Experimental investigation of batter pile groups behaviour subjected to lateral soil movement in sand

Toma-Sabbagh, TM, Al-Salih,, O and Al-Abboodi, I

http://dx.doi.org/10.1080/19386362.2019.1585596

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Type	Article
URL	This version is available at: http://usir.salford.ac.uk/id/eprint/50786/
Published Date	2020

Title: **Experimental Investigation of Batter Pile Groups Behaviour Subjected to Lateral Soil Movement in Sand**

Author 1

- Tahsin Toma Sabbagh , BSc Civil Eng, MSc/PhD Geot. Eng, CIOB, PGCAP, FHEA Lecturer in Civil Engineering, School of Computing, Science and Engineering, University of Salford, Manchester, UK.

Author 2

- Osamah Al-salih, Department of Civil Engineering, University of Basrah, Iraq, currently a PhD student, School of Computing, Science and Engineering, University of Salford, Manchester, UK.

Author 3

- Ihsan Al-abboodi, Department of Civil Engineering, University of Basrah, Iraq, Email: i7san777@gmail.com.

Abstract:

A series of laboratory model tests on batter pile groups embedded in sand was carried out in a specially designed testing box. The lateral responses were investigated for 1 × 2 capped batter pile groups when subjected to lateral soil movements (passive loading) with different configurations; Vertical-Vertical (VVL), Batter-Vertical (BVL), Vertical-Batter (VBL) and Both- Batter (BBL). The effect of pile group arrangement and batter angle on the bending moment, shear force, soil reaction, pile rotation and deflection behaviour of the passive batter pile groups were studied. It is observed that the behaviour of the individual piles in a group was significantly affected by the batter angle and the pile group arrangement. It is also shown that under passive loading, batter pile groups with (BBL) configuration of (-10^o, $+10^o$) offered more resistance to the lateral soil movement compared to other pile group arrangements, while (VVL) configuration offered the least resistance.

Keywords

Laboratory tests, Lateral soil movements, Passive piles, Batter pile group.

Introduction

Batter or inclined piles are piles driven at an angle with the vertical to resist large lateral force from winds, water waves, soil pressures, and impacts (Meyerhof and Yalcin, 1993). Their distinct advantage over vertical piles is that they transmit the applied lateral loads partly in axial compression and/or tension rather than only through shear and bending, while vertical piles carry lateral loads through shear and bending. Thus, batter piles offer larger stiffness and lateral bearing capacity than vertical piles of the same dimensions and material (Giannakou *et al.* 2010). Accordingly, batter piles are usually used as foundations for bridge piers and abutments, oil production platforms, under tall chimneys, anchored bulkheads, high retaining walls, high rise buildings, high-pile wharfs, and transmission towers. Pile foundations can be subjected to direct external lateral loads applied at the head of the pile or pile cap, for example wind loading on a high-rise building or piles in bridge abutments. This type of loading is called “active” loading and the piles subjected to these loadings are known as “active” piles”, as shown in Figure 1 (a). However, there are many cases where piles are subjected to indirect loads due to the lateral movement of the surrounding ground. This type of loading is called “passive” loading, and piles subjected to these loadings are called “passive piles”, (Figure 1 (b)). Numerous studies (experimental and theoretical) have been conducted to investigate the lateral behaviour of vertical passive piles and pile groups under lateral soil movement. A special focus has been given to the experimental investigations that were conducted before. Numerous experimental studies were made through small-scale experiments and centrifuge modelling. These studies were conducted to investigate the response of single vertical piles and pile groups under lateral soil movement (e.g. Poulos *et al.*, 1995; Pan *et al.*, 2002; White *et al.*, 2008; Guo and Ghee, 2010; Al-abboodi and Sabbagh, 2017).

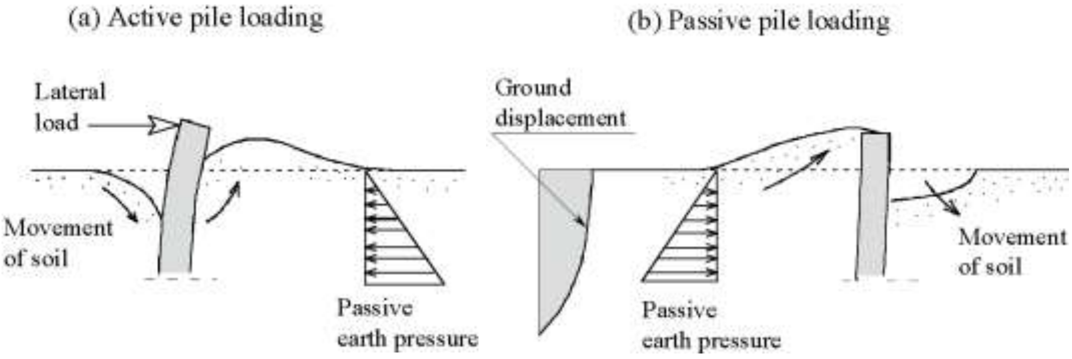
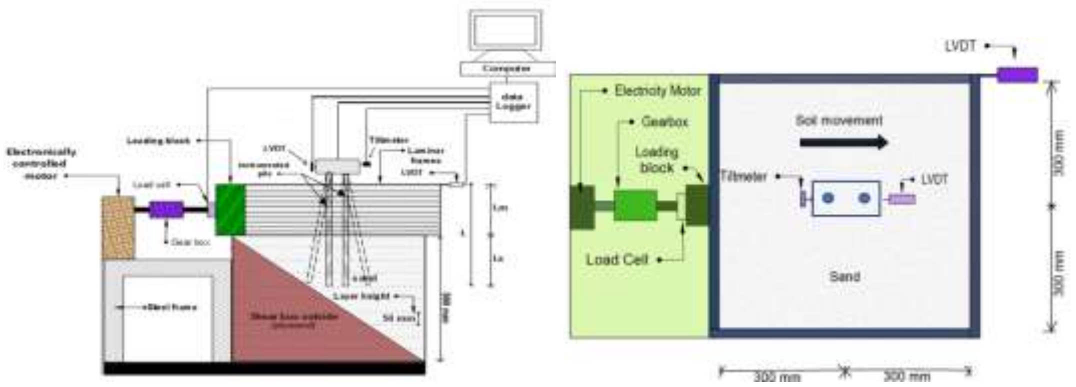


Figure 1 Schematic illustration of lateral loading of piles (Cubrinovski and Ishihara, 2007)

Similarly, studies on ‘active’ batter piles subjected to combined lateral and vertical loads have significantly attracted research efforts for the last four decades (Meyerhof and Ranjan, 1972; Meyerhof and Yalcin, 1993; Zhang *et al.*, 1999; Zhang *et al.*, 2002; Wang *et al.*, 2014; Singh and Arora, 2017). Additionally, there are some theoretical investigations to evaluate the behaviour of batter piles and batter pile groups under ‘passive’ loads (Poulos, 2006; Chen and Tsai, 2014). Nevertheless, previous studies did not address the behaviour of batter pile and pile groups subjected to lateral soil movement (inducing ‘passive’ type of load) in the laboratory. Therefore, little experimental information is available assessing the impact of batter angle and the pile group arrangement on the response of batter pile groups. Consequently, further studies on batter pile groups subjected to lateral soil movement using experimental methods are necessary.

