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Vertical dynamic response of a pipe pile in saturated soil layer

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ABSTRACT

An analytical solution is developed in this paper to investigate the vertical time-harmonic response of a pipe pile embedded in a viscoelastic saturated soil layer. The wave propagation in the saturated soil is simulated by Biot's 3D poroelastic theory and that in the pipe pile is simulated by 1D elastodynamic theory. Potential functions are applied to decouple the governing equations of the soil. The analytical solutions of the outer and inner soil in frequency domain are obtained by the method of separation of variables. The vertical response of the pipe pile is then obtained based on the continuity assumption of the displacement and stress between the pipe pile and both the outer and inner soil. The solution is compared with existing solutions to verify the validity. Numerical examples are presented to analyze the vibration characteristics of the pile.

1. Introduction

Pile foundations are often subjected to dynamic loads such as traffic, earthquake, machinery, wind or impact. The coupled vibration of pile and soil has attracted the attention of many researchers. By considering the soil–pile interaction, Novak et al. [1] developed a simplified theoretical approach to study the vertical vibration of a pile in viscoelastic soil medium based on the plane strain assumption. Following Novak's plane strain assumption, Militano and Rajapakse [2] deduced the frequency domain solutions for an elastic pile subjected to transient torsional and axial loadings in multi-layered elastic soil, and the time domain solutions were obtained by using a numerical Laplace inversion procedure. However, the stress gradient of the soil in the vertical direction was neglected, resulting that the soil–pile interaction was only considered in the horizontal direction and the waves could only propagate in the horizontal direction.

There are two methods of considering the soil–pile interaction in the vertical direction. The first one is Rajapakse's integral equation method [3,4]. The soil was considered as an elastic half-space and the pile was considered as a virtual rod. Using Green's functions, the frequency-domain solutions of the soil and pile were presented based on Lagrange's equation of motion. As the solution was expressed as integral equation form, this method required considerable computational effort. Another one is Nogami and Novak's continuum medium method [5]. The soil around pile was considered as a viscoelastic layer and the pile was considered as an Euler–Bernoulli rod. The displacement and resistance factor of the soil layer were obtained by ignoring the radial displacement of the soil layer. A closed-form solution of vertically loaded end-bearing pile was proposed based on the continuity assumption of the displacement and stress between the pile and soil layer. Hu et al. [6] used this method to study the vertical vibration of a pile with elastic bottom boundaries, which assumed the soil resistances beneath the pile and soil as Winkler springs. Wu et al. [7] developed an extended soil–pile interaction model to investigate the dynamic response of an end-bearing pile by taking both the radial and vertical displacement of the soil layer.

The above studies are based on the assumption that the soil around a pile is a single-phase medium. However, the soil is generally a multi-phase medium which can be assumed as a two-phase medium when the soil is saturated with fluid. Nogami et al. [8] studied the effects of porewater pressure on the dynamic response of a pile foundation based on the Winkler model. Biot [9,10] developed a theory for stress wave propagation in porous elastic solid containing compressible viscous fluid. This theory has been widely applied in studying the dynamic response of piles in saturated soil. Zeng and Rajapakse [11] studied the steady-state dynamic response of an axially loaded elastic pile partially embedded in a homogeneous poroelastic half-space medium using the integral

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equation method. Then Zhou et al. [12] developed a solution for the vertical transient response of the pile in an incompressible saturated medium. Cai and Hu [13] investigated the vertical vibration of a rigid, cylindrical massive foundation embedded in a poroelastic soil. Senjuntichai and Rajapakse [14] studied the transient response of a pressurized long cylindrical cavity in an infinite poroelastic medium by introducing potential functions to decompose the consolidation equations of the soil. Using the potential function method, Li et al. [15] investigated the vertical vibration of an end-bearing pile embedded in a saturated elastic soil layer.

A new type of pile called cast-in situ concrete large diameter pipe pile (referred as PCC pile) has been developed and widely applied in China for reinforcing soft ground [16–20]. Besides PCC pile, many other pipe piles are also widely used in practical engineering, such as prestressed concrete pipe pile and steel pipe pile. For pipe piles, apart from the soil around the pile, soil exists inside the pile as well. The way in which the inner soil interacts with the pipe pile is worthy of study. Only the interaction between the outer soil and pile was considered in previous studies, and therefore their solutions cannot be used to analyze the dynamic response of pipe piles. In this paper, an analytical solution for the vertical dynamic response of a pipe pile in viscoelastic saturated soil due to vertical load is developed by taking the interaction of the pipe pile with both the outer and inner soil into account. Numerical results are presented to analyze the vertical vibration characteristics of the pile–soil system.

2. Basic assumptions and computational model

The main assumptions adopted in this paper are:

1. The outer and inner soil layers are viscoelastic, homogeneous and isotropic, and the soil medium is a two-phase material consisting of soil grains and fluid. The material damping is of the frequency dependent viscous type.
2. The normal stresses and pore pressures are zero at the free surfaces of the outer and inner soil layers and the soil layers overlie a frictionless rigid base.
3. The pile is elastic, vertical and has perfect contact with the outer and inner soil during the vibration. The pile is laterally rigid with impermeable surfaces and the supporting medium is rigid and impermeable.
4. The deformation of the pile–soil system is small.

