Centrifuge Model Study of Laterally Loaded Pile Groups in Clay

T. Ilyas; C. F. Leung; Y. K. Chow; and S. S. Budi

Abstract: A series of centrifuge model tests has been conducted to examine the behavior of laterally loaded pile groups in normally consolidated and overconsolidated kaolin clay. The pile groups have a symmetrical plan layout consisting of 2, 2×2, 2×3, 3×3, and 4×4 piles with a center-to-center spacing of three or five times the pile width. The piles are connected by a solid aluminum pile cap placed just above the ground level. The pile load test results are expressed in terms of lateral load–pile head displacement response of the pile group, load experienced by individual piles in the group, and bending moment profile along individual pile shafts. It is established that the pile group efficiency reduces significantly with increasing number of piles in a group. The tests also reveal the shadowing effect phenomenon in which the front piles experience larger load and bending moment than that of the trailing piles. The shadowing effect is most significant for the lead row piles and considerably less significant for subsequent rows of trailing piles. The approach adopted by many researchers of taking the average performance of piles in the same row is found to be inappropriate for the middle rows, of piles for large pile groups as the outer piles in the row carry significantly more load and experience considerably higher bending moment than those of the inner piles.

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Introduction

The performance of pile foundations subject to lateral load is of considerable importance in geotechnical practice. In the field, piles are often arranged in groups, and the behavior of a pile group may differ substantially from that of a single pile. The elasticity interaction factor approach (Poulos and Davis 1980) is commonly employed to evaluate the degree of interaction among piles in a pile group. Several full-scale field tests on pile groups subject to lateral loads have also been reported. These include studies on piles in sand (for example, Brown et al. 1988; Ruesta and Townsend 1997) and in clay (for example, Matlock et al. 1980; Brown et al. 1987; Rollins et al. 1998). Some degree of understanding on the performance of laterally loaded pile groups has been gained from these field studies.

Laboratory studies such as centrifuge model tests could provide further insight on the behavior of deep foundations. At present, much of the centrifuge model studies on laterally loaded pile groups were carried out in sand (for example, McVay et al. 1994, 1995, 1996, 1998; Remaud et al. 1998). Relatively few centrifuge model studies were conducted to investigate the performance of laterally loaded piles in clay and majority of these studies concentrated on the study of single piles (for example, Hamilton et al. 1991; Kitazume and Miyajima 1994). A series of centrifuge model tests was, therefore, initiated to examine the behavior of laterally loaded pile groups in normally consolidated (NC) and overconsolidated (OC) clay. In addition, the test observations are compared with those obtained from field studies. The observed pile–soil–pile interaction behavior is compared to that obtained from the elasticity interaction factor approach.

Experimental Setup

All the tests were conducted at 70 g on the National University of Singapore (NUS) Geotechnical Centrifuge, which has a radius of 2 m and comprises a balanced arm with dual swing platforms. The centrifuge has a capacity of 40 g tones and a maximum acceleration of 200 g. Details of the NUS Centrifuge are given in Lee et al. (1991). Fig. 1 shows a sketch of the model setup. The cylindrical stainless steel model container has an internal diameter of 550 mm and a height of 375 mm. An inverted U-shaped metal frame consisting of vertical and horizontal actuators was bolted onto the model container. The vertical actuator was attached to the center of the top of the metal frame while the horizontal actuator was attached to the left leg of the frame.

The model pile is made of a hollow aluminum square tube instrumented with ten levels of strain gauges to enable bending moment measurements along the pile shaft. At each level, two active strain gauges were glued onto the opposite faces of the model pile shaft and connected to two dummy gauges on a strain

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meter mounted on board the centrifuge to form a Wheatstone full bridge circuit. The instrumented pile was protected by a thin layer of epoxy having a final pile width of 12 mm that is equivalent to 840 mm in prototype scale. The flexural rigidity $E_I$ of the model pile is 384 kN cm$^2$, resulting in a prototype $E_{Ip}$ of 922 kN m$^2$. The model pile is 260 mm long with the lower 210 mm pile length to be inserted into the clay. At 70 g, the simulated prototype pile embedment pile length is 14.7 m. For calibration, the model pile was loaded as a cantilever beam at 1 g to calibrate the pile bending moment against the strain gauge circuit output from the strain meter. The model pile cap is made of 20 mm thick solid aluminum and placed at 50 mm (3.5 m prototype scale) above the ground level. The piles were tightly secured through openings in the pile cap using screws.

