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Research Paper

Analysis of laterally loaded rigid monopiles and poles in multilayered linearly varying soil

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ABSTRACT

A new method for calculation of head displacement and rotation of laterally loaded rigid monopiles and poles in multilayered heterogeneous elastic soil is presented. The analysis considers the soil as a layered elastic continuum in which the modulus vary linearly with depth within each layer. Rational pile and soil displacement fields are assumed, and the interaction between the pile and soil is taken into account by using the principle of virtual work. Two sets of equilibrium equations, one describing the pile displacement and rotation and the other describing the displacements in the soil, are obtained and solved analytically and numerically following an iterative algorithm. The new method produces pile responses as accurate as those obtained from three-dimensional finite element analysis but does not require any elaborate input for geometry and mesh.

1. Introduction

Large diameter monopiles are commonly used in offshore wind turbines [1–3]. These are typically hollow pipe piles with length equal to 5–6 times the diameter [4], and are subjected to lateral forces and moments at the head arising from wind, waves, and water currents. Finite element (FE) analyses of monopiles show that these piles undergo rigid-body rotation and translation when subjected to lateral forces and moments [5]. Similar observations of rigid displacement and rotation of laterally loaded monopiles have been observed in centrifuge and 1-g model tests [6–8]. Rigid rotation and translation are also exhibited by short stubby piles like large diameter drilled shafts with low slenderness ratio when subjected to lateral forces and moments at the head [9,10].

Analysis of laterally loaded monopiles is generally performed using the p–y method as recommended in the American Petroleum Institute [11] and Det Norske Veritas [12] codes of practice. In fact, the standard practice for analysis of any laterally loaded pile irrespective of its stiffness and slenderness ratio is to use the p–y method. However, it was found that the p–y method underestimates monopile displacement [2,13–15] because the method is strictly valid for long slender piles. Sorensen et al. [16] concluded from three-dimensional (3D) finite difference analyses and laboratory scale lateral load tests that the p–y method is non-conservative for analysis of large diameter monopiles. There is evidence in the literature that the p–y method does not always work well, even for slender piles, because it is empirical in nature and lacks the rigor of a continuum-based analysis typically expected in soil-structure interaction problems like that of laterally loaded piles [17–21]. Thus, there is a need to develop an analysis of rigid piles particularly to calculate the head displacement, as restricting the head displacement within a tolerable limit is often the criterion used in practical design.

The research studies reported in the literature on laterally loaded rigid piles and piers focus primarily on the estimation of ultimate capacity either using limit state theories [22–25] or using 3D nonlinear FE analysis [26,27]. There are a few studies available in which pile load–displacement response was numerically investigated using the modulus of horizontal subgrade reaction theory [28–30]. Explicit expressions for pile head displacement and rotation using the Fourier finite element method [31,32] and subgrade modulus method [33] are also available for a limited number of practical cases.

Most studies mentioned above are restricted to soil deposits consisting of a single layer or of multiple layers with constant modulus within each layer. In real field conditions, there can be a wide variability of soil properties within a single soil layer. For example, shear strength and modulus in normally consolidated and overconsolidated clay layers vary (often increase) gradually with depth. Therefore, it is reasonable to assume a linear variation of soil modulus with depth within each layer [34].

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In this paper, a new method for analysis of laterally loaded rigid piles in multilayered elastic soil with the soil shear modulus varying linearly with depth in each layer is presented. In the analysis, the soil surrounding the pile is assumed to be a layered elastic continuum, and force diagrams of the monopile and soil are considered separately to obtain the equilibrium configuration of the pile–soil system. The principle of virtual work is applied to the force diagrams to obtain the equilibrium equations of the pile–soil system. The equations are solved analytically and numerically using which pile head displacement and rotation can be easily calculated in a matter of seconds. Pile responses obtained from this analysis are found to be in good agreement with those obtained from equivalent 3D FE analysis. The advantage of the analysis is that it produces results fast without any elaborate input of pile–soil geometry and mesh, as required in 3D FE analysis.

