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Vertical vibration of a large-diameter pipe pile considering the radial inhomogeneity of soil caused by the construction disturbance effect

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ABSTRACT

This paper presents an analytical solution for the vertical vibration of a large-diameter pipe pile considering the radial inhomogeneity of both the outer and inner soil caused by the construction disturbance effect. The radial inhomogeneity of the soil is simulated by gradually varying the soil parameters in the radial direction. The complex impedance at the pile head is obtained by introducing the variable separation method and impedance function transfer method. The proposed solution is compared with existing solutions to verify its reliability. Parametric studies are conducted to investigate the vertical vibration characteristics of the pile.

1. Introduction

Pile vibration theory has been widely researched and offers valuable theoretical references for dynamic foundation design and various nondestructive detection methods in piles. Over the past few decades, the presentation of various types of pile-soil dynamic interaction models has illustrated the tremendous advances in this field. Various researchers, such as Nogami and Konagai [1,2], Wang et al. [3] and Gao et al. [4], have used the Winkler model, known for its simplicity and convenience, to simulate the dynamic interactions of the pile and soil. The accuracy of this model is limited because it cannot consider the wave effect of the soil adjacent to the pile, and the model parameters are assigned by experience rather than theoretically. Novak [5] proposed a plane strain model in which the soil surrounding the pile was assumed to consist of a series of infinite thin layers to allow for wave propagation in the horizontal direction. Although this model has been widely applied [6–10], it also suffers from certain drawbacks because the stress gradient of the soil in the vertical direction is neglected. Nogami and Novak [11] and Wu et al. [12] presented a three-dimensional axisymmetric model to address this limitation. In this model, the surrounding soil is considered as a three-dimensional continuum layer that neglects the radial displacement and considers the strain in the vertical direction. Furthermore, Wu et al. [13] and Lü et al. [14] did not neglect the soil radial displacement because both the vertical and radial displacements of the soil were considered in their studies by introducing the potential functions into the solution of the functions of the pile-soil system. Furthermore, Zheng et al. [15] proposed a new analytical method to determine the vertical vibration of an end bearing pile. In this method, the governing equations of soil were directly solved without introducing the potential functions.

The aforementioned studies focus on the solid pile. However, large-diameter pipe piles, such as cast-in-situ concrete large-diameter pipe piles, large-diameter pre-stressed concrete pipe piles and large-diameter steel pipe piles, are also increasingly used in engineering. In practice, large-diameter pipe piles are often subjected to dynamic loads, particularly vertical dynamic loads if used in the foundations of high-rise buildings, machinery, towers, or wind turbines. Thus, it is important to investigate the vertical dynamic characteristics of large-diameter pipe piles.

Unlike solid piles, soil exists inside large-diameter pipe piles, and the soil's dynamic interaction with the pipe pile should also be considered to obtain a more realistic understanding of the

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dynamic characteristics of this type of pile. Currently, two methods are commonly used to simulate the interaction between the pipe pile and inner soil. One method simulates the inner soil using the Voigt model [16,17], namely a spring and a dashpot connected in parallel, and in some cases, only the spring constant is considered for simplicity[18,19]; the other method builds the dynamic governing equation of the inner soil based on a three-dimensional axisymmetric model in a manner similar to that for the outer soil and solves the dynamic vertical resistance to the pile shaft. The former method still lacks a basis in determination of the related model parameters. Additional attention has been devoted to the latter method. Ding et al. [20] and Zheng et al. [21] proposed an analytical solution for the vertical vibration of a pipe pile by simultaneously considering the vertical wave effect of the outer and inner soil and built a more rigorous solution by considering the true three-dimensional wave effect of the soil [22–24]. Zheng et al. [25] also used this method to investigate the three-dimensional effects in the low-strain integrity detection of a pipe pile, in which the stress gradient in the vertical direction was neglected. However, the majority of the aforementioned studies are based on the assumption that the soil is a homogenous and isotropic medium, which does not truly reflect engineering practice.

