Geomechanics and Engineering, *Vol. 20, No. 4 (2020) 333-343*
DOI: https://doi.org/10.12989/gae.2020.20.4.333

Response of passively loaded pile groups – an experimental study

Ihsan Al-abboodi *[1], Tahsin Toma Sabbagh[2a] and Osamah Al-salih[1a]

[1]*Department of Civil Engineering, University of Basrah, Iraq*
[2]*School of Computing, Science and Engineering, University of Salford, Manchester, U.K.*

(Received August 18, 2018, Revised January 29, 2020, Accepted January 30, 2020)

Abstract. Preventing or reducing the damage impact of lateral soil movements on piled foundations is highly dependent on understanding the behavior of passive piles. For this reason, a detailed experimental study is carried out, aimed to examine the influence of soil density, the depth of moving layer and pile spacing on the behavior of a 2×2 free-standing pile group subjected to a uniform profile of lateral soil movement. Results from 8 model tests comprise bending moment, shear force, soil reaction and deformations measured along the pile shaft using strain gauges and others probing tools were performed. It is found that soil density and the depth of moving layer have an opposite impact regarding the ultimate response of piles. A pile group embedded in dense sand requires less soil displacement to reach the ultimate soil reaction compared to those embedded in medium and loose sands. On the other hand, the larger the moving depth, the larger amount of lateral soil movement needs to develop the pile group its ultimate deformations. Furthermore, the group factor and the effect of pile spacing were highly related to the soil-structure interaction resulted from the transferring process of forces between pile rows with the existing of the rigid pile cap.

Keywords: pile group; lateral soil movements; model test; passive piles

1. Introduction

Passive loadings on piles could be defined as 'hidden loadings' caused by the lateral movement of the surrounding soil. Passive piles could be either functionally designed to resist and prevent soil movements as in the case of slope stabilizing piles, or accidently subjected to soil movements due to some nearby construction activities and unavoidably natural phenomena. Piles might be affected negatively due to this passive loading, and failure of piles could happen in some cases (Shen *et al.* 2017, Ong *et al.* 2015, Haigh and Madabhushi 2011).

The interaction of piled foundations with the surrounded soil may involve soil-pile interaction when a single pile being subjected to lateral soil movements. This geotechnical problem has been extensively studied experimentally through small-scale models and centrifuge tests. A wide range of soil and pile properties has been tested and investigated by several researchers, e.g., (Guo and Qin 2010, Leung *et al.* 2000, Pan *et al.* 2000, Poulos *et al.* 1995, Qin and Guo 2016, White *et al.* 2008). Practically, piles are usually used in groups, and results of parametric studies conducted on single piles might not be suitable to adopt for piles in groups. This is due to the fact that changing parameter in single pile test does not change other parameters, unlike pile group tests. For example, the influence of pile spacing should be taken into account when conducting a parametric study for the effect of pile diameter on the response of pile group, resulting in two influencing parameters instead of one. The interaction effect of these parameters could result in an unexpected behavior of pile group when compared to the behavior of single pile tested under the required parameter. In the case of free head pile groups installed with a close spacing, each pile affects and affected by other piles making the pile group to be under a pile-soil-pile interaction. An example of this type of interaction is a row or multi-rows of soil stabilizing piles. Investigating the response of soil stabilizing piles has attracted a significant amount of research effort, e.g., (Chen *et al.* 1997, Ito and Matsui 1975, Kahyaoglu *et al.* 2012, Lirer 2012, Song *et al.* 2012).

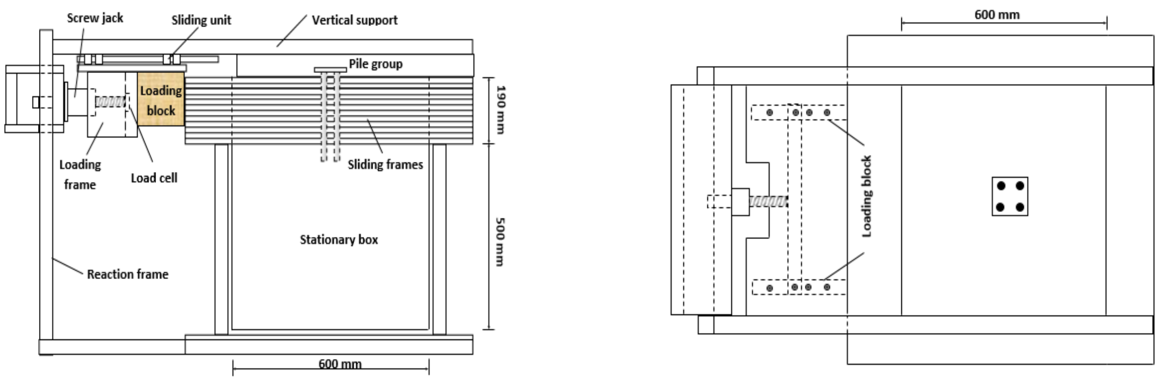
The majority of the available passive piles tests were carried out on free or pinned head pile group even though pile heads are usually capped in actual foundations. When lateral soil movements being applied to a group of piles connected to a rigid cap (known as passively loaded pile group), the analysis may involve pile-soil-cap interaction making the problem even more complicated. Available information concerning parameters affecting the response of passively loaded pile groups is limited and mainly focuses on the influence of axial loads, pile head condition, pile diameter and pile group configuration, e.g., (Chen *et al.* 1997, Leung *et al.* 2003, Miao *et al.* 2008, Tasiopoulou *et al.* 2013). Ghee (2009) investigated the influence of axial loads and pile spacing on the behavior of capped-head pile group. However, only two pile spacings were considered in Ghee's study ($3D$ and $5D$, where D is the pile diameter). Furthermore, pile heads were not fully fixed to the pile cap.

According to the above, it is not clear how the response of individual piles within a group is related to parameters such as pile spacing, soil density and the depth of moving layer.

In the current study, these parameters have been

*Corresponding author, Ph.D.
E-mail: ihsan.qasim@uobasrah.edu.iq
[a]Ph.D.

ISSN: 2005-307X (Print), 2092-6219 (Online)



(a) Elevation view (b) Plan view

Fig. 1 Experimental apparatus

investigated by conducting laboratory tests on a 2×2 capped-head free-standing pile groups subjected to uniform lateral soil movements.

2. Experimental details

The experimental apparatus and testing procedure are briefly described here and more details can be found in Al-abboodi and Sabbagh (2017).

Fig. 1 shows a schematic diagram of the testing box and the loading system used in the current study. The internal dimensions of the testing box were 600 mm × 600 mm, and 690 mm in height, and made of timber. The total height of the box was divided into 500 mm fixed box and 190 mm smooth laminar frames. A desired depth of soil (L_m) can be moved laterally depending on the number of laminar frames which allowed to move at each time. Displacement-controlled loads were applied laterally to the laminar frames by means of a screw jack. Two loading blocks were used to transfer loads from the screw jack to the laminar frames.

The aluminium model piles used in the current study were all of 300 mm in length and 20.0 and 18.0 mm outer and inner diameters respectively. A 2×2 free-standing pile group configuration with an embedded depth (L_e) of 285 mm was utilized throughout the tests. Pile heads were connected to a rigid pile cap using a screw of 10 mm in diameter. A vertical screw jack was used to drive the pile group into the soil. Details of model pile group are presented in Fig. 2.

