Performance of Piled-Raft System under Axial Load

Performance du système radier pieux sous chargement axial

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ABSTRACT: Many high rise buildings are founded on piled raft foundation systems, which generated a significant interest in understanding the performance characteristics of this foundation system. The soil-structure interaction for piled raft foundations involves the interaction of different components including: the pile-soil interaction; pile-soil-pile interaction; raft-soil interaction; and piles-raft interaction. To account for this complicated interaction scheme, three-dimensional consideration of the problem is necessary. In this paper, a 3D finite element model is established to analyze the response piled raft foundation system installed in cohesionless soil with linearly increasing stiffness with depth. The model was calibrated/verified using geotechnical centrifuge test data. The calibrated model was then employed to investigate the effect of raft dimensions and piles diameter and spacing on the load sharing between piles and raft.

RÉSUMÉ : Durant ces dernières années, un grand nombre de projets ont été construit en utilisant le concept du système de fondation de radier sur pieux. C'est ainsi que de nombreuses études ont été menées afin d'examiner et de comprendre la performance de ce système soumis à des charges verticales. L'interaction sol-structure pour ce système implique différentes interactions comme l'interaction pieux-sol, pieux-radier, radier-sol et finalement l'interaction pieux-radier. Par conséquent, une analyse numérique tridimensionnelle est nécessaire dans un cas aussi complexe. Dans cet article, une modélisation 3-D par éléments finis a été effectués pour analyser la réponse d'un système radier pieux sur un sol sans cohésion et qui présente une rigidité qui augmente linéairement avec la profondeur. Ce modèle a été calibré à partir de résultats expérimentaux obtenus sur des essais en centrifugeuse. Les résultats numériques ont été utilisés pour étudier l'effet de plusieurs paramètres, comme l'épaisseur et la largeur du radier, l'espacement et le diamètre des pieux, sur le transfert des charges entre le radier et les pieux.

KEYWORDS: piled raft foundation, soil-structure interaction, 3D FEM, centrifuge, cohesionless soil, piled-raft load sharing.

1 INTRODUCTION

A piled raft foundation is a composite structure with three components: subsoil, raft and piles. These components interact through a complex soil-structure interaction scheme, including the pile-soil interaction, pile-soil-pile interaction, raft-soil interaction, and finally the piles-raft interaction.

The construction of a piled raft foundation system generally follows the same practices used to construct a pile group foundation in which a cap is normally cast directly on the ground. Although the construction of the cap in this manner should allow a significant percentage of the load to be transmitted directly from the cap to the ground, the pile group is usually designed conservatively by ignoring the bearing capacity of the raft (i.e. the pile cap). In many cases, the raft alone can provide adequate bearing resistance; however, it may experience excessive settlement. Therefore, the concept of employing piles as settlement reducers was proposed by Burland et al. (1977), where the piles are used to limit the average and differential settlements.

The vertical load applied to a piled raft foundation is assumed to be transmitted to the ground by both the raft and piles, which differentiates the design of a piled raft from a pile group. The percentage of load taken by each element depends on a number of factors, including: the number and spacing of piles, subsoil conditions, and the raft thickness.

A piled raft design 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 to control the settlement and differential settlement at serviceability load while the raft will provide additional capacity at ultimate load. The raft in a piled raft design transmits 30% to 50% of the applied load to the soil (Clancy and Randolph, 1993). Typically, a piled raft design will require fewer piles in comparison to a pile group design to satisfy the same capacity and settlement requirements. Additionally, if any of the piles in a piled raft becomes defective, the raft allows re-distribution of the load from the damaged pile to other piles (Poulos et al. 2011). Furthermore, the pressure applied from the raft to the subsoil may increase the confining pressure for the underlying piles, which in turn increases the pile load carrying capacity (Katzenbach et al. 1998).