For the soil sample preparation, a 30-mm-thick sand layer was first placed at the bottom of the model container before placement of kaolin clay slurry. The kaolin clay has the following properties: average bulk unit weight $\gamma=16$ kN/m$^3$; average water content $=66\%$; liquid limit LL = 79.8%; plastic limit PL = 35.1%; compression index $C_v=0.55$; recompression index $C_{vp}=0.14$; and coefficient of permeability $k=2 \times 10^{-10}$ m/s. The NC kaolin clay sample was prepared in the following manner. First, kaolin clay slurry was thoroughly mixed at 150% of its LL and deaired for 24 h. The clay slurry was then placed in the model container to a height of about 380 mm and then consolidated under its self-weight in the centrifuge at 70 g to allow the excess pore water pressure in the clay to dissipate through the clay surface and the openings located close to the bottom of the container via the bottom sand layer. Ground settlements and pore water pressures in the soil were measured to monitor the progress of soil consolidation. In general, 6 h soil consolidation time was required to achieve an average degree of consolidation of at least 95% resulting in a final clay thickness of about 245 mm.

T-bar penetrometer tests, which were first introduced by Stewart and Randolph (1991), were carried out in-flight to determine the soil strength profile after soil consolidation. The penetrometer adopted in the present study has a cross bar of 25 mm long and 5 mm in diameter attached perpendicularly to the end of a vertical shaft to form a T. The penetrometer was pushed into the soil at a rate of 20 mm/s and its penetration resistance was monitored by a load cell mounted immediately behind the penetrometer. Stewart and Randolph (1991) recommended a bearing capacity factor of 10.5 to derive the soil strength from the penetration resistance. The test results revealed that the undrained shear strength of the NC clay varies linearly with depth from 0 at the ground surface increasing to about 20 kPa at about 15 m (prototype depth) below the ground level. Thus, the clay can be considered as soft clay.

For OC kaolin clay sample, a surcharge of 60 kPa was gradually placed on top of the clay slurry (also at 150% LL) in the model container at 1 g for about a week. The clay was then further consolidated under its self-weight in the centrifuge for about 6 h to achieve an average degree of consolidation of at least 95%. The final clay thickness was also about 245 mm. Results from in-flight T-bar tests after soil consolidation reveal that the soil strength increases from about 10 kPa at the ground surface to about 25 kPa at 15 m below the ground surface. The overconsolidation ratio gradually decreases from about 8 at the ground surface to almost unity at about 8 m below the ground surface.

**Test Procedure and Configurations**

After completion of consolidation for both NC and OC clays, the centrifuge was stopped to facilitate pile installation. The model pile/pile group was carefully jacked into the soil at 1 g by the servocontrolled vertical actuator using a closed-loop displacement feedback obtained from the vertical displacement transducer. The pile installation had to be done at 1 g, as it was very difficult to control the pile penetration depth in soft clay under high-g condition. Craig (1985) reported that unlike sand, the difference in the pile capacity for piles installed in clay at 1 g and at high g is relatively insignificant as the volume change during pile installation is relatively small. The pile installation was completed when the midheights of the pile cap and horizontal load cell were exactly aligned at the same elevation. The centrifuge was then spun up to 70 g again for about 1 h to enable the pore water pressure developed during pile installation to dissipate completely. A lateral load test was then conducted on the pile/pile group by displacing the pile cap using the servocontrolled horizontal actuator with a closed-loop feedback from the horizontal displacement transducer. The pile was displaced using displacement-control mode at a rate of 0.05 mm per second. The lateral load was monitored by a load cell mounted at the tip of the horizontal actuator. The lateral displacement of the pile cap was recorded by a highly accurate noncontact microlaser displacement transducer. The transducer used has a 40 mm measurement range and a sensitivity of 0.02 mm. The lateral load and displacement of the pile/pile group and strain gauge readings were recorded at regular intervals during the entire load test.