In order to measure bending moments along the pile shaft, one pile at each row (denoted as pile F in the front row and pile B in the back row) have been instrumented with 7 strain gauges 42 mm intervals each along their length with the first strain gauge placed at 6 mm under the pile cap. Each strain gauge has a code name illustrated in Fig. 2. In order to obtain a relationship between the strain gauge signals and the induced bending moments, calibration tests were carried out for the instrumented piles.

The sand used in the experimental investigations was classified as poorly graded sand with C_c and C_u of 0.95 and 2.06 respectively and a mean grain size of 0.29 mm. Angle of internal friction was 39^o at 16.0 kN/m^3 of sand density as deduced from direct shear test. Pouring and tamping

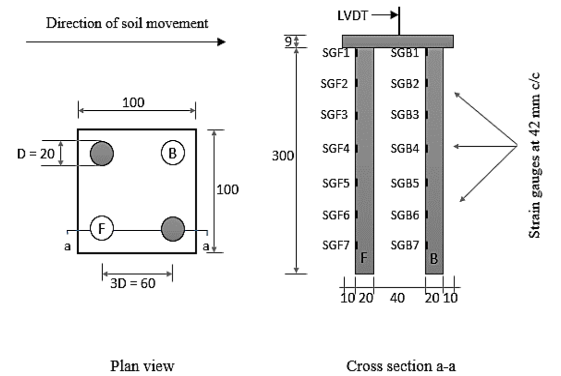


Fig. 2 Details of model pile group for the case of 3*D* pile spacing, dimensions in mm

method was used to achieve a reasonably constant density of the sand in the testing box.

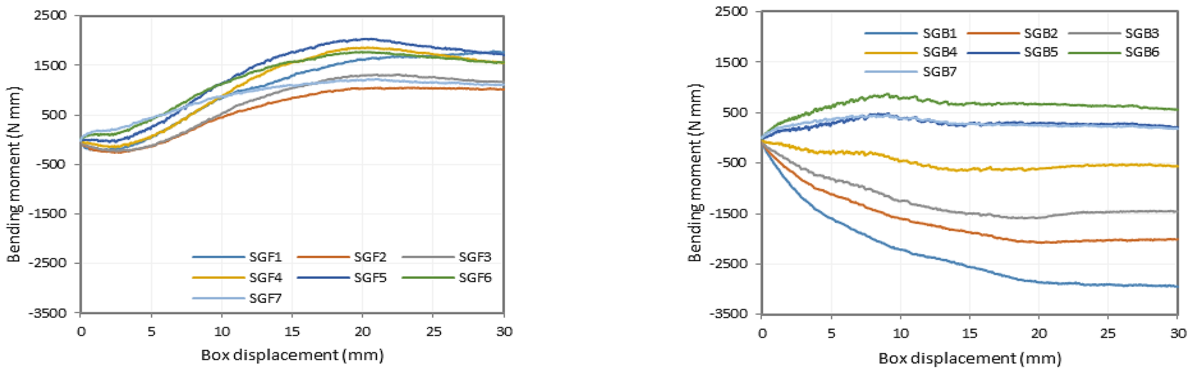
A total of eight tests were carried out including three tests in different states of sand compaction with 3*D* pile spacing and 135 mm of L_m, two tests with L_m = 117 and 110 mm conducted in dense sand with 3*D* pile spacing, and three more tests with 4*D*, 5*D* and 6*D* of pile spacing embedded in dense sand using L_m = 135 mm.

3. Results and discussion

3.1 Results of the standard test (PG1)

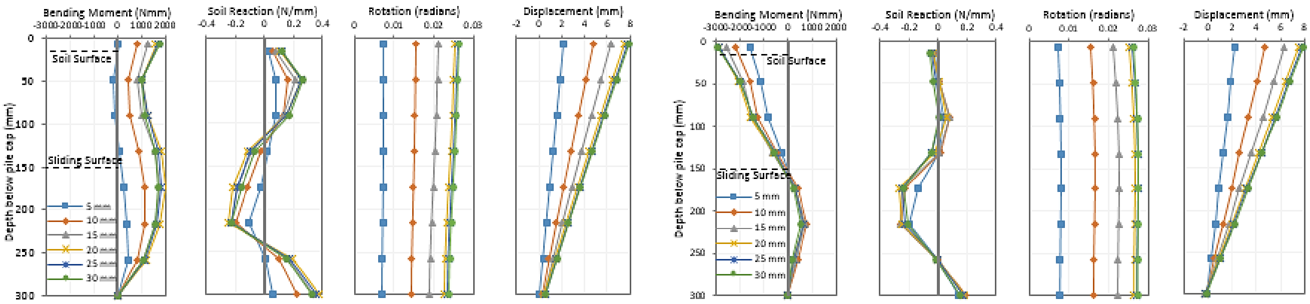
This test has been conducted on a 2×2 free-standing pile group having 3*D* of pile spacing subjected to a uniform profile of soil movement of 135 mm depth. Dense sand with a density of (16.0 kN/m^3) was used in the test. The resulting bending moment at each strain gauge measured during the test is illustrated in Fig. 3.

It can be noticed that at an early stage of this test, pile F recorded some negative moments up to 7 mm (0.35*D*, where *D* is the pile diameter) of box displacement (Δ_B), after which the pile was completely under positive moments. However, moments at the front pile reached their peak values after 20 mm (or 1*D*) of (Δ_B). The portion of the back pile row embedded in the stationary layer tends to record constant bending moments at 10 mm (0.5*D*) of soil movement, while strain gauges located in the moving layer



(a) Front pile (b) Back pile

Fig. 3 Measured moments at each strain gauge



(a) Front pile (b) Back pile

Fig. 4 Front and back pile behavior

continued to show increased readings of strains up to 20 mm (1D) of (Δ_B).

Front and back piles responses in terms of bending moment, soil reaction and deformations are illustrated in Fig. 4. The response measured along the pile length was recorded at each 5 mm and up to 30 mm of (Δ_B). A number of conclusions can be drawn from this figure:

• Bending moment distributions for the front and back piles were distinctly different in shape. Front pile developed positive bending moments at the pile head, while back pile recorded a negative moment at its head. This behavior agreed well with the general trend observed by Ghee (2009).

• Although its head exhibited a significant positive moment, the front pile showed a maximum bending moment developed in the stationary portion of the sand (at depth 174 mm below the pile cap or (0.58L_p, where L_p is the pile length). Unlike those recorded at the back pile which showed their maximum values at the pile head. The negative bending moment at the back pile head may be attributed to the influence of restraint that pile cap provided. On the other hand, the front pile seems to be influenced by soil movement more than the cap restraint.

• The variation of bending moment values measured along the back pile is almost linear up to the maximum positive bending moment, while it tends to have an arc shape with double curvature along the front pile. It is worth pointing out that both profile shapes remain almost constant during the test with maximum bending moments recorded at the locations mentioned previously.