Analytical, numerical and physical modeling approaches were employed to evaluate the performance of piled raft foundations. The simplified Poulos-Davis-Randolph (PDR) method (Poulos 2001) combines the analytical methods proposed by Poulos and Davis (1980) and Randolph (1994) for the analysis of piled rafts. Clancy and Randolph (1993) proposed a plate-on-spring method in which the raft is represented by a plate and the piles are represented by springs. Additionally, there are methods that combine the finite element analysis for the raft and the boundary element analysis for the piles (e.g. Ta and Small, 1996), and methods that are based on three-dimensional finite elements modeling (e.g. Katzenbach et al.,1998). Piled raft behavior was also investigated employing physical modeling such as centrifuge testing (e.g. Horikoshi et al., 2002, 2003a and b; Matsumoto et al., 2004a and b).

This paper investigates the performance of piled raft foundations and their load sharing mechanism employing a 3D finite element model calibrated/verified using geotechnical centrifuge data.

2 DEVELOPMENT OF FINITE ELEMENT MODEL

The development of the FEM in this study consisted of three main steps. First, a 3D FEM was established to simulate the behavior of piled raft foundation considering an appropriate size mesh and number of elements. Second, the results of a centrifuge study of piled raft performed by others were used to calibrate the FEM created in this study. Lastly, the calibrated FEM was employed to perform a parametric study to evaluate the effect of different parameters on the overall performance of piled raft foundation.

2.1 *Description of FEM*

A finite element model (FEM) was developed using the Plaxis 3D software package (Plaxis bv. 2011). A quarter of the piled raft foundation system was modeled taking advantages of symmetry across the x and y-axes to reduce the computation effort and time. The boundaries of the model were set at a distance equal to 1.5B~2B (where B is raft width) measured from the edge of the raft, and the depth of the model was approximately two times the pile length as shown in Figure 1.

The model was built using about 275,000 3D 10-node tetrahedral elements. The average size of the element was approximately 110 mm. The large number of small size elements assured high accuracy of the results at locations where non-linear behavior is anticipated (e.g. raft base, pile base and pile circumference). The load was applied using uniform prescribed displacement applied at the top of the raft, and the corresponding load was evaluated.

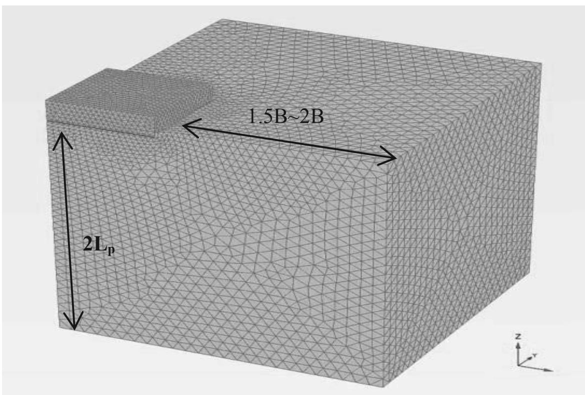

Figure 1. The FEM used in the current study.

2.2 *Centrifuge testing used to calibrate FEM*

Horikoshi et al. (2002, 2003a, b) employed geotechnical centrifuge testing in order to simulate the complicated soil-structure interaction problem for a piled raft under different types of loading. The results of the vertical loading case from their studies will be considered herein to calibrate the 3D finite element model. The tests were conducted under 50g centrifugal acceleration. The model consisted of four piles rigidly connected to the raft. The raft and piles models were made of aluminum. Toyoura sand was used as the model ground (Horikoshi et al. 2003a). Table 1 summarizes the dimensions of the model in both model and prototype scales.

Table 1. The dimensions of the model in both model and prototype scales.

	Model	Prototype (n=50)
Diameter (mm)	10	500
Wall thickness (mm)	1	Solid
Materials	Aluminum	Concrete
Pile length	170 mm	8.5 m
Modulus of Elasticity	71 GPa	41.7 GPa
Raft thickness	40 mm	2.0 m
Raft width (square)	80 mm	4 m
Pile Spacing	40 mm	2 m
Number of piles	4	4

Cone penetration tests (CPT) were performed in-flight to evaluate the sand strength using a miniature cone penetrometer. The cone tip resistance profile is shown in Figure 2. It is noted that the strength (and stiffness) increased with depth, which is expected for sand soil. This strength profile will be simulated in the FEM through the input parameters such as the initial modulus of elasticity and the incremental modulus of elasticity, which will account for the increase in stiffness with depth.