Testing Box

The internal dimensions of the box are 600 mm by 600 mm, and 700 mm in height. A schematic diagram of the wooden box and the loading system used in the experiments are shown in Figure 2. The lower section of the box is 500 mm high, while the upper part of the box is made of a series of 20 mm thick square laminar timber frames. These frames have smooth upper and lower surfaces to facilitate sliding of the frames in the horizontal direction. The frames, which are allowed to slide horizontally, contain the "moving layer of soil" of thickness *Lm* (*Lm* ≥ 200 mm). By changing the number of movable frames in the upper section, the thicknesses of the stable layer (*Ls*) and moving layers (*Lm*) are varied accordingly. The inner faces of the test box were marked at 50 mm intervals to assist accurate formation of sand stacking inside the test box during the tests. The dimensions of the test box have been chosen according to previous researches taking into consideration the boundary conditions influence of the test box (Khari *et al.*, 2013; Al-abboodi and Sabbagh, 2017).



(a) Elevation view (b) Top view

Figure 2 Schematic diagram of testing box

Lateral loading system

The lateral loading system consists of a loading block (Figure 3) and a screw jack connected to an electronically controlled motor with maximum capacity of 25 kN. The loading block is used to apply lateral force on the laminar frames, which is made into triangular and rectangular shape to impose the corresponding soil movement profiles. Throughout all the test programmes, the rate of movement of the upper box (the laminar frames) is controlled by the motor screw jack loading system. Loading rate of 3 mm/min was chosen in this study according to the model tests adopted by Poulos *et al*. (1995).

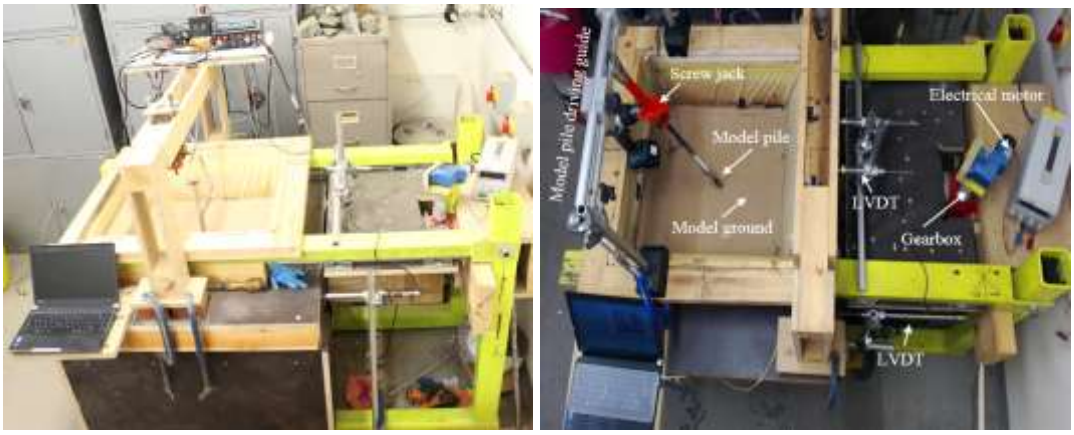


Figure 3 Photos showing the testing box and lateral loading system.

Soil Properties

The sand properties were obtained through various laboratory tests conducted on sand in accordance to BS specifications. The gradation curve of the sand used in the experiments are shown in Figure 4, while all other properties of the sand are given in Table 1.

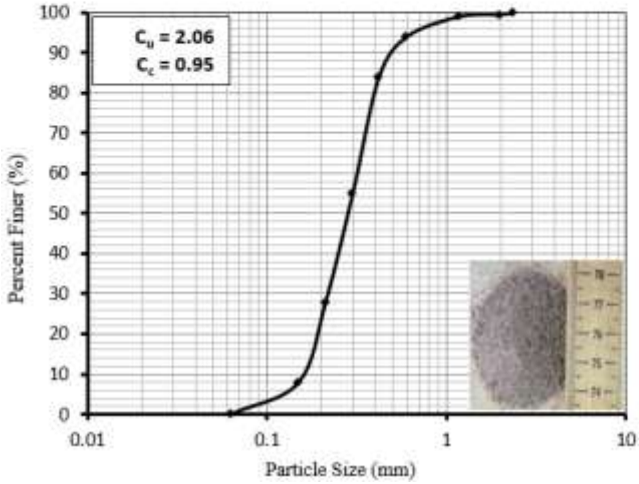


Figure 4 Gradation curve of the sand.

Table 1 Properties of the model sand soil.

Property	**Value**	**Specification**
Specify grafity G_s	2.7	BS 1377-2
Effective size D_{10} mm	0.15	BS 1377-2
D_{30} mm	0.21	BS 1377-2
Mean grain size D_{50} mm	0.29	BS 1377-2
D_{60} mm	0.31	BS 1377-2
Particle size range mm	0.063 – 1.18	Sieve analysis
Coefficient of uniformity C_u	2.06	ASTM
Coefficient of curvature C_c	0.95	ASTM
Soil classification	SP	USCS
Soil description	Poorly graded sand	
Max. dry unit weight kN/m^3	16.63	BS 1377-4
Min. dry unit weight kN/m^3	14.0	BS 1377-4
Max. void ratio	0.9	BS 1377-4
Min void ratio	0.6	BS 1377-4
Dry unit weight (γ_d)	15.2 kN/m^3	
Angle of internal friction (θ)	38^o	BS 1377-7

Model piles

Two model piles were fabricated from a hollow circle aluminium tube with outer diameter of 16 mm and a wall thicknesses of 1.2 mm. The total length of the pile is 350 mm with embedded pile length changes depending on the test type. Table 2 shows the dimensions and the material properties of the piles used. The piles were instrumented with six strain gauges to measure the bending moment along the embedded lengths numbered from SG1 to SG6, as shown in Figure 5. Each strain gauge was glued to the pile surface at a vertical interval of 50 mm. The gauges were covered with clear heat shrink tube along the entire length of the pile to protect them from damage. The piles surfaces were made rough by gluing dry sand particles to simulate the contact surface generated between a concrete pile and the soil in actual cases.

Table 2 Pile dimensions and its material properties.