The following observations can be concluded from the soil reaction/resistance profiles drawn from the soil surface down to the pile tip:

• In the vicinity of the sliding surface (135 mm below soil surface), there was a noticeable change in the reaction distribution. This change is expected as both moving and stationary soil layers have opposite actions on the pile shaft.

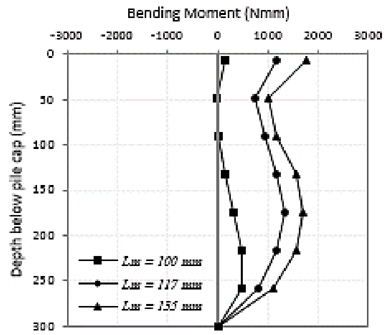
• The back pile developed some negative soil reaction at the region close to the soil surface up to a depth of 50 mm from the soil surface. This means that some active force acts on this part of the pile as a result of front pile-cap-back pile interaction which makes the cap to act as a direct active load at the back pile head.

• Soil reaction recorded at the portion of back pile that exists in the moving layer is less than that measured on the front pile. This response suggests, for this pile spacing, that the front pile row shields the back pile row from a substantial part of the effects of direct soil movements (shadowing effects). This makes the active and passive soil pressure along the upper portion of the back pile approximately the same but in an opposite direction in which the net pressure tends to be almost zero.

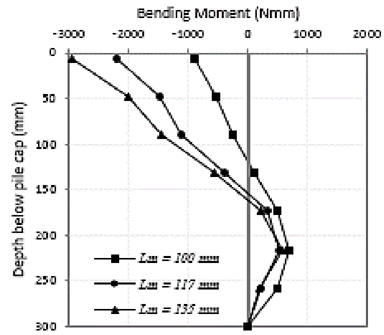
Fig. 4 revealed, also, that both piles developed a positive angle of rotation with a very small differences among the rotations measured along piles length. Therefore, it can be concluded that both piles behaved like rigid piles. Furthermore, the piles recorded a horizontal displacement of about 8 mm at 30 mm of (Δ_B).

3.2 Effect of moving / embedded depth ratio

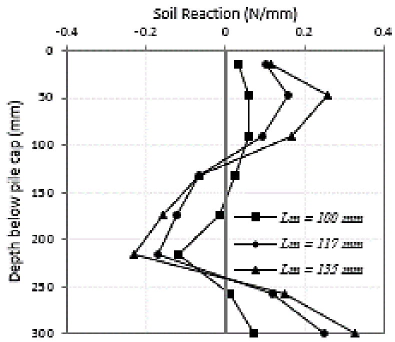
Three tests with different moving depths (L_m) were



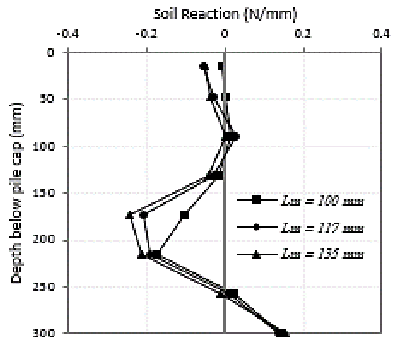
(a) Bending moment of pile F



(b) Bending moment of pile B



(c) Soil reaction of pile F



(d) Soil reaction of pile B

Fig. 5 Front and back pile response at various L_m values (at Δ_B = 30 mm)

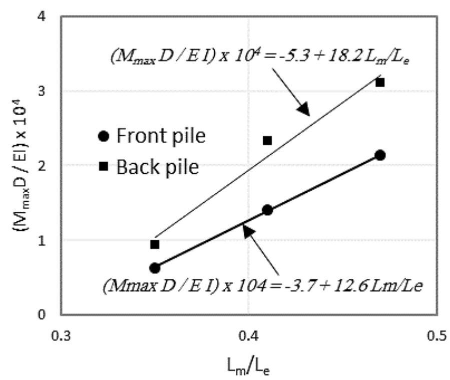


Fig. 6 The relationship between the normalized M_{max} and L_m/L_e

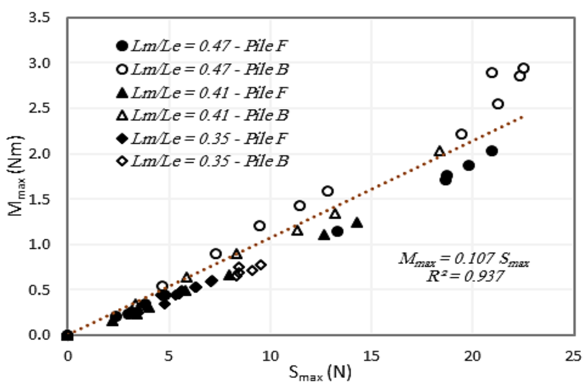


Fig. 7 M_{max} against S_{max}

conducted with a soil density of 16.0 kN/m^3 on a 2×2 pile group having 3D of pile spacing. The depths of moving layer are (135, 117, and 100 mm), i.e., the corresponding Lm/Le ratios are 0.47, 0.41 and 0.35 respectively. The comparison was performed in terms of pile group response at Δ_B = 30 mm.

Bending moment profiles for both piles are presented in Figs. 5(a)-5(b). It can be seen that although the shapes of the moment curves were somewhat identical, moment values increase as L_m/L_e ratio increases for both piles. In this context, bending moment values recorded at the front pile head tested in L_m = 135 mm was about 11 fold and 1.5 fold higher than those measured on the same pile tested in L_m = 100 and 117 mm respectively. It is also noted that the depth of maximum bending moment was shifted downwards as L_m/L_e ratios decreased. The curves of lateral soil reaction acting along the front and back pile length are consistent with each other (Figs. 5(c)-5(d)). In the moving layer, soil reactions on pile F are almost increased proportionally with Lm, while those measured on pile B did not appear to be influenced by changing the moving depth. Shadowing effects of the front pile could be the main reason for this response.

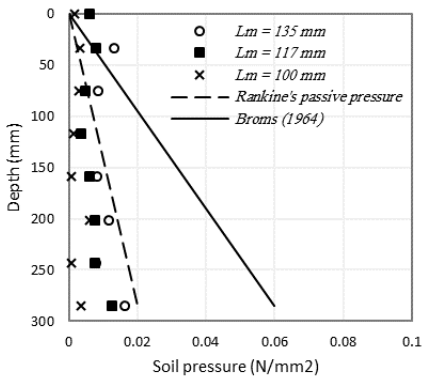
The relationship between the normalized maximum bending moment (M_{max}) and L_m/L_e is presented in Fig. 6. It can be seen that the normalized M_{max} is linearly related to the L_m/L_e ratio (in the range of $0.35 \le L_m/L_e \le 0.47$) for both front and back piles. The relationships can be expressed as follows:

For the front pile row:

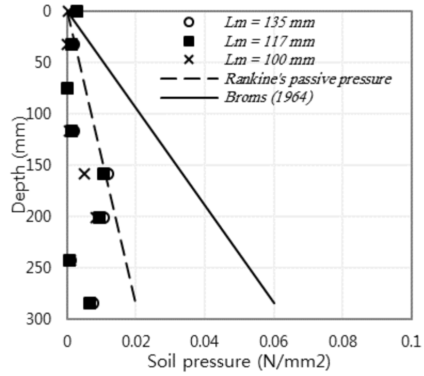
$$(M_{\max} D/EI) \times 10^4 = -3.7 + 12.6\, L_m / L_e \tag{1}$$

