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Research Paper

# Vertical response of a thin-walled pipe pile embedded in viscoelastic soil to a transient point load with application to low-strain integrity testing

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ABSTRACT

This paper presents an analytical method to compute the dynamic response of a thin-walled pipe pile due to a vertical transient point load acting on its head. Inspired from challenges faced during the interpretation of low-strain integrity tests on pipe piles, the proposed method moves beyond the widely used one-dimensional wave theory to consider the asymmetric nature of the problem, and stress wave propagation along both the vertical and circumferential directions. Coupling of pipe pile–viscoelastic soil vibration is considered via modeling the outer and inner soil as a series of infinitesimally thin layers in perfect contact with the pile, and their low-strain properties are directly introduced in the solution. The methodology is validated against numerical results, before discussing the mechanisms governing the dynamic response of the pipe pile–soil system to the impact load, with emphasis on the vertical velocity measured at a hypothetical receiver placed on the pile head. Additional results from a parametric analysis are used to provide insights on the accurate estimation of the arrival time of the receiving wave, and the optimal location of the receiver.



## 1. Introduction

Low strain integrity testing techniques have been used extensively for the assessment of the quality of foundation piles. The test consists of applying an impact load on the pile head with a hand-held hammer. An accelerometer placed on the pile head captures the vertical vibrations due to the hammer impact in the form of a velocity time history, which is used to determine the as-built properties of the pile. The theory behind the interpretation of low-strain pile test results is based on the analysis of the axial response of a cylinder embedded into the soil to a transient point load, which is the subject of a number of studies in the literature. For example, Smith [1] first applied the wave equation method for pile driving analysis to determine the response of a discrete hammer-pile-soil model. Goble et al. [2] developed the Wave Equation Analysis Program (WEAP87) in the 1970s, newer versions of which are now applied widely to predict the drivability of piles and process field test data. Rausche et al. [3] proposed a simple soil resistance model and deduced a quasi closed-form solution for driven piles subjected to impact loads. Morgano [4] discussed the use of non-destructive methods for the determination of the embedment depth of deep foundations. Wang et al. [5] investigated the vertical dynamic response of an inhomogeneous viscoelastic pile embedded in layered soil. In more recent studies Ni et al. [6] proposed a new numerical signal processing method to explore the time–frequency component of recordings from tests on drilled piles with high slenderness ratio. Later, Ni et al. [7] adopted the continuous wavelet method with time–frequency distribution to enhance the interpretation potential of both numerical simulations and experimental measurements.

Most studies in the literature, including the ones mentioned above, focused on the common case of solid piles. The above theoretical studies for solid piles are all based on one-dimensional (1D) wave theory, which implies that wave propagation satisfies the plane-section assumption; that is, the impact waves propagate along the vertical direction only. For small diameter solid piles, the plane-section assumption is reasonable, and 1D wave theory suffices for the description of the problem. However, the plane-section assumption is not valid for large diameter thin-walled pipe piles which are also commonly used in practice [8–11], because the stress field produced by a transient point load is no longer axisymmetric. In addition to that, the stress waves generated by the impact load propagate not only in the vertical but also in the circumferential direction. Gazis [12,13] was the first to propose a three-dimensional solution for wave propagation in

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an infinite hollow cylinder. Although Gazis' solutions contribute to the understanding of three-dimensional wave propagation in a hollow cylinder, they cannot be directly applied to the pipe pile problem, as piles feature a finite length. With that in mind Ding et al.[14–16] derived the frequency- and time-domain solutions for a pipe pile of finite length, while simulating the resistance of the soil along the pile shaft by means of a Winkler or Voigt model. However, one drawback of Winkler or Voigt models is that they cannot capture coupling of vibrations between the pile and its surrounding soil. Furthermore, the calibration of the spring and dashpot parameters is cumbersome, even though they have a prominent effect on the vibration response of the soil-pile system.

The purpose of this paper is to tackle this deficiency of existing methods. We present a formulation to describe the vertical response of a thin-walled pipe pile to a transient point load, by considering coupling of pipe pile and the outer and inner viscoelastic soil vibrations along the shaft of the pipe pile. The cyclic response of the viscoelastic soil can be accounted for straightforwardly via its low-strain shear modulus and damping ratio, which can be estimated from laboratory tests. For the reasons discussed above, wave propagation in the thin-walled pipe pile is considered in both the vertical and circumferential directions. The frequency domain analytical solutions are derived based on the assumption of perfect contact between the pipe pile and the soil, with the latter modeled as a series of infinitesimally thin layers. Accordingly, the time domain results are obtained by the means of inverse Fourier transformation. Results from the proposed model are verified by comparison with numerical analyses. Finally we discuss the mechanisms governing vibration propagation in pipe piles and investigate the influence of the key parameters on the vertical vibrations of the pile head via arithmetic applications, which lead to certain important findings of practical interest.

