Effect of vertical loads on pile group response subjected to lateral cyclic loading with different configuration of piles: experimental study

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Abstract. Many previous studies have mainly investigated only the effect of cyclic loading on the behaviour of group pile without taking in to account the influence of axial load in the other mean (without the effect of vertical load on the behaviour on the group pile), which is represented most realistic case. In addition, due to the large number of variables in soil and piles, which make these studies not fully understood, so deep studies of the behaviour of the group pile is needed. This study aiming to knowing the effect of axial load and piles shape on the performance of piles group under cyclic loads and identifying the best configuration of piles also to study the effect of pile spacing on lateral displacement under pure and combined loading. by developing cyclic laboratory system that can test the pile of group. Aluminium pile with slenderness ratio L/D of 40 in-groups (1×2), (2×1) is used in this study. The most important results explained that the presence of vertical loads on the pile group cap according to allowable vertical load capacity and the pile shape have positive effect. Where it is reducing the lateral displacement of the head group pile a rounded of 60 %and 30% respectively.

Keywords: Lateral Load; Pile Groups; Dynamic Load; shape factor and Load Test.

1. Introduction
Many structures need deep foundations in order to develop the bearing capacity of deeper and stronger soil layers. Group piles are one particular type of deep foundation most widely used for high structures. In addition to the vertical loads that must be carried by the piles, lateral loads may be present and must be considered in design. These lateral loads can be caused by a variety of sources such as earthquakes, high winds, wave action, ship impact, liquefaction, and slope failure [1]. Numerous preceding works were taken into account the influence of only pure lateral load on the group pile such as [2, 3, 4, 5] and others. However, the pile foundation is subjected to both vertical and lateral loads at the same time. In addition, lateral load test experiments on pile foundation and most case studies have been performed with circular piles. however, pile used in engineering practice may also have square section. [6].

Hussien et.al. [7] illustrated how the axial load effects on the lateral response of group piles made of concrete and it embedded in medium sand using 2D finite element analysis. The results observed that the lateral response depended on vertical loads amount and piles row position.
Relative studies are also presented, the studied the effects of industrial wastewater on the geotechnical properties of clayey soil and the behavior of free-headed pile driven into clayey soil and subjected to lateral cyclic loading. The lateral resistance of pile decreased with increasing concentration of contaminant in the soil. The results explained that the total lateral displacement of the pile head for e/L = 0.5 was larger than that for e/L = 0.25 by 22–30% under the same loads [8]. Also, the impact of soil contamination on the behavior of a pile group driven into clayey soils. The results represented that the lateral resistance of pile group decreased with increasing the concentration of contamination in the soil [9]. In addition, the studied the behavior of the impacts of Medium Fuel Oil (MFO) on the behavior of passive pile foundation constructed in clayey soil. The pile foundation is loaded axially and subjected to the movement of soil resulting from the construction of a nearby embankment. The results represented that the increasing the percentage of MFO in the soil causes increasing the effects of adjacent embankment load on the response of the passive pile. Also, increasing the distance between the pile and the edge of embankment decreases the effects of embankment loading on the behavior of pile [10].

Because of the high cost and logistical difficulty of conducting lateral load tests on pile of group and requires many time and great efforts, only a few full-scale load test results are available. Therefore, most of studies were theoretical. Due to this, there is very little information to guide engineers in the design of group pile especially of closely spaced pile groups [11]. In addition, the pile in-group will be influenced on the behavior of an adjacent pile and creates failure zones for both leading and rear row pile due to pile soil pile interaction (shadow effect) [12, 13].

This experimental study presents a small scale-testing model in the laboratory that is a reliable within certain limit, by applying a similar field conditions as close as possible to the full scale to simulate the effect of the combined load on the behavior of group pile with different variables to increase the database for this problem such as knowing the effect of axial load and piles shape, configuration and pile spacing on the performance of piles group under combined loads.

2. Experimental work

2.1. Soil Type

Dry sandy soil is used in this test. The physical properties of the used soil are explained in Table 1. This type of soil is used to explain the behaviour of group pile in sandy soil free of the salt and mud.

| Property | gravity, Gs | (O)Degrees | (D10) mm | (D30) mm | (D50) mm | (D60) mm | $\gamma_d$ (test) kN/m$^3$ |
|----------|-------------|------------|----------|----------|----------|----------|--------------------------|
| Value    | 2.65        | 36         | 0.18     | 0.26     | 0.38     | 0.45     | 16.7                     |

2.2 Model of Pile and Pile Cap

Hollow piles made of aluminium with circular and square section have 16mm diameter with slenderness ratio L/D of 40 are used in groups configuration of (2×1) and (1×2) with pile spacing of (3D, 5D, 7D and 9D), where D is the diameter of pile as shown in Figure 1. The piles are provided with four pairs of strain gauges on each leading pile row and rear pile row to measure bending moment. The strain gage has 5mm length and resistance 120 ±0.3Ω. These piles are capped by using steel plate consist of two parts.
This models are used to be the behaviour of bending of piles is clear and to study the effect of configuration and spacing pile on pile group behaviour. Mechanical properties of aluminium piles are explaining in Table 2.

