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Longitudinal vibration of a pile embedded in layered soil considering the transverse inertia effect of pile

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ABSTRACT

The dynamic response of a viscoelastic bearing pile embedded in multilayered soil is theoretically investigated considering the transverse inertia effect of the pile. The soil layers surrounding the pile are modeled as a set of viscoelastic continuous media in three-dimensional axisymmetric space, and a simplified model, i.e., the distributed Voigt model, is proposed to simulate the dynamic interactions of the adjacent soil layers. Meanwhile, the pile is assumed to be a Rayleigh–Love rod with material damping and can be divided into several pile segments allowing for soil layers and pile defects. Both the vertical and radial displacement continuity conditions at the soil–pile interface are taken into account. The potential function decomposition method and the variable separation method are introduced to solve the governing equations of soil vibration in which the vertical and radial displacement components are coupled. On this basis, the impedance function at the top of the pile segment is derived by invoking the force and displacement continuity conditions at the soil–pile interface as well as the bottom of pile segment. The impedance function at the pile head is then obtained by means of the impedance function transfer method. By means of the inverse Fourier transform and convolution theorem, the velocity response in the time domain can also be obtained. The reasonableness of the assumptions of the soil-layer interactions have been verified by comparing the present solutions with two published solutions and a set of well-documented measured pile test data. A parametric analysis is then conducted using the present solutions to investigate the influence of the transverse inertia effect on the dynamic response of an intact pile and a defective pile for different design parameters of the soil–pile system.

1. Introduction

Pile vibration theory provides the theoretical basis for dynamic foundation design, earthquake-resistance design and various methods of dynamic pile testing. Many investigations have been devoted to studying the dynamic behavior of piles, and many types of dynamic interaction models have been proposed. The Kelvin–Vogit model, for instance, was used to simulate the dynamic interaction at the interface of soil–pile by Randolph and Deeks [1], Nogami et al. [2], Wang et al. [3], Michaelides et al. [4], and Ding et al. [5]. This model cannot consider the wave effect of the soil adjacent to the pile. To allow for the frequency-dependency of the dynamic interaction between the embedded footings and soil, Novak and Beredugo [6] presented a generalized Winkler model by assuming the surrounding soil to be a set of independent, infinitesimally thin horizontal layers that extend to infinity, which is well-known as the plane strain model. It was extended to study more cases on the dynamic interaction of soil–pile systems by Novak et al. [7,8], Nogami and Konagai [9], Lee et al. [10] and Rajapakse and Shah [11] among others. The above models were combined to analyze the nonlinear behavior of the surrounding soil by El Naggar and Novak [12,13]. By using the vibration theory of three-dimensional axisymmetric continuum and ignoring the radial displacement of soil, Nogami and Novak [14] developed an approach to investigate a vertically vibrating pile embedded in the soil layer with hysteretic damping. Soon afterward, more comprehensive solutions were derived by Senjuntichai et al. [15], Que et al. [16,17], in which the vertical axisymmetric motion of saturated porous medium and viscoelastic medium were considered, respectively. In the above mentioned research, the radial displacement of the soil–pile interface was neglected or assumed to be

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zero; thus, the soil–pile vibration in the radial direction was uncoupled, although the three-dimensional wave effect of soil was still considered.

On the other hand, with the increase in bearing capacity of pile foundations required in the design of modern superstructures, the pile diameter is getting larger than before. For the large diameter pile, the wave dispersion effect has been proven to be an important reason for the differences between the field test results and the one-dimension solutions from numerical analyses [18–20]. To approximately allow for the 3D effect of wave propagation in a round rod, the Rayleigh–Love bar motion equation was introduced, where the effects of Rayleigh and Love waves are combined, in which the transverse inertia effect was deemed as a reflection of the 3D wave effect. This method has previously been applied to the vibration analysis of piles as follows: Li et al. [21] assumed the pile to be a Rayleigh–Love bar to study the vertical vibration of a large diameter rock-socketed pile embedded in homogeneous saturated soil; Wu et al. [22] conducted a study of dynamic longitudinal impedance of tapered piles by considering the transverse inertial effect of tapered pile; Yang and Tang [23] also applied this approach to analyze the dynamic response of piles in combination with the Novak layer method. However, several limiting assumptions were adopted in the above works, including either homogeneous soil, a fixed pile tip or the specified displacement of soil layer at the soil–pile interface, which was set to zero.

In light of this, this paper proposed an improved solution to investigate the longitudinal vibration of a viscoelastic bearing pile embedded in multilayered soil considering the transverse inertia effect of pile. Both the vertical and radial displacement continuity conditions at the soil–pile interface are taken into account here. A parametric analysis is further conducted to study the influence of the transverse inertia effect on the dynamic response of an intact pile and a defective pile for different design parameters of soil–pile system.

