# Effects of Axial Loads and Soil Density on Pile Group Subjected to Triangular Soil Movement

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***Abstract*—**Laboratory tests have been carried out to investigate the response of 2x2 pile group subjected to triangular soil movement. The pile group was instrumented with displacement and tilting devices at the pile cap and strain gauges on two piles of the group. In this paper, results from four model tests were presented to study the effects of axial loads and soil density on the lateral behavior of piles. The responses in terms of bending moment, shear force, soil pressure, deflection, and rotation of piles were compared. Test results indicate that increasing the soil strength could increase the measured moment, shear, soil pressure, and pile deformations. Most importantly, adding loads to the pile cap induces additional moment to the head of front-pile row unlike the back-pile row which was influenced insignificantly.

***Keywords*—**Pile group, passive piles, lateral soil movement, soil density, axial loads.

## I. Introduction

In some circumstances, piles are subjected to progressively increasing soil movements in the lateral direction making the piles under overestimated or even unexpected stresses. This kind of "hidden" loadings can be generated in piles located in the close vicinity of a site which undergo excavation activities, pile driving operations, surcharge loads, and tunnelling operations as illustrated in Fig. 1. The profile in which the soil moves with can take several shapes depending on the nature of the ground and the activity itself. One of the most common profiles is the triangular shape of soil movements. This kind of movement has been observed by several investigators from in-situ measurements and laboratory tests, as in [1]-[3]. The impact of moving soil on piles can be summarized in inducing additional lateral deflections and bending moments which could lead to damage effects. In order to provide a protection to the piles adjacent to the above construction activities, numerous studies were made to investigate the response of single "passive" piles taking into account a wide range of influencing factors, e.g. [4]-[8]. These efforts provided a good understanding on the behavior of laterally loaded piles with loads applied beneath the ground level. Practically, piles are usually used in groups in which the pile-soil-pile interaction plays an important role in the performance of individual piles within a group. In the analysis of passively loaded pile groups, researchers have conducted laboratory investigations through small scale experiments and centrifuge modelling, e.g. [9]-[12]. On the simulation of soil movements, laboratory tests were carried out by either direct mobilization of soil movement or simulation of field conditions. However, most of these studies were focused on the influence of parameters such as pile spacing, pile head condition, and number of piles within a group. Although some experimental investigations have studied the influence of axial loads and soil density on the behavior of single passive piles, relatively few studies were conducted taking into account the effect of those two parameters on the performance of passively loaded pile group. In this context, [13] developed a shear box consists of upper aluminum laminar frames and lower fixed timber box in order to study the behavior of pile groups exposed to axial loads and horizontal soil movement in the condition of free standing pile group. In those experiments, holes in the cap were made 0.5 mm larger than pile diameter to enable the pile fitting into the pile cap holes. This gap allows the pile to rotate slightly during the test causing the pile head bending moment to be lower than that of a fully fixed pile head.

In this paper, for experiments were conducted on 2x2 free standing pile group subjected to triangular soil movement. The main purpose of this study is to explore the influence of axial loads and soil density on the performance of passively loaded pile group.

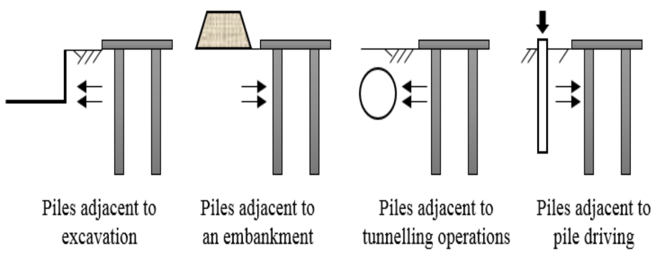


Fig. 1 Examples of passive piles

## II. Experimental Details

### *A. The Testing Box*

A specially built box was fabricated to simulate the problem of moving soil around piles as shown in Fig. 2. The box consists of 500 mm height lower stationary timber box and an upper movable part comprised of a number of smooth laminar plywood frames of 190 mm height. Both stationary and moving parts had 600 mm x 600 mm plan internal dimensions. The internal surfaces of the testing box were covered by a latex sheet. The lateral loading system consists of a screw jack