## 2. Conceptual model and basic assumptions

The following equations are formulated on the cylindrical coordinate system shown in Fig. 1. The conceptual model is presented in Fig. 2. The pile is discretized into three segments, with the Young's modulus and wall thickness of each segment being $E_{pk}$ and $h_k$, respectively, where $k = 1, 2, 3$. The elevation of the bottom of each segment is $H_k$. The mean radius of the pipe pile is $r_0$. Possible pile defects considered include two types: an anomaly in the pile shape, which results in a local variation of the area of the cross section, and a local degradation of the pipe pile material properties. The first type of defect corresponds to bulging/necking, and can be introduced in the solution by locally varying the thickness of the pipe pile wall $h_k$ while keeping $r_0$ constant. The second type corresponds to a weak material zone due to e.g. poor concrete compaction, and can be introduced in the analysis by locally reducing the Young's modulus of the pipe pile material $E_{pk}$. Furthermore, certain assumptions are introduced to simplify the solution [17]:

(1) The outer and inner soil are modeled as a series of homogeneous infinitesimally thin layers. Furthermore, it is reasonable to neglect the gradient of the vertical stresses of the thin soil layers [18].
(2) The pile is elastic and is in perfect contact with the outer and inner soil, which is a reasonable assumption given the low amplitude of the excitation.
(3) Only vertical displacements of the pile-soil system are considered, and the vertical displacement of the thin-walled pipe pile is assumed invariant in the radial direction.
(4) The soil-pile system is at rest at $t = 0$. This constitutes the initial conditions of the problem.
(5) The base resistance of the pipe pile can be introduced in the solution via an elastic spring, of stiffness $k_p$ (Fig. 2).
(6) The vertical transient point load $p(\theta, t)$ is simulated as a half-sine pulse [19], described by Eq. (1) and shown in Fig. 3. The coordinates of the point of load application are $(z, \theta) = (0, 0)$.

$$p(\theta, t) = P_0 \sin\left(\frac{\pi}{T} t\right) \delta(\theta) H(T - t) \quad (1)$$

where $P_0$ is the amplitude of the impact force; $T$ is the half-period; $\delta()$ is a Dirac function; and $H()$ is a Heaviside step function.

## 3. Governing equations

Ignoring the stress gradient in the vertical direction, the dynamic equilibrium equations of the outer soil can be expressed as:

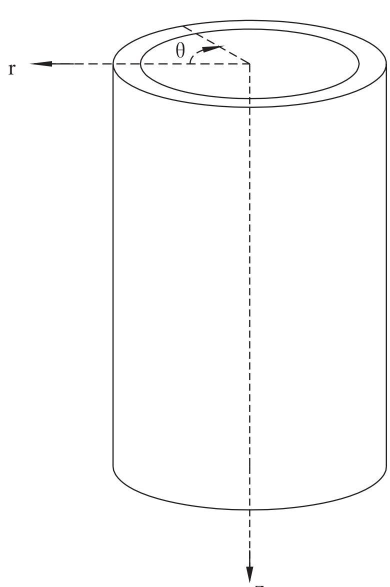


**Fig. 1.** Cylindrical coordinate system originating at the center of the pipe pile head.

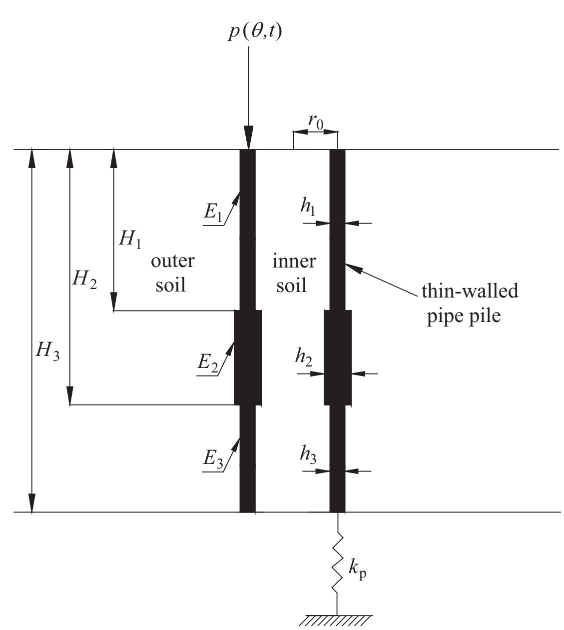


**Fig. 2.** Conceptual model of the pipe pile–soil system.