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BEHAVIOR OF MODEL GROUP PILES SUBJECTED TO LATERAL SOIL MOVEMENT IN SAND

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Abstract: Laboratory model tests have been carried out to explore the behavior of piles subjected to lateral soil movement in sand. The results of a single pile test and ten tests on of group piles arranged in a row (perpendicular to the direction of soil movement) are presented. Different parameters were utilized in these tests, (e.g., pile spacing, number of piles within a group and pile head condition). Group effect was calculated using group factor (F^m) which is defined in terms of the measured maximum bending moments of an individual with group and that of the single pile. The results showed that the maximum bending moment of group piles decreases from the single pile with decreasing pile spacing and the pile behaves essentially the same as a single pile when the pile spacing is 7d or more. The maximum reduction of the maximum bending moments of about (17%) and (28%) as compared with that for the standard single pile may be observed for a pile spacing of 3d for the free and capped headed condition, respectively. The number of piles does not appear to have significant effect on the group factor F^m of piles, except for the free headed inner piles who's the group factors appear to decrease with increasing the number of piles within a group.

Keywords: *pile, sand, soil movement, group factor, bending moment*

سلوك مجموعة الركائز المتعرضة لحركة التربة الجانبية في الرمل

الخلاصة:اجريت عدة فحوصات مختبريه لدراسة سلوك الركائز المتعرضة لحركة التربة الجانبية في التربة الرملية. نتائج الفحوصات المتعلقة بالركيزة المنفردة بالاضافه الى عشرة فحوصات لمجموعة ركائز مرتبة على شكل صفوف (عمودية على اتجاه حركة التربة) تم عرضها في هذا البحث. تم دراسة تأثير عدة عوامل منها المسافة بين الركائز عدد الركائز في المجموعه وكذلك حالة رأس الركائز من حيث منعزلة او مرتبطة مع بعضها البعض. تم حساب معامل المجموعة بالاعتماد على عزم الانحناء الاقصى لكل ركيزة ضمن المجموعة وعزم الانحناء الاقصى للركيزة المنفردة. اظهرت النتائج ان عزم الانحناء لكل ركيزة ضمن المجموعه اقل منه للركيزة المنفردة وان الفرق بين القيمتين يزداد كلما قلت المسافة بين الركائز بحيث وجد ان قيمة العزم عندما تكون المسافة (7d) يكون مقارب لقيمته عند الركيزة المنفردة. وجد كذلك ان عزم الانحناء الاقصى لكل ركيزة ضمن المجموعه المكونة من ركيزتين تفصلهما مسافة (3d) يقل بمقدار (17%) و (28%) مقارنة بالركيزة المنفردة في حالة كون الركائز منفصلة ومرتبطة ببعض على التوالي. وجد ان عدد الركائز ضمن المجموعه له تأثير طفيف على قيمة معامل المجموعة بدلالة عزم الانحناء الاقصى باستثناء قيمته عند الركائز الداخلية لمجموعة الركائز المنفصلة والتي اظهرت ان معامل المجموعه يقل بزيادة عدد الركائز.

1. Introduction

Pile foundations are designed to give resistance against active load (i.e., load from structure that is directly transferred to the pile foundation by the cap).

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However, in many cases, pile foundations are designed to provide resistance against passive load, which that is induced from the lateral soil movements. Earthquakes, landslides and human activities, such as tunneling and deep excavation in the vicinity of piles, might cause irreversible soil movements [1]. These soil movements can generate lateral thrusts on the piles supporting both onshore and offshore structures, in a variety of circumstances. In all these conditions, the externally imposed soil movements will impart extra forces, cause increase in bending moments and lateral deflections in piles which may finally cause problems and even damage to the structure of piles [2,3].

In practice, piles are commonly used in groups. When piles are closely spaced in a pile group, the presence of loaded piles nearby affects the behavior of each individual pile [4]. Many researchers [5-7] found that the piles within a group may suffer some reduction in capacity compared with single isolated piles due to interaction effects. The behavior of an individual pile within group is different from that of single pile, and several factors may be influenced on the behavior of group piles [8].

In this study, a series of laboratory tests were conducted on some pile groups subjected to lateral soil movement for investigating the group effect on the lateral response of an individual pile within a group. Different parameters were utilized in these tests, (e.g., pile spacing, number of piles within a group and pile head condition). The piles arranged in one row perpendicular to the direction of lateral soil movement as shown in Figure (1).