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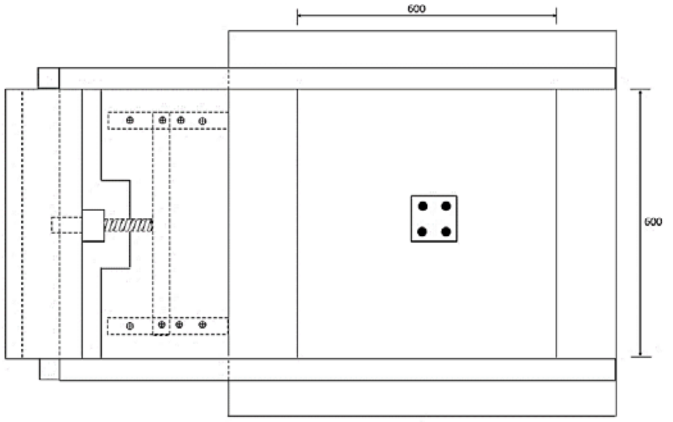
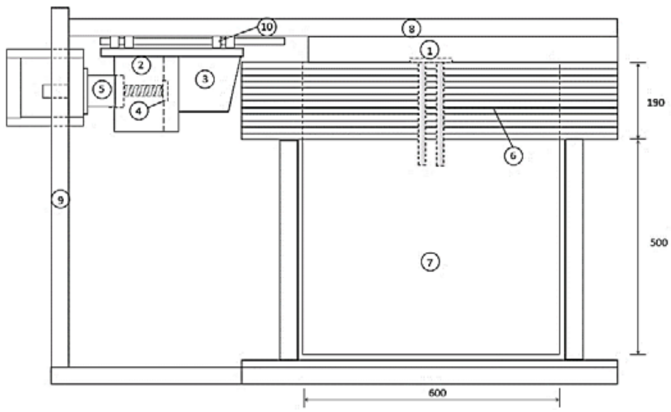
mounted on a horizontal timber beam supported by two vertical steel columns. The screw jack pushes a timber frame consists of timber blocks and two loading blocks. The timber frame transfers the lateral jacking load to the loading blocks which are in a direct contact with the laminar frames causing lateral movement to these frames and to the soil inside the box.




(a) Plan view



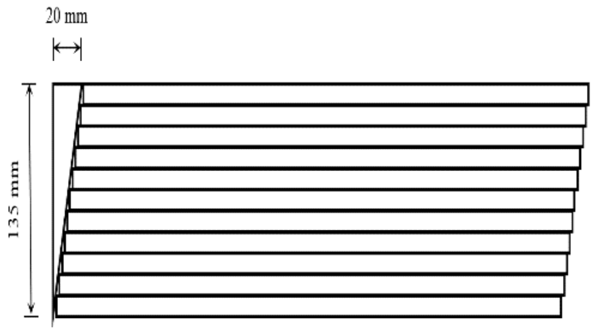

(b) Elevation view

Fig. 2 Experimental apparatus showing testing box and loading frame 1. Pile group model 2. Loading frame 3. Loading block 4. Load cell 5. Screw jack 6. Sliding frames 7. Testing box 8. Vertical support 9. Reaction frame 10. Sliding unit

### B. Triangular Soil Movement Profile

The tests were carried out with a triangular soil movement profile at the box boundaries. This shape of movement can be obtained by using triangular loading blocks in the loading frame (Fig. 3 (a)). The progressive movement of the loading blocks starting from the top laminar frame, which moves first, up to the last frame will create the triangular soil profile. In this set of experiments, the test was terminated once the bottom of triangular block touches the last laminar frame to avoid obtaining a trapezoidal movement profile. The loading blocks were designed to induce 20 mm of movement to the top laminar frame and to apply displacement to a depth of 135 mm of sand as shown in Fig. 3 (b). It is worth noting that as loading blocks move laterally, the depth of moving layer increases accordingly. Therefore, the depth of sliding layer can be obtained at any intermediate loading stage simply by multiplying the top frame displacement ($\Delta_B$) by 135/20. Fig. 4 shows the obtained soil profile resulting from applying a triangular shape of loading block at box displacement ($\Delta_B$) = 5 mm, 10 mm, 15 mm, and 20 mm.