For the back pile row:

$$(M_{\max} D/EI) \times 10^4 = -5.3 + 18.2\, L_m / L_e \tag{2}$$



(a) Front pile



(b) Back pile

Fig. 8 Measured maximum soil pressure compared to the ultimate soil pressure estimated theoretically using Rankin's passive pressure and Broms (1964)

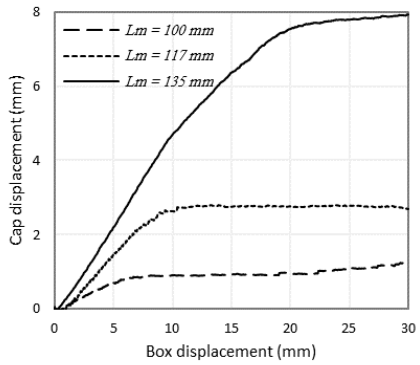


Fig. 9 Pile cap displacement at various L_m values

where *EI* is the pile bending stiffness.

The relationship between the absolute maximum bending moments ($M_{\max}$) and the corresponding absolute maximum shear forces (S_{max}) obtained at intervals of 5 mm and up to 30 mm of soil movement in the front and back piles for this set of tests is illustrated in Fig. 7. It can be seen that M_{max} increases with S_{max} with almost a similar incremental rate, resulting in a linear relationship between them with the following expression:

$$M_{\max} = 0.356\, L_p S_{\max} \tag{3}$$

where Lp is the pile length. The above equation agrees well with the proposed expression of Guo and Qin (2010) of $M_{max} = 0.148 \sim 0.4\, L_p\, S_{max}$.

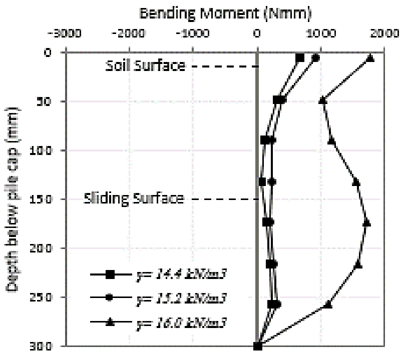
The maximum soil pressures, p_{max} (where p_{max} = maximum soil reaction / pile diameter), exerted along the front and back piles are plotted in Fig. 8. The figure compares the measured soil pressure with the ultimate soil pressure that was estimated using Rankin's passive pressure ($K_p\, \gamma z$) and Broms (1964) method ($3K_p\, \gamma z$). Where K_p is the coefficient of passive earth pressure ($K_p = \tan^2 (45+\theta/2)$), γ is the soil unit weight and z is the depth below soil surface. It can be seen that the portion of the front pile located within the moving soil was under a higher soil pressure compared to the soil pressure acting on the same portion of the back pile. The comparison with the theoretical procedures reveals that the p_{max} values measured along the pile shaft in the case of L_m = 100 mm are generally less than the Rankin's passive pressure ($K_p\, \gamma z$) for both piles. The same can be said to the p_{max} acting on the whole length of the back pile and the portion of the front pile located in the stable layer in the other two moving depths (L_m = 117 and 135 mm). However, for the front pile, the p_{max} values in the moving layer (at z = 33 mm) were greater than $3K_p\, \gamma z$ in the case of L_m = 135 mm and fall between (1~3) $K_p\, \gamma z$ in the cases of L_m = 117 and 135 mm.

Fig. 9 shows the pile cap response in terms of horizontal displacement during the tests. It appears that cap deformation increases as the depth of moving soil increases. Furthermore, it can be noticed that displacement increased linearly with the increase of box movement followed by almost a constant response with further increase of box movement. The value of box displacement at which the response becomes constant is not the same at each test. The cap developed its steady deformation behavior at 6 mm, 9 mm and 21 mm of box displacement for L_m = 100 mm, 117 mm and 135 mm respectively. Based on these results, it can be said that the larger the sliding depth, the larger amount of soil movement needs to develop the pile group its ultimate deformations.

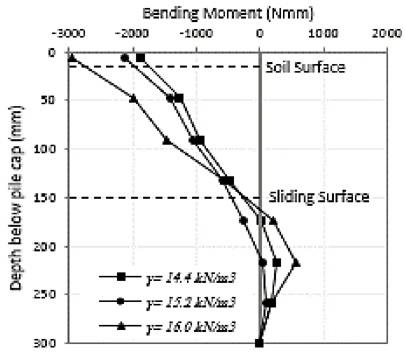
3.3 Effect of sand density

In order to investigate the influence of sand density on the lateral behavior of pile group under progressively moving sand, three tests with soil densities of 16.0 kN/m^3 15.2 kN/m^3 and 14.4 kN/m^3 were conducted. The relative density corresponding to these densities are 80 %, 50 % and 17 %, representing the sand used in its dense, medium and loose state of compaction respectively. The tests were carried out on 2×2 pile group with 3*D* of pile spacing. The moving depth (Lm) was kept at 135 mm for all tests.

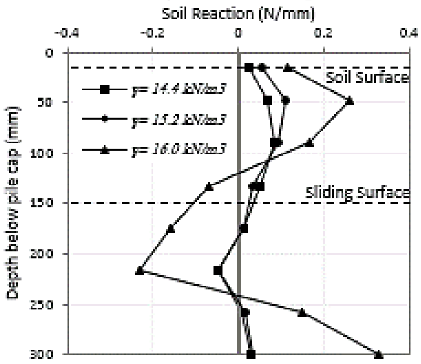
Fig. 10 shows the response of piles in the group at various soil densities at Δ_B = 30 mm. It can be seen that the maximum bending moment measured on the front pile tested in medium sand density is about 32 % higher than that induced on the same pile in loose sand (Fig. 10(a)). Increasing the density from medium to dense caused a further increase in maximum moment of about 96 %. The moment distribution shape of pile F tested in dense sand shows some differences regarding the position of M_{max} induced in the stationary layer compared to the other two profiles, while both piles tested in medium and loose sand show generally identical trend of bending moment curves. For the back pile row, Fig. 10(b) reveals that although the



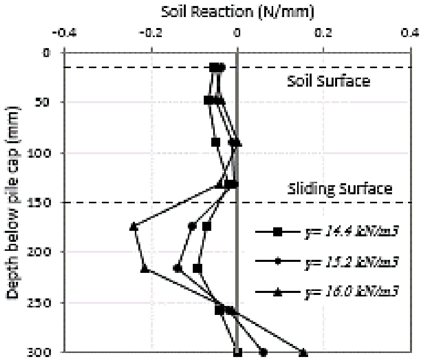
(a) Bending moment of pile F



(b) Bending moment of pile B



(c) Soil reaction of pile F



(d) Soil reaction of pile B

Fig. 10 Front and back pile response at different levels of sand density (at Δ_B = 30 mm)