Pile groups of up to 16 piles were investigated in the present study. Figs. 2(b–e) provide a plan view of the pile configuration for tests involving piles with center-to-center pile spacing of $3D$ ($D =$ pile width), while Figs. 2(f and g) provide the pile group configuration for tests with piles at $5D$ spacing. In most cases,
tests were carried out in both NC and OC kaolin clay. The definition of lead row piles (piles in the row furthest away from the lateral pushing load), middle row piles (middle second and third rows in the case of $4 \times 4$ pile group) and rear row piles as well as outer and center piles for individual pile row is also given in Fig. 2. Owing to limited number of recording channels in the strain meters, only a maximum of five piles can be instrumented in one test. The location of the instrumented piles for each test is also shown in Fig. 2.

### Load–Displacement Responses and Group Efficiency

From this point onwards, all the test results are presented in prototype scale unless otherwise stated. The lateral load test is terminated once the pile head displacement exceeds one pile width of 840 mm. The lateral load–pile head displacement responses of a single pile in NC and OC clay are represented by the top curve in Figs. 3(a and b), respectively. The lateral pile head displacement refers to the displacement of the pile cap at 3.5 m above the ground surface. As expected, the pile displacement increases with applied load and the rate of increase in displacement increases significantly with load after a pile displacement of about 25 cm. As the top part of the OC clay is considerably stiffer than that of NC clay, the load–displacement response of a pile in OC clay is significantly stiffer than that of NC clay.

To evaluate the performance of pile groups against that of a single pile, the average load per pile, which is defined as the total load on the pile group divided by the number of piles in the group, is employed. Figs. 3(a and b) present the average load–pile head displacement responses for the pile groups with center-to-center pile spacing of $3D$ in NC and OC clay, respectively. At relatively small pile head displacements, the displacement of the single pile does not differ significantly with that of pile groups under the same average lateral load. At larger pile head displacements, the average pile group responses are considerably softer than the single pile responses, and the degree of softening increases with the pile group size.

In order to examine the effect of spacing between piles in a group, tests were also carried out on $2 \times 3$ and $3 \times 3$ pile groups with center-to-center pile spacing of $5D$. Figs. 4(a and b) present the average lateral load versus pile head displacement from tests in NC and OC clay, respectively. As the differences in the average

![Fig. 2. Plan view of pile group configuration ($D$=pile width)](image)

![Fig. 3. Average lateral load–pile head displacement response for pile groups with 3D spacing ($D$=pile width)](image)
lateral load/displacement responses between the single pile and the pile groups in both NC and OC clay are insignificant, interaction among piles for pile groups with 5\(D\) spacing is established to be significantly less than that for pile groups with 3\(D\) spacing. This observation on piles in clay is similar to that reported on piles in sand by McVay et al. (1994), who established that group interaction among piles reduces significantly when the center-to-center pile spacing increases from 3 to 5 pile width.

To further evaluate the performance of the pile groups, the pile group load–displacement efficiency is employed. The group efficiency, \(\eta\), is defined as the average lateral load per pile divided by lateral load on a single pile at the same pile head displacement. Figs. 5(a and b) show the magnitude of group efficiency for pile groups in NC and OC clay, respectively, at various pile head displacements ranging from 0.1 to 0.5\(D\). For all cases, the group efficiency decreases considerably with increasing pile head displacement and number of piles in a group. Further, the group efficiency reduces significantly when the pile spacing decreases from 5 to 3\(D\). This is in agreement with the finding of Rollins et al. (1998) who established that the pile group efficiency improves significantly when the pile spacing increases from 3 to 5\(D\).