Pile details	**Value**
Outside diameter (mm)	16
Wall thickness (mm)	1.2
Type of pile	Aluminium
Modulus of Elasticity (MPa)	70000
Density (γa) (kN/m^3)	27
Poisson's Ratio (υa)	0.33

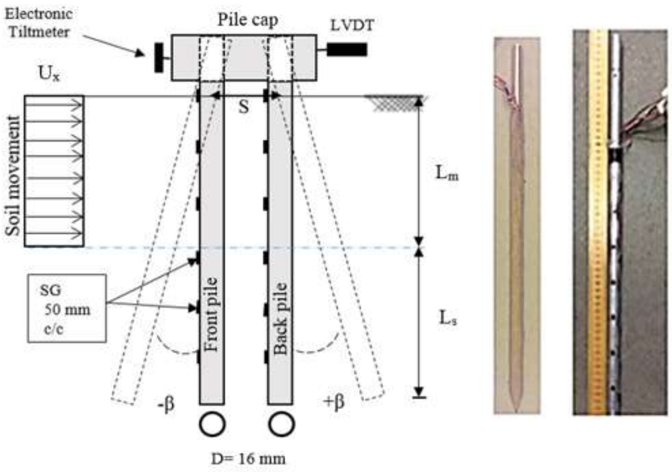
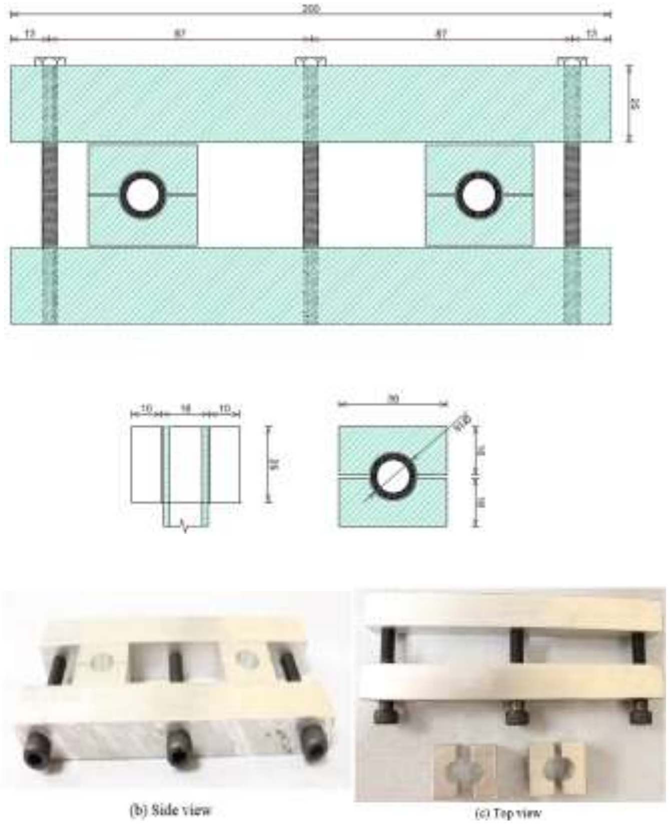


Figure 5 Schematic diagram of a pile subjected to rectangular loading block.

Model pile cap

The pile cap for both vertical and batter piles group was made of two aluminium alloy pieces in order to ensure an easy assembly after piles installation into sand was completed. The details and dimensions of the pile cap, and relevant settings used in the tests are described in Figure 6. The pile cap was specifically designed to enable each pile in the group to be installed in required batter angle. To ensure rigidly connection between the piles and the cap (the head of each pile was completely secured against movement and rotation to the cap), the bolts tightening was performed strongly.



(b) Side view

(c) Top view

Figure 6 The details and dimensions of the pile cap.

Soil preparation

The sand was first placed in layers using tamping technique to maintain a uniform density throughout (Gaaver 2013). Accordingly, the testing box is divided into 14 layers (each layer with 50 mm in height) by marking the interior sides of the box. The quantity of sand for each layer is weighed via an electronic scale. Then, the sand is spread inside the testing box and compacted with a wooden tamping hammer until the required density is achieved by levelling the soil surface with the marked line. The compaction process was carefully chosen to produce a homogeneous sample that is used in a parametric study. This operation is repeated until the box is full.

Pile installation

After the sand is prepared inside the testing box, an installation guide was installed onto the top of testing box as shown in **Error! Reference source not found.** (a). The main parts of the installation guide are a rotational screw jack and an aluminium frame as shown in **Error! Reference source not found.** (b). The installation guide was used to place the batter pile into the sand to a desired embedded length and batter angle. Prior to the installation of the batter pile at exact location into the sand surface, the angle of the pile inclination was adjusted by angle meter. Subsequently, tightening an installed bolt at the head of screw jack to prevent it from rotation. Then the pile was slowly driven into the sand by means rotate screw jack rechargeable drill. After the installation was finished, the driving guide was removed.

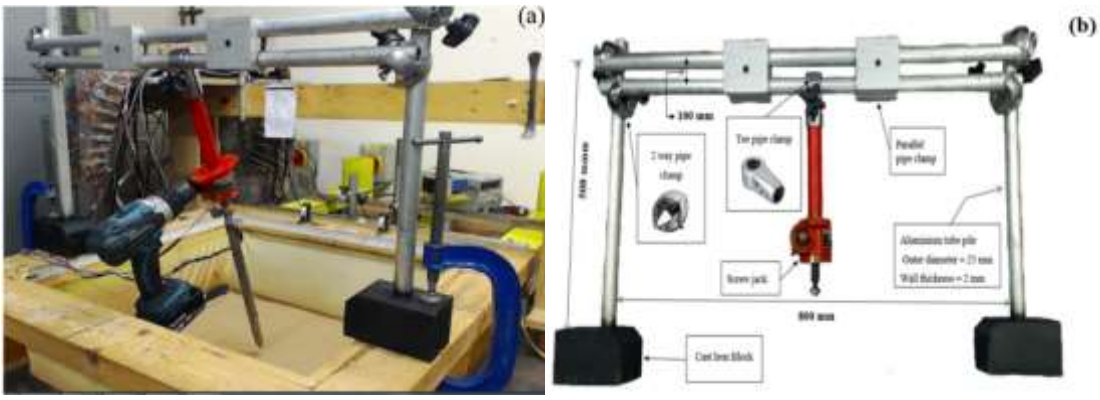


Figure 7 The installation guide of batter pile

Setup of pile group testing programme

For each group test, the response of two instrumented piles in the group was recorded. The instrumented piles (front and back) arrangements used are as follow (see Figure 8):

- Batter-Vertical (BVL), ($-\beta$, 0^o);
- Vertical-Batter (VBL), (0^o, $+\beta$);
- Batter- Batter (BBL), ($-\beta$, $+\beta$);
- Vertical-Vertical (VVL), (0^o, 0^o).

