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Research Paper

Vertical vibration of a partially embedded pile group in transversely isotropic soils

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ABSTRACT

The dynamic response of transversely isotropic soils is simulated by the analytical layer-element method, and each pile in the partially embedded pile group is modeled as a 1D vibration bar. Based on the displacement compatibility and force equilibrium at the pile-soil interface, the pile group-soil interaction equations are established and solved. The accuracy of the proposed method is confirmed by comparing with existing solutions. Finally, some representative results are presented to investigate the influence of embedment ratio, pile spacing and pile-soil modulus ratio on the dynamic impedances of partially embedded pile groups.

1. Introduction

The dynamic analysis of pile groups embedded in soil deposits has been carried out by many researchers over the past decades due to a wide range of applications in the fields of machine vibration, offshore engineering and earthquake engineering. Most of researches focus on the dynamic analysis of fully embedded piles or pile groups in single-phase elastic soils [1–18] or saturated poroelastic soils [18–22]. However, in offshore engineering and harbor engineering, the pile groups are usually partially embedded in soils and the location of their pile caps connecting individual pile heads is far away from the ground surface, which leads to the difference in the dynamic response between partially embedded pile groups and fully embedded pile groups.

Although the dynamic behavior of fully embedded pile groups has been investigated by many researchers with different theoretical methods [1–22] and field test methods [23–26], little attention has been paid to the problem of partially embedded pile groups under dynamic conditions. Lee et al. [27] studied the natural frequencies and the mode shapes of partially embedded tapered piles in Winkler foundation by using the Runge-Kutta method and the determinant search method. With the assumption that the axial force along the pile length and modulus of subgrade reaction for the embedded part of piles are constant, Catal [28,29] investigated the free vibration of partially supported piles with the effects of bending moment, axial and shear force. For vertical response of partially embedded pile groups, Ren and Huang [30] used the dynamic interaction factors and transfer matrix method to estimate the vertical impedances of partially embedded pile groups based on the Winkler model. Similarly, Liu et al. [31] proposed a simplified solution for the laterally dynamic response of a pile group partially embedded in layered saturated soils combined with thin-layer method for Biot's dynamic consolidation equations. However, the Winkler model is partially useful in engineering practice due to its difficulty in obtaining the corresponding parameter accurately and to its ignorance of interaction effect between springs as well as dashpots.

As to the partially embedded pile group, only parts of pile groups are in contact with the soil, which makes the partially embedded pile group-soil system behave unlike the fully embedded one. Meanwhile, the required approaches are also complicated and inconvenient for establishing the pile-soil interaction model. If the solution for the fully embedded pile group problem is approximately applied to the partially embedded pile group, it may overestimate the dynamic impedance of the partially embedded pile group. Consequently, it is of great significance to accurately evaluate the dynamic characteristics of partially embedded pile groups subjected to external loadings transferred from superstructure to their pile-caps.

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Notation

ρ_{sj}	mass density of the jth soil layer
G_{vj}	shear modulus of the jth soil layer
E_{vj}	vertical Young's modulus of the jth soil layer
E_{hj}	horizontal Young's modulus of the jth soil layer
μ_{vhj}	Poisson's ratios of the jth soil layer characterizing the lateral strain response in the plane of transverse isotropy to a stress acting normal to the plane
μ_{hj}	Poisson's ratios of the jth soil layer characterizing the lateral strain response in the plane of transverse isotropy to a stress acting parallel to the plane
β_{sj}	damping ratio of the jth soil layer
d	diameter of pile
E_p	Young's modulus of pile
ρ_p	mass density of pile
L	total length of pile
L_1	length of pile part above soils
L_2	length of pile part embedded in soils
$u_p(z)$	axial displacement of pile
$N(z)$	axial force of pile
$q(z)$	contact shear force per unit length along the pile-soil interface
a_0	dimensionless frequency of motion defined as $a_0 = d\omega\sqrt{\rho_{s1}/G_{v1}}$
ω	circular frequency of motion
s	axis-to-axis distance between two adjacent piles

