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Technical Paper

Simplified non-linear approaches for response of a single pile and pile groups considering progressive deformation of pile–soil system

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Abstract

This work presents a simplified approach for the nonlinear analysis of the load–displacement response of a single pile and pile groups embedded in multilayered soils. A hyperbolic model is used to capture the relationship between the skin friction and the pile–soil relative displacement developing along the pile–soil interface. The shaft displacement is assumed to be composed of the pile–soil relative displacement developing at the disturbed soil around the pile shaft and the elastic vertical soil displacement developing in the soil mass. The relationship between the shaft displacement and the skin friction is then presented. Moreover, a hyperbolic model is also used to capture the relationship between end resistance and pile end displacement. Considering the interactive effect among piles, hyperbolic models of an individual pile in pile groups are proposed. As to the analysis of the response of a single pile and pile groups, considering the progressive deformation of the pile–soil system, a highly effective iterative computer program is developed using the proposed hyperbolic models. Comparisons of the load–settlement responses demonstrate that the proposed method is generally in good agreement with the field-observed behavior and the calculated results derived from other approaches.

Keywords: Single pile; Pile groups; Skin friction; End resistance; Hyperbolic model; Pile–soil relative displacement; Progressive deformation

1. Introduction

A number of theoretical methods have been used for the analysis of a single pile and pile groups. Many of these various numerical methods fall into the following four main categories. (1) The theoretical load–transfer curve method (Kraft et al., 1981; Liu et al., 2004; Zhang et al., 2010; Zhang and Zhang, 2012; Lee et al., 2013) adopts the load transfer function to describe the relationship between the unit skin friction and the pile–soil relative displacement along the pile–soil interface and the relationship between the pile end resistance and the pile end displacement. The theoretical load–transfer curve method is simplified and can be easily used in the analysis of single piles embedded in multilayered soils. However, the theoretical load–transfer curve method cannot consider soil continuity and cannot be directly used in analyzing the response of pile groups. (2) The shear displacement method (Randolph and Wroth, 1979; Lee, 1991; Guo and Randolph, 1999) considers the resulting displacement of the soil induced by the shaft shear stress as a logarithmic relationship of the radial distance away from the pile shaft. The interactive effects among piles can be considered by using the principle of superposition. However, the interaction between two

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soil layers cannot be considered in the shear displacement method. (3) The elastic theory method (Xu and Poulos, 2000; Wang and Yang, 2006) has an excellent theoretical basis and can consider soil continuity. However, the elastic theory method can only consider the influence of the elastic modulus and Poisson's ratio on the pile response; it cannot account for the nonlinear soil behavior or the stratification of soils. (4) The numerical analysis method, including the finite element method (Comodromos et al., 2009; Said et al., 2009), the boundary element method (Ai and Han, 2009), the discrete element method (Chow, 1986; Lee, 1991), and the infinite layer method (Cheung et al., 1988), is considered to be one of the most powerful approaches for analyzing the behavior of a single pile and pile groups. With the numerical analysis method, the nonlinear soil behavior and the complete history of the pile construction procedure can be simulated. However, it is not commonly used in practice because of its high computational requirements and the difficultly of determining the soil parameters.

In practical applications, the load–transfer approach is an efficient method for analyzing a single pile response, and it can be used to consider the nonlinear soil behavior. In the theoretical load–transfer curve method, the load–transfer functions are required to describe the relationship between the mobilized unit skin friction and the pile–soil relative displacement and the relationship between pile end resistance and pile end displacement. For practical purposes, various forms of load–transfer functions, such as the elastoplastic model, the bilinear model, the trilinear model, the exponential function model, the parabolic model, the softening model, and the hyperbolic model are proposed. To account for the nonlinearity in the stress–displacement response of soil, a hyperbolic model is commonly used to capture the relationship between the unit skin friction and the pile–soil relative displacement developing along the pile–soil interface and the load–displacement relationship developing at the pile end.

However, the conventional load–transfer approach is rather difficult to extend to the analysis of pile groups. The interactive effects among piles should be considered when the load–transfer approach is used to analyze the response of pile groups. Poulos (1968) first introduced the interaction factor defined as the additional displacement at the top of a pile due to a loaded adjacent pile divided by the settlement of the pile under its own load to analyze the response of pile groups. The concept of the interaction factor is successfully employed in simplified analytical methods to predict the response of pile groups. However, the conventional interaction factor will overestimate the interactive effects among piles. In reality, the presence of the 'receiver' pile (in the words of Mylonakis and Gazetas (1998)) usually reduces the displacement of the loaded ('source') pile. To account for the reinforcing effects among piles, Mylonakis and Gazetas (1998), Liang et al. (2005, 2014), and Yang et al. (2011) developed analytical formulations to determine the modified interaction factors. The modified interaction factors can be used to establish suitable methods for analyzing the response of pile groups.

Field tests show that the skin friction is gradually mobilized from the pile head to the pile tip, and that deformation of the pile–soil system gradually develops. The results of field tests also show that a hyperbolic model can be used to better describe the shear characteristics of the pile–soil interface. In previous papers (Zhang et al., 2010; Zhang and Zhang, 2012), a hyperbolic model was used to analyze the behavior between the unit skin friction and the pile displacement developing along the pile–soil interface, and a bilinear hardening model was used to simulate the load–settlement response developing at the pile base. As to the response of pile groups, the interaction factor was introduced. The interaction between two piles was assumed to be composed of two aspects: one was the interaction between pile shafts, and the other was the interaction between pile bases. Comparing to the previous works, there are many great improvements in the present method. In the present paper, the shaft displacement is assumed to be composed of the pile–soil relative displacement developing in the disturbed soil around the pile and the elastic vertical soil displacement developing in the soil mass. Moreover, to extend the conventional load–transfer approach to analyze the response of pile groups, new kinds of hyperbolic models of an individual pile in pile groups were established to consider the reinforcing effect of adjacent load-free piles and the interactive effects among piles. Based on the proposed models, a highly effective iterative computer program is developed to analyze the nonlinear response of a single pile and pile groups embedded in multilayered soils.

2. Nonlinear transfer function for a single pile

The results of field tests on instrumented piles are adopted (Zhang et al., 2014) to verify the reliability of the hyperbolic model of skin friction, as shown in Fig. 1. Fig. 1 contains 808 points and presents the observed relationship between the unit skin friction at a given depth and the pile–soil relative displacement with the unit skin friction at a given depth, τ_{sz}, normalized by the limiting unit shaft resistance, τ_{su}, and the measured pile–soil relative deformation at a given depth, S_{sz}, normalized by the measured pile–soil relative displacement at the ultimate skin friction, S_{su}.

Fig. 1 suggests that a hyperbolic model can be used to approximately simulate the relationship between τ_{sz}/τ_{su} and S_{sz}/S_{su} irrespective of soil type, stratigraphy, or loading procedure, and has a high accuracy ($R^2=0.8376$). In this paper, a simple hyperbolic nonlinear model may be conveniently adopted to describe the relationship between the unit skin friction and the relative displacement discontinuity between the disturbed soil zone and the pile shaft surface.

The relationship between the unit skin friction and the pile–soil relative displacement can be simulated using a hyperbolic model (see Fig. 1). The following is obtained (after Lee and Xiao (2001)):

$$\tau_{sz} = \frac{S_{sz}}{a + bS_{sz}} \tag{1}$$

where a and b are empirical coefficients, S_{sz} is the relative displacement along the pile–soil interface at a given depth z, and τ_{sz} is the unit skin friction at a given depth z.