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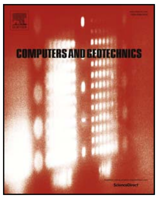

Research Paper

Performance of micropiled rafts in clay: Numerical investigation

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ABSTRACT

The micropiled raft (MPR) offers an efficient foundation system that combines the advantages of micropiles and piled rafts that can be used as primary foundation system or to enhance an existing raft foundation. In this paper, a finite element model (FEM) calibrated and verified with centrifuge tests was used to carry out a numerical investigation on the performance of MPR in clay. A total of 26 different cases were analyzed in this study to assess the behaviour of MPR in clay taking into account a number of factors that may influence its behaviour such as: the number of micropiles (MPs), the spacing to micropile diameter (S/D_{mp}), the raft thickness, and type of loading. The outcomes of this investigation should help in understanding the effect of these factors on the MPR axial stiffness, including; differential settlement; load sharing between the MPs and the raft; the raft bending moment and micropiles skin friction. Moreover, the ability of the Poulos-Davis-Randolph (PDR) method to evaluate the axial stiffness of a MPR for the preliminary design stage is examined. It was found that the MPR system can increase the tolerable bearing pressure by 100% compared to an isolated raft system. In addition, an adjustment factor (ω_{PR}) for PDR method was introduced to account for the raft flexibility. Equations were proposed in order to design MPR systems in terms of load sharing between micropiles and the raft.

1. Introduction

Similar to cast-in-place piles, micropiles are constructed by drilling holes into the ground and filling the holes with cement grout and a reinforcing element. In current practice, micropiles of diameters up to 300 mm are used to support new or existing foundation systems [1]. They can be constructed by placing the grout under gravity action or by applying injection pressure, which is normally about 0.5–1 MPa. A micropile transfers its load through skin friction to the soil in the bonded area between the grout and the soil.

With recent advancements in drilling equipment allowing for drilling in almost any ground condition, micropiles can be installed at any angle and with minimal noise, vibration, and disturbance. In addition, the relatively small size of the equipment has allowed for the underpinning of existing foundations, even in restricted access situations [2]. The capacity range of micropiles has increased considerably, and consequently, micropiles are becoming a preferred foundation option in many applications including high-rise buildings.

The basic concept of a micropiled raft (MPR), is similar to the concept of a piled raft, which is a composite structure with three components: subsoil, raft and piles. These components interact through a complex soil-structure interaction scheme, including pile-soil interaction, pile-soil-pile interaction, raft-soil interaction, and piles-raft interaction. The piled raft foundation system offers some advantages over the pile group design in terms of serviceability and efficient utilization of materials. For a piled raft, the piles will provide sufficient stiffness controlling the maximum and differential settlements at the serviceability load, while the raft will provide additional capacity at the ultimate load. Micropiled rafts combine the advantages of micropiles and piled rafts, but there are no guidelines on their performance or design.

1.1. Objectives and scope of work

An MPR offers an effective foundation system that combines the benefits of micropiles and piled rafts. However, to the knowledge of the author, there have been no studies considering the performance of MPRs or any guidelines for their design. Therefore, there is a need to thoroughly assess the performance of MPRs installed in clay and develop (some) guidelines for their design. In this study, the effects of the number of micropiles, spacing-to-micropile diameter ratio, S/D_{mp}, and raft thickness on different MPR performances are evaluated using 3D finite element analysis. The performance of the MPR is evaluated in

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terms of axial stiffness; differential settlement; load sharing between the micropiles and the raft; and the raft bending moment. The numerical model used in the current study was calibrated using results obtained from geotechnical centrifuge tests of MPRs in clay. In addition, the FEA examined the ability of the PDR method to evaluate the axial stiffness of MPRs for the preliminary design stage.

1.2. Background

Abd Elaziz and El Naggar [3] conducted field load testing to investigate the performance of hollow bar micropiles in cohesive soil. Three axial compression tests and two axial tension tests were performed on single micropiles. It was concluded that the axial capacity of hollow bar micropiles is higher than the values suggested by the FHWA for a Type B micropile. Drbe and El Naggar [4] evaluated the suitability of the FHWA [1] to design hollow bar micropiles in cohesive soil, as well as to evaluate the performance of hollow bar micropiles with different drilling bits to hollow bar diameter ratios. Eight micropiles were installed using 76 mm hollow bars with a total depth of 5.75 m. Six micropiles were constructed using a 228 mm drill bit and two were constructed using a 178 mm drill bit. The micropiles were tested in the field under both axial monotonic and cyclic axial loading. They found that the grout/ground bond strength value suggested by the FHWA [1] for Type B micropiles underestimates the actual bond strength for hollow bar micropiles. They also found that the micropile diameter increased by 10–20% over the size of the drill bit.

Han and Ye [5] performed load testing on a square raft (1.5 m × 1.5 m) supported by four micropiles with the diameter, D_{mp} = 150 mm and spaced at 750 mm (i.e., $5D_{mp}$). The results showed that the micropiles carried about 70–86% of the additional load that was applied to the raft after it was underpinned by the micropiles. Abd Elaziz and El Naggar [6] conducted full-scale load tests on two hollow bar micropile groups installed in clayey soil. The results suggested that the group capacity can be calculated using a group efficiency factor of one. However, these studies did not evaluate the effects of raft flexibility on the interaction between the raft and soil, the load sharing between the raft and the micropiles, and the differential settlement of the system.