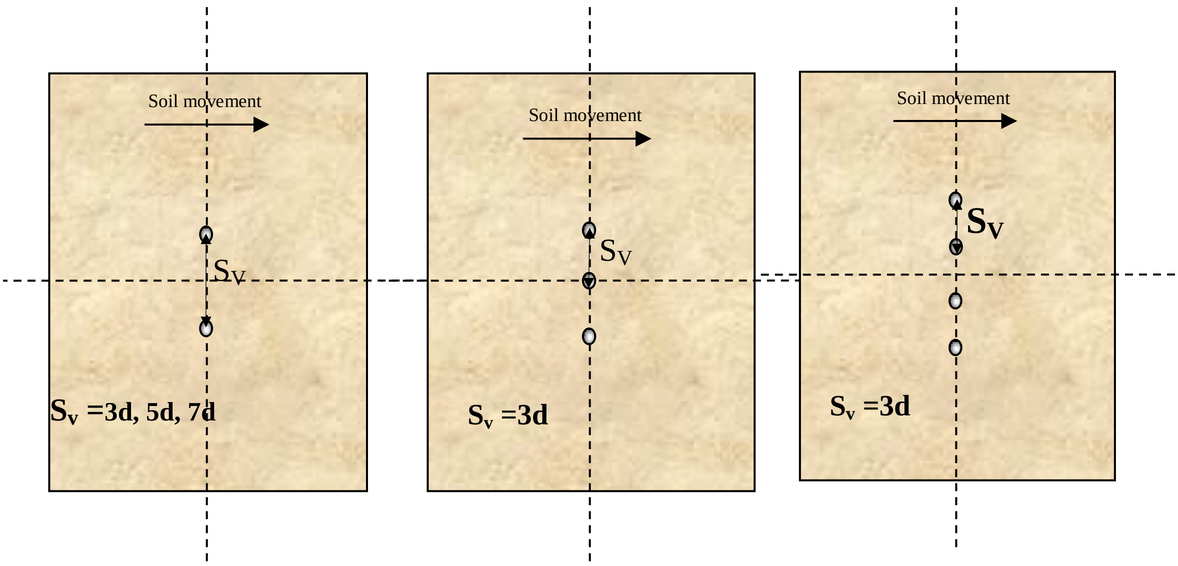


Figure1. Group piles arranged in a row

2. Soil Properties

Dry sand was used in this study and it was sieved on the sieve no. 10 (2 mm) to remove the coarse particles. Figure (2) and Table (1) show the particles size analysis and the Engineering properties of this sand respectively. According to the Unified

Soil Classification System **(USCS),** the sand can be classified as poorly graded sand (SP).

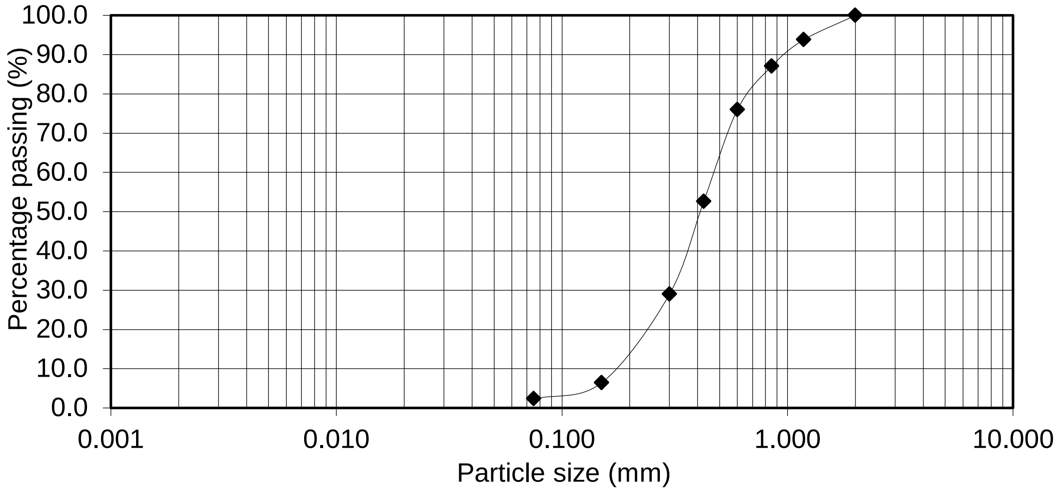


Figure2. Particle size distribution of sand

Table 1. Engineering properties of sand

Property	Value
Specific Gravity, Gs	2.65
Gravel (> 4.75 mm) %	0
Sand (0.075-4.75 mm)%	97
Silt and clay (< 0.075 mm)%	3
D_{10} (mm)	0.18
D_{30} (mm)	0.31
D_{50} (mm)	0.41
D_{60} (mm)	0.48
Coefficient of curvature, Cc	1.11
Coefficient of uniformity, Cu	2.67
USCS-soil type	SP
Maximum dry unit weight, γ_{dmax}, kN/m^3	16.78
Minimum dry unit weight, γ_{dmin}, kN/m^3	14.1
Angle of internal friction ϕ, degree (for Dr = 59%)	35