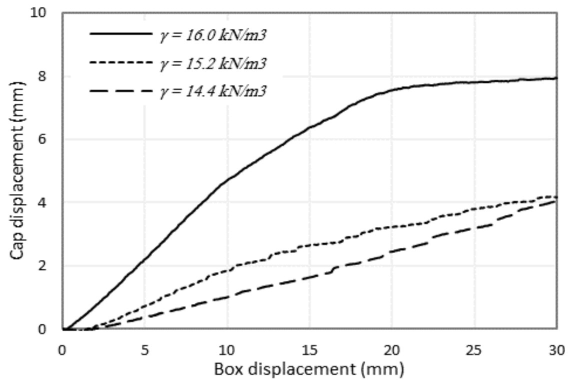


Fig. 11 Cap displacement versus box displacement at different levels of sand density

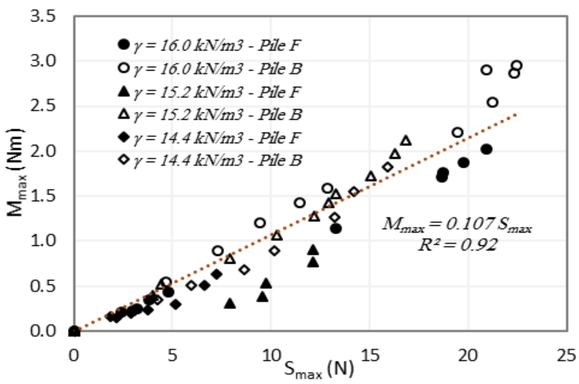
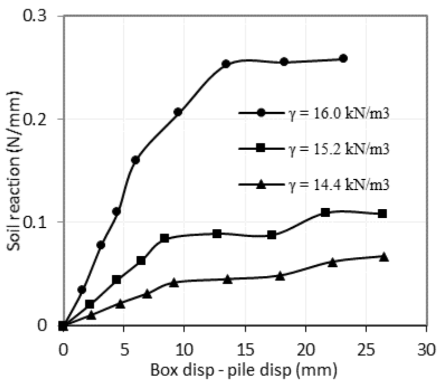


Fig. 12 M_{max} against S_{max}

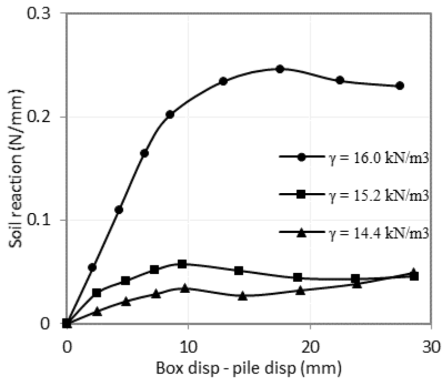
shapes of moment profiles including the position of maximum and zero moments have a common deformation pattern in all the three tests, the difference in moment values was less than that observed in the front pile. A slight increase of about 13% in the pile head moment was observed when sand density increased from 14.4 kN/m^3 to 15.2 kN/m^3. Subsequently, a further increase in density to 16.0 kN/m^3 caused a considerable increase in moment of about 40 % compared to that at 15.2 kN/m^3 of sand density.

Soil reaction values measured along the front pile length generally tend to increase as sand density increases (Fig. 10(b)). Based on the laboratory results, it is found that the trends of curves are generally consistent with each other including the position of maximum soil reaction and the position at which the sign of soil pressure has changed. The maximum soil reaction in the sliding zone for the three tests was located at 33 ~ 75 mm (or 1.65 ~ 3.75 *D*) under the soil surface for both piles. The average of this result (54 mm or 2.7*D*) is consistent with the experimental investigation performed by Suleiman *et al.* (2014) who reported the maximum soil reaction at 2.5*D* under the soil surface. Furthermore, Fig. 10(d) shows that the upper portion of the back pile was not under a passive pressure at Δ_B = 30 mm although its location is within the moving layer. This could be due to the shadowing effect of the front pile row which shields a considerable amount of the sliding soil mass.

Fig. 11 illustrates the pile cap response in terms of horizontal displacement as the box moves laterally. Cap displacement was increased linearly with the increase of box displacement in loose sand. On the other hand, this relation shows some nonlinearity in medium sand deposit. A distinct nonlinear behavior develops as sand strength

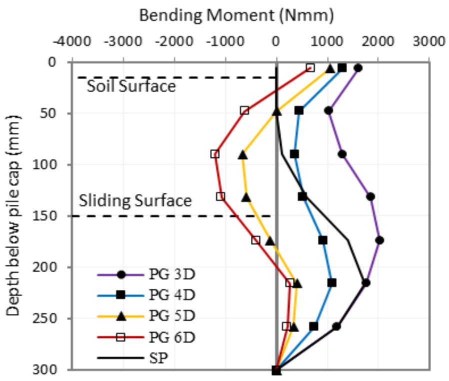


(a) 33 mm below soil surface

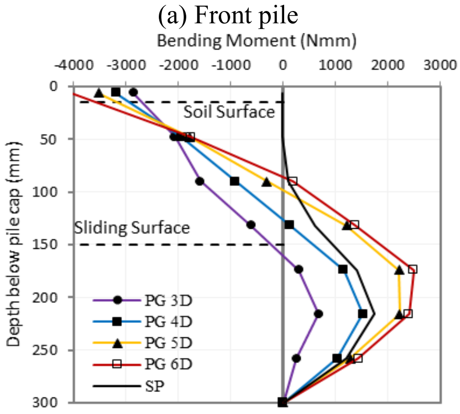


(b) 201 mm below soil surface

Fig. 13 *p*-*y* curves for selected depths, pile F



(a) Front pile



(b) Back pile

Fig. 14 Moment profiles at different pile spacings

increases to a dense state of compaction.

The absolute values of the obtained maximum bending moment M_{max} are plotted against the corresponding maximum shear force for both piles in Fig. 12. It can be seen that the data deduced from the three tests can be correlated linearly with the same expression of Eq. (3) and a value of the coefficient of determination (R^2) of 0.92.

The absolute values of the obtained maximum bending moment M_{max} are plotted against the corresponding maximum shear force for both piles in Fig. 12. It can be seen that the data deduced from the three tests can be correlated linearly with the same expression of Eq. (3) and a value of the coefficient of determination (R^2) of 0.92.

The relationship of soil reaction (also known as soil-pile contact force per unit length, *p*) versus relative soil-pile displacement (*y*) at two depths, i.e., 33 and 201 mm under the soil surface the front pile is shown in Fig. 13. The relative soil-pile displacement at a certain point along the pile shaft is the difference between the lateral displacement of the pile at that point and the lateral box displacement. Test results revealed that load-displacement curves (*p*-*y* curves) are nonlinear. It can be seen that the ultimate soil reaction at depth 33 mm under the soil surface (i.e., within the moving soil) is a function of soil density (Fig. 13(a)). Piles embedded in dense sand need less relative soil-pile displacement to reach the ultimate soil reaction compared to those embedded in medium and loose sand. The *p*-*y* curves in the case of medium and loose sand continue to develop some soil reactions with a less rate of increase compared to that observed in the linear portion of curves which continues up to about 9.0 mm of relative soil-pile displacement. In general, the response of the front pile provides a clear indication how the soil reaction is developed at that portion of pile which lies in the sliding soil. As the soil moves laterally in the testing box, soil density increased accordingly. This is due to the reorientation of sand particles and, also, the resistance of soil flow provided by piles. Dense sand surrounding front piles requires less box movement (or relative soil-pile displacement) to reach its ultimate density compared to medium and loose sands. Reaching ultimate density means no further soil reaction can develop on piles.