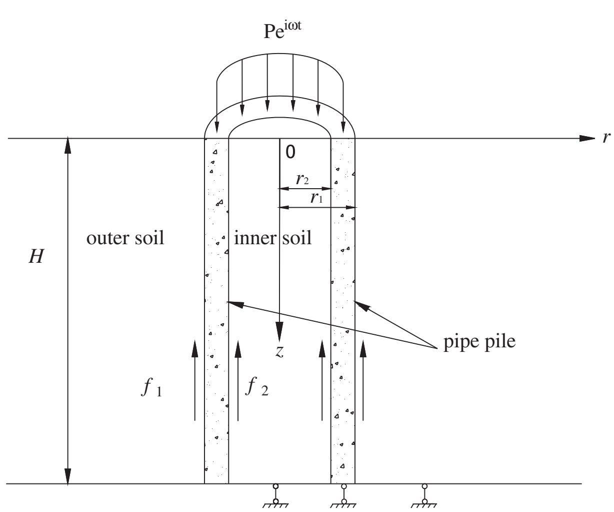

Fig. 1. Computational model.

5. The stresses and vertical displacements at the interfaces between the pile and soils are continuous, and the radial displacements at the interfaces are negligible.

The computational model is illustrated in Fig. 1. A time-harmonic uniform vertical pressure $Pe^{i\omega t}$ is applied on the pile head. H is the pile length. r_1 and r_2 are the outer and inner radiuses of the pile section, respectively. f_1 and f_2 are the vertical resistances of the outer and inner soil to the pile, respectively.

3. Governing equations and boundary conditions

3.1. Dynamic equilibrium equations of the soil

According to the dynamic consolidation theory of Biot [10], the dynamic equilibrium equations of the soil in axisymmetric cylindrical coordinate system can be expressed as:

$$\left(G_i + c_i\frac{\partial}{\partial t}\right)\nabla^2 u_{r1} + (\lambda_{c1} + G_1 + 2c_i\frac{\partial}{\partial t})\frac{\partial e_i}{\partial r} - \left(G_i + c_i\frac{\partial}{\partial t}\right)\frac{u_{ri}}{r^2} - \alpha_i M_i\frac{\partial \zeta_i}{\partial r} = \rho_i\frac{\partial^2 u_{ri}}{\partial t^2} + \rho_f\frac{\partial^2 w_{ri}}{\partial t^2} \tag{1}$$

$$\left(G_i + c_i\frac{\partial}{\partial t}\right)\nabla^2 u_{zi} + (\lambda_{ci} + G_i + 2c_i\frac{\partial}{\partial t})\frac{\partial e_i}{\partial z} - \alpha_i M_i\frac{\partial \zeta_i}{\partial z} = \rho_i\frac{\partial^2 u_{zi}}{\partial t^2} + \rho_f\frac{\partial^2 w_{zi}}{\partial t^2} \tag{2}$$

$$\alpha_i M_i\frac{\partial e_i}{\partial r} - M_i\frac{\partial \zeta_i}{\partial r} = \rho_f\frac{\partial^2 u_{ri}}{\partial t^2} + m_i\frac{\partial^2 w_{ri}}{\partial t^2} + b_i\frac{\partial w_{ri}}{\partial t} \tag{3}$$

$$\alpha_i M_i\frac{\partial e_i}{\partial z} - M_i\frac{\partial \zeta_i}{\partial z} = \rho_f\frac{\partial^2 u_{zi}}{\partial t^2} + m_i\frac{\partial^2 w_{zi}}{\partial t^2} + b_i\frac{\partial w_{zi}}{\partial t} \tag{4}$$

where $\nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{\partial^2}{\partial z^2}$; $e_i = \frac{\partial u_{r1}}{\partial r} + \frac{u_{r1}}{r} + \frac{\partial u_{z1}}{\partial z}$; $\zeta_i = -\left(\frac{\partial w_{ri}}{\partial r} + \frac{w_{ri}}{r} + \frac{\partial w_{zi}}{\partial z}\right)$; $\lambda_{ci} = \lambda_i + \alpha_i^2 M_i$; $\rho_i = (1 - n_i)\rho_{si} + n_i\rho_f$; $b_i = \frac{\rho_f g}{k_{di}}$; $m_i = \frac{\rho_f}{n_i}$; $\alpha_i = 1 - K_i/K_{si}$; $\frac{1}{M_i} = (\alpha_i - n_i)/K_{si} + n_i/K_f$. In addition, u_{ri} and u_{zi} are the radial and vertical displacements of the soil skeleton, respectively; w_{ri} and w_{zi} are the radial and vertical displacements of the pore fluid relative to the soil skeleton, respectively; λ_i and G_i are the Lame's constants of the soil; c_i is the viscous damping of the soil; ρ_i is the mass density of the saturated soil; n_i is the porosity of the soil; ρ_{si} is the mass density of the soil grains; k_{di} is the Darcy permeability coefficient of the soil; m_i is a Biot's density-like parameter of the soil; α_i and M_i are the coefficients defined by Biot which represent the compressibility of the soil grains and pore fluid; K_{si}, K_f and K_{bi} are the bulk modulus of the soil skeleton, pore fluid and the outer saturated soil, respectively. $i = 1, 2$; when $i = 1$ the above equations and parameters correspond to the outer soil, and when $i = 2$ they correspond to the inner soil.

3.2. Dynamic equilibrium equation of the pile

The axial displacement of the pile u_p is governed by the following one-dimensional wave equation:

$$C_p^2\frac{\partial^2 u_p}{\partial z^2} - \frac{2\pi r_1}{\rho_p A}f_1 - \frac{2\pi r_2}{\rho_p A}f_2 = \frac{\partial^2 u_p}{\partial t^2} \tag{5}$$

where C_p is the wave velocity of the pile; A is the area of the pile section; ρ_p is the mass density of the pile.