3.Test Set-up

A special experimental apparatus was designed and manufactured for the current study to investigate the effect of lateral soil movement on pile foundation. It consists of five main parts, (i.e., a steel box, a loading system, a sand raining system, an aluminum piles, and a measurements system). Figure (3) shows the overall arrangement of the testing apparatus.

3.1. *Steel Box*

The designed steel box made of thick steel plate having a thickness of (6.5 mm) with internal dimensions of (80cm×80cm) and (80cm) height was used to apply triangular profile shape of lateral soil movements. Across the width of the box, it was divided into two parts, upper part and lower part. The two parts were connected by two hinges at the mid-height of the box. The upper portion is able to rotate while the lower portion is fixed which makes the soil in the box is divided into two layers (movable and stable). Four wheels were welded at the bed of the box in order to allow the box to travel from underneath sand raining to under the pile jacking system.

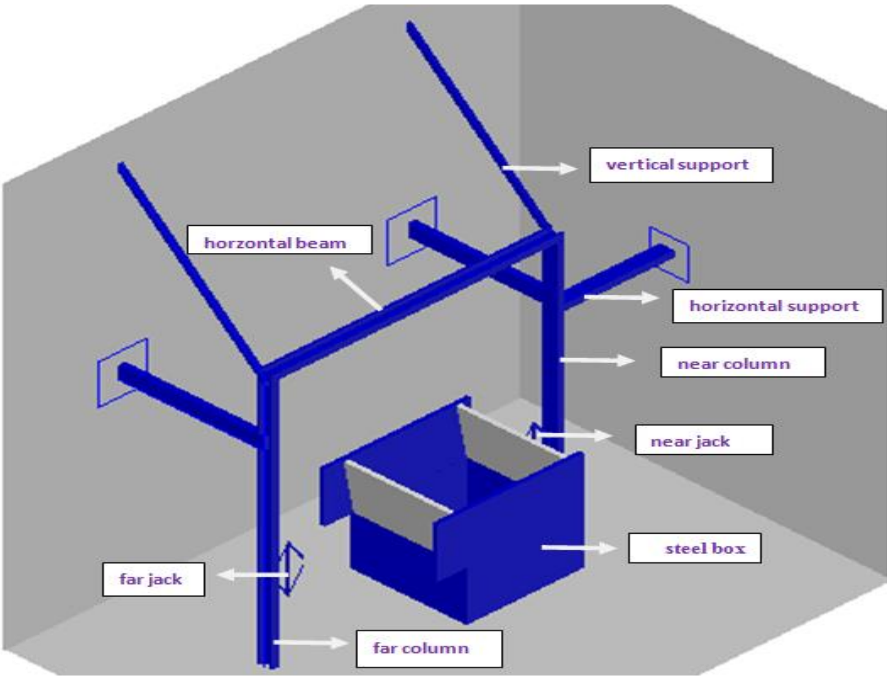


Figure 3. Test set-up

3.2. *Loading System*

Three mechanical jacks with capacity of 3 tons (for each one) were used to apply vertical and horizontal loadings on the instrumented pile and the box respectively. The vertical jack was used to drive the pile into the model ground. A load cell with a capacity of 5 tons was connected with the vertical jack to measure the load required to install the model pile into the sand. The base of the first horizontal (near) jack was welded perpendicular to the near column of the frame in order to apply horizontal force on the near upper part of the box.

A load cell with a capacity of 5 tons was connected with this near jack to measure the horizontal force acting on the near upper part of the box. By turning the near jack, the near upper moveable part of the model steel box was forced to rotate around its joints, and consequently causes the upper part of the soil in the box to move. The moving soil thus is subjected to a triangular profile of horizontal movement, with the maximum displacement at the soil surface and zero displacement at the level of joints of the upper and lower parts.