3.4 Effect of pile spacing

The effect of pile spacing on the behavior of 2×2 passively loaded pile group has been investigated by adopting four different pile spacings (3*D*, 4*D*, 5*D* and 6*D*) in sand with a density of 16.0 kN/m^3. The moving/stable depth ratio was kept as 135/150 for all tests. For the purpose of comparison, the bending moment profiles recorded in the front and back piles are illustrated in Fig. 14.

For the front row, it can be seen from Fig. 14(a) that the bending moments were not only decreased with the increase of pile spacing at the pile head, but also a gradual change from positive to negative values was noticed in the magnitudes of bending moments measured at the upper part. This means that, at this part, the pile surface which facing the soil movement experiences compression stresses with the increase of pile spacing to more than 5*D*. Changing

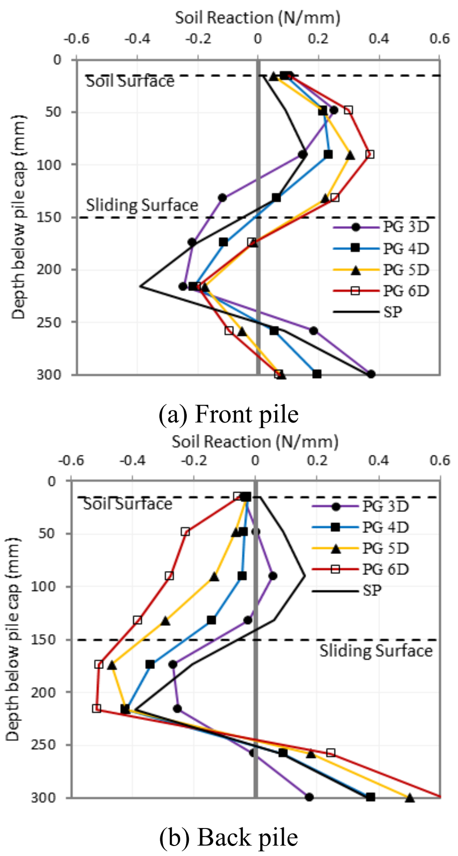


Fig. 15 Soil reaction at various pile spacings

the stresses in the front piles can be attributed to the mobilization of soil-pile-cap interaction while soil moves. Shadowing effect (front-to-back spacing) seems to play an essential role in the performance of front pile row. Furthermore, it is known from the literature that the arching effect (side-by-side spacing) is effecting the pile response (Chen *et al.* 1997, Miao *et al.* 2008, Wang *et al.* 2013). The combined action of shadowing and arching effects in addition to the influence of the restriction of pile cap could be the reason behind this behavior.

In order to explain this response deeply, the contrasting results of pile groups with 3*D* and 6*D* spacings will be discussed in details. The positive bending moment of the front pile of 3*D* spacing indicates that the rotational restraint provided to the pile group by the interaction of the back pile row and pile cap was small. The reduction in rotational restraint makes pile groups with closely spaced piles behave like a huge single pile in terms of rotation and deflection. As front-to-back pile spacing increases, the interaction among the system elements becomes more pronounced. For pile group with 6*D* spacing, the increase in rotational and deflection restrictions provided by the back pile row makes the pile cap works as an active lateral load applied at the front pile head in a direction opposite to the direction of soil movement. The magnitude of this active load increases as pile spacing increases. A state of balance could be achieved between the active pile head force and passive soil pressure at a certain pile spacing. Obtaining the state of balance between active and passive forces leads to minimize the bending moment at the upper part of the front pile to lower values. From Fig. 21(a), it appears that the balance may be achieved with a spacing of 4*D* to 5*D*.

For the back pile row, Fig. 14(b) reveals that although the bending moment distributions tend to be similar for all tests including the position of maximum moment at the sliding and stable layers, significant differences can be noticed. Pile head moment and maximum positive moment increased with the increase of pile spacing. Passive soil pressure has insignificant influence on the back pile row because of the "shielding" that front pile row provided. Therefore, and again, the transferring process of forces between the front and back pile rows with the existing of the rigid pile cap could be the main reason of this increase in bending moment. It is also noticed that, as pile spacing increases, the position of zero bending moment shifts upwards away from the sliding surface.

Soil reaction distributions along the pile length obtained from bending strain data are shown in Fig. 15 for both front and back piles. For the front pile row, it can be seen, in general, that passive soil reaction at the moving soil layer increases as pile spacing increases (Fig. 15(a)). Literature shows that the relation between soil reaction and pile spacing depends on several factors including fixity condition and soil type (Kahyaoğlu *et al.* 2010, Miao *et al.* 2008). Arching effect could be the key factor for the free head and one row capped head pile groups. On the other hand, frame action caused by imposing the cap equal displacements for pile heads in addition to the soil pile interaction is the main reason for other capped head pile groups responses. Fig. 15(a) reveals, also, that soil reaction at pile tip showed decrease in magnitudes with the increase of pile spacing.

Due to the reduction in passive reaction on the back pile as well as the pile-cap interaction, an increase of active soil reaction (acts in opposite direction to that on the front pile) with the increase of pile spacing has been noticed in the upper part of the back pile (Fig. 15(b)). This could be attributed to the increasing resistance of deformations that the pile group was showed when pile spacing increases. Furthermore, the rigid pile cap acts as an active lateral load applied to the back pile head. The reduction in passive soil reaction from the moving soil in conjunction with the increase of active load from the pile cap could be the reason for this response of the back pile row. Soil reactions at back pile tip have recorded an increase in magnitudes with the increase of pile spacing. This is unlike what has been observed in the front pile tip.

3.4.1 Group factor

It is useful to compare the response of the entire pile group or piles within a group to that of single pile by the means of group factor. A wide variety of procedures are usually used to determine the group factor for pile group subjected to lateral load. For example:

1. Group factor in terms of maximum bending moment (F^m) (Chen *et al.* 1997). In which:

$$F^m = M_{\max,i} / M_{\max,s} \tag{4}$$

where $M_{max,i}$ = maximum bending moment of the ith pile in the group and $M_{max,s}$ = maximum bending moment of the

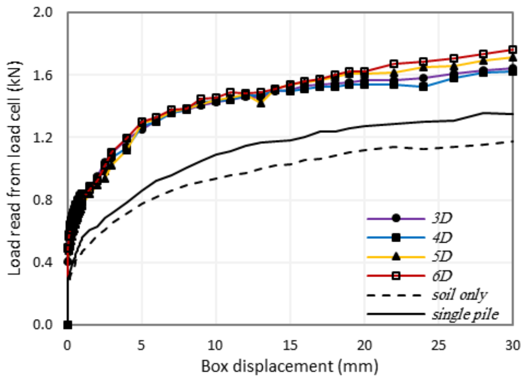


Fig. 16 Total load from load cell versos box displacement

single pile.