(a) Loading block




(b) Final movement profile

Fig. 3 Triangular loading block

### C. Model Pile Group and Instrumentation

The model piles used in this study were made of aluminum tubes having a length of 300 mm, an outer diameter of 20.0 mm, and a wall thickness of 1.0 mm. A 2x2 pile configuration with 3D pile to pile spacing (i.e. 60 mm) was used in the model test with triangular movement profile. A gap of 15 mm was left between the pile cap and the soil surface to simulate free-standing pile group. An aluminum plate was used to fabricate pile cap with dimensions of 100 mm x 100 mm and a thickness of 9 mm. Four holes were drilled through the cap thickness represent a 2x2 pile configuration. The head of each pile was fixed against movement and rotation to the pile cap through a screw of 10 mm in diameter and 50 mm in length. Details of piles and pile cap are presented in Fig. 5.

In order to measure the bending moment distribution throughout the pile length, seven strain gauges were attached to the outer surface of two piles in the group (one pile at each row). Each strain gauge has a code name starting with (SG) followed by pile name (F or B) and a number which refers to its position (1 to 7). The letters (F or B) are used to describe the pile in terms of its location to the source of lateral loading. Hence, (F) refers to the front pile which is nearest to the source of lateral loading and influenced by the soil displacements before pile (B) or the back pile. Two LVDTs were used to measure the displacements of the sliding frames and the pile cap, respectively. An inclinometer senor was used to measure the inclination of pile cap.

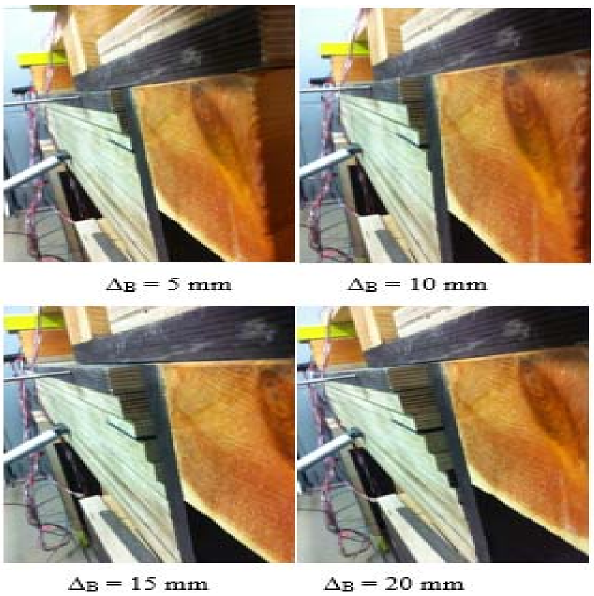



Fig. 4 Soil profile resulting from applying a triangular shape of loading block at $\Delta_B$ = 5 mm, 10 mm, 15 mm, and 20 mm

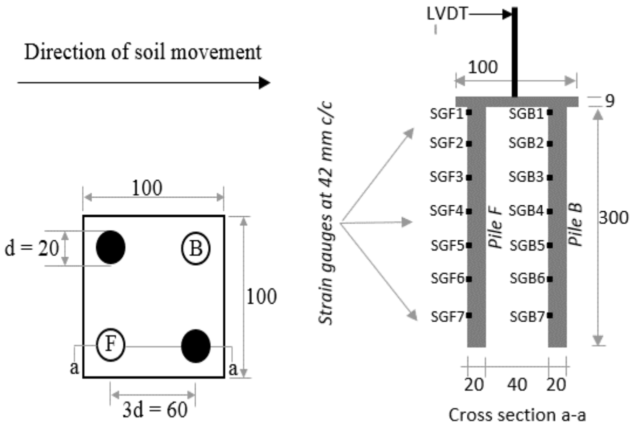



Fig. 5 Details of model piles and cap

### D. Sand Properties

The dry sand with particle size ranging from 0.063 to 1.18 mm was used in the present study as model ground. The minimum and maximum unit weights were 14.0 and 16.6 kN/m$^3$, respectively. Grading test showed that coefficient of uniformity $C_u$ = 2.06 and coefficient of curvature $C_c$ = 0.95. Pouring and tamping were used to achieve a reasonably constant density of the sand in the testing box. In this method, the box was divided into spaces of 50 mm height. These spaces were then filled with a pre-determined sand weight to achieve the required density. Subsequently, a scoop was used to pour the sand into the testing box. After furnishing the sand layer, a manual compactor was also used to maintain the required height of each layer.