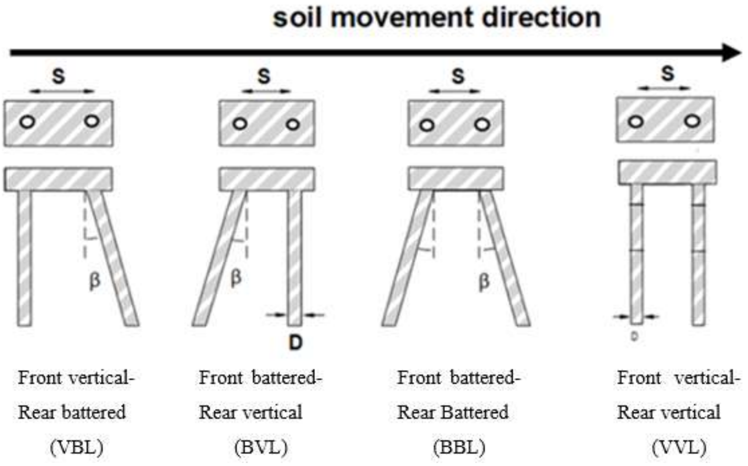
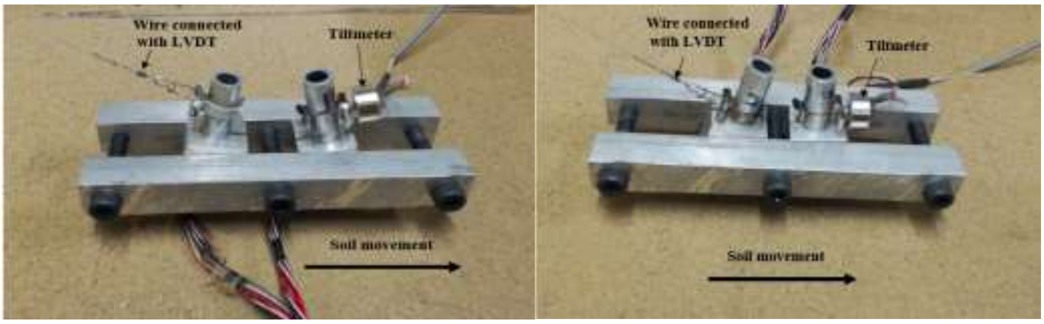


Figure 8 Types of 2x1 pile group configurations.

Linear Variable Displacement Transducers (LVDT) and Electronic Tiltmeter were used to measure the displacement and rotation of the pile cap, respectively (piles at pile cap level have the same rotation and displacement values). The final view of the pile group prior to testing with different configurations is shown in Figure 9.



(a) BBL configuration (b) BVL configuration

Figure 9 Two pile groups prior to testing with different configurations (BBL and BVL).

Results and Discussion

Effect of pile groups arrangement

The following subsections highlight the effect of batter pile groups configuration and batter angle (*β*) on the lateral response of the batter pile group. All the tests were conducted at $S = 3D$ (S: centre to centre spacing between piles in pile group at soil surface level) and Lm, $Ls = 150$ mm.

Results for (VVL) batter pile group configuration test

Bending moment results at each strain gauge along both piles measured during the test are illustrated in Figure 10. It can be noticed that the bending moment recorded at both front and back piles were gradually increased with increasing soil movement (box displacement). At depth of 50 mm (0.16 L, where L is the embedded length of pile), both front and back pile recorded negative moments, while at depth ≥100 mm the bending moment showed positive values for both piles. It is to note that measured moments (negative and positive) at the front and back pile reached their peak values at 15-20 mm of box displacement, after which they remained almost constant.

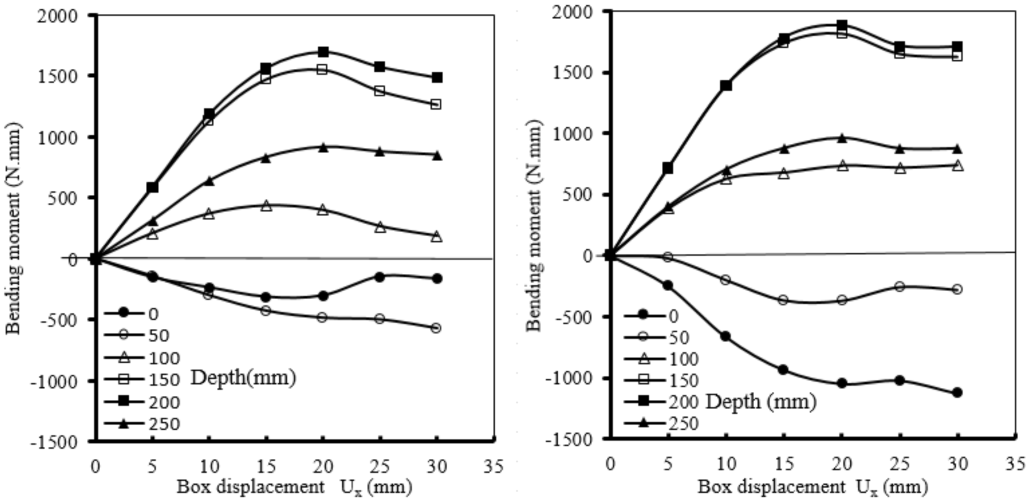


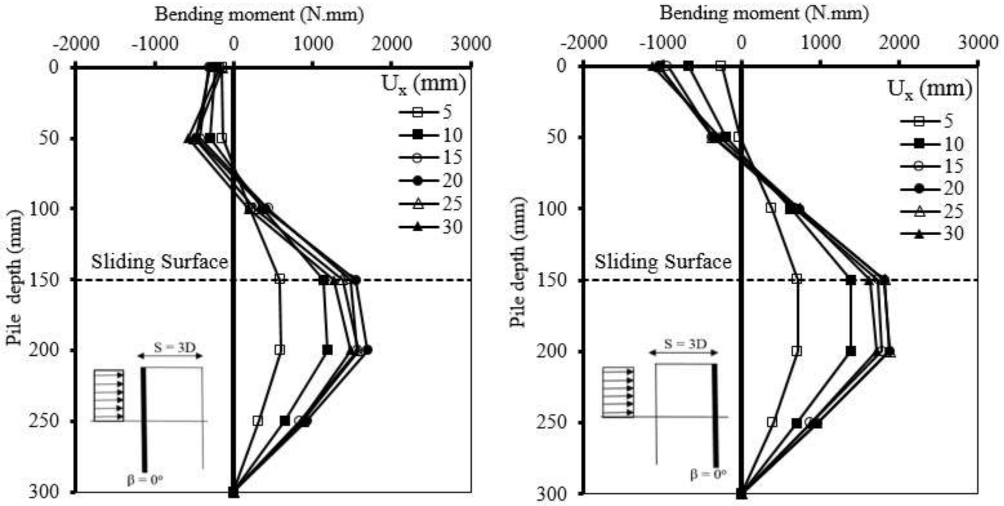
Figure 10 Measured moments at each strain gauge during test.