The main objective of this paper is to present an efficient method to investigate the dynamic behavior of partially embedded pile groups in transversely isotropic layered soils based on the continuum medium model. In order to obtain the fundamental solution of layered soils subjected to a time-harmonic loading, the analytical layer-element method [32] is employed here to establish the global stiffness matrix for layered soils. Since the piles are modeled as 1D vibration bars, the dynamic response of each pile in the pile group can be formulated in terms of a series of matrix equations in a suitable way, which is conducive to solving the dynamic problem of the partially embedded pile group. Combining the global stiffness matrix for layered soils and the matrix equation for the pile group, and considering the compatibility of the displacements and the equilibrium of the interaction forces at the pile-soil interface, the partially embedded pile group-soil interaction problem is solved expediently. The accuracy of the proposed method is demonstrated through comparing the results in this paper with those provided by the existing theory. Finally, selected numerical results are presented to investigate the effects of embedment ratio, pile spacing ratio and pile-soil modulus ratio on the vertical impedances of partially embedded pile groups.

2. Formulation

In this paper, the analysis of partially embedded pile groups under dynamic loadings is based on the mathematical formulation of the model for vertical vibration of a partially embedded single pile. Recently, Ai and Liu [33] proposed a new method to evaluate the vertical dynamic impedance of a single pile fully embedded in layered soils, which is developed here to analyze the partially embedded single pile. Due to the similar theoretical derivation of a fully embedded single pile, solutions for a partially embedded single pile are provided briefly in Appendix A. It is reasonable to assume that the pile part embedded in soils is fully bonded to the embedding soil under the condition of small deformation. Without considering the effect of the embedded pile part, the soil can be still regarded as a continuous medium. Besides, the internal damping of piles is ignored due to its value much smaller than that of the soil.

As depicted in Fig. 1, a pile group of N-piles with a rigid pile cap connecting individual pile heads is partially embedded in transversely isotropic layered soils. A harmonic vertical displacement $u_1 e^{i\omega t}$ as an external loading is applied to the rigid pile cap and transmitted onto each pile through the rigid pile cap. Since the pile

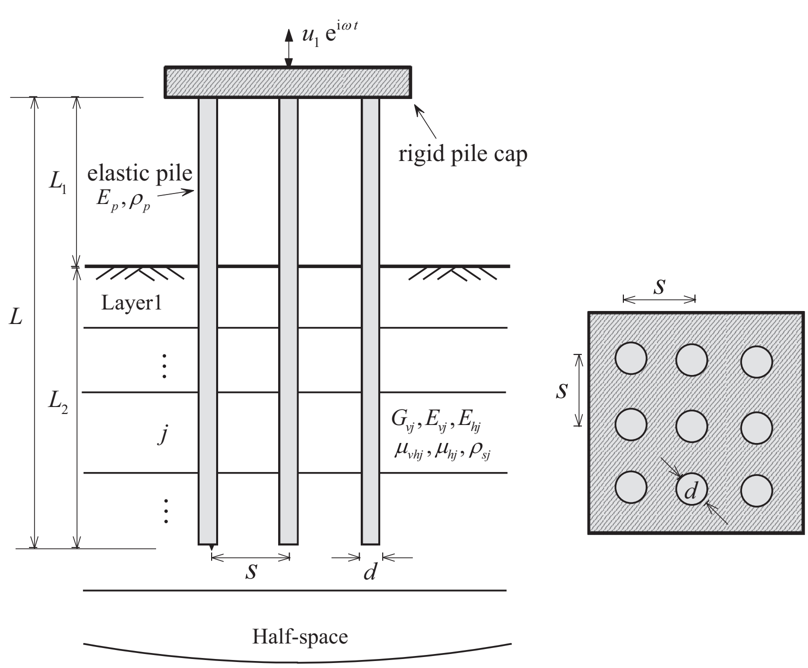

Fig. 1. An axially loaded pile group partially embedded in transversely isotropic layered soils.