Influence of lateral cyclic loading on the piled-raft foundation embedded in layered soil

Wafaa A. Saleh 1,*, Jasim M. Abbas 2

1,2Department of Civil Engineering, College of Engineering, University of Diyala, Iraq

*Corresponding author: wafaaalisaleh78@gmail.com

Abstract. The work includes an experimental analysis was performed to determine the impact of several variables on the behavior of laterally loaded piled raft model (2×2) having a ratio of length to diameter (L/D=40) and a diameter spacing (S / D) ratio of 3, 5 and 7 at frequency (0.2) Hz embedded in layered soil. The results are submitted as load-deflection curves and bending moment profiles. The effects of degree of saturation, number of cycles, level of cyclic loads, and the location of piles in a row are studied in this work. The results illustrated that increasing degree of saturation for clay soil (mid-layer) decreasing the lateral resistance of this model by about (25%, 31%, and 39%) for S/D=3, 5, and 7 respectively and bending moment by about (7%, 15%, and 17%) for S/D=3, 5, and 7 respectively. The piles in the front rows resist the soil with its full capacity, while in the trailing rows (i.e back) the shadowing effect tends to cause a reduction in soil resistance. The results clarified that maximum bending moment for trailing row less than the leading row by about 7%. The presence of vertical loads lead to an improvement in the lateral resistance of the model with dry clay soil about (28%, 26% and 12%) for S/D=3, 5, and 7 respectively, whereas the increase in the horizontal resistance of the model with partially saturated clay soil about (40%, 45%, and 44%) for S/D=3, 5, and 7 respectively, compared with the absence of vertical loads.

Keywords. Piled raft, cyclic loading, lateral resistance, bending moment.

1. Introduction

Piled raft foundations combine pile and raft that covering the whole area underneath a structure and carry walls and columns. In circumstances where a raft foundation alone insufficient to fulfill the design criteria, raft efficiency can be improved by using piles [1]. The environment prevailing in the ocean requires such type of foundations supporting offshore structures that are designed to resist lateral cyclical loading due to wave motion. A deterioration in the strength and rigidity of the soil-pile system occurs as a result of the reflection of the behavior of the semi-static load, which leads to a progressive reduction in the load-bearing capacity and the displacement of the pile head [2]. Many researchers carried out experimental and computational tests on piled raft systems having vertical piles in layer soil [3-7] studied the impacts of industrial wastewater on the clayey soil properties and the performance of free-headed pile embedded into clayey soil and exposed to cyclic lateral loading. The results indicated a non-linear effect on the lateral displacement of the pile due to the presence of contaminants in the soil. The lateral
resistance of the pile decreased as the concentration of pollutants in the soil increased. [8] examined the behavior of pile groups exposed to lateral loads in multi-layer sand where the angle of inclination of the pile batter is changed, the influence of the ratio of the pile spacing (s / d) and the influence of using different numbers of piles and pile group configuration. The results showed that the performance of individual negative (reversed) battered piles with a 10° and 20° slope showed an increase in the ultimate lateral capacity of 32% and 76% over the regular piles. Increasing the distance between piles in groups of the same category shows an increase in the efficiency of the group, also when the number of piles within the group is changed using different patterns, the ultimate lateral resistance of the group of piles is affected.

There is a limited experimental review on the behavior of piled rafts containing vertical piles embedded in layered soil with partially saturated clay soil and subjected to lateral cyclic loading. Therefore, this complex system, resulting in layered soil with different load combination, needs more laboratory and numerical studies to improve the knowledge regarding the performance of such a problem. The behavior of the circular piled raft model (2×2) subjected to laterally cyclic loads, this analysis examines the resistance mechanisms of the foundations under cyclic loading by means of a sequence of load experiments.

2. Outline of the experiments

2.1 Soil

This study adopted two types of soil (clay and sand) from different cities in Iraq. A series of laboratory tests are achieved to specify their properties and classify them. A hydrometer testing revealed that the particles of clay size (<2 μm) made up about 52% by weight of the sample, while the silt particles made up about 42.7% by weight of the sample. Liquid and plastic limits were found as 39% and 22% respectively [plasticity index (PI) = 17%] and that solid particles have specific gravity stated as (G.s= 2.7). The standard results of the proctor compaction testing showed that the maximum dry density (MDD) was 16.8 KN/m³. The layered soil created by the upper layer of dry medium dense sand that overlays a clay soil and fully saturated sand bed. The upper and lower layers were formed by pouring out dry sand (Cu = 2.56; Cc =1.16) using the technique of rainfall from a constant height of (1.15) m with a dry field density, ρd, of 16.7KN/m³ equivalent to the relative density 70%. The peak friction angle Ø was found 35° form direct shear test.