The base of the second horizontal mechanical jack (rear jack) was welded perpendicular to the rear column of the frame to control on the movement of the rear upper part of the box.

3.3. *The Details of Pile and Pile Cap*

Hollow aluminum pipes of 30 mm outer diameter, 1.4 mm wall thickness and 1000mm total length with a bottom plug were utilized as a model piles in this study**.** The flexural stiffness of each model pile was calculated by conducting simply supported beam test. By measuring the central deflection under a known load at the center of the beam (model pile), the flexural stiffness of the pile was found (0.91 kN.mm^2). The pile caps were designed and fabricated from a solid aluminum block of 60 mm thick. On one face of the pile cap, there were predrilled holes of 30 mm deep, with a diameter to fit the piles. The diameter of each hole was made 0.5 mm greater than the pile diameter to assist the piles to the pile cap connection. The caps were not used just for connecting the pile heads together during the test (capped headed case), but also for helping the jacking system to drive the piles into the sand bed.

3.4. *Instrumentations and Measurements*

The data logger, strain gauges and load cell utilized in this study to determine the strains along the pile shaft and load required causing movement in the upper movable part of the model box. A compact and handheld digital data logger (TC-32K) was utilized to measure and store data from strain gauge measurement for each pile test. TML strain gauges type (FLA-5-23-3L) having a gauge resistance of 120 ±0.3 Ohm was used to instrument the model piles. The strain gauges were fixed along the model piles using cyanoacrylate adhesive (type CN). The strain gauges were then coated by 1 mm epoxy resin in order to protect from damage during the pile driving and testing under lateral soil movement. Eight pairs of strain gauges were attached along each instrumented pile to measure the developed bending moment caused by lateral soil movement. The number of instrumented piles within the group depends on the number of piles within the group. Due to the limited channels existing in the current data loggers (maximum ten channels), several separated tests were conducted on pile groups to record the bending moments of the required individual pile, and the number of these separated tests depends on the number of piles.

The strain gauges were calibrated by testing the instrumented pile as a simply supported beam under known applied bending moments. At the center of the beam (instrumented pile), dead loads and a pair of strain gauges were attached to apply bending moment and measure the strain respectively. The main aim of this calibration was to ensure an appropriate relationship between the strain gauge reading and the bending moment. A linear relationship was obtained between the actual calculated bending moment and the strain gauge readings for all piles used in this study. Figure (4) shows this relationship for standard pile (30 mm pile diameter).

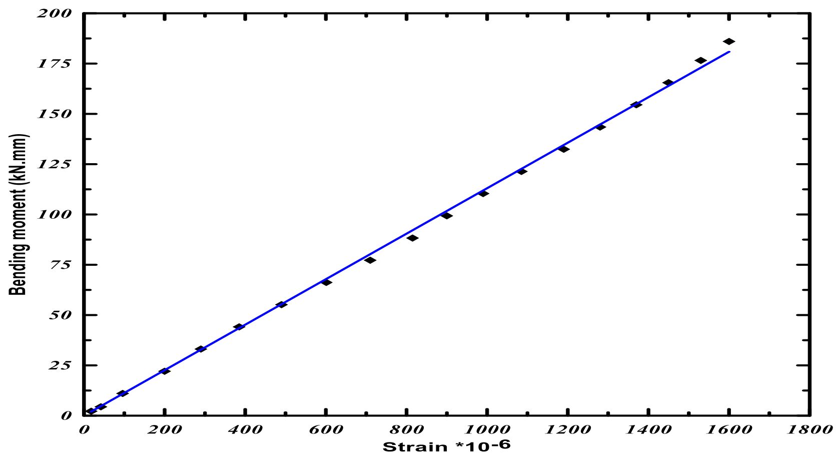


Figure 4. Relationship between the strain and the bending moment

3.5. *Sand Raining Device*

A sand raining device fabricated from timber pieces, having internal dimensions of 790 mm by 790 mm, and 150 mm in height was used to pour the sand in the box. The base of the sand raining consists of two timber plates; the bottom is fixed while the top is moveable. The thickness of the timber plates was 18 mm and 6 mm for fixed and moved respectively. The fixed plate was perforated with 6 mm diameter holes on a 40 mm by 40 mm grid pattern. The moveable plate can slide along the slots on one side of the sand raining. When the top moveable plate is pulled out, the sand is discharged from the sand raining in model box. The falling height of sand was selected as 400 mm, which gave a relative density of sand about 59%, and a unit weight of 15.6 kN/m^3.