The moment distribution measured along the pile length recorded every 5 mm and up to 30 mm of box displacement is illustrated in Figure 11 for front and back pile. A number of conclusions can be drawn from this Figure:

- Bending moment distributions for the front and back piles were different in shape, especially in the upper pile portion. It is noted that negative bending moments are developed along the upper portion of both piles and this is believed to be attributed to the restraint provided by the cap. This behavior agreed well with the general trend observed by Chen *et al*. (1997) and Leung *et al*. (2000).
- The value and position of the maximum positive bending moment $M_{+\,max}$ for both front and back piles are recorded the same values (at depth of 200 mm below the pile cap or 0.67 L).
- The variation of bending moment values measured along the back pile is almost linear up to the maximum value, 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. Furthermore, the point of zero bending moment is located at the vicinity of the sliding surface for both pile, at depth of

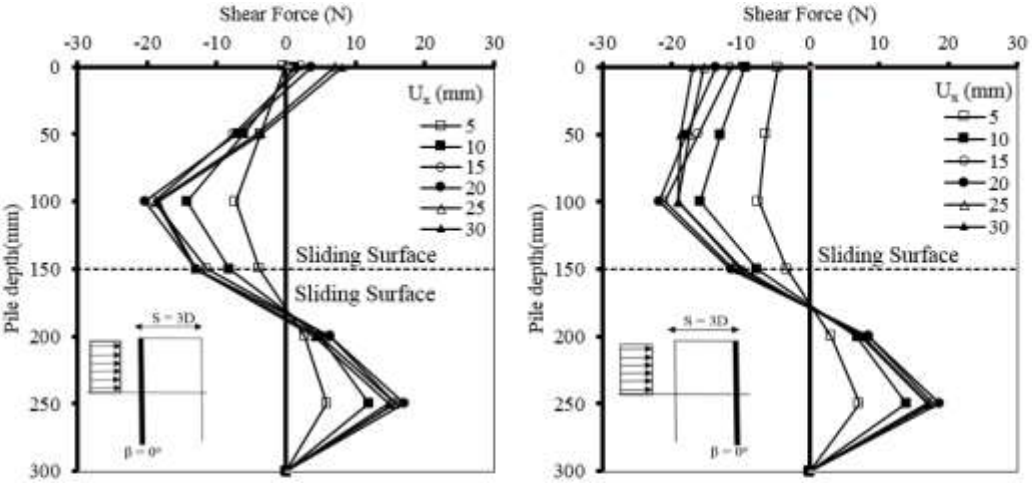
70 mm below sand surface.

Figure 12 shows the shear force profile along the pile length in the group. It can be seen that the maximum shear forces in both piles is (21 N) which occurred at the moving soil layer (at depth of 100 mm or 0.33*L*). Owing to the fact that the bending moment has changed linearly in the upper part of the back pile, it can be seen that this pile showed a relatively constant values of shear forces.



(a) Front pile (b) Back pile

Figure 11 Bending moment profiles, test (VVL configuration).

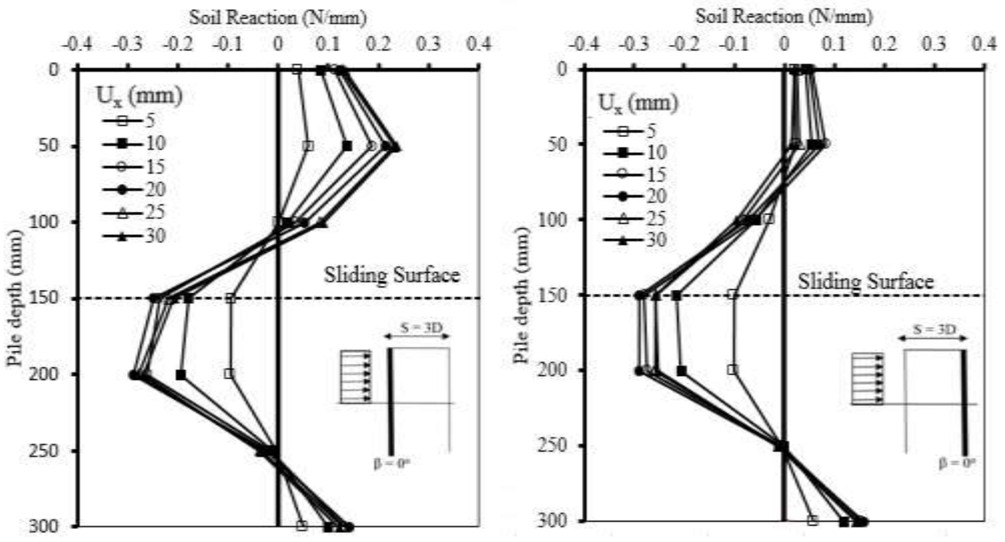


(a) Front pile (b) Back pile

Figure 12 Shear force profiles, test (VVL configuration).

Soil reaction profiles are illustrated in Figure 13. The following observations can be concluded from the Figure:

- The value and location of the maximum soil resistance for the front and back pile were almost the same (0.33 N/mm and, at depth of 200mm). This depth, also, showed a significant amount of soil resistance for the front pile.
- At (135 mm below soil surface), there was a noticeable change in the soil reaction distribution. This change is expected as both moving and stable soil layers have opposite actions on the pile shaft.
- 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 prevents the back pile from a substantial part of the effects of direct soil movements, this is called the shadowing effects (Ilyas *et al*. 2005).