2. Mathematical model construction

2.1. Calculation model

The longitudinal vibration of a viscoelastic pile embedded in layered soil is studied, wherein a dynamic interaction model of the soil–pile system is constructed, as shown in Fig. 1. There are several layers of soil surrounding the pile, which are numbered $1-n$ from the top to the bottom. According to the coordinate system shown in Fig. 1, h_k and H represent the top positions of the kth soil layer and the pile length, respectively. The dynamic interactions at the pile tip are represented by uniform Voigt components, where k_b and δ_b denote the Voigt model parameters of the interface between the bearing stratum and the pile tip. Likewise, the complex stiffness of the soil-layer interactions is assumed to be uniformly distributed in the radial direction, and it is simplified as a series of Voigt models, as shown in Fig. 1. Here, k_a^k and δ_a^k represent the stiffness and the damping that constitute the complex stiffness at the top of layer k, respectively; k_b^k and δ_b^k represent the stiffness and the damping that constitute the complex stiffness at the bottom of layer k, respectively. The accuracy and parameter value of this model will be illustrated in a later section.

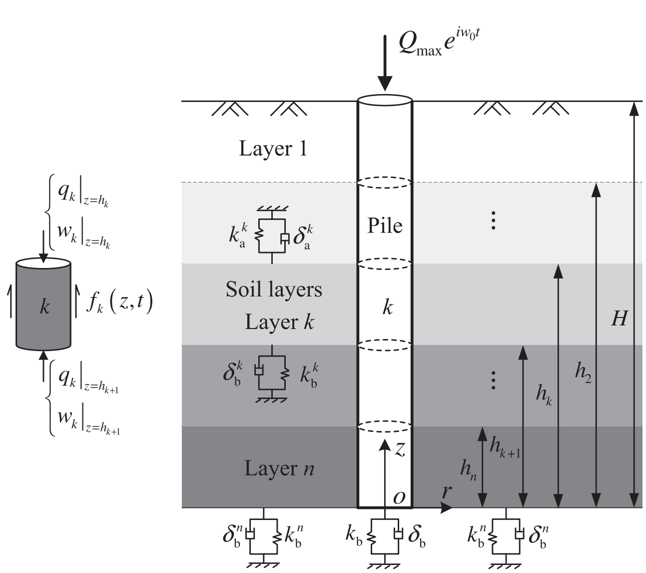

Fig. 1. Dynamic model of the soil–pile system.

2.2. Assumptions

(1) The soil surrounding the pile is layer-wise homogeneous, isotropic and viscoelastic, and the material damping of the soil layers is assumed to be viscous damping. Both radial and vertical displacements of the soil are taken into account.
(2) The soil is infinite in the radial direction. There are no normal and shear stresses on the free top surface of the soil. The stresses and the vertical and radial displacements at the soil–pile interface are continuous.
(3) The pile is a viscoelastic Rayleigh–Love rod with a uniform circular cross-section and has perfect contact with the surrounding soil during the vibration.
(4) The soil–pile system is subjected to small deformations and strains during the vibration.

2.3. Problem definition

2.3.1. Dynamic governing equations

(1) *Dynamic equation of the soil layers:* The axisymmetric vibration in viscoelastic soil layers is taken into account here. Denoting $u_{zk} = u_{zk}(r, z, t)$, $u_{rk} = u_{rk}(r, z, t)$ $(k = 1, 2, \ldots, n)$ to be the vertical and radial displacement in the kth soil layer, respectively, the dynamic governing equation of soil motion can be expressed as

Radial direction:

$$G_{1k}\left(\nabla^2 - \frac{1}{r^2}\right)u_{rk} + 2G_{2k}\frac{\partial}{\partial z}\omega_{\theta k} = \rho_{sk}\frac{\partial^2 u_{rk}}{\partial t^2} \quad (1)$$

Vertical direction:

$$G_{1k}\nabla^2 u_{zk} - 2G_{2k}\left(\frac{\partial}{\partial z} + \frac{1}{r}\right)\omega_{\theta k} = \rho_{sk}\frac{\partial^2 u_{zk}}{\partial t^2} \quad (2)$$

In the above equations, $G_{1k} = (\lambda_k + 2\mu_k) + (\lambda'_k + 2\mu'_k)\frac{\partial}{\partial t}$, $G_{2k} = (\lambda_k + \mu_k) + (\lambda'_k + \mu'_k)\frac{\partial}{\partial t}$, $\omega_{\theta k} = \frac{1}{2}\left(\frac{\partial u_{zk}}{\partial r} - \frac{\partial u_{rk}}{\partial z}\right)$, $\nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{\partial^2}{\partial z^2}$, $\lambda_k = \frac{\nu_{sk}E_{sk}}{(1+\nu_{sk})(1-2\nu_{sk})}$, $\mu_k = \frac{E_{sk}}{2(1+\nu_{sk})}$, $\lambda'_k = \frac{2\nu'_{sk}}{1-2\nu'_{sk}}\mu'_k$; E_{sk}, ν_{sk} and ρ_{sk} denote the dynamic elastic modulus, dynamic Poisson's ratio and density of the kth soil layers, respectively; λ_k and μ_k represent the lame constants associated with volumetric and shear strain, respectively; λ'_k and μ'_k are the viscosity coefficients associated with λ_k and μ_k, respectively; ν'_{sk} represents the transverse ratio of the viscous strain rate.

(2) Vertical vibration equation of a single pile.

To allow for the impact of the transverse inertia effect, the vibration problem of the kth pile segment can be described by the theory of Rayleigh–Love rod as follows: