The influence of pile groups configuration on its stability in dry sand under lateral loads

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Abstract. This paper aims to investigate the effect of the arrangement of aluminum pipe piles closed from both ends on its response under lateral loads in terms of a lateral load and bending moment. Twenty-four model tests for laterally loaded aluminum pipe piles were investigated to study the effect of sand relative density, the ratio \((S/D=3, 4 \text{ and } 5)\) of spacing between pile in the group(s) / diameter of aluminum pipe pile \((D)\), loading direction or piles configuration. It was found that the lateral resistance of the pipe piles loaded with a configuration of \(2\times1\) is higher than that loaded in the direction of the configuration \(1\times2\). Relative sand density has a significant effect on the lateral capacity of the pile group. The increase of the relative density caused increase load resistance but the bending moment increased. The effect of \((S/D)\) is very obviously on the behavior of bending moment and the load resistance of piles models, bending moment increased as \(S/d\) increased as well as for load resistance.

1. Introduction

Pile foundations are used to transmit a superstructure load to the deeper load bearing strata, and to resist lateral loads generated from many sources as well as earthquake, waves, and soil movement (Poulos and Davis, 1980). They are usually constructed from steel, concrete or timber. Piles are usually subjected to the axial or lateral loading or a combination of lateral loads, axial loads and moments. Piles subjected to high lateral loads are called laterally loaded piles. Understanding the behavior of laterally loaded piles is one of the major problems concerned with the soil structure interaction. The laterally loaded piles have a number of uses as foundations of structures, such as high-rise buildings subjected to wind and earthquake loadings and offshore structures (e.g., Platforms) (Al Mandeel, 2000).

(Price and Wardle) (1979) conducted a series of tests on single piles in London clay to observe the deflection of the pile at different times of the year.

The deflection of the pile from an adjacent trench was measured by means of probes under static and cyclic loading applied to the pile head. They concluded that the deflected shape of the pile changes due to seasonal effects and this has an effect on the horizontal subgrade reaction when the piles are statically or cyclically loaded. Monitoring of the adjacent pile showed that the unloaded pile
was affected by the movements of the adjacent laterally loaded pile.

Al-Taie (2004) studied the behavior of laterally loaded piles embedded in sandy soil with cavities. The pile model is made of solid steel metal with a circular cross section of 15 mm diameter. The tests were performed with loose sand with a dry unit weight of 15.6 kN/m³; he considers the load corresponding to a horizontal displacement equals to 2 mm as working load. The results indicated that the number of cavities and their location have a combined effect on the behavior of laterally loaded pile model. The existence of a cavity is in front and in touch with a pile model that face causes decrease in the working load as long as it is located in the upper two-thirds of the pile model length. Whereas a cavity that exists in the back and in touch with the pile model face causes a decrease in working load as long as it is located in the lower one-third of pile model length.

In some works the ground excavation is to construct underground structures as well as reservoir, ground oil tanks and so on, a lateral displacement is occurred causing a lateral loading on the foundation near these projects therefore, this study aims to investigate the influence of the piles arrangement on the response of pipe piles closed from both ends under a lateral load.

2. Testing Equipment
To study the behavior of laterally loaded piles in sand, laboratory tests were conducted on a small scale model of aluminum pipe piles closed from both ends and have a hollow core. The pile model used has the outer diameter of 18 mm and the inner diameter of 15 mm with a thickness equal to (1.5) mm.

The size of the piles model was chosen after reviewing the literature about a suitable pile size that could be considered representative. Although, Vesic (1977) stated that "scale effects will be complex for model of piles smaller than (35 mm) in diameter", many researchers used smaller diameters in their tests: Al-Mhaidib (1999) used steel piles with (30 mm) in diameter, Boominathan and Lakshmi (2000) used aluminum pile with a diameter of (19 mm) and Al-Mhaidib (2006) used steel piles with (25 mm) in diameter. The dimensions of the pile model used in this study were also selected to minimize the boundary effects of the soil container in the experimental setup.

The piles model used is made of smooth aluminum tube covered with a plastic sleeve to protect strain gauges. Pile-embedment ratio (depth to diameter) (L/d) used in testing of single and group piles was (30). Two different arrangements of the pile groups 1×2 and 2×1 with different spacing ratios (S/d) (3, 4 and 5) were used for the testing group of piles. The mechanical properties of the pile used are shown in Table 1.

| The Pile length (mm) | The Outer diameter (mm) | The Wall thickness (mm) | The Bending stiffness, E_P1P |
|---------------------|------------------------|------------------------|-----------------------------|
| 570                 | 18                     | 1.5                    | 0.18×10^6                  |

Along the pile shaft, (8) electrical- resistance-half bridge type strain gauges linked to the logger were pasted to measure the bending strain at distances of (0 L, l/4 L, l/2 L, and 3/4 L) from the top of the pile group embedded in dry sand as shown in Plate 1.
Plate 1. Pile model with strain gauge pasted on pile.

The pile cup used is made from steel with a square cross-section of 150mm length and 6mm thickness. Twenty four laboratory experimental models are conducted by taking the average of them; twelve models were used in result to study the behavior of laterally loaded aluminum pipe piles. The model piles were laterally loaded using a hydraulic jack which controlled by using AC-drive manufactured to control the loading of jack with a loading rate of 2.5 mm/min the jack fixed to a frame that welded with steel container of (750×750×750) mm in cross-section dimension.

Two-dial gauges with an accuracy of 0.01 mm were used to measure the pile's lateral displacements. The dial gauges were attached horizontally on the cap of the pile with the same loading level.

A steel screw shift was connected in between the hydraulic jack and load cell to measure the incremental load came with a digital weighing indicator to take load readings from it, a small steel cone was fixed to load cell for two purposes, first to have a point load and second to set a connection point between load cell and loading point at pile cap. A general layout of the equipment used in the present study is illustrated in Plate 2.

Plate2.(a) The frame holding hydraulic jack,(b) AC drive,(c) and hydraulic jack,(d, e) System of lateral loading.
The lateral displacement of the pile was considered as the average of the two dial gauges readings. Spirit level was used to ensure vertical and horizontal levels of the test setup.

The dimensions of the soil bin are big enough to overcome the effects of the boundary conditions on aluminum pipe piles response, whereas the dimensions of it are (750×750×750 mm) as cubic shape. It is worth mentioning that the aluminum pipe piles length is 570 mm and the sand height is 750 mm, and the loading level is the e=100mm distance between loading point and soil surface.

3. Soil Descriptions
Poorly graded sand is (SP) classified according to Unified Soil Classification System (USCS) which is brought up from the site in the middle of Baghdad at depth of (5-7) m.

Many standard tests are implemented on the soil samples to clarify the physical and mechanical properties of the sand used. The tests are carried out on sand samples with two different relative densities; medium sand (60%) and dense sand (75%). The specifications of tests followed in the experimental work are shown in Table 2 conformity to the ASTM specifications.

Table 2. Physical properties of the sand used.

| Specification          | Value                  | Index Property          |
|------------------------|------------------------|-------------------------|
| ASTM D 422 and ASTM D 2487 (2007) | 0.14, 0.18, 0.22, 0.24 | Effective sizes (mm)   |
|                        |                        | \(D_{10}, D_{30}, D_{50}, D_{60}\) |
| ASTM D 422 and ASTM D 2487 (2007) | 1.7                    | Coefficient of uniformity (Cu) |
| ASTM D 422 and ASTM D 2487 (2007) | 0.96                   | Coefficient of curvature (Cc) |
| ASTM D 854 (2006)      | 2.66                   | Specific gravity (Gs)   |
| ASTM D 4253-(2000)    | 16.7                   | Maximum dry unit weight (kN/m³) |
| ASTM D 4253-(2000)    | 13.8                   | Minimum dry unit weight (kN/m³) |
|                        | 0.93                   | Maximum void ratio      |
|                        | 0.59                   | Minimum void ratio      |
|                        | 75%                    | Relative density (RD)\% |
|                        | 60%                    |                         |
|                        | 15.93                  | Dry unit weight (\(\gamma_d\)) kN/m³ |
|                        | 15.5                   |                         |
|                        | 0.67                   | Void ratio, (e)         |
|                        | 0.72                   |                         |

4. Pile Group Configuration (Or Loading Direction)
The configuration of the piles in a group with two arrangements was designed to be loaded in two directions as 2×1(as a pile in line) and 1×2 (as a pile in raw) as shown in Figure 1.
5. Experimental Procedure
The piles in group vertically placed in the center of soil container according to the testing program and, the sand was formed in the soil container in layers with 50 mm thickness per each layer. To ensure the homogeneity of the sand formation, a designed weight of sand with an accuracy of 0.001 kN, was formed into a certain volume of the soil container by compaction to give the specified relative density of 60%, and 75% according to a planned testing program. The compaction was carried out manually using a rammer weighing of 40.0 N and of \((150 \times 150 \times 6)\) mm square hammer. The top surface of the formed sand was leveled using a sharpened straight steel plate. After the soil had been prepared and the piles installed, then after that a lateral loading system work, where the device is prepared and installed with the system for the test. The load cell connected to the shaft of a hydraulic jack and the strain gauge linked to the logger using the data wire connection. Two dial gauges attached to the pile cap, one of them is attached to the upper surface of a pile cap made to read the vertical displacement and the other dial gauges connected to the thin side of the pile cap made to read the lateral displacement, which face the load cell at the other side of pile cap as shown in Plate (2) previously. After that, the Ac drive operates to run the hydraulic jack and control the rate of movement according to the required work. After this point, the shaft starts to move subsequently to the jack movement to give the incremental load reading which recorded by digital weighing indicator that indicates what load cell had been sensed during jack moving. The loading is stopped when the reading of lateral dial gauge reach to 12 mm displacement reading, the load and strain gauge logger data recorded and analyzed it to give the proper results.

