Computers and Geotechnics 58 (2014) 101–116

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Time-domain analysis of velocity waves in a pipe pile due to a transient point load

Xuanming Ding *, Hanlong Liu, Gangqiang Kong, Changjie Zheng

Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering, Hohai University, Nanjing 210098, China

ARTICLE INFO

Article history:
Received 13 August 2013
Received in revised form 17 February 2014
Accepted 18 February 2014
Available online 13 March 2014

Keywords:
Pipe pile
Transient wave
Analytical solution
Time domain
Low strain testing

ABSTRACT

The propagation of stress waves in a pipe pile subjected to a transient point load cannot be expressed using traditional one-dimensional (1D) wave theory. This paper presents an analytical solution used to investigate the wave propagation in a pipe pile under an axial point load. The soil resistance is simulated using the Winkler model, and the excitation force is simulated with a semi-sinusoidal impulse. A time-domain analytical solution for the three-dimensional wave equation is derived using the separation of variables and variation of constants methods. The solution is verified with a frequency domain analytical solution in which the time-domain response is calculated by numerical Fourier inverse transformation. Furthermore, the solution proposed in this paper is compared with the results of model testing and 3D FEM analysis. The comparisons show that the analytical solution proposed in this study agrees well with the results of previous studies. The proposed solution is subsequently applied in case studies. The vertical velocity responses in the circumferential and axial directions are analyzed to reveal the propagation characteristics of transient waves in the pipe pile. Moreover, the effects of the location and period of the excitation force, the side and tip resistances and high-order modes are studied in detail.

1. Introduction

Large-diameter hollow cylinder structures, i.e., large-diameter cast-in-place concrete pipe piles, are widely used in engineering and may be subjected to vertical, horizontal and torsional dynamic loads. The wave propagation in the pile foundation can be described using elastic wave theory and has been studied by a number of researchers [3,2,17,20,31,1,32].

The body of the hollow cylinder is invisible when it is embedded in the medium, i.e., a pipe pile embedded in uniform soil. Therefore, the integrity of such a structure cannot be directly inspected. Low-strain pile integrity testing is an economical and efficient method used to check the integrity of the cylinder structure [14]. The first small-strain integrity tests applied to drilled shafts were performed in France in 1964 [35]. Since the late 1980s, PIT has gained wide acceptance in the foundation engineering and construction community and has become an important tool for verifying pile integrity or pile length [19]. This problem can be expressed as the axial response of a cylinder due to transient point loading. Rausche et al. [30] presented a summary of the required equipment and available interpretation methods for low-strain testing. Morgano [22] proposed a method for determining the embedment depths of deep foundations using non-destructive methods. Johnsen et al. [12] performed low-strain testing on grout columns to investigate the ability of low-strain testing to detect the depth, shape and continuity of compaction grout columns. A newly proposed numerical signal process method was applied to explore the time–frequency component of the testing results from cast in situ reinforcement concrete piles with high slenderness ratios [23]. A continuous wavelet transform (CWT) method with time–frequency distribution was adopted to enhance the characteristics of the testing signal to improve the identification ability in both numerical simulations and experimental cases [24]. Based on traditional stress wave theory and experimental results, certain factors influencing the stress wave speed were analyzed by Du et al. [8].

The above mentioned methods were based on one-dimensional (1D) wave theory, in which the pile is assumed to be a slender pole and the wave is assumed to propagate only in the axial direction [26,27,33]. However, traditional 1D wave theory is no longer applicable for a pipe pile subjected to a point load because the wave

* Corresponding author. Address: Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering, National Engineering Research Center of Water Resources Efficient Utilization and Engineering Safety, Hohai University, 1 Xikang Road, Nanjing 210098, China. Tel.: +86 13813953213.

E-mail addresses: dxmhhu@163.com (X. Ding), hliuhhu@163.com (H. Liu), gqkong1@163.com (G. Kong), zhengchj1989@163.com (C. Zheng).

http://dx.doi.org/10.1016/j.compgeo.2014.02.004
0266-352X/

propagates not only in the axial but also in the transverse directions. Solution of three-dimensional (3D) wave equations for the given initial boundary conditions is a difficult task, and thus a numerical method is usually adopted to solve three-dimensional stress wave propagation problems. The three-dimensional effects at the top of a pipe pile and a large-diameter pile were studied using the finite element method (FEM) [4,5]. Niederleithinger [25] developed a 2D finite integration technique for cylindrical geometries (CEFIT) in simulations of measurements with the low-strain pile integrity testing method and the parallel seismic technique. A coupled finite element/boundary element model was adopted to predict the pile response and free field vibrations due to low-strain dynamic loading [18]. The 3D characteristics of wave propagation in a pipe pile also were researched using an elasto-dynamic finite integration technique [16].

