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Nonlinear analysis of flexible piled raft foundations subjected to vertical loads in layered soils

Maosong Huang[a,b,*], Yongzhi Jiu[a,c], Jie Jiang[d], Bo Li[e]

[a] Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China
[b] Key Laboratory of Geotechnical and Underground Engineering of the Ministry of Education, Tongji University, Shanghai 200092, China
[c] School of Civil Engineering and Architecture, Zhongyuan University of Technology, Zhengzhou 450007, China
[d] College of Civil Engineering and Architecture, Guangxi University, Nanning 530004, China
[e] Key Laboratory of Geotechnical Mechanics and Engineering of the Ministry of Water Resources, Yangtze River Scientific Research Institute, Wuhan 430010, China

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Abstract

In this paper, a simplified nonlinear approach is proposed to study the behavior of flexible piled raft foundations. The flexible piled raft is modeled as a thin plate with the finite element discretization. By employing the load transfer method, a nonlinear finite differential formulation for the analysis of a single pile is created. Pile groups are analyzed by the superposition principle. The interaction factor between two piles is determined by considering the interaction between a receiver pile and the surrounding soil. Based on solutions for the stress and displacement in layered elastic half space, the interactions between pile and soil surface, soil surface and pile, as well as soil surface and soil surface subjected to vertical loading are also taken into account to determine the flexibility matrix of the pile group-soil system. In order to verify the validity of the proposed nonlinear analysis method, calculated results are compared with the numerical and test results from the literature. The good agreement achieved shows that the proposed method provides a simple and useful tool for engineering design.

Keywords: Piled raft foundations; Flexible raft; Nonlinear response; Interactions; Layered soils

1. Introduction

Piled raft foundations have been widely used for high rise buildings, liquid storage tanks, shipbuilding dock, etc. In conventional design of a piled raft foundation, it is usually assumed that the entire load is carried by the piles, ignoring the load carried by the raft. Studies on large buildings in London have demonstrated that up to 30% of the building load is being carried by the raft despite the assumption that the entire load is carried by the piles in design (Cooke, 1986). The proper use of piles and careful consideration of the load carried by the raft can reduce differential settlements of the raft and lead to considerable economy without compromising the safety of the structures. Various methods for the analysis of piled-raft foundations have been developed.

Shen et al. (2000), and Liang and Chen (2004) presented a variational approach for the analysis of piled raft foundations. Jinhyung et al. (2010) and Leung et al. (2010) considered the interaction between raft and soil in the analysis of piled raft foundations. However, the raft was assumed to be rigid in their analyses. The flexible foundation was analyzed by Brown and Weisner (1975), but they analyzed the

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* Corresponding author at: Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China.
E-mail address: mshuang@tongji.edu.cn (M. Huang).

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pile with the classical beam theory, which limits the scope of application of the method. A simplified hybrid method for the analysis of the deformation and load distribution of axially and laterally loaded piled raft foundations was proposed by Kitiyodom and Matsumoto (2010). In their method, finite elements were used to model the structure elements of the foundation, Winkler's springs were adopted to simulate the interaction between structure members and soils, and Mindlin's solutions were employed for the interaction between structure members. Ta and Small (1997) proposed an approximate method for the analysis of piled raft foundations with the finite layer method for analyzing pile group interaction behavior and the finite element method for analyzing the raft. Although the finite layer method can be used for simulating layered soils, it is not applicable for nonlinear soils. With combination of the finite element method and boundary element method, Mendoca and Paiva (2003) developed a hybrid method to study the behavior of rigid and flexible piled raft foundation. The boundary element method was adopted to simulate the elastic behavior of homogeneous half-space soil, which is difficult to be extended for non-homogeneous layered soils and nonlinear soil behaviors.