6. Test Results and Discussion
A total of 24 tests were carried out on laterally loaded aluminum pipe piles with closed ends embedded in the dry sand. The response of laterally loaded aluminum pipe piles investigated under the effect of sand relative density, \((S/D)\) ratio of spacing between pile in the group(s) / diameter of aluminum pipe pile (d), loading direction or piles configuration. The maximum lateral load reached of vertical piles was obtained from the load-displacement curves. The lateral displacement at pile cap \((L.d)\) is expressed in a non-dimensional form in terms of outer pile diameter \((D)\) as \((L.d/ D)\) present as the aspect ratio. The maximum lateral capacity of the piles is obtained from the load-displacement curve as the pronounced peaks, after which the pile's lateral displacement reached to 12 mm displacement of the test end is equal to \((0.67 \text{ mm/mm})\) aspect ratio.

The maximum loads for the pile in medium and dense sand for different studied parameters are measured and tabulated in Table 3. Variations of lateral force \((P)\) with horizontal displacement, \((L.d)\) of model piles that embedded in medium and dense sand for the ratios \((S/D)=3, 4\) and 5. In this
series, the sand relative density, (Rd equals 60% and 75%), Pile-embedment ratio (depth to diameter) (L/d) used in testing group piles was (30%), embedment ratio, and Load eccentricity (e) were kept a constant while (S/D) of spacing between pile in group(s)/diameter of pile (D) is (S/D) which have different values of 3, 4, and 5.

### 6.1 Lateral Load with Lateral Displacement:
Table 3 shows the summary of maximum lateral load 12 mm lateral displacement (equal to 0.67 mm/mm aspect ratio) at the end of the test.

**Table 3. Maximum lateral load for laterally loaded pile group with different sand relative densities.**

| (S/D) ratio | Maximum load (2×1) | Maximum Load (1×2) |
|-------------|-------------------|-------------------|
| R.D         | R.D               | R.D               |
| 3           | 60% 75%           | 60% 75%           |
| 4           | 151.6 247         | 158.4 252.6       |
| 5           | 169.4 292.3       | 173.6 289.4       |
| 6           | 221.7 304.1       | 184.4 298.7       |

Figures (2a, b) and (3a, b) present the development of the lateral load with the aspect ratio of the pile group constructed in medium and dense sand at different aspect ratios for a lateral load of 2×1 and 1×2 configuration pile group. It can be seen that the lateral load increases as a relative density increased from 60% to 75%, and at the specific load intensity, the aspect ratio decreased as a relative density increased from 60% to 75%, this result is similar to El Wakil and Nazir (2013). In addition, the lateral load increased as S/D increased from 3 to 5 for both configurations of pile groups as observed in Figure (4 a & b).

The comparison results depicted in Figures (2a, b), (3a, b) and Figure (4 a & b), it can be observed that the lateral resistance of the pile group of 1×2 is higher than the pile group of 2×1 configuration at different S/D.

At the same load intensity, a pile group of 1×2 configuration has a lateral displacement less than 2×1 pile group and this behavior may be due to the interaction effect between piles in the group. It is worth to mention that as a closely spaced pile groups move laterally, the failure zones for front or trailing rows piles overlapped with leading row piles and decreases a lateral resistance.

**Figure 2.** Variation of the lateral load with an aspect ratio of 2×1 pile group.a) Dense sand of R.D=60% b) Medium sand of R.D=75%.
6.2 Result of Bending Moment with Pile Depth:
Tables (4) and (5) illustrate the summary of maximum negative and positive bending moments respectively at 12mm lateral displacement (equal to 0.67 mm/mm aspect ratio) at the end of the test. Both the negative and positive bending moment, occurred and the negative bending moment was shown at the upper part of pile depth. Figures (5a, b & c) and Figure (6 a, b, c, d, e & f) show the bending moment of 2x1and 1x2 pile group configurations with a respect to the pile depth constructed in medium and dense sand at S/D=3, 4 and 5.