### E. Analysis of Test Results

Basically, single and double integrations of the bending moment distribution give the rotation and deflection along the pile depth, respectively. On the other hand, shear force and soil reaction profiles can be obtained by differentiating the bending moment profile along the pile depth to the 1$^{st}$ and 2$^{nd}$ order, respectively. Two techniques were tested to deduce shear force and soil reaction along the pile shaft, i.e. the finite difference method and polynomial curve fitting method. A comparison was carried out between the results of finite difference method and those deduced by deriving 5$^{th}$ and 6$^{th}$ order polynomials. The results indicated that the soil reaction obtaining by the second derivative of the polynomial soil reaction profile showed unrealistic increase in magnitudes at pile tip and at the point of rigid body rotation for both front and back-pile rows. Owing to this inconsistency in soil reaction values deduced by polynomial curve fitting method, the finite difference method is used in the current study.

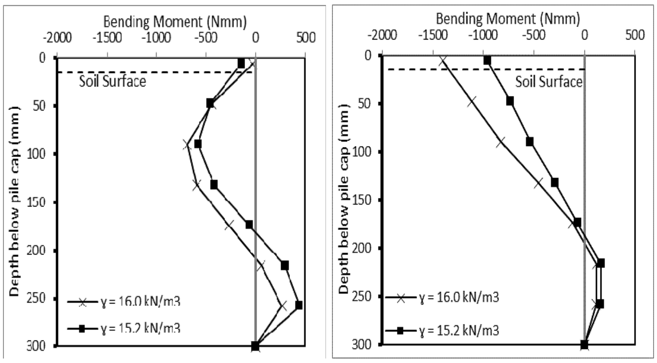
## III. Test Results

A total of four tests were conducted in two states of sand compaction (dense and medium sand with $\gamma$ = 16.0 kN/m$^3$ and 15.2 kN/m$^3$ respectively) with no axial load on the pile cap, and two levels of axial loads (100 N and 200 N) at soil density of 16.0 kN/m$^3$ to investigate the influence of sand strength and axial load on passively loaded pile group.

### A. Effect of Sand Density

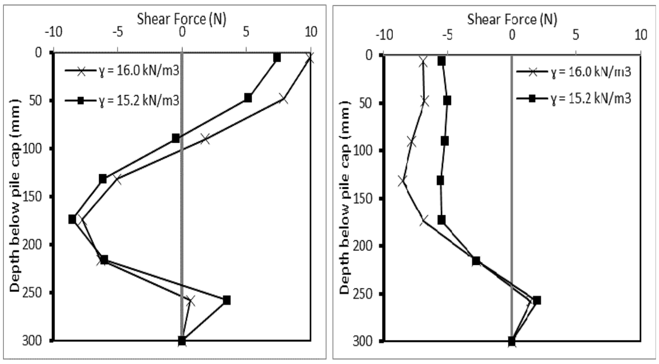
Fig. 6 shows bending moment profiles for piles F and B at $\Delta_B$ = 20 mm. It can be seen that the shapes of moment curve for both piles are different. Moment distribution had an arc shape with double curvature in pile F, while pile B developed approximately a linear variation of moment along its upper half. Front pile showed its maximum moment at 90 mm under the pile cap (0.3 L), while the head of back-pile row recorded maximum moment. The two model test results appeared that the maximum pile response occurred with pile group tested in dense sand. In this context, bending moments recorded in the front and back piles tested in sand with $\gamma$ = 16.0 kN/m$^3$ were about 19% and 47% higher than those recorded with $\gamma$ = 15.2 kN/m$^3$ respectively. The ratio of maximum positive to maximum negative bending moment ($M_{-max}/M_{+max}$) in the front pile was ranging from 2.7 to 1.3 for both tests, while that recorded in pile B was about 5.6 to 9.3.

Shear force distribution along the pile lengths recorded at 20 mm of soil displacement is shown in Fig. 7. It reveals that shear force profiles for both tests are identical in shape including the position of maximum and zero shear force. The maximum shear force carried by pile F occurred at the pile head, while pile B showed maximum shear at a location close to the final sliding depth. Owing to the fact that shear force is the first derivative of bending moment, shear force distribution was almost constant along the upper part of the back pile, where this portion was under a linear variation of bending moment.