The degree of saturation for the middle layer (clayey soil) was changed using dry soil (Sr=0%) and again partially saturated soil (Sr=50%) was used to simulate the reality of environmental conditions represented by the rise and low of groundwater levels witnessed in most countries of the world and its impact on engineering structures under the influence of periodic loading. The partially saturated clay soil is prepared by mixing it thoroughly with enough water (moisture content = 12.73%) to obtain the desired consistency and degree of saturation (Sr = 50%). The mixing process is done by hand with a large sprinkle jar. After thorough mixing, the moist soil was kept in polyethylene bags for at least three days to maintain an even distribution of water content.

The steel container with dimensions (1×1×1) m is used, which big enough to avoid edge effects. The container coated with an epoxy resin to prevent rust and also the silicone material is used from the inside along the wall edges to prevent water from escaping and to secure it well. The total height of the tank is divided into three intervals from the inside using signs to bring a certain weight to a certain volume and to get the required density for each soil. The bottom layer (35cm) height filled with fully saturated sand, the mid-layer (30cm) height filled with clay soil, after preparation of the bottom bed (the two lower layers), the installation of piles in the model soil performed by using a hand auger manufactured for this purpose as shown in Figure 1. The top layer (35cm) height filled with dry sand.
2.2 Model of piled raft foundation

Pile foundations carrying the main structures, comprising transport infrastructures, offshore platforms etc., were consisted of a significant number of piles, mostly installed in a rectangular or square pattern, and subjected to cyclic loading [9]. Piled raft model (2 × 2) was chosen to ensure accuracy of test results and ease of use. The fact that the use of a piled raft model consisting of a large number of piles is impractical for model tests which requires a considerable amount of preparation for the test tank. Experiments were performed using piled raft (2×2) made of square steel plates their dimensions (96x96)mm, (128x128)mm and (160x160)mm depending on the spacing of the pile (3D, 5D and 7D) respectively and piles made of circular aluminum tubes (EI= 124.78×10^6 N. mm²) with outer diameter 16-mm, thickness 1.5mm, and overall length 730-mm (depth of embedment = 640 mm and L/D=40). Pile cap made of a 6 mm thick rigid plate with two parts, the upper part of the cap being used to apply the dead load, whereas the lower part used for applying the cyclical horizontal load as illustrated in Figure 2. The cap of pile was brought into contact with the ground to represent the pile-raft foundation. Piles are fixed to the cap with screws.
3. Test Procedure

For each experiment, similar test beds were set up for accuracy. Piled raft was installed into the prepared test bed until it was reached the required embedding depth. Subsequently, static loading experiments were conducted laterally and vertically to determine the total vertical and lateral static capacity of the piled raft model. During these experiments, the cap of pile was attached to the static-loading apparatus to push at a regular rate of movement and load-displacement data logging based on deflection criteria. The ultimate lateral capacity was taken in this analysis as the load equivalent to a deflection equal to 20% of the pile diameter suggested by [10] and the ultimate vertical capacity of the pile group is adopted as the load relating to overall axial movement equivalent to 15% of the diameter of pile or width according to the [11] and this value is divided by (F.S = 2.5) to determine the allowable load capacity (Q) of the pile group. For imparting cyclic horizontal loading, the cap of pile was attached to the device of cyclic loading. Depending on the static stage results the ultimate lateral capacity of this model is directed to the piled raft at various cyclic load ratio which is defined as the proportion of lateral cyclic loads to the pile’s ultimate static lateral capability [9]. The cyclic load applied comprised different levels of cyclical horizontal load, equivalent to a CLR of 0.2, 0.4, 0.6 and 0.8 [12,13] at a frequency (0.2 Hz). To generate different cyclic loads using two load cells. The deflection of the piled raft head is controlled using inductive linear variable displacement transducers (LVDTs), which are connected to a data logger. The information is mechanically read and stored during the lateral displacement. The automatic timer controls the charging time (5 seconds/cycle) and in this study, the test was continued up to 100 cycles. A dial gauge is installed at the top of pile group cap to record the vertical displacement during the test as shown in Figure 3. The reading of strain gauges which installed at certain points along the pile converted into bending moments with different level of the cyclic load ratio (CLR) via the simple beam theory (Euler-Bernoulli beam theory)

\[ M = \varepsilon \left( \frac{EI}{r} \right) \]  ...(1)

