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Analytical solution for the dynamic response of a pile with a variable-section interface in low-strain integrity testing

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ABSTRACT

Considering the displacement and stress continuity conditions at the pile-soil interface, ring-soil pile theory (RSPT) and an amended impedance function transfer method (AIFTM) are proposed as models of rigid pile-soil interaction that consider the interaction at the variable-section interface of a pile with the surrounding soil. The interactions between adjacent three-dimensional soil layers are simplified as uniformly distributed Voigt models to derive the impedance function at the pile top. An inverse Fourier transform is applied to derive the velocity response at the top of the pile under transient excitation. An engineering example is described to confirm the rationality of the proposed solution. The solution simplifies into other previously proposed solutions for specific geometric parameters of the pile shaft. The proposed solution is compared with one that neglects the interaction at the variable-section interface of the pile with the surrounding soil; additionally, the coupled effects of the related pile-soil parameters and the interaction at the variable-section interface with the surrounding soil are analyzed.

1. Introduction

Low-strain integrity testing is a quick and inexpensive method of assessing the condition of foundation piles, and the interpretation of the results of such tests is a commonly studied subject. Nogami and Konagai [1] proposed a solution for the axial response of dynamically loaded single piles in the time domain. Baranov [2] proposed the first calculation for the excited vibration of an embedded foundation. Subsequently, additional comprehensive studies have been conducted [3–6]. Zhang et al. [7] used a transversely isotropic saturated soil model to investigate the dynamic torsional response of an end-bearing pile. Wu et al. [8] studied vertical pile vibration considering the true three-dimensional wave effect in soil. Zheng et al. [9] presented the vertical impedance of an end-bearing pile considering both the radial and vertical displacements of the surrounding soil. Wu et al. [10] studied the vertical dynamic response of a pile embedded in layered transversely isotropic soil. Shi et al. [11], Ai et al. [12,13] and Kuo et al. [14] used numerical models to study the dynamic responses of piles and groups of piles. These works focused on the dynamic characteristics of piles with uniform cross sections; however, the focus of low-strain integrity testing is the detection of a defective pile, whose dynamic characteristics differ from those of an intact pile. Therefore, the dynamic characteristics of defective piles have considerable theoretical and engineering value.

Piles with a neck or bulb constitute a major category of defective piles. Liao and Roesset [15] used axisymmetric finite

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element models to study the responses of defective piles to impact loads. Using a wavelet transform approach, Ni et al. [16] conducted time–frequency analyses of pile integrity testing. Additional studies based on numerical methods have been conducted with regard to the interpretation of test results obtained via low-strain integrity testing [17,18]. An analytical solution can more profoundly reflect the dynamic characteristics of a variable-section pile than can empirical results alone; therefore, finding an analytical solution is of great theoretical importance. However, little work has been conducted on the search for analytical solutions for defective piles because of the mathematical difficulty of the problem. Gao et al. [19] presented an analytical solution for the excited vibrations of a pile with variable-section impedance in the time domain. Wang et al. [20] proposed an impedance function transfer method (IFTM) for studying the longitudinal vibrations of piles with variable sections; however, the interaction at the variable-section interface of the pile with the surrounding soil was neglected and the soil was modeled using Winkler's model, a discrete model that neglects the coupled vibrations between a pile and the surrounding soil.

Considering the interaction at the variable-section interface of a pile with the surrounding soil, an analytical solution for a pile in three-dimensional soil is proposed in this paper. For a pile with a neck, ring-soil pile theory (RSPT) is proposed to solve the problem; for a pile with a bulb, an amended impedance function transfer method (AIFTM) is applied to derive a solution. An engineering example is described to confirm the rationality of the solution. Then, a parametric study is conducted to provide insight into the coupled effects of the pile-soil parameters and the interaction at the variable-section interface of a pile with the surrounding soil. A dynamic theory for a pile with a variable-section interface is developed, and the solution proposed in this paper is shown to provide guiding significance for low-strain integrity testing.