**Table 2. Mechanical properties of aluminium piles**

| Pile No. | Cross Section | Embedded Length L(mm) | Outside Dimension (diameter-width) (mm) | Wall thickness(mm) | Bending stiffness |
|----------|---------------|------------------------|----------------------------------------|-------------------|------------------|
| 1        | circular      | 640                    | 16                                     | 1.5               | 124.78           |
| 2        | square        | 640                    | 14                                     | 1.5               | 136.2            |

![Experiment Model Diagram]

**Figure 1.** Configuration of pile group. a) 2x1. b) 1x2.

**2.3 Experimental Model**

The experimental model is made of rigid steel container (4mm thickness) with dimensions (1000x1000x1000) mm to prevent the effect of wall test container to the results of test. This model contains loading frame to carry the sliding system of raining system device, which has the dimensions of (200 x 200 x 800) mm with two opening strips of 10 mm for the purpose of sand deposit preparation and to achieve soil relative density of 70%. In addition, this model contains of static and cyclic loading device. The cyclic loading device is achieved the cyclic load test by using two load cells, which have ±500 kg capacity. The work is operated by using motor-gear system connected to automatic electronic circuit unit that is controlled to the horizontal sinusoidal translation, which is applied to the piles cap by the load cells. This experimental work needs ancillary equipment such as a dial gauge to measure the pile head deflection in the axial direction, LVDT which is a Linear Variable Differential Transducer having ±50 mm displacement to measure lateral deflection and Digital Indicators (Data Loggar) which is used to display and record the Load Cells action, LVDT and Strain gauges' readings digitally. Figure 2) illustrate the details of experimental static lateral loading device and cyclic loading device.
2.4 Test Procedure

At the beginning raining technique device is created the sand soil with Dr of 70% and after preparing the test model; the ultimate vertical and lateral load capacity for each group model can be obtained separately from static device. Estimation of ultimate vertical load capacity for each group model be according to the (ASTM D 1143-07) as shown in Figure 3. Safety factor equal to 2.5 is used to evaluate the allowable axial load. In addition, the ultimate lateral load capacity can be obtained from gradually loading by lateral cable. It is taken as the load corresponding to a deflection equal to 20% of the diameter of pile according to [14] as shown in Figure 4. After that, cyclic lateral load test starts by applying two-way cyclic load with (0.2Hz) frequency (not static), which represents wave loading with different cyclic load ratios (0.4, 0.6 and 0.8). This ratio defines as the proportion of ultimate cyclic lateral load capacity to ultimate static lateral capacity of the model (poluse1982). This cyclic test be in two stage, the first one is pure lateral cyclic test for each group (without axial load) and the second stage, the test be under combined load (axial and cyclic load at the same time) where, the cyclic load test continues until 100 cycles. The axial loading is applied on the pile group head as (100% from allowable axial load capacity for model).

Figure 2. Sketch showing the static and cyclic lateral device-loading
3 Results and Discussion

3.1 Effect of Pile Spacing, Cross-Section and Configuration on Load-Deflection Behaviour

The influence of vertical load on lateral response of group pile model (1x2 and 2x1) is represented in Figure 5. The test results explain that the lateral displacement for each group at S/D=5, 7 and 9, (i.e. circular pile group) without axial load reduce about is about of (5%, 8% and 13%) and (7%, 12% and 16%) respectively. In addition, the lateral displacement for pile group models (2×1) less than (1×2) about of (12 %). On the other hand, when the axial load is applied this proportion increase at 100 cycles a rounded of 45% and 50% respectively. This is because of group interaction (i.e. shadow effect) and overlying of stress zones that occurs at closely spaced pile that is caused reduction in resistance of soil inside the pile group for sequent cycles of loading. Also, when the axial load was applied on the cap of group pile, variation of settlement occurred with time. Finally, the bearing groups was more than the first at stopped group movement due to redistribution of soil particles.