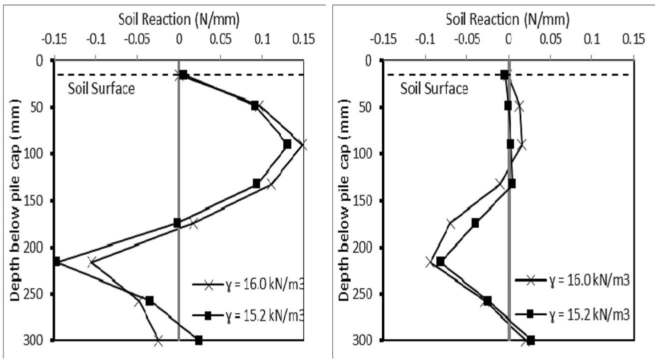

(a) Pile F (b) Pile B

Fig. 6 Moment profiles of piles at ΔB = 20 mm




(a) Pile F (b) Pile B

Fig. 7 Shear force profiles of piles at $\Delta_B$ = 20 mm

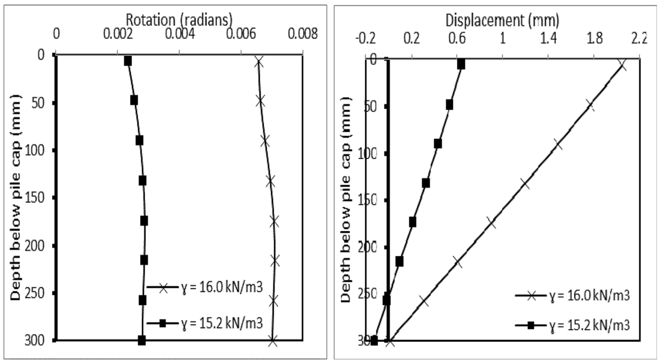



(a) Pile F (b) Pile B

Fig. 8 Soil reaction profiles of piles at $\Delta_B$ = 20 mm

Soil reaction profiles for piles F and B are shown in Fig. 8. It appears that passive loading on that part of the front and back piles located in the sliding layer exhibits higher soil pressure with increasing sand density. Maximum soil pressure occurred at a depth of 75 mm under the soil surface for both cases. It can be seen that in the case of γ = 15.2 kN/m$^3$, the front pile did not show a positive soil reaction at the region closed to the pile tip. The point of zero soil reaction at that part of the pile refers to the point of pile rotation where no horizontal displacement occurred. Since the soil reaction at a certain point is a function of the bending moments measured at the nearest two locations, the error in the soil reaction recorded in the front pile may be attributed to the missing of bending moment readings between strain gauge SGF6 and SGF7.

Fig. 9 investigates the rotation and deflection profiles of the front pile. It can be seen that maximum deformations occurred when the sand was in its dense state of compaction.




(a) Rotation of pile F (b) Rotation of pile F

Fig. 9 Rotation and deflection profiles of pile F at $\Delta_B$ = 20 mm

Pile cap rotation and horizontal displacement patterns measured at successive increments of box movements are shown in Fig. 10. It can be seen that the magnitude of box displacement at which the pile cap was started to rotate and deflect is a function of soil density. In the case of γ = 16.0 kN/m$^3$, moving sand caused first deformations to the pile cap at about 7.5 mm of box movement, while decreasing the sand density to 15.2 kN/m$^3$ caused the foundation system to be more stable in which it needed about 15.0 mm to start its deformations. It is worth noting that tilting device has recorded some very small magnitudes of cap rotation at early stages of loading process. This is mainly due to the high sensitivity of the tilting device.

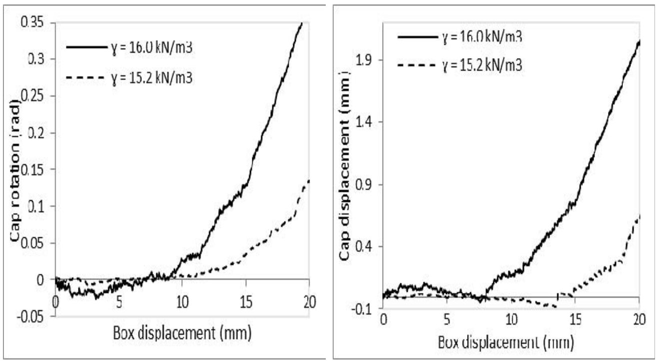
### *B. Effect of Axial Loads*

In order to evaluate the influence of axial loads on the lateral behavior of passively loaded pile group, two tests, namely (PG100) and (PG200), have been conducted with two levels of axial loads applied at the pile cap (100 N and 200 N), respectively. Disc weights were placed and connected to the pile cap simulating the axial loads applied on the pile group. The results obtained from these tests were compared with the one carried out with no axial load (test PG0). Regardless the change in axial loads, the three tests have been conducted under the same conditions, i.e. 16.0 kN/m$^3$ of sand density and 3D of pile spacing. Fig. 11 shows the response of the front and back-pile rows in terms of bending moment measured at 20 mm of the top laminar frame displacement for the three tests. According to this figure, the following observations can be drawn:

