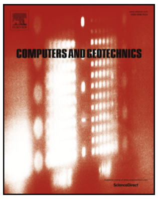
Computers and Geotechnics 103 (2018) 165–178

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo



Research Paper

Normalized settlement of piled raft in homogeneous clay

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ARTICLE INFO

Keywords:
Piled raft
Clay
Boundary element method
Normalized settlement
Design chart
Factor of safety

ABSTRACT

Based on the three-dimensional boundary element method, a practical analysis method for piled raft in clay is presented and validated against the results from the existing numerical simulations and field measurements. A parametric study is performed to investigate the variation of the normalized settlement of the piled raft, including the effects of soil condition, pile dimensions and soil-pile adhesion. Then, a design chart considering the variation of normalized settlement with soil rigidity under different factors of safety is recommended to facilitate the practical engineering design, which is verified against the field and laboratory measurements.

1. Introduction

Piled raft is widely employed as an effective foundation by high-rise buildings for their efficiency in reducing the settlements and improving bearing capacity [1–5]. To achieve an economic and safety design, the load-settlement behavior of the piled raft need be well predicted, especially for the piled raft in clay, in which excessive settlement is usually encountered [1,6].

The piled raft foundation consists of raft, piles, both of which interact with each other and as well as with the around soil. Since these interactions are in the manner of three-dimensional (3D), the load transfer mechanism of the piled raft foundation is rather complicated. According to the modeling techniques, the methods available in current literatures can be generally classified into three groups: (1) simplified Winkler methods [7–10], (2) soil continuum-based methods [11–14], (3) rigorous 3D finite element (FEM) or finite difference (FDM) methods [15–20]. Due to the computational efficiency and conveniences in obtaining the input parameters, the soil continuum-based methods are widely used in the industry design [14].

In addition to the prediction of the piled raft settlement, the estimation of the bearing capacity is also an important aspect in an industrial design. However, these two aspects (i.e. estimation of the settlement and bearing capacity of piled raft) are often evaluated separately in current industrial practice. For example, the load-settlement behavior of the piled raft is checked after the bearing capacity of the piled raft satisfies the desired factor of safety [21]. To obtain a reasonable and economical design, a large amount of computation time is consumed under current design philosophy. In order to improve the efficiency of piled raft design, a combination analysis of settlement behavior with the foundation factor of safety is preferred, in which the allowable settlement and bearing capacity of the piled raft can be considered simultaneously. However, the design of the piled raft foundations in this area has very little information available.

Based on the finite element modeling, Lee et al. [18] and Cho et al. [19] conducted parametric studies on the piled raft foundation in clayey soil, and the settlement behavior of piled raft was discussed in detail. The results show that the average settlement ratio decreases nonlinearly with the increasing of the overall factor of safety and is affected by the soil stiffness. However, for the long computational time needed in the FE modeling, the influences of soil conditions and pile configurations are not investigated thoroughly, and the design formulas or charts that can account for the settlement variation characteristic with the foundation factor of safety under different soil conditions are not presented.

Based on the boundary element method, a practical analysis method for the piled raft foundation is presented in this paper. The 3D interactions between the soils, piles and raft are considered, and the soil is assumed as continuous medium. The accuracy of this method is validated against the results of the existing numerical simulations and field measurements. Based on this study proposed analysis method, an extensive parametric study is performed to investigate the relationship between the normalized settlement and the overall factor of safety of the piled raft in clayey ground, and then a design chart considering the variation of normalized settlement with soil rigidity under different factors of safety is recommended to aid the practical design.

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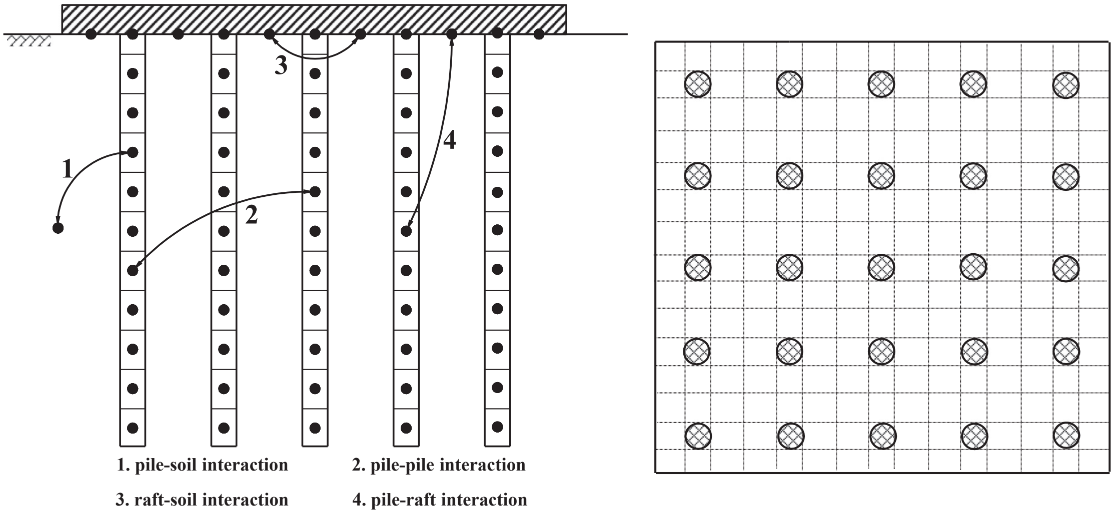
https://doi.org/10.1016/j.compgeo.2018.07.023
Received 10 April 2018; Received in revised form 4 July 2018; Accepted 22 July 2018



(a) side view (b) plan view

Fig. 1. Analysis model of rigid piled raft: (a) side view; (b) plan view.