On the other hand, the reduction of the maximum lateral displacement in square pile, comparison with circular pile in-group model 1×2 and 2×1 is a rounded of (18% and 20%) respectively under pure...
cyclic loads. It is necessary to note that these proportion increasing by (30%) under combined loads. Where, the square pile group is more responsive to vertical loads than the circular pile group by average of 40%. This is due to large surface area that contacts between piles and surrounded soil, which is improved lateral soil and bending resistance. In addition, the cracks failure is beginning from the edge of square piles. While, it is developed to be more propagate with circular piles due to the cracks failure do not began on the edge but toward the center of pile therefor, the mass, which is resisting the lateral loading for square pile, is more than circular pile as supported by [6, 13].

Figure 5. lateral load- displacement to diameter under pure and combined load for (i.e. square and circular section a) 1x2. b) 2x1

3.2 Bending Moment along Pile

The groups pile is subjected to (two- way symmetric cyclic loading) therefor, half- cycle data has been approved to present and analysis the results. The similar behavior is observed in bending moment for other half of its cycle. Where, the positions of row be changed in the current two-way cyclic load, the leading row become rear row during other half of the loading cycle.

Simple beam theory mentioned by [15] is used to compute bending moment along shift of pile in-group depend on the data of strain.

\[
M = \epsilon \frac{E I}{r} \]

Where

- \( M \) = Bending moment (N.mm)
- \( \epsilon \) = Measured strain (mm/mm)
- \( E \) = Modulus of elasticity for aluminum pipes (N/mm²)
\[ I = \text{Moment of inertia of the pipe section (} \text{mm}^4 \text{)} \]
\[ r = \text{Outside radius of the aluminum pipe (} \text{mm} \text{)} \]

It is clearly from Figure 6, an increasing in number of cycles and cyclic load level lead to increase bending moment profiles. The rate of increasing in maximum bending moment at 100 cycles of loading is a rounded of (30-50) % more than at first cycle for all group models.

The increase in bending for all models group with number of cycles and cyclic load level as results of the pile passes in two stage of deformation under the influence of two-way cyclic load. The first one is rearranging the soil particles that is began directly after the first cycle of lateral cyclic loading. This lead to reduce the voids among the soil grains, after that and with continuity of cyclic loading number, the second stage of deformation begins. Where in this stage, the cyclic load is controlled on the pile and soil behaviour causing displacement the particles from each other's. This lead to form the gap at soil – pile interface and weakness the soil [16, 17].

In order to understand the influence of shadowing, a comparison can be prepared between the leading and rear row piles, after the large number of cyclic loading. Each row is plotted separately and the moment's differences until 100 cycle are compared. Figure 6 represent the moment drawing for the pile in the leading and rear rows at load cycle 100 under pure and combined loads for model i.e. (2×1). This Figure depicts that the maximum bending moment of pile in leading row greater than rear row at shallow depth a rounded by (18) %. In addition, the reduction ratio of bending moment under combined load about (50) % comparison with pure case. This is indicated that the leading row piles has share the greater load, and resists stiffer soil. The soil resisting the leading row of piles is more confined than resisting the rear row of piles. This, because of the soil between the two rows of piles is loosen by the cyclic movement. Therefore, in practice engineers design the piles for maximum bending moment of the leading row this also recommended by [18].

In addition, these figures present the effect of pile shape in-group on bending moment profile under CLR=80% at 100 cycle. it is explained, the higher values of bending moment are saw for group with circular pile is about of (50) % than for group with square pile. This higher value is because of the lateral displacement and cross-sectional area of circular pile. In addition, the results explain that the bending moment for model (1×2) higher than model (2×1) a rounded of (25-50) %. This result, because of a large lateral deflection that subjected during the cyclic loading. This mean that the response of the pile group (1×2) for lateral cyclic loading is similar to single pile.
4. Conclusions

1. The presence of vertical loads on the pile group cap according to allowable vertical load capacity have positive effect on lateral deflection and bending moment for all models. In fact, the amount of the reduction of lateral displacement and bending moment is a rounded of 60 % and 50 % respectively.

2. The shape of the pile in-group has clear effect on lateral displacement where the group with square pile appeared reduction in lateral displacement about (25-30) % than group with circular pile under the same load level.
3. The lateral resistance is a function for the location of the row in-group. Where, the leading row in the groups carried the greatest load and moment than rear row piles about (18) % at the same given displacement.

4. For all models, the maximum bending moment is acted on the first quarter of the pile-embedded length. In addition, the bending of circular pile in-group is more than square about of (50) %.

5. The lateral displacement and bending moment for model (1×2) higher than (2×1) a rounded of (25-50) %.

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