Where

- \( M \) = Bending moment (N.mm)
- \( \varepsilon \) = Measured strain (mm/mm)
- \( E \) = Modulus of elasticity for aluminum pipes (N/mm²)
- \( I \) = Moment of inertia of the pipe section (mm⁴)
- \( r \) = Outside radius of the aluminum pipe (mm)
4. Results and Discussion

4.1 Effect of Degree of Saturation on the Load-Deflection Curves

Past earthquake observations have indicated that piles generally perform well in hard soils, while piles installed in soft or liquefiable soils are further likely to experience difficulties resulting from excessive soil motions or surface amplification. The behavior of the laterally loaded pile is affected by the groundwater level [14]. In this study, the behavior of circular piled raft model (2×2) with S/D=3, 5 and 7 at the frequency (0.2) Hz and CLR=0.2, 0.4, 0.6 and 0.8 are tested under the effect of changing the degree of saturation of clay soil which is simulated the lowering water table level. Figures 4 and 5 show that the lateral deflection values are considerably lower in dry case (Sr=0%) than partially saturated soil (Sr=50%), but both situations show a reduction with increasing S/D ratios. These results are expected as the shear strength of the clayey soil decreases with the presence of water in addition to the effect of excess pore water pressure which increases with increasing the magnitude of cyclic load ratio (CLR). At the first cycles of loading, pore water pressure is high, and thus the effective stresses decrease, but after a period of time the pore water pressure will dissipation and effective stresses increase. These results agree with the experimental work of [15]. The reduction of the lateral deflection for the dry case about (25%, 31% and 39%) respectively for S/D=3, 5 and 7 under pure lateral cyclic loading conditions whereas the reduction under combined loading are (11%, 8%, and 4%) respectively.

4.2 Effect of Pile Spacing and Vertical Loads on the Piled Raft Response

The load-deflection curves obtained for piled raft (2×2) with different pile spacing at 100 number of

Figure 3. Piled raft model (2×2) under the influence of lateral cyclic loading (A) Pure lateral loading condition (B) Combined loading condition
cycles of loading are shown in Figures 4 and 5. For the same given load, the deflection at 100 cycles with S/D=7 is lesser in both cases (even when the partially saturated clay soil layer is replaced by dry clay), whereas the large deflection occurred with S/D=3 and 5. This is because of the influence of group interaction (i.e. shadowing effect) which in turn caused by overlapping of stress zones when the spacing between piles is smaller. This effect of group interaction is expected to decline as the distance between the pile's increases because adjacent failure areas overlap less [16] When designing piles, the group effects for the lined piles disappear at a spacing equal to five diameters or more [17]. When pile spacing enlarges, the load on the piles decreases. As pile spacing enlarges, the maximum bending moment reduces under the same applied load as shown in Figures 6 and 7. The effect of the above behavior appears clearly on the embedded model of partially saturated soil than the dry soil model. Therefore, the presence of water altered the distribution of the moment. The results indicated that the increase in the horizontal resistance of the model with dry clay soil layer using (S/D=5 and 7) compared to S/D=3 about (13% and 32%) at 100 cycles, whereas for the model with partially saturated clay soil about (7% and 17%) respectively.

Furthermore, the magnitudes of the vertical load have a large impact on the soil resistance and horizontal pile displacement [16]. The current study demonstrated that when vertical loads are applied on the group, the overall lateral piled raft model resistance increases due to increasing confining pressures in the soil deposit confined by the piles as well as the presence of vertical loads make the mass of the group larger and thus its resistance is higher [18] and the axial loads are made of the lateral soil pressure redistributes [19]. The outcomes indicated that the presence of vertical loads lead to an improvement in the lateral resistance of the model with dry clay soil about (28%, 26% and 12%) for S/D=3, 5, and 7 respectively, whereas the increase in the horizontal resistance of the model with partially saturated clay soil about (40%, 45%, and 44%) for S/D=3, 5, and 7 respectively, compared with the absence of vertical loads.