2. Analysis

2.1. Problem definition

A rigid pile with circular cross-section of radius r_p and length L_p embedded in a soil deposit with $n+1$ layers is considered (Fig. 1). Each soil layer i except the bottom layer has a thickness $H_i - H_{i-1}$, where H_i is the depth to the bottom of the ith layer from the ground surface (with $H_0 = 0$), and the bottom layer has infinite thickness (i.e., $H_{n+1} = \infty$). All the layers extend to infinity in horizontal directions. Each layer is assumed to be elastic and isotropic characterized by Lame's constants λ_{si} and G_{si} (the subscript i represents the ith layer). The shear modulus G_{si} within each layer varies linearly with depth while the Poisson's ratio ν_{si} within each layer remains spatially constant. Thus, $\lambda_{si}[= 2\nu_{si}G_{si}/(1-2\nu_{si})]$ also varies linearly with depth within each layer. Mathematically, the variation of G_{si} with depth z within the ith layer is given by

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

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 $z = H_{i-1}$), $s_i(= dG_{si}/dz)$ is the rate of change of shear modulus with depth in the ith layer, and z is measured from the ground surface.

The pile head is at the ground surface and subjected to a horizontal force F_a and a 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 center 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 the applied force F_a, and the angular distance θ, measured from r_0, is clockwise positive when looked downward from the top of the pile.

2.2. Pile displacement profile

For the rigid pile, a linear horizontal displacement profile is assumed (Fig. 2). Mathematically, the horizontal pile displacement w is given by

$$w(z) = w_h - z\sin(\Theta_h) \approx w_h - \Theta_h z \tag{2}$$

where w_h is the pile head displacement, and Θ_h is the pile head rotation (Θ_h is considered small such that $\sin\Theta_h \approx \Theta_h$). The slope of the pile axis dw/dz remains constant with depth and is equal to $-\Theta_h$. The pile base displacement $w_b = w_h - \Theta_h L_p$. The vertical displacement of the pile is assumed negligible.

2.3. Soil displacement field

The horizontal soil displacement field, generated by the pile displacement, is described as a product of three functions each of which varies with one of the three dimensions. The vertical soil

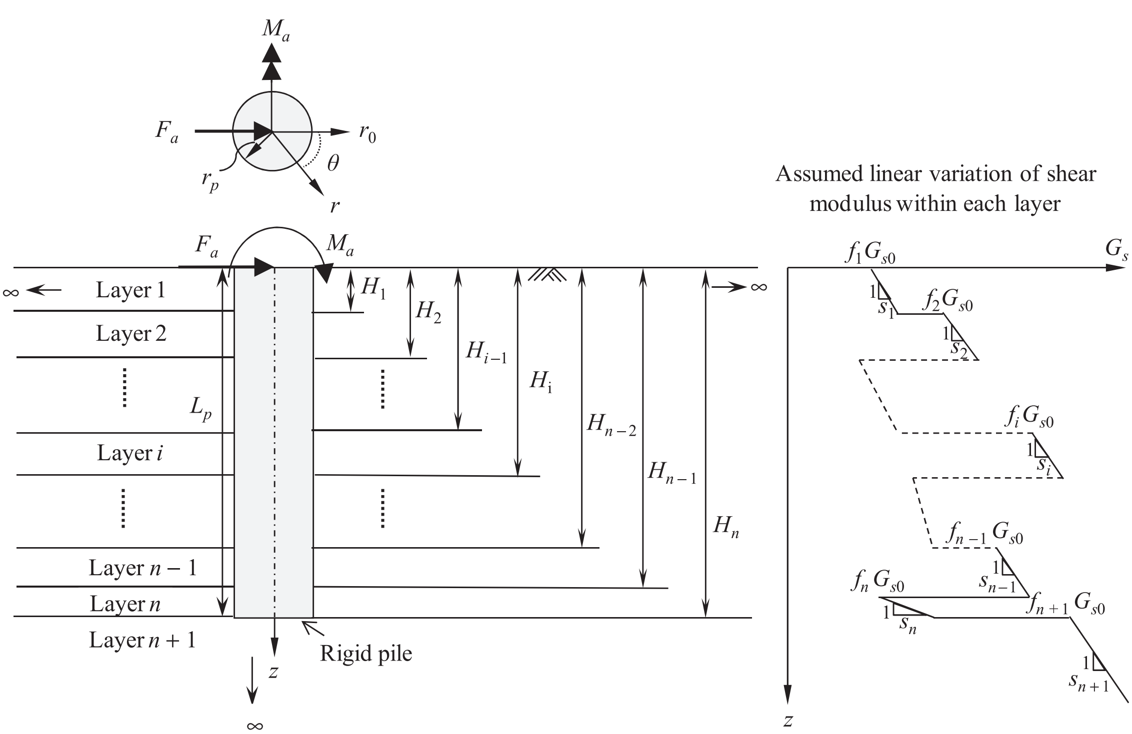

Fig. 1. A laterally loaded rigid pile in a multilayered soil with linearly varying shear modulus in each soil layer.