4. Comparison Method

To explore the group effects on the lateral response of piles, the pile group results were compared with that of the single pile test and hence a suitable comparison method was needed to be adopted. The group factor in term of bending moment (F^m) represents the ratio of the maximum bending moment of individual piles within a group M_{maxi} to the maximum bending moment of single pile M_{maxs} [9].

5. The Test Results

This section describes the results of free headed single pile (standard) test and the tests of two, three and four piles arranged in one row for free and capped headed cases. The results of the effect of pile spacing and number of piles on response of piles in a row are presented and discussed in the following subsections.

5.1. *Single Pile (Standard)*

This test was performed on free headed single pile of 30 mm in diameter; the box was filled with sand to the top. The pile length in the upper movable part (Lm) was 400 mm, while that in the lower stable part was 350 mm. The falling height of sand raining was (400mm) gave a relative density of about 59%. Figure (5) shows the response of pile in terms of bending moment. It can be seen that the profiles of the bending moment along the pile shaft at different values of the lateral soil movements are analogous to a parabolic shape. The measured bending moment increases with increasing the lateral soil movement but the rate of the increase reduces, especially when the soil surface movement is greater than 60 mm.

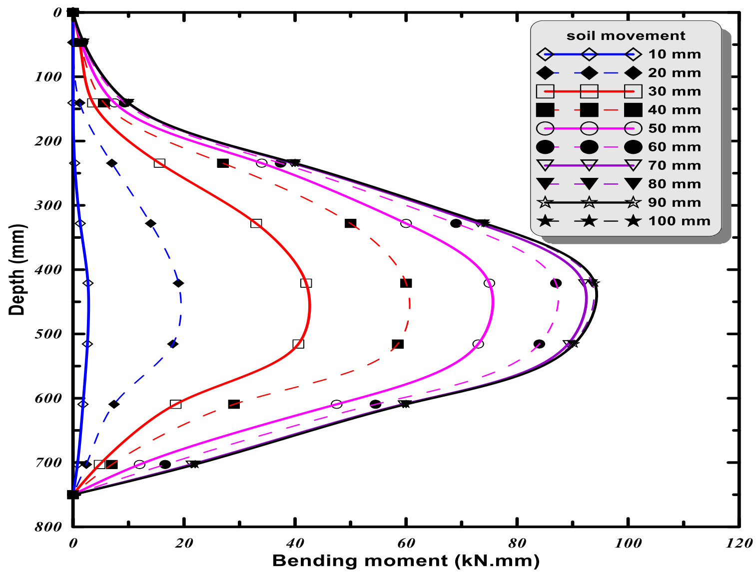


Figure 5. Bending moment distributions from the standard test

5.2. *Pile Group*

5.2.1. *Effect of pile spacing*

For investigating the effect of pile spacing on the lateral response of pile, many tests were carried out on two piles arranged in a row for both free and capped headed cases. Three different spacing (i.e., 3d, 5d and 7d) were adopted in these tests as shown in Figure (1). Due to symmetrical arrangements of the piles in this type of pile groups, the results of the two piles were suggested to be basically identical and hence only the re results of one pile were presented.

5.2.1.1 Free headed pile group

The bending moment profiles for different pile spacing together with that for the single pile test are illustrated in Figure (6). It can be seen that the bending moment profiles are very similar in shape for all cases; including the depth of the maximum bending moment, but different in the magnitudes of the bending moments. It can be also seen that the variation of the calculated bending moment with pile spacing is mainly within the middle part of the pile length (which includes the position of the maximum bending moment); while the variation is very small in the upper and lower portions of pile. Also the maximum bending moment decreases from the single pile test with decreasing pile spacing. Since each pile in all cases was subjected to the same magnitude movement, this reduction in the bending moment may be due to a reduction of pile–soil contact pressure resulting from pile-soil interaction. It can be observed from Figure (6) that a spacing of 7d seems to be large enough to eliminate abolish the group effect. It can be indicated the pile behaves essentially the same as a single pile when the pile spacing is 7d or more.

5.2.1.2. *Capped headed pile group*

The bending moment profiles for capped headed two piles in a row for different pile spacing together with that for the single pile test are shown in Figure (7). Although the pile cap tends to develop a negative bending moment at the pile head level, the value of this negative bending moment was very small. Therefore, the bending moment profile for all pile spacing was basically the same as that for the free headed case, but its magnitude appears to be smaller. It can be noticed that, similarly to the free headed case, the maximum bending moment decreases with decreasing pile spacing.