Figs. 5(a and b) clearly show that the group efficiency for pile groups in OC clay is considerably greater than that of pile groups in NC clay. This observation suggests that interaction among piles is more significant for pile groups in NC clay. It also appears that at larger pile head displacements, the magnitude of group efficiency remains fairly constant for pile groups with nine or more piles. For NC clay, the group efficiency falls to about 45% at a pile head displacement of 0.5\(D\). This is in line with the finding of Rollins et al. (1998) who reported that for a field case study involving a laterally loaded nine-pile group in clay, the group efficiency falls to below 50%. For smaller pile groups, the group efficiency is considerably greater than that of larger pile groups, being about 68% for a four-pile group in NC clay, 76% for a two-pile group in NC clay, and 74% for a four-pile group in OC clay; all cases refer to a pile head displacement of 0.5\(D\).

**Performance of Individual Piles**

The bending moment along an instrumented pile can be determined from the readings of the strain gauges installed along the pile. The strain gauge circuit setup and the calibration of the

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**Fig. 4.** Average lateral load–pile head displacement responses for pile groups with 5\(D\) spacing

**Fig. 5.** Pile group efficiency at various pile head displacements
model piles for bending moment have been described in an earlier section. Figs. 6(a and b) show the development of bending moment profile with pile head displacement for a single pile in NC and OC clay, respectively. It is worthy to note that the measured bending moment at the ground level for each pile is equal to the applied moment on the pile (i.e., applied load multiplied by eccentricity of load above ground level), thus verifying the accuracy of the strain gauge responses. The depth to the maximum bending moment is observed to be at around 7–8\(D\) below the ground surface. The bending moment increases with applied load in all cases. At the same pile head displacement, the pile in OC clay resists higher bending moment than that of the pile in NC clay. This is as expected as the pile in NC clay would resist considerably less load as compared to the pile in OC clay at the same pile head displacement, as illustrated in Fig. 3.

The development of bending moment for piles in a group follows a similar trend as that for a single pile as the pile bending moment increases with applied load. However, there are considerable differences in the bending moment profiles among individual piles in a group. The bending moment profiles for the lead and rear piles of the two- and four-pile groups with center-to-center pile spacing of 3\(D\) in NC clay at pile head displacement of 0.5\(D\) are shown in Figs. 7(a and b), respectively. For the two-pile group, the maximum bending moment of the lead pile is slightly larger (about 5\%) than that of the rear pile. However, for the four-pile group, the maximum bending moment of the lead pile is considerably larger (about 15\%) than that of the rear pile. This observation is contrary to that assumed in the elasticity interaction factor approach for laterally loaded pile group proposed by Poulos and Davis (1980), whereby all piles in two- and four-pile groups with symmetrical plan configuration are expected to experience identical bending moment and deflection profiles. The tendency for a rear pile to exhibit less lateral resistance due to a pile in front of it is commonly termed as the “shadowing” effect; see, for example, Brown et al. (1988). In the present study, the shadowing effect is noted to increase when the group size increases from 2 to 4 piles.

The measured bending moment (\(M\)) profiles are used to derive the soil reaction (\(p\)) profile by double differentiation and displacement (\(y\)) profile by double integration. The formulas are formulated using the elastic beam theory as follows:

\[
p = \frac{d^2M}{dz^2} \tag{1}
\]

\[
y = \int \int \frac{M}{EI} dzdz \tag{2}
\]

where \(z\) = depth below ground surface. The bending moment profiles are analyzed using curve fitting involving a seventh order polynomial. Two boundary conditions are required to solve Eq. (2). The first condition is the measured pile head displacement and the second is the zero pile displacement elevation to be determined from the soil reaction profile. Fig. 8(a) shows the soil reaction profile of the lead and rear piles for a two-pile group in NC clay at a pile head displacement of 0.5\(D\) derived using Eq. (1). Fig. 8(b) presents the pile deflection profiles of the lead pile of the two-pile group at various pile head displacements derived.
using Eq. (2). Fig. 8(b) reveals that the point of rotation for the pile is close to the pile tip at a depth of about 12.5 m below the ground surface.