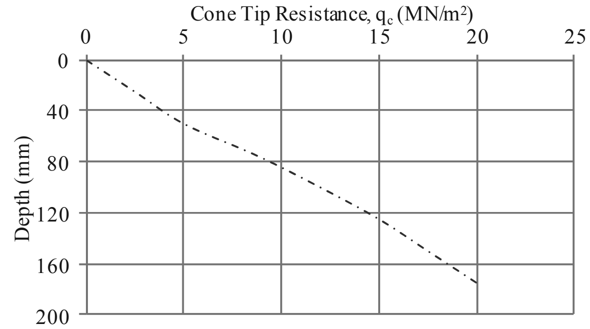

Figure 2. In-flight results for CPT (after Horikoshi et al. (2003a).

2.3 *Calibration of FEM*

The behavior of the Toyoura sand was simulated using a linear elastic-perfectly plastic Mohr-Coulomb constitutive model. Matsumoto et al. (2004b) reported that the peak friction angle, ϕ, for Toyoura sand is about 45° and the reduction factor, R_{int}, at the interaction surface between the pile and Toyoura sand is 0.43 (Horikoshi et al., 2003a). The modulus of elasticity was correlated to the cone tip resistance, q_c, using the relationship proposed by Tomlinson (1996), i.e.

$$E = 2\sim4\, q_c \tag{1}$$

All input parameters used in the FEM are listed in Table 2.

The process of calibration was performed by refining the soil and interface properties in the FEM. This was done by adjusting the values of the interface reduction factor values at the pile-soil interface; and the estimated initial modulus of elasticity and incremental increase of modulus of elasticity with depth (i.e. within the range stipulated in Eq. 1). After a number of trials, the FEM a reasonable match with the centrifuge test results was achieved as demonstrated in Figure 3.

The slight nonlinear behavior observed at relatively low displacement is attributed to the movement of the pile caused by slippage at pile-soil interface and increased strains at the pile base, reaching plastic condition. This piles movement resulted in more intimate contact between the raft and soil, which resulted in a portion of the load to be transmitted through the contact at the raft-soil interface.

Table 2. The parameters used in the FEA.

	Soil	Concrete
Constitutive Modeling	Mohr-Coulomb	Linear Elastic
Unit Weight (kN/m^3)	14.6	23.6
Angle of internal friction	45°	-
Modulus of Elasticity	4500 kN/m^2	23.6 GN/m^2
Poisson's ratio	0.175	0.21
Stiffness increases with depth	Yes	No
Incremental Modulus of Elasticity (kN/m^2/m)	6500	-
Interface reduction factor	0.43	-

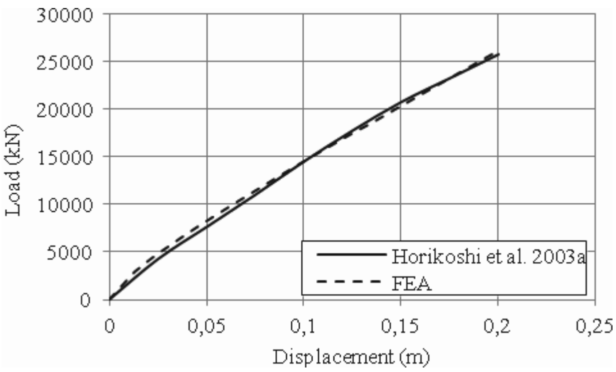

Figure 3. Comparison of the FEA and centrifuge test results.

3 EFFECT OF PILED RAFT PARAMETERS ON ITS LOAD SHARING SCHEME

In a piled raft, different factors affect the load sharing between the raft and piles but with varying influence on the load sharing. The raft flexibility, which is governed by its thickness and the spacing between the piles, affects the load sharing between the raft and piles, and will be investigated. For example, increasing the raft width is expected to increase the load transmitted by the raft. On the other hand, increasing the pile diameter is expected to increase the load transmitted through the piles. The effects of these two parameters are examined and the results obtained are discussed in this section. The load carried by the piles will be presented as a percentage of the total vertical load applied on the raft.