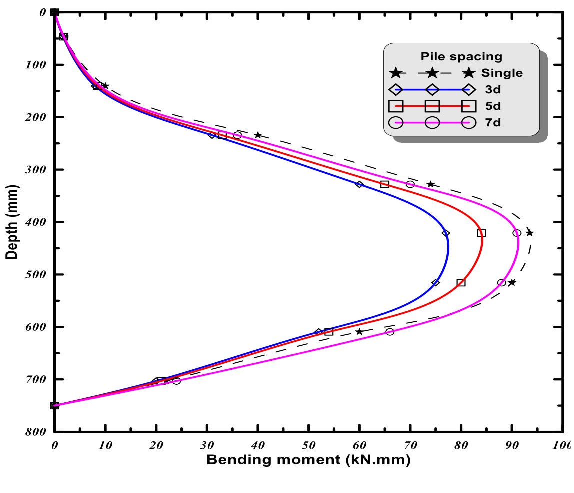


Figure 6. Bending moment profile for free headed two piles in a row

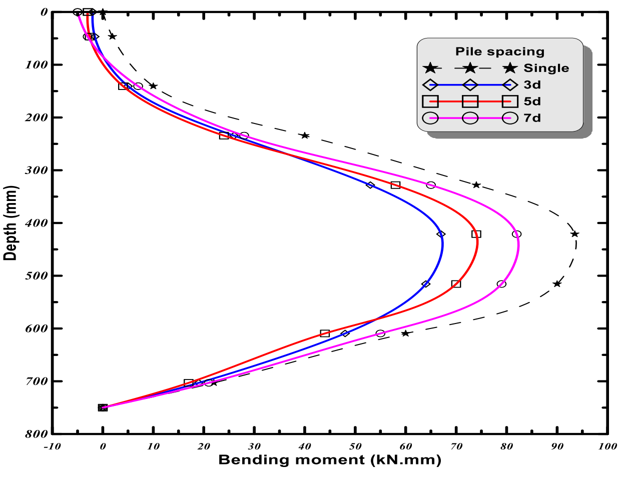


Figure 7. Bending moment profile for capped headed two piles in a row

5.2.1.3. *Group factor*

Figure (8) shows the plot of the group factor F^m for both free and capped headed conditions and different pile spacing. It can be seen that, (F^m) decreases with decreasing pile spacing for both headed cases and capped case, and it is smaller than unity for all cases. The group factor was also seen to be greater for the free headed case than that for the capped case, which may be attributed to a developed negative bending moment and a larger load sharing between the adjacent piles for the capped condition. The maximum reduction of the maximum bending moments of about (17%) and about (28%) as compared with that for the standard single pile may be observed for a pile spacing of 3d for the free headed condition and capped condition, respectively. It seems that the provision of a pile cap for two piles in a row tends to results in a smaller bending moments. Therefore, the provision of a pile cap appears to be an advantage for piles in a row utilized for resisting soils from moving laterally.

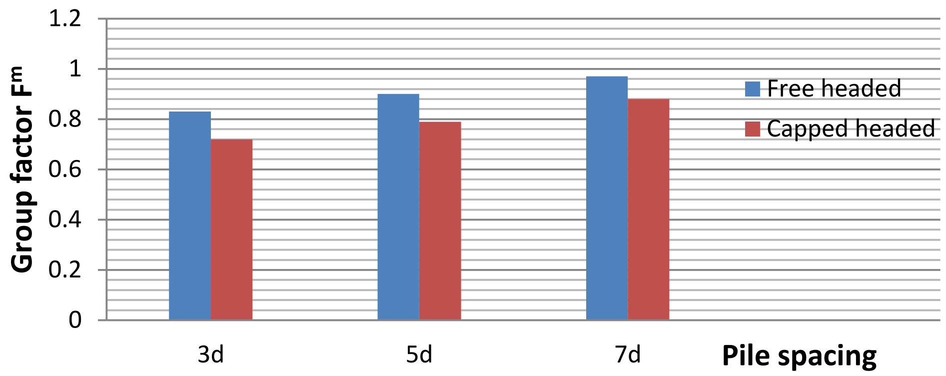


Figure 8. The group factor against pile spacing for two piles in a row

5.2.2. *Effect of number of piles*

To explore the effect of number of piles on the lateral response of piles in a row, four tests were carried out on three piles and four piles groups for both free head and caped cases with pile spacing 3d. As shown in Figure (1), for both the three piles and four piles groups, the outside piles were defined as an outer piles, while the inside pile(s) were defined as inner pile(s).