Upon application of lateral load on the pile cap at 3.5 m above the ground level, the relatively rigid pile cap is observed to displace and tilt slightly as a rigid body, as revealed by the video camera during the centrifuge tests. It is believed that this causes the rotation of the piles at the pile head as illustrated in Fig. 8(b).

To further evaluate the performance of individual piles in a group, the lateral load taken by a pile in the group can be deduced by integrating the corresponding soil reaction response profile [see, for example, Fig. 8(a) for a two-pile group in NC clay]. The load–displacement response of the lead and rear piles for the 2 and 2×2 pile groups in NC clay are, hence, determined and plotted in Figs. 9(a) and b, respectively. The average applied load per pile for the pile groups, as determined by the applied load on the pile cap divided by the number of piles in the group, are also shown in Figs. 9(a and b) for comparison purpose. It is noted that the sum of individual pile loads is reasonably close to the total applied load for both pile groups verifying the accuracy of the measured data. At a pile head displacement of 0.5D, the loads carried by the lead piles are 22 and 28% larger than that by the rear piles for the 2 and 2×2 pile groups, respectively. Fig. 3(a) shows that the corresponding load on a single pile is 230 kN. Thus, the average lateral load per pile at 0.5D pile displacement is 200 kN, and 165 kN for the 2 and 2×2 pile groups, which are 87 and 72%, respectively, of the lateral load of a single pile. For the two-pile group, the lead pile experiences 96% of the load of a single pile while the rear pile only experiences 78% of that of a single pile at the same pile head displacement. For the 2×2 pile group, assuming the left and right piles behave identically, each of the front row piles experiences only 80% of the load of a single pile, while each of the rear row pile only experiences 63% of that of a single pile. This analysis further reinforces the shadowing effect phenomenon reported earlier, and the shadowing effect increases considerably when the pile group size increases from 2 to 4.

Fig. 10(a) shows the bending moment profiles of the five instrumented piles [see Fig. 2(d) for location of the instrumented piles] of a 3×3 pile group (pile spacing 3D) in NC clay at a pile head displacement of 0.5D. The outer lead pile again resists the largest maximum bending moment among piles in the group. In contrast, the outer rear pile (which is supposed to experience the same bending moment as the outer lead pile due to geometrical symmetry according to interaction factor approach) exhibits about 27% less maximum bending moment than the outer lead pile. The difference in the magnitude of the maximum bending moment is larger than that of 2 and 2×2 pile groups. As the outer rear pile is located two rows behind the outer lead pile, the shadowing effect becomes even more significant. The center middle pile experiences the least maximum bending moment, being 46% less.
than that of the outer lead pile and 22% less than that of the outer pile in the same row. In many reported studies on laterally loaded pile groups (see, for example, Rollins et al. 1998), the average performance of an individual row of piles in a group is usually adopted for simplicity in the analysis. For the $3 \times 3$ pile group in the present study, such simplification is acceptable for the rear row pile where the outer and center piles experience similar maximum bending moment magnitudes. However, the simplification is erroneous for the middle row piles as the center middle pile experiences slightly less maximum bending moment than that of the outer middle pile. This matter will be further evaluated using the $p$-multiplier concept later.

The load carried by each of the five instrumented piles in the $3 \times 3$ pile group can be determined using the same approach adopted for the $2 \times 2 \times 2$ pile groups and the results are shown in Fig. 11(a). As expected, the outer lead pile exhibits the largest lateral load as compared to other piles within the group. The load carried by the outer middle and center rear piles lies in between that by the outer lead and outer rear piles. The center middle pile carries the least load. Comparing Fig. 11(a) with Fig. 7 for the $2 \times 2 \times 2$ pile groups, the larger difference in the magnitude of load carried by the piles in the $3 \times 3$ pile group reveals that both shadowing and pile–soil–pile interaction effects increase with the number of piles in a group.

