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Analysis of laterally loaded short and long piles in multilayered heterogeneous elastic soil

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Abstract

A continuum-based method is developed for the analysis of laterally loaded piles in multilayered, heterogeneous elastic soil. The analysis considers the soil as a layered elastic continuum in which the modulus varies linearly or non-linearly with depth within each layer. Rational soil displacement fields are assumed and differential equations describing the pile and soil displacements are obtained using the principle of minimum potential energy. The differential equations describing the pile and soil displacements are solved using the Ritz method and the finite difference method, respectively, following an iterative numerical scheme. The analysis is used to study different pile geometries embedded in layered soil deposits with heterogeneity in each layer. The pile displacement, rotation, and maximum bending moment obtained from the analysis were found to be in good agreement with those obtained from an equivalent three-dimensional finite element analysis and from other studies available in the literature. The analysis can be used to obtain the pile head displacement, rotation, and maximum bending moment that can then be used in design.

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Keywords: Pile; Elastic analysis; Lateral load; Minimum potential energy; Ritz method

1. Introduction

The analysis of laterally loaded piles is generally done using the *p-y* method (Matlock, 1970; Reese et al., 1974, 1975; Cox et al., 1974; Briaud et al., 1984; Gabr et al., 1994; Ashour and Norris, 2000). In this method, each pile is assumed to behave as a beam supported by a series of lateral soil springs, and the lateral load displacement response of the pile is captured by characterizing the soil springs with *p-y* curves at different soil depths (*p* is the horizontal soil reaction acting on the pile per unit length and *y* is the corresponding lateral pile displacement). However, the *p-y* method sometimes fails to give accurate results for pile displacements because it does not rigorously capture the three-dimensional pile-soil interaction necessary to predict the lateral pile behavior (Yan and Byrne, 1992; Anderson et al., 2003; Kim et al., 2004; Higgins et al., 2010; Haldar and Basu, 2014). Consequently, research on laterally loaded piles has continued to be unabated and several studies have been conducted in which the soil is modelled as a continuum. In these studies, different solution methods, such as (i) the finite difference (FD) method (Poulos, 1971a,b; Verruijt and Kooijman, 1989; Zhang et al., 2000), (ii) the finite element (FE) method (Randolph, 1981; Trochanis et al., 1991; Filho et al., 2005; Higgins et al., 2013), (iii) the boundary element (BE) method (Banerjee and Davies, 1978; Budhu and Davies, 1988; Ai et al., 2013), and (iv) the variational method (Sun, 1994; Shen and Teh, 2002; Yang and Liang, 2006; Basu et al., 2009; Salgado et al., 2014), have been used to obtain solutions for laterally loaded piles

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embedded in continua. A few of these studies account for the effect of multiple soil layers (Randolph, 1981; Chow, 1987; Verruijit and Kooijman, 1989; Basu et al., 2009; Ai et al., 2013; Salgado et al., 2014) and soil heterogeneity, such as linear or nonlinear variations of the soil modulus with depth (Poulos, 1973; Randolph, 1981; Banerjee & Davies, 1978; Budhu and Davies, 1988; Zhang et al., 2000).

In actual field conditions, soils are stratified with layers of sandy, silty, and clayey deposits; and thus, it is necessary to consider the multiple discrete soil layers in the analyses. However, the properties within each soil layer often vary with depth. For example, in overconsolidated clay layers, a parabolic variation in the soil modulus with depth is often assumed (Scott, 1981). In the case of normally consolidated clays or sandy deposits, a linear variation in the soil modulus with depth is often assumed (Reddy and Valsangkar, 1971). Due to the wide variability of soil types and the heterogeneity of the soil properties within each layer, an analysis method needs to be developed for laterally loaded piles in which multiple soil layers are considered and variations in the soil modulus with depth within each layer can be easily taken into account.