Table 4 a, b. Negative maximum bending moment of laterally loaded piles group.

a) Maximum bending moment in line (1×2).

| (S/D) ratio | Maximum bending moment in line (1×2) | (S/D) ratio | Maximum bending moment in raw (2×1) (N.m) |
|-------------|-------------------------------------|-------------|------------------------------------------|
|             | R.D=60%                             | R.D=75%     |                                          |
|             | Front pile (A)                      | Rear pile (B) | Front pile (A)                      | Rear pile (B)                          |
| 3           | 7.6                                 | 9.6         | 13                                      | 14                                      |
| 4           | 4.05                                | 9.2         | 17                                      | 14                                      |
| 5           | 7.7                                 | 10          | 11                                      | 13                                      |

b) Maximum bending moment in raw (2×1).

| (S/D) ratio | Maximum bending moment in raw (2×1) |
|-------------|-------------------------------------|
| R.D=60%     | Both pile facing load               |
| R.D=75%     | Both pile facing load               |
| 3           | 6.5                                 |
| 4           | 9.4                                 |
| 5           | 8                                   |
Table 5 a, b. Positive maximum bending moment of laterally loaded piles group with different sand relative densities.

a) Maximum bending moment in line (1×2).

| (S/D) ratio | Maximum bending moment in line (1×2) (N.m) |   |   |
|-------------|------------------------------------------|---|---|
|             | R.D=60%                                   | R.D=75%     |
| Front pile  | Rear pile                                | Front pile  | Rear pile |
| (A)         | (B)                                      | (A)         | (B)       |
| 3           | 8.975                                    | 8.3         | 11.33      | 13.9       |
| 4           | 8.8                                      | 6.83        | 11.28      | 12.6       |
| 5           | 6.13                                     | 8           | 9.65       | 14         |

b) Maximum bending moment in raw (2×1).

| (S/D) ratio | Maximum bending moment in raw (2×1) (N.m) |
|-------------|------------------------------------------|
|             | R.D=60%                                   | R.D=75%     |
| Both pile facing load | Both pile facing load |
| 3           | 8.4                                      | 11.5        |
| 4           | 9.53                                     | 11.6        |
| 5           | 7.23                                     | 12.13       |

In general, it can be concluded that the maximum bending moment increases as a relative density increased from 60% to 75% and this behavior is due to the increases of shear strength as the relative density increases. This behavior also supported with Albuhlale (2015) for single pile result. Also, it can be mentioned that the bending moment has no significant differences in magnitude as S/D increases from 3 to 5.

The negative bending moment for a font pile (A) is higher than for a rear pile while the positive bending moment of a front pile is higher than for a rear pile. This may happen because the lateral load subjected at pile cap causing tilting to the pile cap that making the front pile to uplift and the rear pile to compression this behavior make the bending moment decrease. This behavior is due to the increase of interaction effect of pile group where the front pile works as an active pile making the rear pile having the largest bending moment.

The comparison results between 2×1 and 1×2 pile groups showed that the bending moment of 2×1 pile group configuration has a bending moment higher than 1×2 pile group configuration at different S/D ratios.

The position of the maximum bending moment occurred approximately at the midpoint of pile shaft and generally, the bending moment of a single pile is higher than for the pile group. Also, the position of maximum bending moment increases with a depth as a result of the increase in the relative density of sandy soil due to increasing in the rigidity of pile-soil interaction zone which developed by confining zone available by a high relative density that agreed with Allami (2017).
Figure 5. Bending moment of 2x1 pile group configuration with respect to pile depth constructed in medium and dense sand at a) S/D=3, b) S/D=4, c) S/D=5.
**Figure 6.** Bending moment of 1×2 pile group configuration with respect to pile depth constructed in medium and dense sand at (a, b, c) for front (A) pile and (d, e, f) of the rear pile (B).
7. Conclusions
From the analysis of experimental results, the following conclusions are obtained:

Sand relative density has a significant effect on the lateral load and bending moment of the pile group. The high sand relative density make high lateral load of the piles in the group. Bending moment increased when the relative density increased but S/D ratio increase has less effect on the bending moment.

The increases in aspect ratio cause a decreasing in the lateral displacement for both pile group configurations. At different S/D ratio, the bending moment of 2×1 pile group configuration has bending moment higher than 1×2 pile group configuration at different S/D ratio.

The lateral resistance of 1×2 pile group configuration is higher than in the pile group of 1×2 configurations. A Front pile in pile group with 1×2 configuration has lateral load more than rear pile but has a bending moment lower than rear pile.

At same load intensity pile group of 1×2 configuration has lateral displacement less than 2×1 pile group. The maximum bending moment approximately occurring at the midpoint of pile shaft.

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