3.1 *Effect of raft thickness*

Brown (1969) evaluated the foundation flexibility using finite element analysis. He proposed a relationship between the thickness of the raft and its flexibility, given by:

$$K_f = \left[E_f/E_s\right]\left(\frac{2t}{s}\right)^3$$
(2)

Where E_f = Young's modulus for raft; E_s= average soil elastic modulus; t= raft thickness; and s= spacing between piles.

Thin or flexible rafts tend to deform more than rigid or thick rafts. This increased deformation of a flexible raft establishes intimate contact with the subsoil, resulting in increased load carried by the raft. Equation 2 may be used for the assessment of the flexibility of a piled raft, but considering the spacing between the piles instead of the raft width, B. Using the spacing between piles is appropriate in representing the flexibility of the piled raft as small pile spacing results in a s smaller deformation at the raft center in comparison with large spacing. Considering Eq. 2, the raft can be characterized according to the following conditions: (i) perfectly rigid if $K_f > 10$; (ii) perfectly flexible when $K_f < 0.01$; and (iii) intermediate flexibility at K_f varies between 0.01 to 10 (Mayne and Poulos 1999). The load sharing scheme for piled rafts with varying flexibility is investigated. Figures 4 and 5 show the load carried by the piles for two different pile spacing with various raft thicknesses as a function of the piled raft total displacement.

At initial small displacement, most of the load is carried by the piles; this is believed to be due to the lack intimate contact between the raft and subsoil. Similar behavior was reported by Horikoshi and Randolph (1996). As the displacement increases, the proportion of the load carried by the piles dropped significantly at about 7% of the total displacement and continued to decrease gradually after that. At about 80% of displacement, the load transmitted by the piles reached a plateau and became almost constant. The variation in load carried by the pile is noticeable at S/D=4; the load carried by the piles is about 35% and 45% for raft thickness, t= 0.3 m and t= 2 m, respectively. The raft flexibility, K_f = 0.2 and 8.73 for these two cases. On the other hand, K_f = 0.29 and 0.02 if the spacing is S/D=10 for the same raft thickness values. Due to the narrow range of K_f for the large spacing case, the variation in percentage of load carried by the piles is insignificant, and it is approximately 25%. This is attributed to the large pile spacing, which renders even the thick raft flexible, resulting in increased raft soil interaction, compared to the case of the raft with small pile spacing. Poulos (2001) reported a similar percentage of 25% of the load carried by the piles.

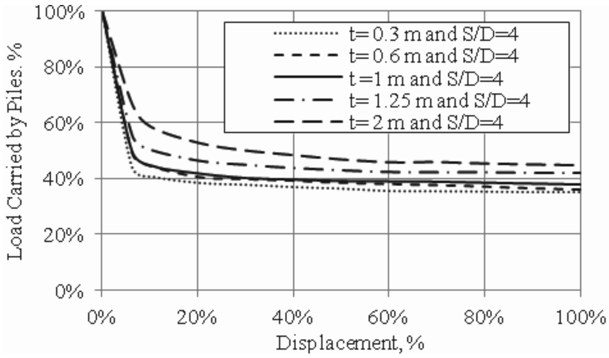

Figure 4. Load carried by piles with different raft thicknesses and S/D=4.

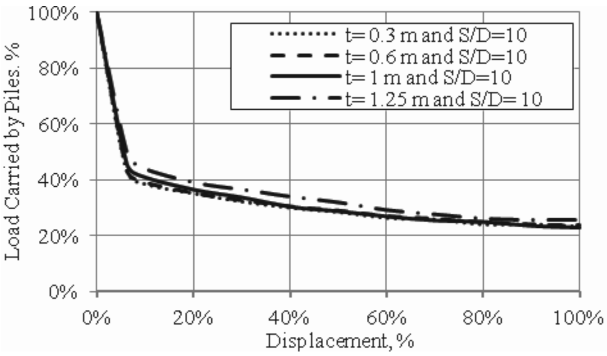

Figure 5. Load carried by piles piles with different raft thicknesses and S/D=10.