1) For the front-pile row, the measured bending moment at the pile head showed tendency towards negative values when axial loads applied. This behavior could be explained by the additional restraint that axial loads have provided to the pile head movement and rotation. In

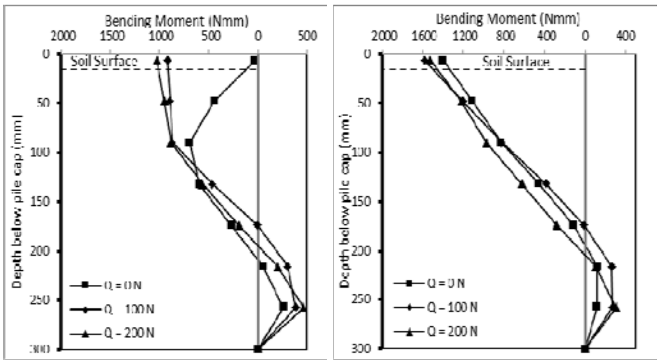
addition to this factor, the rotation of pile cap which induced tilting to the load vertical axis away from its original position causing overturning moment (p-delta effect) is also influencing the response of front-pile row. Despite the difference in pile head moments, the three profiles showed almost the same trend regarding the position of zero moment and maximum positive moment. Furthermore, insignificant difference was observed by increasing the axial load from 100 N to 200 N.

2) The back-pile row did not appear to be affected much by adding axial load on the pile cap, in which the maximum bending moments recorded at Q = 200 N was only 8% greater than that measured when Q = 0 N.




(a) Rotation (b) Displacement

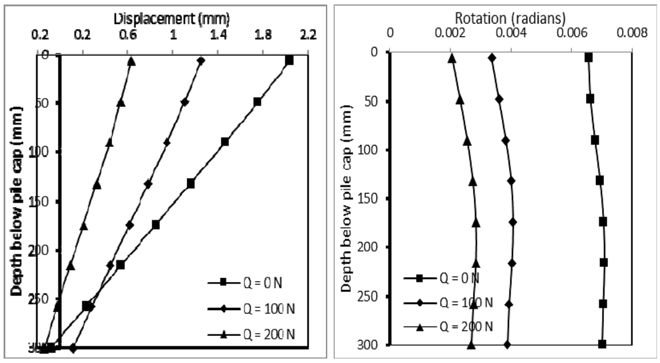
Fig. 10 Rotation and deflection of the cap versus box movement




(a) Pile F (b) Pile B

Fig. 11 Bending moment profiles of piles at $\Delta_B$ = 20 mm

Fig. 12 shows the response of front pile in terms of deflection and rotation measured along the pile length at the three levels of axial loads. It can be seen that both rotation and deflection are decreased as the axial load intensity increased. The deflection and rotation recorded in test PG200 were about 1/3 of those recorded in the standard test (PG0). This is an expected finding owing to the additional fixity which has been provided by the axial load. It is also observed that the presence of axial load does not change the rigidity behavior of piles.




(a) Deflection of the front pile (b) Rotation of the front pile

Fig. 12 Rotation and deflection profiles at different levels of axial load

## IV. Conclusions

Laboratory tests were carried out to investigate the effect of axial load and soil strength on the lateral behavior of pile group subjected to triangular soil movement. The response of piles was presented in terms of bending moment, shear force, soil pressure, rotation, and deflection of piles.

1) The model tests confirmed the notable influence of axial loads applied to the pile cap on the response of passively loaded pile group especially on the front-pile row. Significant negative bending moment was developed at the front-pile head when axial loads added. On the other hand, the back pile showed insignificant difference in bending moment profiles caused by adding the axial loads.
2) The maximum pile response in terms of bending moment, shear force, soil pressure, rotation and deflection of piles occurred with pile group tested in dense sand compared to that observed in medium sand.

## Acknowledgment

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