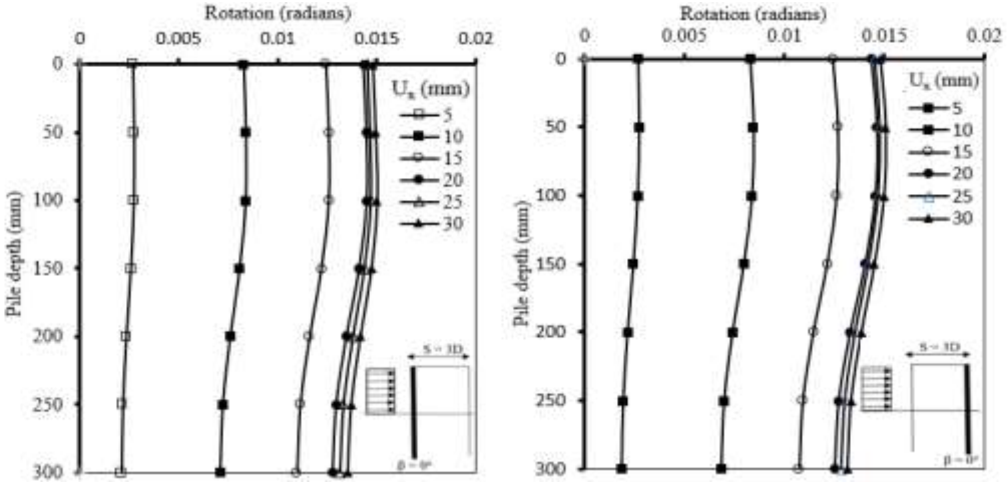
(a) Front pile

(b) Back pile

Figure 13 Soil reaction profiles, test (VVL configuration).

Figure 14 presents the response of both piles in terms of rotation. It can be seen that both piles develop a positive angle of rotation with a very small difference for the rotations measured along their lengths. Therefore, it can be concluded that both piles behaved as rigid piles.

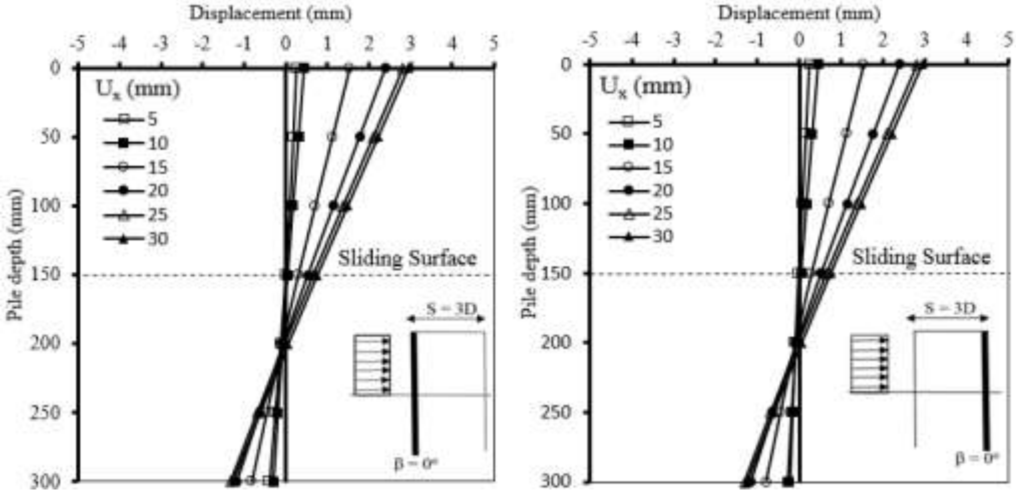
Figure 15 describes the deflection profiles for two piles in the group. Both piles recorded a maximum horizontal displacement of about 3.5 mm (at sand surface) corresponding to 30 mm of box movement. At each soil movement interval, it can be noticed that piles move horizontally less than the corresponding lateral soil movement. This refers to the fact that the moving sand is flowing around the piles. Furthermore, both piles rotated approximately at depth of 200 – 250 mm below the sand surface.



(a) Front pile

(b) Back pile

Figure 14 Rotation profiles, test (VVL configuration).



(a) Front pile (b) Back pile

Figure 15 Deflection profiles, test (VVL configuration).

Results for (VBL, BVL and BBL) configuration tests

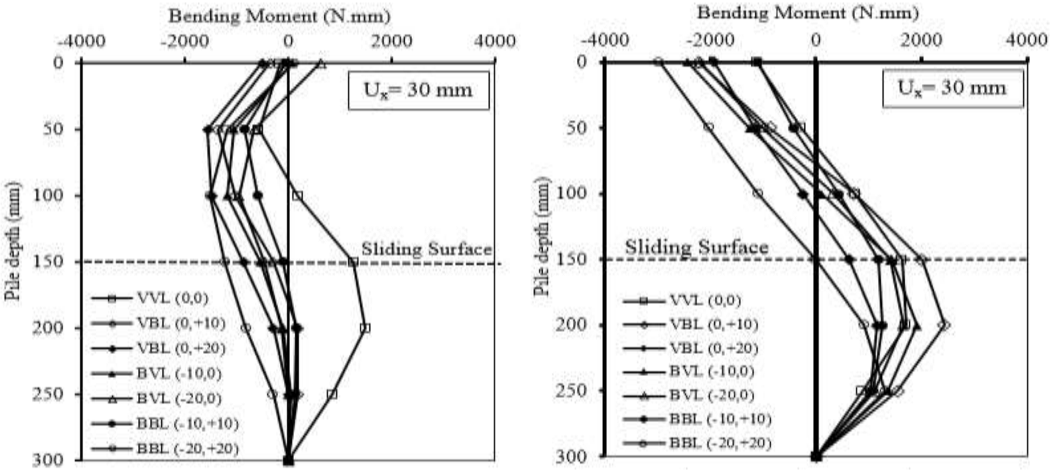
In order to complete the series of tests related to investigation of the influence of the inclined piles on the lateral behaviour of passively loaded pile group, six more tests namely (VBL, β = +10^{o} and +20^{o}), (BVL, β = -10^{o} and -20^{o}) and (BBL, β = ±10^{o} and ±20^{o}) have been conducted. The results obtained from these tests were compared with the test result of the 2×1 vertical pile group (test VVL). It is worth noting that all graphs of this test series had almost the same general trends with the corresponding graphs plotted for the first test (VVL).

Figure 16 shows the response of the front and back pile in terms of bending moment measured at 30 mm of box displacement for the seven tests. According to this Figure, the following observations can be drawn:

- The positions of maximum negative and positive bending moments and the shape of moment profile for the all tests are almost similar. However, the negative bending moments developed along the front pile for all tests except that of vertical pile group (VVL) in which the moment showed positive values.
- The measured bending moments at the front pile heads are showing positive and negative values depending on the batter angle of the pile and pile group configurations.
- Owing to the pushing force (active load) by the front pile through the pile cap, a significant negative bending moment was observed to develop at the head of the back pile for all tests.
- The lateral loading on the front pile caused by soil movement was mainly

resisted by the upper pile shaft.