2. Group factor in terms of ultimate soil pressure (F^p) (Miao *et al.* 2008). In which:

$$F^p = P_{\max,i} / P_{\max,s} \tag{5}$$

where $P_{max,i}$ = maximum (ultimate) soil pressure of the ith pile in the group and $P_{max,s}$ = maximum (ultimate) soil pressure of the single pile.

3. Group factor in terms of load carried by piles in the group (F^q) (Kahyaoğlu *et al.* 2010). In which:

$$F^q = Q_g / nQ_s \tag{6}$$

where Q_g = load carried by the entire pile group, Q_g = load carried by single pile and n = number of piles in the group.

In the current study, all these methods were tested to quantify the group factor and to assess the group efficiency. Chen *et al.* (1997) used the maximum positive bending moment of the single pile to compare with the positive bending moment of piles in the group. From Figs. 14(a)-14(b), it can be noticed that the shape of moment distribution along the single pile length is differ from that of pile group. Single curvature with positive bending moment along the pile shaft was observed in the single pile test, while piles in groups experienced some negative bending moment and double curvature in profiles. This difference in moment distribution makes group factor values in terms of bending moment not logical for some pile spacings.

On the other hand, using the maximum soil pressure criterion to evaluate the group factor seems to be more reliable compared to the bending moment group factor especially for the front pile row. Soil pressure profiles obtained indirectly from strain gauges coincide with that of a single pile regarding the position of maximum soil pressure at both sliding and stable layers (see Fig. 15). However, for back pile row, some spacings led to induce an active soil pressure in the sliding layer as shown in Fig. 15(b). Therefore, the comparison is not valid between the passive pressure of the single pile and the active pressure of piles in groups at that layer.

In evaluating the group factor using the load carried by piles, it is assumed that the difference between the load applied to mobilize movement to the testing box (with pile group) and that recorded in the case of no piles (soil only) was distributed equally among the piles in the group. Then, the load carried by one pile from a group test is divided by that of a single pile test at the same amount of box displacement to obtain the group factor (Kahyaoğlu *et al.* 2010).

Table 1 Group factor obtained using F_m, F_p and F_q

Spacing	Front pile			Back pile			Pile group
	F^m	F^p Sliding layer	F^p Stable layer	F^m	F^p Sliding layer	F^p Stable layer	F^q
3*D*	1.17	1.57	0.63	0.39	0.36	0.69	0.66
4*D*	0.63	1.45	0.55	0.88	n/a	1.07	0.63
5*D*	0.23	1.90	0.45	1.28	n/a	1.19	0.76
6*D*	0.16	2.30	0.51	1.44	n/a	1.32	0.83

Fig. 16 shows the total load measured by the load cell versos box displacement for pile groups, single pile and soil only tests. It can be noticed that all graphs share the same trend. Values of the applied load are increasing at decreasing rate with the increase of box displacement from 10 mm up to 30 mm of box displacement.

Table 1 presents the group factor for the front and back piles and the entire pile group for each spacing test using the above criteria. A number of conclusions can be drawn from this table:

1. For the front pile, F^m decreases with the increase of pile spacing. It seems that the 3*D* pile spacing is the more similar to the single pile with F^m of 1.17. At sliding layer, F^p was found to increase, in general, with the increase of pile spacing. On the other hand, maximum and minimum F^p calculated at the stable layer were recorded at 3*D* spacing (0.63) and 5*D* spacing (0.45) respectively.

2. For the back pile, increasing of pile spacing caused increasing in F^m values. This is due to the increase of bending moment associated with the increase of pile spacing (see Fig. 14(b)). Pile spacings of 4*D*, 5*D* and 6*D* showed negative values of soil pressure (active), hence only 3*D* pile spacing test had a value of F^p (0.36). Furthermore, the part of the back pile lies in the stable layer showed increase in F^p values with the increase of pile spacing.

3. For the entire group, as pile spacing increased from 3*D* to 6*D*, the group factor (F^q) was also increased from 0.66 to 0.83.

3.4.2 Comparison with results from literature

Table 2 compares the calculated group factors (F^m and F^q) from the current study with those obtained by different researchers for a 2×2 passively loaded pile group. The reported literature group factors were obtained in terms of bending moment or ultimate soil pressure on piles. The group factors for the entire pile group were found to be consistent with the results of Miao *et al.* (2008) for both 3*D* and 6*D* pile spacings. However, the table shows a wide variety of group factor values for individual piles within the group. The values presented by Chen *et al.* (1997) were close to or larger than 1.0 for both front and back piles, while those deduced by Miao *et al.* (2008) were less than 1.0. Furthermore, the results of the current study did not follow the general trend of increasing the group factor with

Table 2 Comparison of the group factor

Test name	Soil type	Fixity	Soil Profile	L_m/L_s	(S/D)	Pile position	F^m for piles	F^g for *pile* group	Reference
Four piles in a group 2×2	Sand	Capped head	Rectangle	0.47	3.0	Front	1.17	0.66	Current study
						Back	0.39		
					4.0	Front	0.63	0.63	
						Back	0.88		
					5.0	Front	0.23	0.76	
						Back	1.28		
					6.0	Front	0.16	0.83	
						Back	1.44		
	Clay	Head-tip-pinned	Rectangle	1.0	3.0	Front	0.89	0.65	Miao *et al.* (2008)
						Back	0.41		
					6.0	Front	0.98	0.83	
						Back	0.68		
	Sand	Free head	Triangle	0.52	2.5	Front	1.08	n/a	Chen *et al.* (1997)
						Back	0.96		
					5.0	Front	1.36	n/a	
						Back	1.03		
	Sand	Capped head	Rectangle	0.4	3.0	Front	0.39	n/a	Ghee (2009)
						Back	n/a		

the increase of pile spacing which was observed by Chen *et al.* (1997) and Miao *et al*. (2008). This could be attributed to:

1. The laboratory tests of Chen *et al.* (1997) were carried out using a triangular soil movement profile which makes the applied soil pressure on the front piles more concentrated at the upper third of the moving layer. Furthermore, free head piles were used in their tests. On the other hand, the soil movement is equally distributed along the front piles in the moving layer when using rectangular soil movement. Also, the “supporting effect” of the front pile row provided by the back pile row in the capped head piles is an additional influencing factor which does not exist in the case of free head piles.

2. On the other hand, Miao *et al*. (2008) have conducted their tests on piles with pinned head and pinned tip conditions in clay. In this case, and because the fixity condition which involves zero pile head deflection, the contribution of the pile cap in the interaction process among the system elements was the same at each pile spacing. Therefore, and again, their results were not affected by the front pile-cap-back pile interaction which was highly influenced the results of the current tests.

