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Numerical analysis of unconnected piled raft with cushion

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Abstract The analysis of piled raft foundations has improved over the last few decades to account for the combined contribution of raft and piles to provide a more efficient system. Unconnected piled raft foundation (UCPRF) is an economical and efficient system where the piles are separated from the raft by a structural fill cushion. The cushion acts to redistribute the load between raft and piles. In this study, ABAQUS finite element analysis software was used to investigate the load sharing capacity of the system. The effects of cushion, piles number, diameter, and length as well as raft thickness in reducing settlement were investigated. The study showed that UCPRF provides an economical alternative for a connected piled raft foundation subject to vertical axial loads. In the unconnected system, plain concrete piles are adequate, without the need of reinforcement, where their basic function is to strengthen the top and reduce the maximum settlements.

1. Introduction

Raft foundations are generally used to support buildings and structures, with or without basements, in dry or high water table conditions. When the shallow subsoil conditions are unfavorable (unsafe bearing capacity or excessive settlements) then load bearing piles are used to transfer the entire load to more competent soil layers. In many cases, the maximum and differential settlements are the controlling factors for the selection of piled raft foundations. The piled raft foundation consists of three load-bearing elements; namely piles, raft and subsoil. According to their relative stiffness, the raft distributes the total load transferred from the structure to the top soil and the connected piles. In conventional design of piled foundations, it was usually postulated that the overall load is supported by the piles. In piled raft foundation systems, the contribution of the raft is taken into consideration to verify the ultimate bearing capacity and the serviceability of the overall system. The concept of using piles to reduce raft settlement was first proposed by Burland et al. [1] who placed one pile under each column of a building. As reported by Solanki et al. [2] several reports were published on the use of piles as settlement reducers. Zhuang and Lee [3] used a finite element method to study the load sharing between the piles and the raft. They observed that load sharing between the piles in piled raft system was affected by pile stiffness, raft rigidity and pile length to width ratio. They also observed that as pile length

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increases the pile rigidity decreases and the load distribution become more uniform. Ta and Small [4] developed a method, which was based on finite layer method, for the analysis of piled raft foundation in layered soil. They found that load sharing between the piles in piled raft system was influence by thickness and stiffness of soil layer. Ta and Small [5] observed that load shared by piles increases as the bearing strata becomes stiffer. Russo [6] developed a numerical method for piled raft system, which considers non-linearity of the unilateral contact at the raft–soil interface and the nonlinear load–settlement relationship. They stated that non-linear analysis should be considered for the piled raft system because piles act as settlement reducers and their ultimate load capacity may be reached. Poulos [7] developed a simplified analysis method as a tool for preliminary design of piled raft foundation system. Poulos [7] reported that when a raft foundation alone does not satisfy the design requirements, using a limited number of piles might improve the performance of such foundations in terms of ultimate load capacity, total and differential settlements. Reu and Randolph [8] used a finite element method to model piled raft foundation in over consolidated clay. Reu and Randolph [8] observed that pile–raft interaction leads to an increase in the skin friction with an increase of the load or increase of the settlement.

Nakai et al. [9] performed centrifuge model tests followed by a parameter survey based on the finite element analysis for structures supported by piled foundations and piled raft foundations. Nakai et al. [9] showed that the effect of the pile head connection condition on the response characteristics of a superstructure is fairly small when compared to the type of the foundation. They also showed that the load bearing characteristics of piles were not affected, even when piles are not connected to the raft foundation. Nakai et al. [9] concluded that even for the case where piles are not connected to the raft, they have significant contribution to the dynamic soil–structure interaction.

El-Mossallamy et al. [10] reported that the settlement and the load sharing between the raft and piles are the main factors that control the design of piled-raft foundations. Comodromos et al. [11] observed that in case of pile cap loaded by a non-uniform vertical load, the load is mainly carried by the piles in the vicinity of the loaded area if the cap thickness is less than the pile diameter. They found that if the cap thickness is greater than the pile diameter, the type and the location of the applied load have no effect on the distribution of the load to the piles. In traditional pile–raft systems, piles are connected to the raft and extend down into competent soil at depth. While these piles are effective in reducing raft settlement, they may lead to significant shear forces and bending moments that will affect the structural design of the raft. In order to overcome problems of high stresses in the piles and raft, Cao et al. [12] and Wong et al. [13] suggested that the piles be disconnected from the raft and to treat these piles as reinforcement to the subsoil rather than as structural members. Moreover, the gap between the raft and the unconnected piles can be filled with a cushion of structural fill material. Liang et al. [14] stated that the cushion, which is composed of a sand-gravel mixture compacted in layers between the raft and top of piles, plays an important role in mobilizing the bearing capacity of the subsoil and modifying the load transfer mechanism of piles. Since then it has been described by many authors, including Lee et al. [15], Eslami and Malekshah [16] and Sharma et al. [17].

2. Methodology and developed model

A three-dimensional finite element commercial software (ABAQUS) is used in the analysis. Site investigation data are collected from Lake Mariout area, west of Alexandria city in Egypt, where large industrial and residential development have been recently planned and constructed. In general, the subsoil at the site consists of a top layer of medium dense sand and having an average thickness of 4 m. The top sand is followed by soft to very soft silty clay, extending down to a depth of 10 m. The soft clay is followed by a layer of stiff-to-very stiff clay extending down to a depth of 15 m. The fourth layer is dense sand and extends down to a depth of 35 m. Groundwater table exists at ground surface. The soil parameters are summarized in Table 1. In the analysis, raft and piles are modeled as elastic materials. The nonlinear behavior of soil is modeled with elastic ideally plastic constitutive model. The soft clay layer is modeled as an elastoplastic material with a non-associated flow rule and using the modified cam clay plasticity model. The other soil layers are modeled by elastic ideal plastic constitutive model following Mohr–Coulomb yield criterion. Soil mass is described by an eight-node brick, tri-linear displacement and tri-linear pore pressure element (C3D8P). Raft, pile and cushion are modeled as elastic materials by an eight-node linear brick element with reduced integration and hourglass control (C3D8R). A vertical pressure of 215 kPa is imposed on the raft, as a distributed load. The cushion, which is composed of coarse grained soil compacted in layers, is shown schematically in Fig. 1. Fig. 2 shows the finite element mesh for the unconnected system, which is comprised of the raft, the soil and the piles.

3. Parametric study

The main purpose of the parametric study is to investigate the performance of the unconnected piled raft of various geometries and dimensions. The parameters studied included, cushion thickness and properties, number of piles, pile's diameter and length and raft thickness. Details of the unconnected piled rafts that analyzed in this study are described below and are summarized in Table 2.

3.1. Verification of developed model

To validate the results of the developed model (ABAQUS 3-D model), an example of a piled raft presented by Poulos [18] is demonstrated. Poulos [18] presented this example of a raft supported on 9 piles, one under each column to evaluate the efficiencies of different analyses methods for predicting the behavior of piled-raft foundations. The rectangular raft is 10 m × 6 m and has a thickness of 0.5 m. The piles are 0.5 m in diameter and 10 m in length. The raft and soil are modeled with elastic properties. In addition, a 0.25-m-thick cushion of the same properties of soil is used to study the effect of unconnected system on the maximum settlement, corner pile settlement and percent of load taken by piles. Poulos [18] predicted the settlement and percent of load taken by piles of this piled-raft example using 6 analyses methods; (1) simplified PDR, (2) Geotechnical analysis of raft with piles (GARP5 software), (3) Geotechnical analysis of strip on piles (GASP