Because of there are only ten channels in the current data loggers (as shown previously), three separate tests were carried out on each three pile and four pile groups tests. In the first test, both inner and outer piles were instrumented with four pairs of strain gauges, and these pairs were attached at the middle portion of the piles. In the second and third tests, the inner and outer piles were instrumented by eight pairs of strain gauges, respectively.

The purpose of the first test was to compare the results of the inner and outer piles in the middle portion of the piles with those of the second and third tests, respectively.

5.2.2.1. Free headed pile group

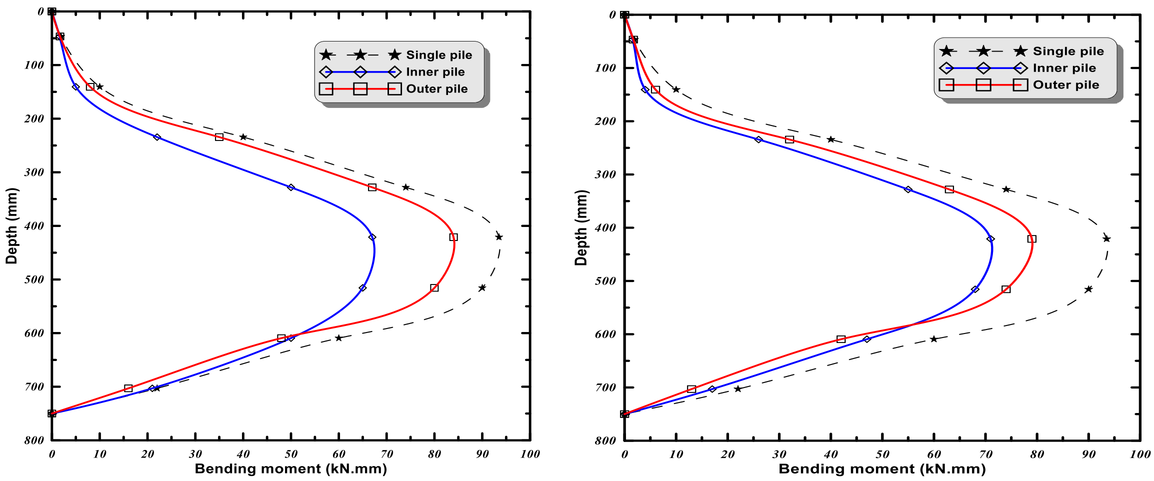
Figure (9a) presents the bending moment profiles for the inner and outer piles for free headed three piles group (for 3d pile spacing), together with that of the single pile test. It can be noticed that, the shape of the bending moment profiles is very similar for each pile, but the maximum bending moment for the outer pile is larger than the maximum bending moment for the inner pile. It can be also seen that the bending moments of the inner pile and the outer pile are smaller than the bending moment of the single pile. The similar trend is also observed for bending moment profiles for the four pile groups, but the differences in the magnitudes of the bending moments for the inner and outer piles appears to be greater than for the three piles group, as presented in Figure (9b). Also, the bending moments of the inner pile and the outer pile are smaller than the bending moment of the single pile.

5.2.2.2 Capped headed pile group

Figure (10a) presents the bending moment profiles for the inner and outer piles for capped headed three piles group (for 3d pile spacing) together with that of the single pile test. Similar to the test of two piles, the cap tends to develop a negative bending moments at the pile head level piles, but it is value is far less than the maximum positive bending moment.