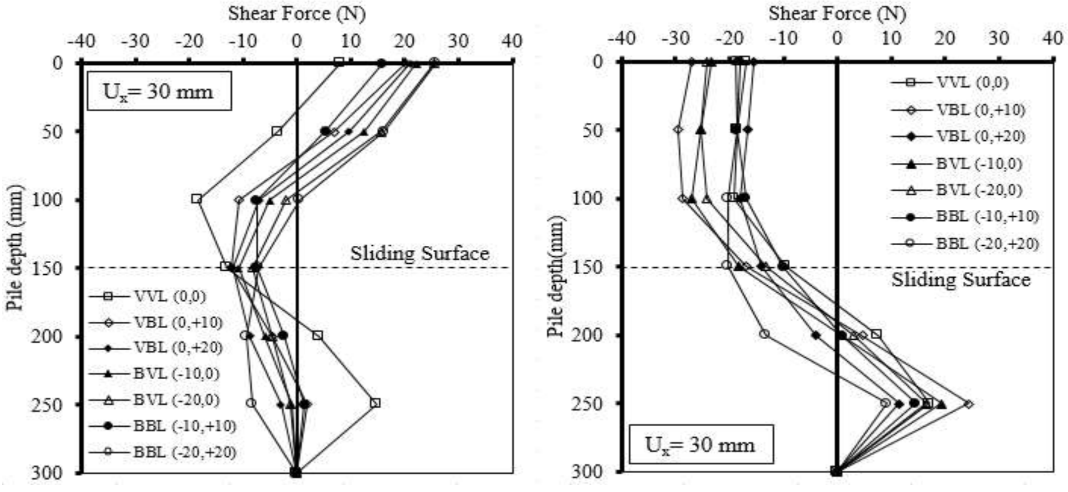
- The recorded positive bending moment for back pile was at maximum values at depth of 200 mm in stable layer.



(a) Front pile (b) Back pile

Figure 16 Moment profiles for (2 × 1) batter pile groups with different configurations.

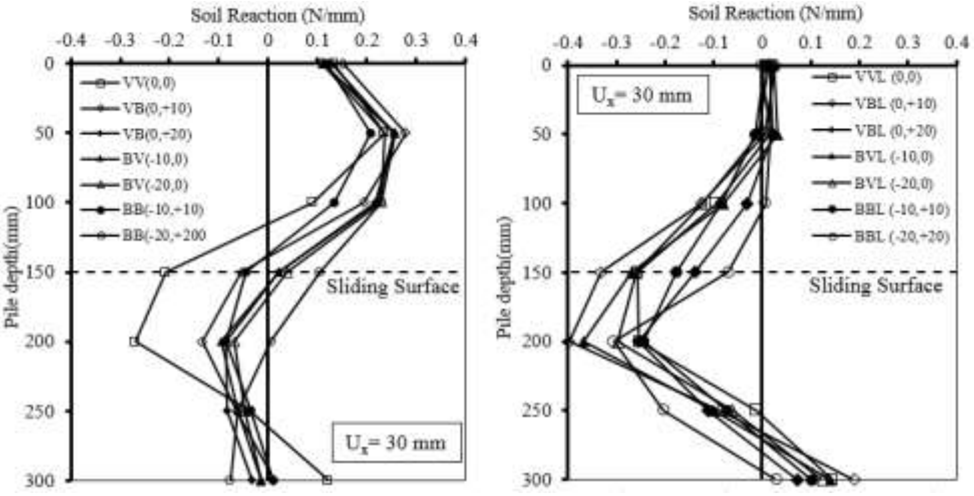
For the purpose of comparison, the variation of shear forces recorded with respect to pile depth at the end of all tests, (U_x = 30 mm), are plotted together in Fig. 17. The resulted shear force values reveal similar profiles for all tests. Front pile showed maximum shear forces of about 25 N at pile head for two configurations, (-20^o, +20^o) and (-20^o, 0^o). Moreover, a new position of maximum shear force appeared at depth 0f (100-150) mm, that is to say nearly in the middle of the embedded pile depth. Figure 17 (b) showed that the shear force profile along the back pile for the all tests do not appear to be dependent on the batter pile group configurations, while the measured values of shear force were dependent on these arrangements. For instance, in the moving soil layer, the recorded value at the state of BBL (-20^o, +20^o) is about twice as much as when compared to that obtained with VVL (0^o, 0^o).



(a) Front pile (b) Back pile

Fig. 17 Shear force profiles for (2 × 1) batter pile groups with different configurations.

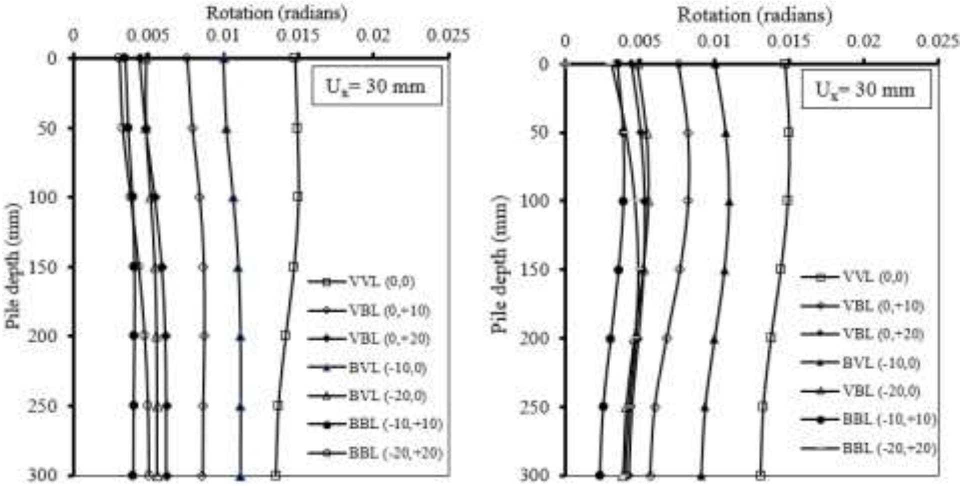
Figure 18 reveals that the shape of soil reaction profile is independent on the batter pile group configurations, but the values are highly related to these arrangements. On the other hand, the upper portion of the back pile for all cases was not under a passive pressure although its location is within the moving layer. This could be due to the shadowing effect of the front pile.



(a) Front pile (b) Back pile

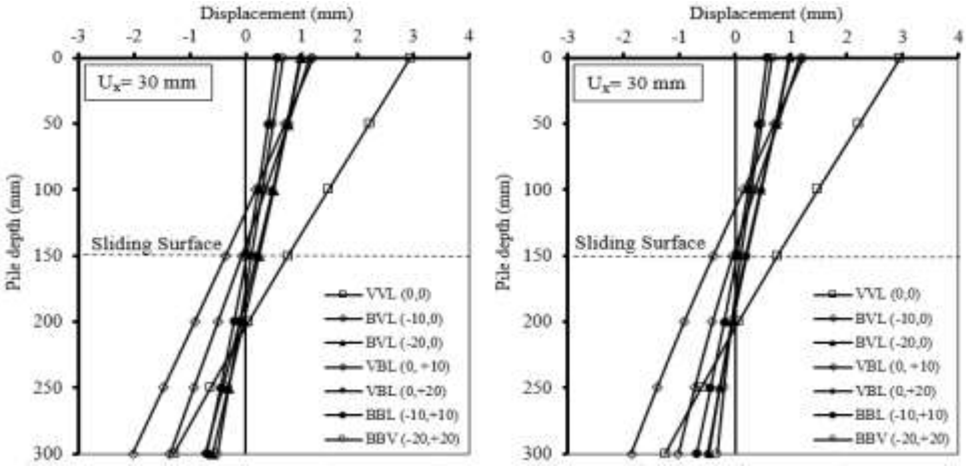
Figure 18 Soil reaction profiles for (2 × 1) batter pile groups with different configurations.