![Figure 4. Load-Deflection curve of the group (2×2) embedded in layered soil including dry clay soil](image-url)
Figure 5. Load-Deflection curve of the group (2×2) embedded in layered soil including partially saturated clay soil

Figure 6. Bending Moment profile of the group (2×2) embedded in layered soil including dry clay soil with different spacing between piles

Figure 7. Bending Moment profile of the group (2×2) embedded in layered soil including partially saturated clay soil with different spacing between piles
4.3 Effect of Number of Cycles and Cyclic Load Ratio on Piled Raft Behavior

A pile lateral load cycled in both directions with equal load magnitude is called a two-way loading. To analyse the behavior of a group of piles under cyclic loading, it was essential to study it under the influence of a high number of cycles. In this study, cycle (100) was adopted to predict the behavior of the piled raft response under two-way cyclic loading. Figure 8 showed that load-deflection behavior increases with an increasing number of cycles for all spacing of piled raft models embedded in layered soil (with dry and partially saturated clay). This is due to soil degradation with the first cycles of loading and the initial load-deflection behavior is highly nonlinear and after a certain number of cycles degree of non-linearity progressively decreases due to clay compaction and sand densification as a result of pile movement [20]. From the Figures 9 and 10 it can also be seen that at the low level of loading (CLR=0.2 and 0.4) the deflection of group head increases progressively with the number of cycles, but non-linearly up to a specified number of cycles and then the relationship become constant whereas with high cyclic loading magnitude (CLR=0.6 and 0.8), a steep rise in deflection occurs with a few numbers of cycles due to degradation of the stiffness of the soil and high cyclic load leads to reducing passive soil resistance [21]. The same behavior is observed for the groups with S/D=5 and 7.

![Figure 8](image_url)

**Figure 8.** Load-Deflection curve of the group (2×2) with S/D=3 at different number of cycles (a) Soil including dry clay (b) Soil including partially saturated clay
Figure 9. Deflection with number of cycles for piled raft model (2×2) embedded in layered soil including dry clay soil.

Figure 10. Deflection with number of cycles for piled raft model (2×2) embedded in layered soil including partially saturated clay soil.
4.4 Effect of Location of Pile in a Row

As illustrated in Figure 11, the rows were defined as the leading row and the trailing rows in the loading direction. It is very important to refer to the influence of the location of piles in a row. The piles in the front rows resist the soil with its full capacity, while in the trailing rows (i.e. back) the shadowing effect tends to cause a reduction in soil resistance. Therefore, the maximum bending moment for an imparted load on the piled raft tends to be in the front row pile. The optimum moment in the back row for the piles happens at a greater depth, because of the reduction in the load transfer near the surface. This was also found by other researchers [13, 22, 23] and [16] as shown in Figure 12. The results illustrated the maximum bending moment for trailing row less than the leading row for circular piled raft models (2×2) about 7%. The results show that the pile in the first row attracts higher moments, while the pile in the back row attracts lower moments. This is because the front row attracts more pile head loads due to the higher soil resistance, while the piles in the back row attract less because of the aforementioned shadow effect of the sand.

![Figure 11. Typical pile group adopted in the parametric study](image1)

![Figure 12. Effect cyclic loading on bending moment behavior considering the position of the pile in row (A) Soil including dry clay (B) Soil including partially saturated clay](image2)
5. Conclusion

1. With an increasing degree of saturation for clay soil, the lateral resistance of the piled raft decreases.
2. The behavior of piles embedded in layered soil containing dry clay was similar to the piles embedded in layered soil containing partially saturated clay, but deflection and bending moment were higher in the latter under the same condition of cyclic loading.
3. The shadow effect depends on the distance between the piles within the group, the density of soil, and the load level. Piles forming the leading rows have received a higher load per head of pile, which has led to higher deflections and higher bending moments.
4. An increasing number of cycles lead to decreasing pile group lateral resistance at the first cycles, then the deflection of the group became constant approximately because of the densification of the soil.
5. The pile spacing has a major impact on the load distribution in pile groups. The pile load decreases with increasing pile spacing which in turn decreases the lateral deflection of the group as well as bending moment for all groups in different conditions.
6. The presence of vertical loads on piled raft system leads to reduce the horizontal displacement and bending moment with all spacing, which leads to more economical foundation construction.

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