [17] has received a widespread application.

Mylonakis [18] developed an improved plane–strain model to study the dynamic response of large-diameter end-bearing cylindrical shafts. By means of a simplified wave interference analysis, Mylonakis and Gazetas [19,20] used the Winkler model to determine the pile-to-pile interaction factor for axial and lateral vibrations of piles in layered soil by considering the presence of receiver pile. The influence of an additional axial load on the interaction factors between piles was studied by Jiang et al. [21]. Ghasemzadeh and Alibeikloo [22] analyzed the interaction factors between two adjacent piles with an inclination angle.

However, for the Winkler foundation the soil pressure at any point is assumed to be proportional only to the deflection at that

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point. Therefore, it cannot represent the real situation of continuous deformation of the soil medium. To overcome this limitation, the Pasternak foundation [23–27] has been introduced to include the shear effect of soil. Wang et al. [27] used the Euler beam model on Pasternak foundation to analyze the interference between two identical long piles. De Rosa and Maurizi [28,29] investigated the vibration frequencies of a beam and multistep pile based on the Pasternak foundation. Qetin and Simsek [30] studied the free vibration of a graded pile embedded in uniform Pasternak foundation and analyzed the variation of the non-dimensional frequency of the pile with respect to the two elastic parameters. Their works have been done within the scope of classical Bernoulli–Euler theory to investigate the dynamic characteristics of piles for mathematical simplicity. It is well known that only the lateral inertia and the elastic forces caused by bending deflections are considered in the Euler theory. On the other hand, for those piles with small slenderness ratio or piles under high frequency excitations, the Timoshenko beam theory [31–35], which takes into account the effects of shear deformation and rotational inertia, may give a better approximation to the general behavior of the piles. Hu et al. [34] studied the dynamic response of a single pile based on the Timoshenko beam theory. Comparing with other beam models, Kampitsis et al. [35] demonstrated the advantage of Timoshenko theory on the kinematic and inertial interaction of soil–pile-structure.

Following the work of Mylonakis and Gazetas [20], and the authors [27], the double-shear model (the shear deformation and rotational inertia of piles, and the shear effect of soil are simultaneously considered) is developed and applied to analyze the dynamic interaction of adjacent piles in multilayered soil medium. A parametric study is focused on the shear effects of soil and pile as well as the effect of rotary inertia on the pile-to-pile dynamic interaction factors of both identical piles and long–short piles.

2. Model for analysis

To better understand the behavior of dynamic interaction factor for two piles with the same material property but different lengths, the double-shear model to be developed is shown in Fig. 1. Here, the long pile and short pile are adopted as the source pile and the receiver pile, respectively. The present model can also be extended to the case that the short pile is adopted as the source pile. In such a case, the fictitious soil pile method [36] could be used to obtain the additional effect from the soil pile under the short pile to the long pile. The Pasternak foundation is used to represent the reaction of the soil against the pile deformation. Along the pile-shaft, it is a system of infinitely close linear springs and dashpots, which connect through an incompressible shear layer. The current methods for determining the parameters of these mechanical components can be classified into experimental method and simplified theoretical formulations [17,37–40]. The Timoshenko beam theory is used to describe the transverse vibration of the pile taking into account the shear deformation and the rotational inertia. According to the specific distribution of the soil medium, the source pile and the receiver pile are divided into a number of segments within each soil layer such that the soil within each segment has more or less uniform mechanical properties.

3. Formulation

3.1. Vibration of the source pile

The local coordinate system for the i-th segment is shown in Fig. 1(b). By using the Hamilton principle and the Timoshenko beam theory, the translational and rotational equilibrium conditions of the i-th segment of the source pile are given by

$$\rho_{pi}A_{pi}\frac{\partial^2 u_{1i}(z,t)}{\partial t^2} = -\frac{\partial}{\partial z}\left[\kappa G_{pi}A_{pi}\left(\theta_{1i}(z,t)-\frac{\partial u_{1i}(z,t)}{\partial z}\right)\right] - \left(k_{xi}u_{1i}(z,t)-g_{xi}\frac{\partial^2 u_{1i}(z,t)}{\partial x^2}+c_{xi}\frac{\partial u_{1i}(z,t)}{\partial t}\right) \quad (1)$$

$$\rho_{pi}I_{pi}\frac{\partial^2\theta_{1i}(z,t)}{\partial t^2} = E_{pi}I_{pi}\frac{\partial^2\theta_{1i}(z,t)}{\partial z^2}-\kappa G_{pi}A_{pi}\left(\theta_{1i}(z,t)-\frac{\partial u_{1i}(z,t)}{\partial z}\right) \quad (2)$$

where A_{pi}, I_{pi} and $\kappa=6(1+\nu_p)/(7+6\nu_p)$ are the area, the inertia moment and the shear coefficient [30] of the i-th segment of the pile, ν_p, ρ_{pi}, E_{pi}, G_{pi}, are Poisson's ratio, the mass density, Young's modulus, the shear modulus of the pile, u_{1i} and θ_{1i} are the lateral deflection and the bending rotation of the i-th segment of the pile, respectively.

In Refs. [17,37], the expressions of compressive stiffness and damping ratio for the i-th segment are recommended as

$$\begin{cases} k_{xi}=1.75(L/d)-0.13E_{si} & \text{for} \quad L/d<10 \\ k_{xi}=1.2E_{si} & \text{for} \quad L/d\geq 10 \end{cases},$$

$$c_{xi}=6a_0{}^{-1/4}\rho_{si}V_{si}d+2\beta_{si}k_{xi}/\omega,$$

in which, $V_{si}=\sqrt{G_{si}/\rho_{si}}$ is the shear wave velocity; E_{si}, G_{si}, ν_{si}, β_{si} and ρ_{si} are Young's modulus, the shear modulus, Poisson's ratio, the radiation damping and the mass density of i-th soil layer, respectively; L and d are the length and the sectional diameter of the pile; $a_0=\omega d/V_s$ is the normalized angular frequency of the excitation. The shear stiffness of the i-th segment are given

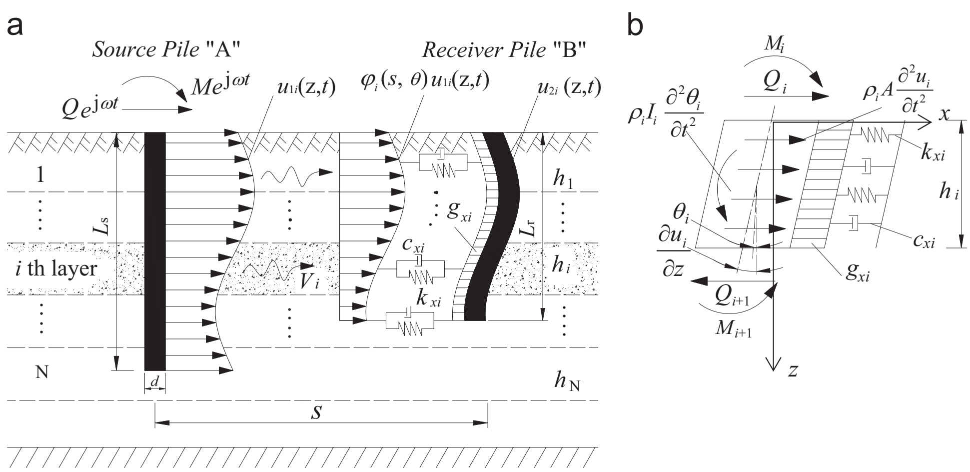

Fig. 1. Model description: (a) pile-to-pile dynamic interaction in the Pasternak layered foundation; and (b) pile element in a soil layer.