3.2 *Effect of raft size*

The raft width contributes to the bearing capacity of the raft. As the raft width increases, the contact area with the subsoil increases and hence the load carried by the raft increases. The load carried by the piles was evaluated for different raft widths varying from 4 m to 7 m with the same pile diameter (0.5m), spacing ratio (4D) and raft thickness (1.25 m) (i.e. relatively rigid raft) and the results are presented in Figure 6. As expected, Figure 6 shows that the load transmitted by the piles was reduced as the raft width increased. It is noted that the piles load decreased sharply until it reached a constant value at about 18% of the total displacement. As the raft width increased from 4 m to 7 m, the load transferred through the piles decreased by about 22%. As the load carried by the raft increases, however, it is important to carefully examine the total and differential settlements, which may rise due to the high level of stress beneath the raft.

3.3 *Effect of pile diameter.*

The pile diameter has a significant effect on its load carrying capacity and stiffness, which can affect the performance of the piled raft. To examine the effect of pile diameter on its load share in piled raft design, a raft with width, B = 7.2 m and piles spaced at S/D =4 is considered with pile diameter varying from 0.3 m to 0.9 m. Figure 7 demonstrates the percentage of load carried by the piles as the pile diameter changes. The load transferred by the piles increased from 18% to 33% of the total load as the pile diameter increased from 0.3 m to 0.9 m. The increase occurred because the piles started to interact with the soil across a larger surface area and thus more load carried by the piles. However, the effect of the pile diameter on the piles load share diminishes as the diameter reaches the higher end of the range considered. For example, the percentage of load taken by the piles increased by about 2% as the diameter increased from 0.7 to 0.9 m, while the difference for a smaller diameter was about 9% as the diameter increased from 0.3 to 0.5 m.

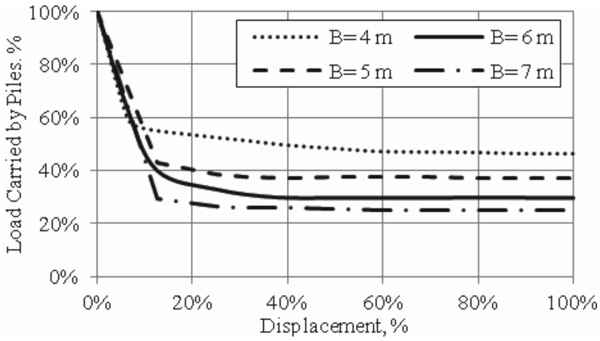

Figure 6. Load carried by the piles with different raft width.

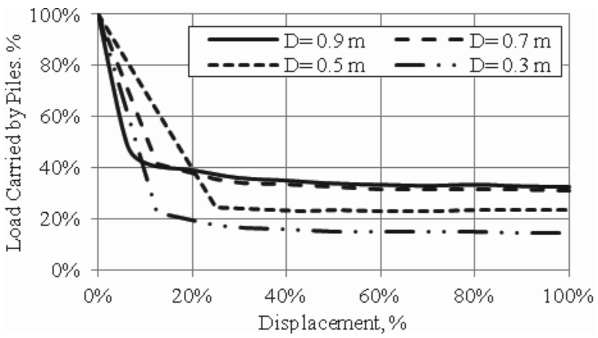

Figure 7. Load carried by the piles with different pile diameters.

4 CONCLUSIONS

Some of factors that affect the load sharing between the piles and raft in a piled raft foundation were examined using a 3D finite element model that has been calibrated/ verified by comparing its predictions with measurements made in a geotechnical centrifuge study. Based on the results of the 3D-FEA, a number of conclusions can be drawn as follows:

- The load share carried by piles is higher for a rigid raft ($K_f >$ 10) due to the minimal interaction between the raft and subsoil compared to the perfectly flexible raft ($K_f < 0.01$).
- The spacing between piles can be used to evaluate the raft flexibility instead of its width using Eq. 2.
- The percentage of load transmitted by the piles decreases by about 22% as the raft width doubled within the range considered.
- The percentage of load carried by piles increases as the pile diameter increases. However, the rate of increase is higher for small size piles and diminishes as the pile diameter increases.

Additional studies are required to evaluate the performance of a flexible piled raft considering the number of piles, pile length and loading scheme.

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