In this paper, a method is developed for the analysis of laterally loaded piles in multilayered elastic soil with the soil modulus varying with depth within each layer. The analysis assumes each pile to behave as an Euler-Bernoulli beam supported by a three-dimensional (3-D) soil continuum surrounding it. The behavior of the 3-D soil continuum is simplified by assuming the soil displacements as products of separable variables. Using the principle of minimum potential energy and variational calculus, the problem is posed as a beam on an elastic foundation for which the foundation parameters are rigorously related to the elastic constants of the soil continuum. The advantage of this method is that the simplicity of the beam-on-foundation approach is maintained, yet the rigor of the continuum approach is incorporated. The developed differential equations for pile and soil displacements are solved analytically and numerically in an iterative numerical scheme. The time required for the analysis is significantly less than that required by the 3-D numerical analysis because the 3-D problem is represented by a set of one-dimensional differential equations that can be solved quickly.

2. Analysis

2.1. Problem definition

A pile with a circular cross-section having a radius r_p, length L_p, Young's modulus E_p, and moment of inertia I_p, embedded in a soil deposit with $n+1$ layers, is considered (Fig. 1). The thickness of any generic soil layer (except for the bottom layer) is $H_i - H_{i-1}$, where H_i is the depth to the bottom of the ith layer from the ground surface (with $H_0 = 0$), and the bottom $(n+1)$th layer has infinite thickness (i.e., $H_{n+1} = \infty$). All the layers have infinite horizontal extents and follow the laws of linear elasticity with Lame's constants λ_{si} and G_{si} (subscript i represents the ith layer). The shear modulus G_{si} within each layer varies with depth, while the Poisson's ratio ν_{si} within each layer remains spatially constant. Thus, λ_{si} $[=2\nu_{si}G_{si}/(1-2\nu_{si})]$ also varies with depth within each layer. Mathematically, the variation in G_{si} with depth z within the ith layer is given by

$$G_{si} = f_i G_{s0} + s_i (z - H_{i-1})^{\omega_i} \quad (1)$$

where G_{s0} is a reference shear modulus (=100 MPa), f_i is a scalar coefficient such that $f_i G_{s0}$ gives the value of the shear modulus at the top of the ith layer (i.e., at $z = H_{i-1}$), s_i is a constant for the ith layer that has the physical meaning of the rate of change in shear modulus with depth if G_{si} varies linearly with depth, ω_i is an exponent that determines how G_{si} varies with depth, and z is the depth measured from the ground surface. For physical problems, the typical range in exponent ω is 0.5–2 (Scott, 1981), where $\omega = 0.5$ represents a parabolic variation (i.e., the slope of G_s versus depth curve decreases with depth), $\omega = 1$ represents a linear variation (i.e., the slope of G_s versus depth curve remains constant with depth), and $\omega = 2$ represents a hyperbolic variation (i.e., the slope of G_s versus depth curve increases with depth) in the modulus with depth. For simplicity, the variation in shear modulus G_s with depth below the pile base (i.e., in the $(n+1)$th layer) is always assumed to be linear (with $\omega = 1$). This is because it was found in several simulations that the actual variation (linear or nonlinear) in G_s in the $(n+1)$th layer does not affect the pile response to any significant extent. Note that, for any layer, a constant shear modulus with depth can also be assumed in the analysis by setting $s_i = 0$.

The pile head is at the ground surface and subjected to horizontal force F_a and moment M_a, as shown in Fig. 1. The pile base rests on top of the $(n+1)$th (bottom) layer (i.e., $L_p = H_n$). No slippage or separation between the pile and the surrounding soil or between the soil layers is allowed. For analysis, a right-handed cylindrical (r-θ-z) coordinate system is chosen such that its origin lies at the centre of the pile head, the z axis coincides with the pile axis and points downward, the reference radial direction r_0 coincides with the direction of applied force F_a, and angular distance θ, measured from r_0, is clockwise positive when looking downward from the top of the pile.

2.2. Soil displacement, strain, and strain energy density

The horizontal soil displacement field, generated by the pile displacement, is described as the product of three functions each of which varies with one of the three dimensions. The vertical soil displacement, u_z, is assumed to be negligible. Mathematically, the radial (u_r) and the tangential (u_θ) soil displacements are assumed as follows (Basu, 2006):

$$u_r = w(z)\phi_r(r)\cos\theta \quad (2a)$$

$$u_\theta = -w(z)\phi_\theta(r)\sin\theta \quad (2b)$$

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