The bending moment profiles of the five instrumented piles [see Fig. 2(e) for location of the instrumented piles] for the $4 \times 4$ pile group (pile spacing $3D$) in NC clay at a pile displacement of $0.5D$ are shown in Fig. 10(b). As before, the outer lead pile also exhibits the largest bending moment among all piles in the group. The variation in the pile bending moment is significant as the center lead pile resists almost 100% higher maximum bending moment than that of center rear pile, although the two piles are expected to experience the same bending moment according to the interaction factor approach. This can be attributed to the center rear pile being located three rows behind the center lead pile resulting in a more significant shadowing effect as compared to smaller pile groups. Among all piles, the center middle third row pile experiences the least bending moment. On the other hand, the outer second row pile experiences a maximum bending moment of 480 kN. As the shadowing effect does not affect the trailing row piles as significantly as the lead row piles, the outer middle third row pile would, hence, experience only slightly less maximum bending moment than that of the outer middle second row pile. Hence, it can be deduced that for both middle second and middle third row piles, the maximum bending moment experienced by the outer piles is considerably greater than that by the center piles. This is similar to that observed for the $3 \times 3$ pile group and further illustrates that the simplification of all piles in the same row behave similarly is not appropriate for the middle pile rows.

The distribution of loads among the five instrumented piles in the $4 \times 4$ pile group are determined and shown in Fig. 11(b). The outer lead pile carries the largest lateral load, followed in descending order by the center lead pile, the outer middle second row pile, the center rear pile and the center middle third row pile. In addition, very large variations in the load distribution among piles are noted. Thus, for large pile groups, the effect of shadowing of front piles over rear piles is more significant as there are more rows of piles and pile–soil–pile interaction among piles also increase significantly due to larger number of piles.

To further evaluate the performance of single pile and pile groups of different sizes, Fig. 12(a) compares the maximum bending moments in the outer lead piles from all tests in NC clay. It is evident that the bending moment in the outer lead pile decreases as the number of piles in a group increases. This provides further evidence that the shadowing and pile–soil–pile interaction effects increase with increasing number of piles in a group.

The behavior of pile groups in OC clay essentially follows a similar trend as that of pile groups in NC clay in terms of bending moment profiles and load distribution among piles in a group. However, the pile–soil–pile interaction appears to be less significant than that in NC clay. This appears to suggest that group interaction decreases with increase in strength of the top soil. Owing to limitations of space, only the maximum bending moment–pile head displacement responses of the outer lead pile for the pile groups in OC clay are presented here. The results shown in Fig. 12(b) also reveal that a pile group with larger number of piles would experience a smaller bending moment at the same pile head displacement as the load carried by the outer lead pile decreases with increasing number of piles in a group.

**Experimental $p$-Multiplier for Piles in NC Clay**

To account for the pile group effect, Brown et al. (1987) employed the concept of “$p$-multiplier” to correlate the $p$ (lateral soil reaction)–$y$ (lateral displacement) curve for an individual pile in a group to that of a single pile, see Fig. 13. The
experimental \( p \)-multipliers in the present study can thus be determined by comparing the lateral soil resistance between an individual pile in a group and a single pile under the same pile head displacement. As an illustrative example, the distribution of pile load and the experimental \( p \)-multiplier for each individual pile obtained for the \( 3 \times 3 \) pile group in NC clay with 3D pile spacing at pile head displacement of 0.5\( D \) are shown in Fig. 14. In this test, only five piles were instrumented [see Fig. 2(d)] to physically monitor the lateral load carried by each of the five piles. The load carried by the other three outer piles on the right-hand side of the pile group may be taken to be the same as those of the outer piles on the left-hand side due to symmetry. The load carried by the center lead pile can hence be back-calculated as the total lateral load on the pile group is known. The average \( p \)-multiplier for each of the three pile rows is also given in Fig. 14. The results essentially confirm the earlier observation that the average load of the lead row piles is 30% higher than that of middle row piles. As the average load of the middle row piles is only 4% higher than that of the rear row piles, it can be deduced that shadowing affects mostly the lead row piles and that it is considerably less significant in all other trailing pile rows. This finding is in reasonably good agreement with that reported by Rollins et al. (1998) on laterally loaded pile group in clay in the field. However, the finding differs from that on piles in sand as Brown et al. (1988) found that the difference in the average load carried by each pile row is distinguishable.

