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Influence of soil plug effect on the torsional dynamic response of a pipe pile

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ABSTRACT

The additional mass model is introduced to simulate the dynamic interaction of soil plug and pipe pile under small deformations and strains. In the additional mass model, the inertia and damping effect of soil plug, and the displacement phase difference between soil plug and pipe pile are taken into consideration. Based on the additional mass model, the analytical solutions of the torsional dynamic response of a pipe pile in the frequency domain are derived by utilizing the Laplace transform technique and impedance transfer function. The corresponding quasi-analytical solution in the time domain for a pipe pile subjected to semi-sinusoidal exciting force is obtained by using the inverse Fourier transform. A parameter sensitivity analysis of the additional mass model is conducted to determine the approximate range of the parameter values of the distributed Voigt model. The validity of the presented solutions is also verified by comparing the torsional dynamic behavior of the pipe pile calculated via the additional mass model with those based on the plane strain model. Utilizing the developed solutions, a parametric study is conducted to investigate the influence of the properties of soil-pile system on the torsional vibration characteristics of pipe pile.

1. Introduction

Pile foundations are often subjected to dynamic torsional loadings caused by dynamic eccentric force of superstructure and due to wind, wave force or mechanical vibrations. The investigations of the torsional dynamic response of pile foundations can provide the theoretical basis for earthquake-resistant design, dynamic foundation design and various methods of dynamic pile testing [1]. Novak and Howell [2,3] studied the torsional vibrations of an end-bearing pile embedded in uniform and stratified viscoelastic soil medium with the plane strain model, of which the surrounding soil is simulated to be

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composed of a set of independent infinitesimally thin horizontal soil layers that extend to infinity radically. The plane strain model is widely used in practical application for its high efficiency and relative simplicity. Rajapakse et al. [4] investigated the torsional time-harmonic response of an elastic pile partially embedded in a homogeneous elastic half-space by using the fictitious pile model. As the continuation work of Rajapakse et al. [4], Militano and Rajapakes [5] and Chen et al. [6] researched the transient torsional dynamic response of a pile embedded in transversely isotropic media using Laplace transform and transfer matrix method with the plane stain assumption. Meanwhile, Wang et al. [7,8] investigated the torsional dynamic response of an end bearing pile embedded in homogenous isotropic and transversely isotropic soil by applying the separation of variables technique and impedance transfer method. Following Wang's approach, Wu et al. [9] studied the influence of sediment at the pile toe on the torsional dynamic response of a single pile with the fictitious soil pile model [10]. Based on the Muki's model [11], Cai et al. [12] and Wang et al. [13] investigated the torsional dynamic response of single piles embedded in a homogeneous poroelastic and poroelastic saturated elastic half-space by utilizing the Hankel transform and Fredholm integral equation schemes, respectively. Shi et al. [14] and Ai et al. [15] utilized various numerical models to investigate the vertical and torsional dynamic response of piles and group of piles. It can be noted that extensive and in-depth research work has been done in the field of torsional dynamic response of pile foundations. However, in most case, the obtained solutions are only suitable for solid piles and the corresponding semi-analytical solutions are often required large amount of numerical calculations.

In recent decades, the pipe pile has been widely used in supporting various structures all over the world for its obvious advantages such as good adaptability, high bearing capacity and remarkable economic results. Therefore, the corresponding theoretical basis for nondestructive integrity testing and dynamic foundation design of pipe pile foundations has attracted increasing attention in recent years. In the context of the vertical dynamic response of pipe pile, Chen and Luo [16] employed the finite element method to analyze the influence of dimension effect on the low strain integrity of pipe pile, and presented a formula to calculate the different arrival times of the preliminary reflect signal of pile toe at different point of the pile top. Fei et al. [17] investigated the influence of the three-dimensional effect of pipe pile on the integrity testing of PCC and PHC piles by means of the finite element method and finite difference method. However, the above two mentioned studies ignored the interaction of the pipe pile and the soil surrounding and inside it. Ding et al. [18] presented an analytical solution for the vertical dynamic response of a large-diameter pipe pile subjected to a transient point loading in the frequency domain, where the frictional resistance of soil surrounding and inside the pipe pile is calculated based on the Winkler model. Zheng et al. [19] simulated the soil surrounding and inside the pipe pile as a set of infinitely thin layers in perfect contact with the pipe pile, and gave an analytical solution for the vertical dynamic response of a thin-walled pipe pile in the time domain with application to low-strain integrity testing. In the field of the torsional dynamic response of pipe pile, several attempts have also been made. For instance, through the practical engineering testing, Bao et al. [20] proved that compared with the vertical wave under equal conditions, the torsional wave has higher resolution and smaller testing bind area, and it is more sensitive to the shallow small defects in pile during low strain-testing. Zheng et al. [21] analyzed the torsional dynamic response of a large-diameter end-bearing pipe pile embedded in saturated soil with the assumption that the soil plug and the surrounding soil are simulated by the Biot's two-phase linear theory. Jin et al. [22] further studied the complex stiffness characteristics of a pipe pile embedded in layered saturated soil and subjected to a harmonic torsional loading within the low frequency range concerned in dynamic foundation design.

Compared with the solid cross-section pile, the interaction mechanism between soil and pipe pile is more complicated. The existence of soil plug inside the pipe pile can not only influence the shaft resistance to static load, but also affect the dynamic characteristics of pipe pile subjected to dynamic loads. For example, according to Wu's experiments [23], as the height of soil plug increases, the testing velocity of driven pipe pile during low strain integrity testing decreases gradually. Therefore, the interaction mechanism between soil plug and pipe pile plays an important role in both the static resistance capacities and dynamic behaviors of pipe pile. Large amounts of attentions have been focused on the interaction mechanism between soil plug and pipe pile during the dynamic driving process. The existing dynamic interaction models to simulate the soil plug effect during the driving process fall into four main categories: the equivalent mass model [24], the plugging effect model [25], the Voigt model [26] and the “pile within a pile” model [27–29]. In the “pile within a pile” model, the soil plug is simulated as a series of masses and springs. The “pile within a pile” model is a more rigorous interaction model than the three above-mentioned models for it can take into account both the soil weight and the frictional resistance between soil plug segments and pipe pile segments. It is worthy noting that significant progress has been made in the field of the interaction mechanism between soil plug and pipe pile during the dynamic driving process. In contrast, little attention has been paid to the interaction mechanism between soil plug and pipe pile subjected to small deformations which is widely used in the dynamic foundation design and nondestructive pile testing of pipe pile foundations. The existing dynamic interaction models to simulate the soil plug effect during the dynamic foundation design and nondestructive pile testing can be mainly categorized as: the Winkler model and the continuum model. In the Winkler model, the contact interaction between the soil plug and the pipe pile is modeled as a series of Winkler model that is consisted of a linear spring and a dashpot connected in parallel [18]. The Winkler model can consider the dynamic resistance of the soil plug acting on the pipe pile, but it can not account for the influence of the soil plug weight on the dynamic response of the pipe pile, as well as the propagation of stress wave in the soil plug. In the continuum model, the soil plug is often simulated as elastic or viscoelastic medium, and the dynamic resistance of the soil plug acting on the pipe pile is then obtained through the elastodynamic theory [19,21]. The continuum model can consider the propagation of stress wave in the soil plug but the displacement phase difference of torsional vibration between the soil plug and the pipe pile is not taken into consideration. In addition, compared with the