Figure 19 and Fig. 20 investigate the rotation and deflection profiles of the front and back piles. It can be seen that the shape of rotation and deflection profiles of both piles are independent on the batter pile group configurations, but the values are highly related to these arrangements. Where, the maximum deformations occurred when the batter pile group configuration in the case of (VVL), whereas minimum values recorded was at the state of BBL (-10^o, +10^o).



(a) Front pile (b) Back pile

Figure 19 Rotation profiles for (2 × 1) batter pile groups with different configurations.



(a) Front pile (b) Back pile

Fig. 20 Deflection profiles for (2 × 1) batter pile groups with differentm configurations.

Conclusions

The following conclusions can be drawn:

- The extent of the group effect on the lateral response of a pile with a group depends on a number of factors, (i.e. the arrangement of the pile and the inclination angle of piles.
- A rigid cap has a significant effect on the pile response, which tends to reduce the positive bending moment, while developing a relatively large negative bending moment in the upper portion of pile
- The M_{+max} and M_{-max} on front pile showed lower values compared to that on back pile for all pile group configurations.
- Batter pile groups with (BBL) configuration of (-10^o, +10^o) offer more resistance to lateral soil movement compared to other pile group arrangements with the same pile spacing. This is confirmed by the development of higher bending moments in the back piles rather than the front piles. On the other hand, (VVL) configuration offered the least resistance.

References

Al-Abboodi, I., and T. T. Sabbagh. 2017. “Model Tests on Piled Raft Subjected to Lateral Soil Movement.” *International Journal of Geotechnical Engineering* **12** (4): 357–367. doi:10.1080/19386362.2017.1296061.

Chen, C. Y. and C. X. Tsai. 2014. “Batter Pile Behavior Modeling Using Finite Difference Analysis.” *Applied Mechanics and Materials* **566**: 199–204.

Chen, L. T., H. G. Poulos and T. S Hull. 1997. “Model Tests on Pile Groups Subjected to Lateral Soil Movement.” *Soils and Foundations* **37** (1): 1–12.

Cubrinovski, M., and K. Ishihara. 2007. “Simplified Analysis of Piles Subjected to Lateral Spreading: Parameters and Uncertainties.” Proceedings of the 4th international conference on Earthquake Geotechnical Engineering-invited lectures, Thessaloniki, Greece, June 25–28.

Gaaver, K. E. 2013. “Uplift Capacity of Single Piles and Pile Groups Embedded in Cohesionless Soil.” *Alexandria Engineering Journal* **52** (3): 365372.

Giannakou, A., N. Gerolymos, G. Gazetas, T. Tazoh and I. Anastasopoulos. 2010. “Seismic Behavior of Batter Piles: Elastic Response.” *Journal of Geotechnical and Geoenvironmental Engineering* **136** (9): 1187–1199.

Guo, W. D., and E. H. Ghee. 2010. “Behavior of Axially Loaded Pile Groups Subjected to Lateral Soil Movement.” Proceedings of GeopShanghai, Shanghai, China, June 3–5.

Ilyas, T., C. F. Leung, Y. K. Chow, and S. S. Budi, 2005. “Closure to Centrifuge Model Study of Laterally Loaded Pile Groups in Clay.” *Journal of Geotechnical and Geoenvironmental Engineering* **131** (10): 1308–1308.

Khari, M., K. A. Kassim, and A. Adnan. 2013. “An Experimental Study on Pile Spacing Effects Under Lateral Loading in Sand.” *The Scientific World Journal* **2013**: 1–8.

Leung, C. F., Y. K. Chow, and R. F. Shen. 2000. “Behavior of Pile Subject to Excavation-Induced Soil Movement.” *Journal of Geotechnical and Geoenvironmental engineering* **126** (11): 947–954.

Meyerhof, G. G., and G. Ranjan. 1972. “The Bearing Capacity of Rigid Piles Under Inclined Loads in Sand. II: Batter Piles.” *Canadian Geotechnical Journal* **10**: 71–85.

Meyerhof, G. G., and A. S. Yalcin. 1993. “Behaviour of Flexible Batter Piles Under Inclined Loads in Layered Soil.” *Canadian Geotechnical Journal* **30**: 247–256.

Pan, J. L., A. T. C. Goh, K. S. Wong, and C. I. The. 2002. “Ultimate Soil Pressures for Piles Subjected to Lateral Soil Movements.” *Journal of Geotechnical and Geoenvironmental Engineering* **128** (6): 530–535.

Poulos, H. G. (2006). “Raked Piles—Virtues and Drawbacks.” *Journal of Geotechnical and Geoenvironmental Engineering* **132** (6): 795–803.

Poulos, H. G., L. T. Chen, and T. S. Hull. 1995. “Model Tests on Single Piles Subjected to Lateral Soil Movement.” *Soils and Foundation* **35** (4): 85–92.

Singh, T., and V. K. Arora. 2017. “Influence of Pile Inclination on Batter Pile Groups Subjected to Lateral Loading in Sand.” Proceedings of 29th research world international conference, Las Vegas, USA, March 16–17.

Wang, L., G. Zheng, and R. Ou. 2014. “Finite element analysis of couple effect of soil displacement and axial load on single inclined pile.” *Journal of Central South University* **21** (9): 3656–3664.

White, D. J., M. J. Thompson, M. T. Suleiman, and V. R. Schaefer. 2008. “Behavior of Slender Piles Subject to Free-Field Lateral Soil Movement.” *Journal of Geotechnical and Geoenvironmental Engineering* **134** (4): 428–436.

Zhang, L., M. C. McVay, and W. Lai Peter. 1999. “Centrifuge Modelling of Laterally Loaded Single Batter Piles in Sands.” *Canadian Geotechnical Journal* **36** (6): 1074–1084.

Zhang, L. M., M. C. McVay, S. J. Han, P. W. Lai, and R. Gardner. 2002. “Effects of Dead Loads on the Lateral Response of Batter Pile Groups.” *Canadian Geotechnical Journal* **39** (3): 561–575.