2. Method of analysis

A reasonable compromise between excessive complexity and unacceptable simplicity is provided by boundary element methods (BEM), in which only the pile–soil and raft –soil interfaces are discretized and the number of sets of equations to be solved is generally smaller than the finite element or finite difference methods. Solutions such as stresses and displacements can be obtained directly by solving these sets of equations. As this method provides a direct and fast solution for the analysis, and requires a moderate amount of computer storage space, it has been developed by a number of researchers and are widely used for the analysis of large piled raft foundation in practice [22].

In this study, based on the boundary element method, a practical analysis method for rigid piled raft foundation under vertical load is employed, the model of which is shown in Fig. 1. Similar to the discretization of the pile–soil interface into a number of cylindrical elements, the raft–soil interface is discretized into a number of rectangular elements. The behavior of each element is considered at a node (located at the centre of the element). Each raft element is acted upon by vertical uniform normal stress. Thus, only the vertical displacement is considered in the study. Since a rigid raft is assumed, the head settlement of each pile under the raft is identical and the differential settlement of raft is ignored. Based on the assumption of rigid raft, the computational efficiency will be significantly improved. As discussed by Basile [14], except for thin rafts, the maximum settlement and the load sharing between the raft and the piles are little affected by the raft rigidity. In practical applications, a simple verification of the assumption of rigid raft may be performed by calculating the raft–soil stiffness ratio (K_{rs}) as recommended by Horikoshi and Randolph [23]

$$K_{rs} = 5.57\frac{E_r}{E_s}\frac{1-\nu_s^2}{1-\nu_r^2}\left(\frac{B_r}{L_r}\right)^{0.5}\left(\frac{t_r}{L_r}\right)^3 \tag{1}$$

where the subscripts r and s denote the raft and soil properties, respectively, E is the Young's modulus, ν is the Poisson's ratio, B_r is the raft width, L_r is the raft length, and t_r is the raft thickness. For values of $K_{rs} > 5$–10, the raft can be considered as rigid while a lower limit $K_{rs} > 1.5$ may be assumed for practical purposes [24].

Four interactions between the foundation elements and around soil are considered in this study: (1) pile-soil interaction, (2) pile-pile interaction, (3) raft-soil interaction, and (4) pile-raft interaction. The steps of the pile-soil-raft interactions analysis are briefly given below.

(1) piles in total number of n_p are analyzed in the model, with each pile is discretized into n_{ep} nodes as depicted in Fig. 1, and it is assumed that there are a total number of k and n ($= n_p \times n_{ep}$) nodes for the raft and pile shaft, respectively.

(2) The vertical soil deformation at the nodal is determined using the principle of superposition, see Eq. (2).

$$\{w_s\} = [F_s]\cdot\{P_s\} \tag{2}$$

where $\{w_s\}$ and $\{P_s\}$ are column vectors of soil vertical displacements and soil reaction respectively, the expansions are in Eq. (3).

$$\begin{cases}\{w_s\} = [w_s^{r1}, w_s^{r2}, \ldots, w_s^{rk}, w_s^{p1}, w_s^{p2}, \ldots, w_s^{pn}]^T \\ \{P_s\} = [P_s^{r1}, P_s^{r2}, \ldots, P_s^{rk}, P_s^{p1}, P_s^{p2}, \ldots, P_s^{pn}]^T\end{cases} \tag{3}$$

$[F_s]$is the flexibility matrix of the piled raft system and is expressed in Eq. (4).

$$[F_s] = \begin{bmatrix}[F_{rr}] & [F_{rp}] \\ [F_{pr}] & [F_{pp}]\end{bmatrix} \tag{4}$$

where:

(1) $[F_{rr}]$ is the submatrix of raft-soil-raft interaction, and it can be calculated by Eq. (5), which is suggested by Kitiyodom and Matsutum [9]:

$$F_{ii} = \frac{(1-\nu_s)(1-\exp(-H_{soil}/(2r_{equ})))}{4G_s r_{equ}} i = j \tag{5}$$

where H_{soil} is depth of compressible soil layer, typically H_{soil} is equal to three times of pile length L_p; r_{equ} is the equivalent radius of raft element; G_S is the soil shear modulus; ν_s is the Poisson's ratio of the ground soil. The flexibility coefficients (off-diagonal elements) of raft-soil-raft interactions are calculated by Eq. (6) suggested by Chow [25]:

$$F_{i,j} = \frac{(1-\nu_s^2)}{\pi E_s r_{equ}}\sin^{-1}\left(\frac{r_{equ}}{r_{i,j}}\right) i \neq j \tag{6}$$

where $r_{i,j}$ is the radial distance between the centers of element i and element j of the raft. E_s is the soil Young's modulus.

(2) $[F_{pp}]$ is the submatrix of pile-soil-pile interaction; $[F_{rp}]$ and $[F_{pr}]$ are the submatrices of pile-soil-raft interaction. The elements of these matrices are obtained via the Mindlin's displacement solution [26], and the detailed expressions are illustrated in Appendix A.

(3) The raft is discretized into sub-elements and the piles are discretized into two-node elements with an axial mode of deformation. Based on the finite element analysis of the pile-raft system, the load-deformation relationship of the pile-raft system may be written as in Eq. (7).