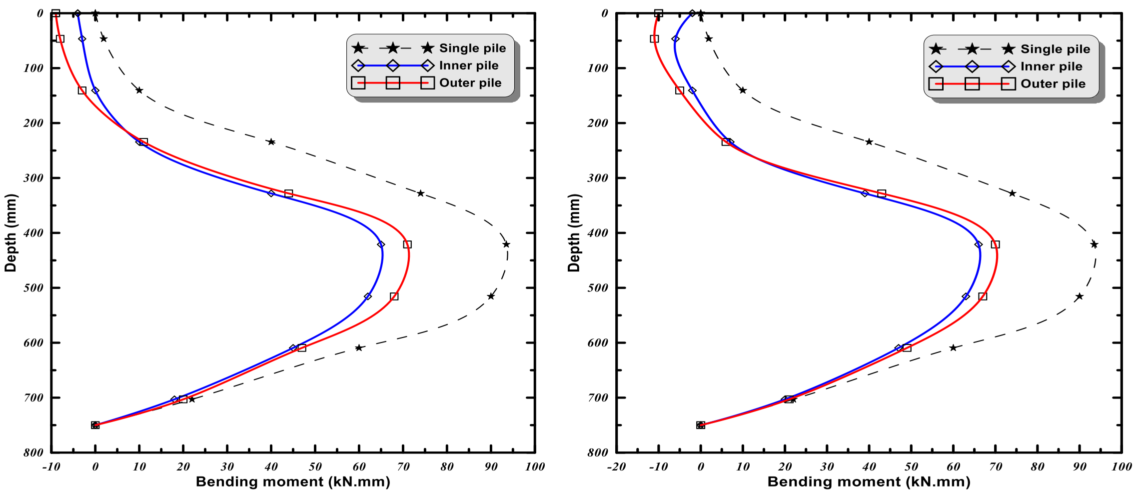
The bending moment profiles for the inner pile and the outer pile for capped headed four piles group (for 3d pile spacing) together with that of the standard single pile test are presented in Figure (10b).

Similar to the case of capped headed three piles group, the cap tends to develop a negative bending moments at the pile head level piles. The negative bending moment appears to increase (but stay less than maximum positive bending moment) with increasing the number of piles with the group, but the maximum positive bending moment is approximately constant.



(a): Three piles (b): Four piles

Figure 9. Bending moment for profiles for free headed 3 and 4 piles in a row



(a): Three piles (b): Four piles

Figure 10. Bending moment for profiles for capped headed 3 and 4 piles in a row

5.2.2.2.Group factor

The group factor F^m is plotted with the number of piles to explore the influence of the number of piles on the lateral response and the resisting force provided by piles. As shown in Figure (11) the effect of the number of piles within a group on the group factor F^m, for both the free headed and capped cases is seen to be different for the inner pile and outer pile due to load sharing which develops between the adjacent piles. The number of piles does not appear to have significant effect on the group factor F^m of piles, except for the free headed inner piles (i.e., the group factors appear to decrease with increasing the number of piles within a group).

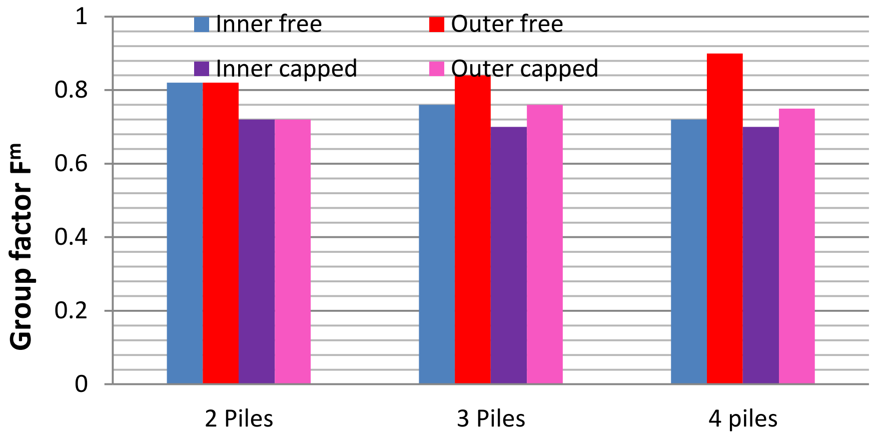


Figure 11. The group factor against pile spacing for piles in a row

6. Conclusions

Laboratory model tests have been conducted on group piles arranged in arrow in additional to single pile subjected to lateral soil movement in sand to investigate the effects of the pile's spacing, number of piles and piles headed condition on lateral response of piles. The results of the tests indicate that the maximum bending moment for both free and capped headed cases decreases from the single pile with decreasing pile spacing and the group piles behaves essentially the same as a single pile when the pile spacing is 7d or more. The maximum reduction of the maximum bending moments of about (17%) and about (28%) as compared with that for the standard single pile may be observed for a pile spacing of 3d for the free and capped headed conditions, respectively. The maximum bending moment for the outer pile was larger than the maximum bending moment for the inner pile. For four piles group, the differences in the magnitudes of the bending moments for the inner and outer piles appears to be greater than those for the three piles group. The number of piles does not appear to have significant effect on the group factor F^m of piles, except for the free headed inner piles whose the group factors appear to decrease with increasing the number of piles within a group.

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