2. Mathematical model

This paper focuses on the vibration characteristics of a pile with a neck or bulb in response to a transient excitation in three-dimensional layered soil. The geometrical models of the considered pile-soil systems are depicted in Fig. 1.

To allow for varying soil properties and a pile with a variable cross section, the pile-soil system is subdivided into n layers that are numbered $1-n$ from the bottom to the top of the pile. H denotes the length of the pile. r_k and h_k denote the radius

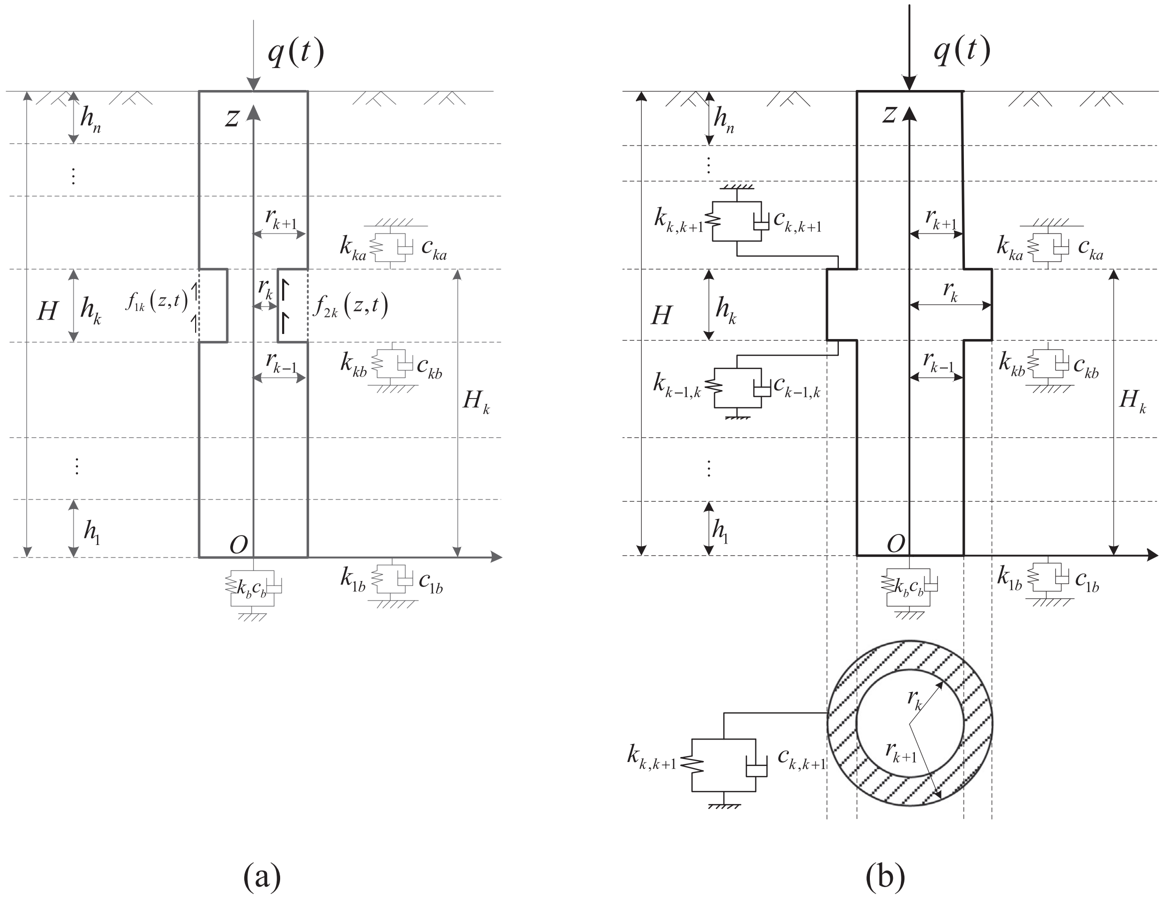

Fig. 1. Geometric models: (a) Pile with a neck; (b) Pile with a bulb.