4. Conclusions

The response of passively loaded piles under a uniform soil movement was investigated by conducting a series of instrumented laboratory tests on a 2×2 free-standing pile group in sand. An experimental parametric study was carried out aimed to examine the influence of soil density, the depth of moving layer and pile spacing on the behavior of the front and back pile rows. Tests were performed with three soil densities, three depths of moving soil and four values of pile spacings. Based on tests results, the following conclusions can be drawn:

1. Test results generally indicate that the behavior of the front and back pile rows has significantly affected by the depth of moving layer. A noticeable increase in bending moments, shear forces and soil reactions has been observed as L_m increased. However, as a result of the shadowing effect of the front pile, changing the moving depth has a little impact on the soil reaction measured on the back pile. The results of the tests indicated that the larger the moving depth, the larger amount of lateral soil movement requires to develop the pile group its ultimate deformations (displacement and rotation). Also, maximum bending moments for both piles were linearly related to the moving/embedded (L_m/L_e) depth ratio. These results need further future investigations including higher values of L_m ($> 0.5\ L_e$).

2. It is noted that the response of each pile in a group is a function of soil density. Piles response in terms of moment, shear, soil resistance and deformations tends to increase as sand density increases. Unlike the behavior of single pile performed by Ghee (2009), maximum bending moments were nonlinearly related to the soil density. Pile group tested in dense sand tends to develop its final deformations at about (D) value of box movement, while that tested in loose and medium sands continues to show deformations even beyond (1.5D) of box movement. This was reflected on the *p-y* curves for selected points along the pile shafts. Therefore, piles embedded in dense sand need less relative soil-pile displacement to reach the ultimate soil reaction compared to those embedded in medium and loose

sands.

3. Soil structure interaction and the group factor resulting by adopting various pile spacing values were found to be significantly influenced by the transferring process of forces between the front and back pile rows with the existing of the rigid pile cap. Unlike the measured values at the back pile head, bending moments at the front pile head was found to be inversely related to the increase in pile spacing. For the front pile row, passive soil resistance at the moving soil layer increases as pile spacing increases. On the other hand, an increase of active soil reaction with the increase of pile spacing has been noticed in the upper part of the back pile row.

References

Al-abboodi, I. and Sabbagh, T.T. (2018), "Model tests on piled raft subjected to lateral soil movement", *Int. J. Geotech. Eng.*, **12**(4), 357-367. https://doi.org/10.1080/19386362.2017.1296061.

Brom, B.B. (1964), "Lateral resistance of piles in cohesionless soils", *J. Soil Mech. Found. Eng. Div.*, **90**(3), 123-156.

Chen, L.T., Poulos, H.G. and Hull, T.S. (1997), "Model tests on pile groups subjected to lateral soil movement", *Soils Found.*, **37**(1), 1-12. https://doi.org/10.3208/sandf.37.1.

Ghee, H. (2009). "The behavior of axially loaded piles subjected to lateral soil movements", Ph.D. Dissertation, Griffith University, Griffith, Australia.

Guo, W. and Qin H.Y. (2010), "Thrust and bending moment of rigid piles subjected to moving soil", *Can. Geotech. J.*, **47**(2), 180-196. https://doi.org/10.1139/T09-092.

Haigh, S.K. and Madabhushi, S.P.G. (2011), "Centrifuge modeling of pile-soil interaction in liquefiable slopes", *Geomech. Eng.*, **3**(1), 1-16. https://doi.org/10.12989/gae.2011.3.1.001.

Ito, T. and Matsui, T. (1975), "Methods to estimate lateral force acting on stabilizing piles", *Soils Found.*, **15**(4), 43-59. https://doi.org/10.3208/sandf1972.15.4_43.

Kahyaoglu, M.R., Onal, O., Imancli, G., Ozden, G. and Kayalar, A.S. (2012), "Soil arching load transfer mechanism for slope stabilized with piles", *J. Civ. Eng. Manage.*, **18**, 701-708. https://doi.org/10.3846/13923730.2012.723353.

Leung, C.F., Chow, Y.K. and Shen, R.F. (2000), "Behavior of pile subject to excavation-induced soil movement", *J. Geotech. Geoenviron. Eng.*, **126**(11), 947-954. https://doi.org/10.1061/(ASCE)1090-0241(2000)126:11(947).

Leung, C.F., Lim, J.K., Shen, R.F. and Chow, Y.K. (2003), "Behavior of pile groups subject to excavation-induced soil movement", *J. Geotech. Geoenviron. Eng.*, **129**(1), 58-65. https://doi.org/10.1061/(ASCE)1090-0241(2003)129:1(58).

Lirer, S. (2012), "Landslide stabilizing piles: Experimental evidences and numerical interpretation", *Eng. Geol.*, **149-150**, 70-77. https://doi.org/10.1016/j.enggeo.2012.08.002.

Miao, L.F., Goh, A.T.C., Wong, K.S. and The, C.I. (2008), "Ultimate soil pressures for pile groups in soft clay subjected to lateral soil movements", *DFI J. J. Deep Found. Inst.*, **2**(1), 42-51. https://doi.org/10.1179/dfi.2008.005.

Ong, D.E.L., Leung, C.F., Chow, Y.K. and Ng, T.G. (2015), "Severe damage of a pile group due to slope failure", *J. Geotech. Geoenviron. Eng.*, **141**(5), 04015014. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001294.

Pan. J.L., Goh, A.T.C., Wong, K.S. and The, C.I. (2000), "Model tests on single piles in soft clay", *Can. Geotech. J.*, **37**(4), 890-897. https://doi.org/10.1139/t00-001

Poulos, H.G., Chen, L.T. and Hull, T.S. (1995), "Model tests on single piles subjected to lateral soil movement", *Soils Found.*, **35**(4), 85-92. https://doi.org/10.3208/sandf.35.4_85.

Qin, H. and Guo, W.D. (2016), "Response of piles subjected to progressive soil movement", *Geotech. Test. J.*, **39**(1), 106-125. https://doi.org/10.1520/GTJ20140148.

Shen, Y., Wu, Z., Xiang, Z. and Yang, M. (2017), "Physical test study on double-row long-short composite anti-sliding piles", *Geomech. Eng.*, **13**(4), 621-640. https://doi.org/10.12989/gae.2017.13.4.621.

Song, Y.S., Hong, W. and Woo, K. (2012), "Behavior and analysis of stabilizing piles installed in a cut slope during heavy rainfall", *Eng. Geol.*, **129-130**, 56-67. https://doi.org/10.1016/j.enggeo.2012.01.012.

Suleiman, M.T., Ni, L. and Helm, J.D. and Raich A. (2014), "Soil-pile interaction for a small diameter pile embedded in granular soil subjected to passive loading", *J. Geotech. Geoenviron. Eng.*, **140**(5), 04014002. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001081.

Tasiopoulou P., Gerolymos N., Tazoh T. and Gazetas G. (2013), "Pile-group response to large soil displacements and liquefaction: Centrifuge experiments versus a physically simplified analysis", *J. Geotech. Geoenviron. Eng.*, **139**(2), 223-233. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000759.

Wang, Z., Zhang, Y., Yang, C. and Li, X. (2013), "Load-bearing arching between cantilever piles and influencing factors", *Elect. J. Geotech. Eng.*, **18**, 6163-6172.

White, D.J., Thompson, M.J., Suleiman, M.T. and Schaefer, V.R. (2008), "Behavior of slender piles subject to free-field lateral soil movement", *J. Geotech. Geoenviron. Eng.*, **134**(4), 428-436. https://doi.org/10.1061/(ASCE)1090-0241(2008)134:4(428).

CC