A further examination of individual pile performance in Fig. 14 reveals that the difference between the load carried by the

![Fig. 12. Maximum bending moment (BM)–pile head displacement responses of outer lead pile](image)

![Fig. 13. \( p \)-multiplier concept](image)

![Fig. 14. Load distribution of piles and \( p \)-multiplier for \( 3 \times 3 \) pile group in normally consolidated clay (pile head displacement = 0.5\( D \))](image)
Table 1. Comparison of p-Multiplier Values from Various Experimental and Field Studies (All Pile Groups with Pile Center-to-Center Spacing of 3 Pile Widths)

<table>
<thead>
<tr>
<th>Author/soil type and shear strength</th>
<th>Size of pile group</th>
<th>Average p-multiplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td></td>
<td>Lead row</td>
</tr>
<tr>
<td>Present study/normally consolidated clay: undrained shear strength=0–20 kPa</td>
<td>2×1</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>2×2</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>3×3</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>4×4</td>
<td>0.65</td>
</tr>
<tr>
<td>Brown et al. (1987)/overconsolidated clay: strength=70–180 kPa</td>
<td>3×3</td>
<td>0.7</td>
</tr>
<tr>
<td>Meimom et al. (1986)/silty clay: strength=25 kPa</td>
<td>2×2</td>
<td>0.9</td>
</tr>
<tr>
<td>Rollins et al. (1998)/clayey silt: strength=50–75 kPa</td>
<td>3×3</td>
<td>0.6</td>
</tr>
<tr>
<td>Sand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brown et al. (1988)/clean medium sand: friction angle $\phi=38^\circ$</td>
<td>3×3</td>
<td>0.8</td>
</tr>
<tr>
<td>McVay et al. (1995)/medium dense sand</td>
<td>3×3</td>
<td>0.8</td>
</tr>
<tr>
<td>McVay et al. (1998)/medium dense sand</td>
<td>4×3</td>
<td>0.8</td>
</tr>
<tr>
<td>Ruesta and Townsend (1997)/loose fine sand: $\phi=32^\circ$</td>
<td>4×4</td>
<td>0.8</td>
</tr>
</tbody>
</table>

1. The average lateral load per pile decreases with increasing number of piles in the group. The reduction in pile group efficiency is less severe for piles installed in OC clay than that of piles installed in NC clay.

2. Group efficiency for pile groups with a center-to-center pile spacing of $3D$ decreases as the number of piles in a group increases for both NC and OC clay. However, when the center-to-center pile spacing increases to $5D$, the group interaction effect becomes insignificant.

3. In line with the findings of Brown et al. (1988) and Rollins et al. (1998), the shadowing effect of lead piles over trailing piles is observed and such effect increases with increasing number of piles in a group. This results in a higher lateral load for the lead row piles as compared to that on the trailing piles. The shadowing effect is most significant for the lead row piles and less significant on subsequent rows of trailing piles. Hence, if uniform pile type and size have been adopted for a pile group, appropriate checks should be conducted to evaluate whether the lateral load carrying and bending moment capacity of the lead row piles, in particular the outer lead piles, would be exceeded.

4. In many previous research studies, the average performance of piles in the same row rather than the performance of individual piles is employed in the analysis. This simplification is found to be acceptable for the lead and rear row piles where the behavior of the outer and center piles do not differ much. However, for the middle pile rows (middle row in the case of the 3×3 pile group and middle second and third rows in the case of the 4×4 pile group), the present study reveals that the center pile(s) often carries much less load and bending moment than those of the outer piles in the same row. Thus, appropriate caution should be taken when designing piles in the middle row(s) of a large pile group in view of the large difference in the load and bending moment between the outer and center piles.

Conclusions

Centrifuge model tests have been performed to investigate the behavior of laterally pile groups in normally consolidated and overconsolidated kaolin clay. The tests involved single piles and pile groups with the number of piles ranging from 2 to 16 with center-to-center pile spacing of 3 or $5D$. The following conclusions can be obtained from the present study:

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