Although numerical methods can be used to solve 3D stress wave propagation problems, an analytical solution is much preferred for application via software for pile dynamic analysis (PDA). In an attempt to obtain a simplified analytical solution, a study was carried out on an infinite hollow cylinder, and the expressions of the displacement components were obtained by Gazis [9,10]. The influence of the 3D geometrical dispersion of an infinite linear visco-elastic cylindrical bar was studied using a three-dimensional analytical method [34]. However, this study could not be applied directly to a pipe pile with a finite length subjected to a transient concentrated load. Ding et al. [6,7] derived a frequency-domain analytical solution for a pipe pile with finite length. However, the time domain results could not be obtained directly by the analytical method, and numerical Fourier inverse transformation must be used to derive an approximate solution in the time domain; furthermore, the action point of the load was assumed at the center of the pile wall.

In this study, a time-domain analytical solution of the vertical dynamic response of a pipe pile under a transient point load is deduced, and the load is applied at an arbitrary location on the pile top. The longitudinal and transversal propagations of the waves are investigated.

2. Assumptions and computational model

As shown in Fig. 1, the column coordinate system is adopted in this paper. The computational model is shown in Fig. 2, where R_1 is the outer radius, R_2 is the inner radius and L is the length of the pipe pile. The thickness of the wall of the pipe pile is $h = R_1 - R_2$. The following assumptions are applied:

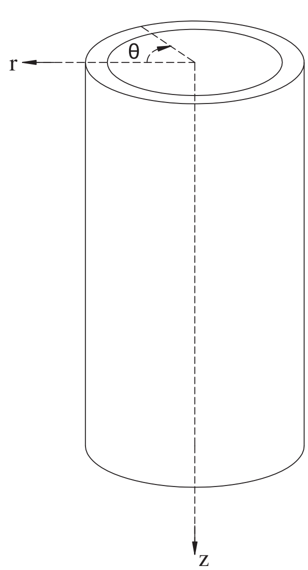

Fig. 1. Column coordinate system.

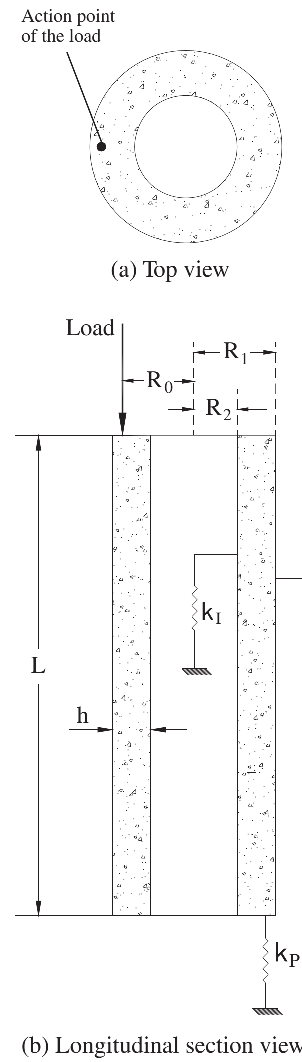

Fig. 2. Computational model.

(1) Wave equations with three dimensions and three components of displacement (3D3C) can be used to describe the wave propagation in 3D space. However, it is notably difficult to obtain the analytical solution for 3D3C wave equations in a special finite area; therefore, the wave equation with three dimensions and one component of displacement (3D1C) has been adopted in this study.
(2) The soil resistance is modeled using the Winkler model [28,29,11,21], as shown in Fig. 2, where the linear elastic coefficients of the outer soil, inner soil and pile bottom soil are k_O, k_I and k_p, respectively.
(3) The deformation of the pipe pile is small and elastic.
(4) The self-weight of the pipe pile is not considered in the wave equation.
(5) The load is simulated with a half-sine curve [5], shown in Eq. (1) and Fig. 3. The coordinate of the action point is $(z, \theta, r) = (0, 0, R_0)$.

$$f(z,\theta,r,t) = P_0 \sin\left(\frac{2\pi}{T}t\right) H\left(\frac{T}{2} - t\right)\delta(r - R_0)\delta(\theta)\delta(z) \tag{1}$$