However, all the methods mentioned above have one common limitation: they do not account for the nonlinear behavior of the piled raft. Poulos (2001) pointed out that the conventional elastic theory of piled rafts overestimates the interaction between pile and soil. Especially in the design of the settlement reducing pile, the nonlinear deformation characteristic of piled raft foundations must be taken into account. O'Neill (1981) described patterns of measured load transfer in a full-sized, instrumented pile group and single piles, and the field test results show significant non-linear characteristics. Caputo and Viggiani (1984) stated that the nonlinearity is essentially concentrated at the interface of pile-soil, and that the interactions between pile and pile, pile and cap, as well as cap and soil can use a linear model with sufficient accuracy. Lee and Xiao (2001) proposed a simplified method for the nonlinear analysis of the behavior of pile foundations under vertical loads. This method can only be used for the pile groups, but is not capable of considering the interaction between cap and soil. A hyperbolic transfer function between the shaft shear stresses and relative shaft displacements was chosen to simulate the pile-soil interaction. For the calculation of interaction coefficients of pile to pile, the interaction between a receiver pile and the surrounding soil was not considered. Elastic soil displacement solutions surrounding the pile proposed by Randolph and Wroth (1978) were used for calculating the interaction factor. Huang et al. (2011) presented a simplified nonlinear analysis method for rigid piled raft foundations in layered soils under vertical loading, with only an elastic-perfectly plastic transfer function of pile-soil interaction used. Interactions of pile to pile and soil surface to pile were also determined by the soil displacement solution given by Randolph and Wroth (1978), which might not be suitable for layered soils. Jiu and Huang (2014) developed a simplified approach for simulating the nonlinear behavior of pile groups in layered soils under vertical loads considering pile cap flexibility. However, the method is not suitable for use for piled raft foundations.

Considering the nonlinear behavior of soil and pile-soil interaction, three-dimensional finite-element analyses were conducted by Sanctis and Mandolini (2006) to investigate the nonlinear behavior of rigid piled rafts. Comodromos et al. (2009) used Flac3D to analyze the piled flexible raft foundation. A three-dimensional nonlinear analysis based on the finite element method or finite difference method usually needs a very large amount of calculations. Hence, simplified nonlinear analysis methods for flexible piled raft foundations are required for the engineering design. However, no such approach has been found in the literature.

As mentioned above, a simplified nonlinear analysis method was introduced by the authors (Huang et al., 2011) to describe the rigid piled raft foundations. However, several issues arising from the shortfalls of the method will be addressed and improvements are suggested in this paper. In what follows, a simplified method for the nonlinear analysis of piled raft foundations in layered soils under vertical loading is presented. The flexible raft will be modeled as a Mindlin plate with finite element discretization, and the elastic-perfectly plastic transfer function of pile-soil interface will be replaced by the more realistic nonlinear model proposed by Kraft et al. (1981). Interactions of pile to pile as well as soil surface to pile will be estimated by solutions for the displacement in layered elastic half-space. To verify the efficiency and accuracy of the proposed approach, the calculated results obtained by the present method are compared with well-documented field test results and numerical results. The predicted results are shown to be in good agreement with the results of field tests and numerical simulations for all cases.

2. Formulation of the problem

Fig. 1 shows a piled raft system in layered soils under vertical loads. Based on the theory of Mindlin plate, the raft of the foundation is analyzed by the FEM. The equation for equilibrium at the raft is as follows:

$$[K_r]\{w\} = \{F\} - \{P_{sp}\} \tag{1}$$

where $[K_r]$ is the stiffness matrix of raft; $\{w\}$ is the displacement vector of the raft; $\{F\}$ is the vector of the external load at the raft; $\{P_{sp}\}$ is the force vector of the pile group-soil system under the raft.

The load-settlement relationship for the pile group-soil system is

$$[K_{sp}]\{w_{sp}\} = \{P_{sp}\} \tag{2}$$

where $[K_{sp}]$ is the stiffness matrix of the pile group-soil system which has the order of $(ns + np) \times (ns + np)$, ns is the number of soil element, np is the number of piles; and $\{w_{sp}\}$

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