It is difficult to carry out full-scale testing on a micropile group (MPG) or micropiled raft (MPR), especially with a large number of micropiles due to the limitation in equipment and high costs of such tests. Alternatively, the geotechnical centrifuge is employed in order to study the behaviour of micropiles and MPGs subjected to different loading conditions. Rose et al. [7] investigated the performance of different configurations of groups of small diameter piles (300 mm), installed in clay using geotechnical centrifuge testing and numerical modeling. It was found that the failure mechanism for the perimeter groups consisting of 14–20 piles, with $1.75D_p$ spacing, was a block failure with a group efficiency ratio of about 0.9. Several micropile load tests were conducted in order to evaluate the lateral performance of micropiles. For example, Richards and Rothbauer [8], Long et al. [9], Shahrour and Ata [10], and Teerawut [11].

Many researchers used the finite element method (FEM) to perform comprehensive parametric studies of MPG and MPR. Shahrour et al. [12] conducted a 3D finite element analysis on a single micropile and an MPG in order to evaluate their performance under seismic loading. They found that the behaviour of micropiles was affected by the number and spacing of micropiles; as well as the locations of the micropiles within the group. They used 20-node solid elements to represent the soil. To eliminate the boundary effect, the base of the model was placed at a depth equal to 1.5 times the micropile length and the lateral boundaries were placed at 6 L_{mp} from the micropile axis. Sadek and Shahrour [13] investigated the behaviour of inclined micropiles subjected to dynamic loading using 3D FEA. They compared the behaviour of a vertical MPG with a group of inclined micropiles ($\alpha_i = 7^\circ$, 13° and 20°) with a spacing-to-diameter ratio, $S/D_{mp} = 5$. The soil was considered to be homogeneous and was modeled as linear elastic material. The 10 m micropiles were modeled using 3D-beam elements. The lateral boundaries were placed at a distance of 240 micropile diameter (D_{mp} = 0.25 m) from the central axis of the MPG. They demonstrated that the numerical model has successfully modeled the behaviour of the micropiles.

Abd Elaziz and El Naggar [3] investigated the behaviour of hollow bar micropiles installed in clay using a 2D axisymmetric finite element model, which was calibrated using field test results. The calibrated model was then used to study the effect of installation methodology, the geometry of hollow bar micropile and shear strength of surrounding soils on the overall capacity of a micropile. The hollow bar was modeled as a linear elastic material and the grout was simulated using a nonlinear elastic-plastic model. The soil was simulated as an elastic-plastic material with Mohr-Coulomb failure criterion. The horizontal boundary at the base of the model was placed at 1.75 L_{mp} from the top of the model and the side boundary was located at 25 D_{mp} from the micropile center. Abd Elaziz and El Naggar [6] extended this study to evaluate the performance of the hollow bar micropile groups in cohesive soil. The vertical boundaries were located at 3.5 times the width of the pile cap and the base boundary was at a depth equal to 1.75 L_{mp} from the ground surface. Their study showed that the group efficiency factor was approximately 1. In addition, they produced interaction factors diagrams that can be used to calculate the group settlement using the interaction factors method.

Numerous studies have been conducted in order to evaluate the piled raft performance and the use of piles as a reducer for maximum and differential settlements of raft foundation. Of particular note, the studies by Poulos and Davis [14]; Clancy and Randolph [15,16]; Randolph [17]; and Poulos [18] resulted in an analytical method widely known as the Poulos-Davis-Randolph (PDR) method, which can be employed to evaluate the axial stiffness of piled raft for preliminary design purposes. Katzenbach et al. [19] reported 10 case histories of piled raft foundations constructed in Frankfort clay between 1983 and 2001. These foundations support high-rise buildings with heights ranging from 52 m to 257 m. The piled raft foundations reduced the maximum and differential settlements compared to shallow foundations and conventional rafts. In addition, the internal forces and bending moment of the rafts were reduced due to the use of piles. It was found that the load carried by the raft ranged between 20% and 70% of the total load. They concluded that the piled raft design concept could reduce the number of piles by up to 60% compared to conventional pile foundations.

Centrifuge testing was used as an effective technique to investigate the behaviour of piles, pile groups and piled rafts in clay. For example, Horikoshi and Randolph [20] investigated the differential settlement of a piled raft foundation in clay soil with an average undrained shear strength of 40 kPa. They considered three different configurations as follows: 9, 21 and 69 piles placed at a spacing to diameter ratio, $S/D_p = 8$. The piles were 3.15 mm in diameter and the circular raft was 140 mm in diameter (model scale n = 50). They concluded that the raft differential settlement could be reduced by 30% using nine piles uniformly distributed at the raft center.

FEA was also used to conduct comprehensive parametric studies of piled raft foundations in clay. Maharaj and Gandhi [21] performed a 3D analysis of a piled raft foundation installed in clay soil. They investigated the effects of the soil elastic modulus and raft thickness on the load-displacement curve for both a raft and a piled raft. The side boundaries were placed at a distance equal to the raft width, B_r, from the raft center and the bottom boundary was a distance B_r from the bottom of the piles. Reul and Randolph [22] demonstrated the ability of FEA to predict the overall settlement, differential settlement and the load carried by the piles for various piled raft foundations supporting existing high-rise buildings resting on overconsolidated clay. The finite element model was 4.8 B_r wide and 2.2 B_r deep. The results from the finite element analyses were in good agreement with the measured