Under most engineering conditions, the soil becomes extensively disturbed because soil compaction or relaxation may occur during the installation of the pile, which changes the soil properties, particularly for the soil region adjacent to the pile shaft. Because the soil adjacent to the pile shaft is more disturbed than that of the far field, the soil properties change gradually in the radial direction, making the soil radially inhomogeneous. This phenomenon is called the construction disturbance effect. As a result, the soil is typically not only multi-layered but also radially inhomogeneous because of the construction disturbance effect caused during the installation of the pile. Previous research has shown that the radial inhomogeneity of the soil greatly affects the dynamic characteristics of the pile [26,27] and thus must be considered in the dynamic response analysis of the pile. Many researchers have focused attention on this problem and have proposed a series of models to simulate the inhomogeneity of the soil in the radial direction [28–33]. Among these, the model proposed by Yang et al. [32,33], in which the soil parameters are allowed to vary gradually in the radial direction, is more rigorous and practical. However, only the outer soil was considered in these previous studies, and therefore, the solutions cannot be used in study of large-diameter pipe piles considering the construction disturbance effect. To address this issue, this paper proposes an analytical solution for the vertical vibration of a large-diameter pipe pile that considers the radial inhomogeneity of both the outer and inner soil caused by the construction disturbance effect. Recently, a new type of pipe pile, namely cast-in-situ concrete large-diameter pipe piles (i.e., PCC piles), has been widely used in engineering. In addition to PCC piles, many other large-diameter pipe piles, such as large-diameter pre-stressed concrete pipe piles and large-diameter steel pipe piles, have also been increasingly applied all over the world. For different types of pipe piles, the influence of the construction disturbance effect on the soil is different. For PCC piles, concrete is poured in situ, and thus, the soil may be weakened. For pre-stressed concrete pipe piles installed using the static pressure method, the soil may be strengthened. To obtain a more general understanding of the construction disturbance effect and provide a theoretical basis for the vibration analysis of the types of pipe piles mentioned above, both the strengthening and weakening of the soil are simulated in this paper. The complex impedance of large-diameter pipe piles, which reflects the abilities of a pile to resist vertical deformation and vertical vibration, is investigated based on a parametric study to provide a reference for the aseismic design and dynamic foundation design of these piles.

2. Mathematical model

2.1. Pile-soil interaction model and assumptions

This paper investigates the vertical vibration of a large-diameter pipe pile considering the construction disturbance effect. The pile-soil interaction model is shown in Fig. 1. The length, outer radius, inner radius and wall thickness of the pile are l_p, r_w, r_c and r_b, respectively. According to the layered properties of the soil in the vertical direction, the pile-soil system is divided into a total of n segments numbered 1, 2,...,i,...,n from the pile tip to pile head. The thickness of the ith soil layer is l_i, and the depth of the upper interface of the ith soil layer is h_i. Both the outer and inner soil are discretized into a total of m vertical annular zones numbered 1, 2,...,k, ...,m in the radial direction. The inner radii of the kth outer and inner soil zone within the ith layer are $r_{i,k}$ and $r_{ci,k}$, respectively. The dynamic interactions of the adjacent soil layers are simulated using distributed Voigt models independent of the radial distance. As shown in Fig. 1, the spring constant and damping coefficient of the Voigt model at the upper interface of the kth outer soil zone within the ith layer are represented by $k_{i+1,k}$ and $\delta_{i+1,k}$, respectively, and those for the kth inner soil zone within the ith layer are $k_{ci+1,k}$ and $\delta_{ci+1,k}$, respectively. The corresponding values of the Voigt model at the lower interface of the kth outer soil zone within the ith layer are $k_{i,k}$ and $\delta_{i,k}$, respectively, and those for the kth inner soil zone within the ith layer are $k_{ci,k}$ and $\delta_{ci,k}$, respectively. Similarly, the corresponding values of the Voigt model at the pile tip are represented by k_b and δ_b, respectively.

The following assumptions are adopted in this paper:

(1) The pile is vertical, elastic and circular in cross-section and has perfect contact with the outer and inner soil during the vibration;
(2) The soil medium of the same annular zone within the same layer is homogeneous but might vary from zone to zone or layer to layer;

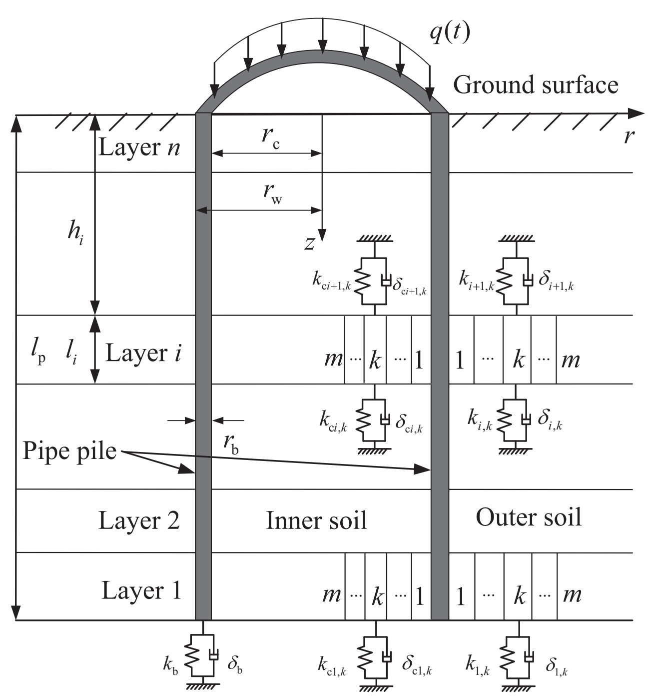

Fig. 1. Schematic of the pile-soil interaction model.