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Interactive Analysis of Pile/Pile Groups Subjected To Vertical, Lateral and Combined Loading

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Abstract—In many cases, the lateral pressure acting on piles due to horizontal soil movements is calculated with empirically or analytically based approaches respectively. In the scope of this project, the soil movements were analysed from 1G model test by use of LVDT sensors, The 1G model test was investigated the lateral response of pile subjected to lateral load, vertical load, combined vertical and lateral load and also found out the displacement rate of pile. The tests were carried out single pile, four pile and nine pile groups. In all the three cases tests where carried on a free standing pile and a pile group where in the cap was touching the ground and then Comparative Analysis was made after the 1G model test. Compare the loads and deflection of 3 types of group pile and conclude the variation between each pile groups. Deformation and bending moments developed in the pile sections were measured by LVDT sensors attached on the pile cap. The results obtained from the lateral, vertical and combined loading experiments are analysed theoretically with the methods found in the literature to contribute to a better understanding of this complicated geotechnical problem. Then FEA and MODEL test results are compared and analysed. Conclusions are drawn regarding theoretical analysis of pile subjected to lateral load.

Keywords—Pile foundation, pile-soil interaction, vertical loading, lateral loading, combined vertical and lateral loading, load settlement behaviour

1. INTRODUCTION

Pile foundations are usually used when the enormous amount of superstructure loads have to be transmitted through weaker subsoil. Piles are also subjected to significant amount of lateral loads and moments in addition to that of axial loads, when they are used under tall chimneys, high rise structure and offshore structures. In case of onshore structures, lateral loads are acting in the order of 10 – 15% and in offshore structures it exceeds 30% of vertical loads. Particularly due to complex soil structure interaction between the piles and the pile cap – the problem of laterally loaded piles or group of piles involves, this is because the pile deflection depends on soil reaction and in turn influences soil reaction through pile deflection. These pile groups are usually connected by using pile cap through which superstructure loads are transmitted. Pile caps are usually massive blocks of concrete placed directly on the ground after driving the pile groups. The pile caps are built to provide a connection between the structure and multiple single piles, which are often subjected to vertical and lateral loads as well as moment of overturning. Resistance to vertical and lateral loading is generally provided by pile-soil-pile cap interaction, base and side friction between pile and soil, position of the pile cap plays a major role on the pile soil interactions. The rotational resistance is provided by pile to pile cap connection and passive earth pressure. In many cases the lateral resistance provided by the pile caps are larger than the piles themselves. Most caps can be partly or completely embedded in the soil. However, the design often neglects the contribution of pile caps to the lateral resistance of pile groups. In the case of a group of piles, overlapping stress zones create a group effect " which reduces the lateral load capacity of piles in a group relative to that of an isolated single pile. This group effect is caused by the piles' interaction with surrounding soils. Burlandet al.(1977)first proposed the concept of using piles as "settlement reducers'. 'common perception of engineers is that more piles can lead to greater decrease in raft settlements. However, as Paulo and Davis (1980)have pointed out, the number of piles required to reduce settlements below the working load to a tolerable limit is usually small, and any additional piles may result in only marginal further settlement reductions.

Pile and pile groups subjected to static independent vertical, lateral and combined loading conditions. The effects of the position of pile cap, length of the pile, number of piles in the group and arrangement of piles with respect to the direction of loadings are studied in detail. Theoretical analysis is also used to predict single-pile and pile group behaviour and then compare the resuts with the experimental test results.

2. MATERIALS

A. Sand

The soil sample used is river sand and is collected near sulur. The basic properties of sample was analyzed, it is classified as Poorly Graded Sand (SP). The basic properties and gradation of sand is shown in Table 1.

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TABLE 1.Physical Properties of Foundation Medium

Gradation	Values
Coarse sand	2.9%
Medium sand	34%
Fine sand	61.3%
Silt and clay	1.8%
D_{10}	0.20 mm
D_{30}	0.32 mm
D_{60}	0.56 mm
Coefficient of Uniformity C_u	2.8
Coefficient of Curvature C_c	0.91
Is classification	SP

B. Pile

In the present work, laboratory model tests were carried out to study the load settlement behavior of pile using mild steel piles of diameter and thickness of 8 mm and height of 180 mm under vertical and lateral loading condition on medium dense sand. Three sets of pile was used single, four and nine pile groups. Tests were performed by placing a pile cap on the bed and placed above the bed. Pile model shown in Fig.1.

TABLE 2: Pile layout and dimension

Description	Single Pile	Four Piles	Nine Piles
Pile length	180mm	180mm	180mm
Pile dia	8mm	8mm	8mm
Pile cap	60*60 mm	60*60 mm	60*60 mm
Cap shape	square	square	Square

Fig. 1 pile models

C. Testing Tank

A circular test tank is fabricated for performing the experiments on model pile in the laboratory. It is a strong metal box having inner dimensions of $0.9m^3$ with 2mm wall thickness. The test box is chosen to be with sufficient depth for the reason that the load deflection predictions must solely be taken from the pile model's performance and it should not be overestimated because of the tank's wall confinement. Experimental analysis was carried out for vertical, lateral and combined loading.

3. METHODOLOGY

This paper presents the deflection behavior of pile and pile groups. The arrangement has made on two conditions **1.** pile cap placed on the bed **2.** pile cap placed above the bed. The three sets of piles was used with a spacing of 2.5d (d=diameter of pile). Loads and deflections were measured on two conditions by testing sets of pile groups.

4. EXPRIMENTAL TEST SETUP

Test's was carried out using a loading frame of capacity 50kN. The vertical compressive load was applied to pile raft model through a hydraulic jack of 50kN capacity, which was supported centrally at the bottom flange of the steel girder made of channel sections. The load was measured with a proving ring fixed at the bottom of jack and the rigid loading platen was connected to the proving ring through an extension rod. The lateral load is applied to the piled raft model through the hydraulic jack by motor. The representation of loading setup is shown in Fig.2.

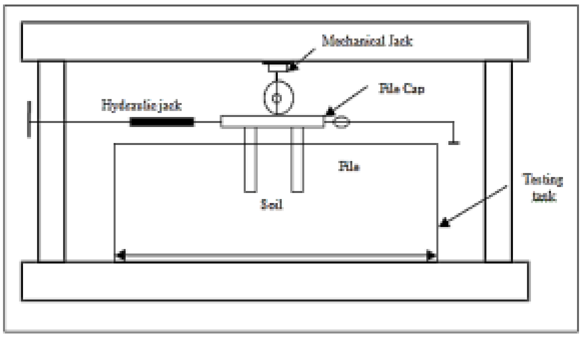

Fig. 2 Diagrammatic representation of experimental setup

A. Preparation of foundation medium

The foundation medium was prepared by using river sand with relative density of 41%. The sand was filled in the tank in five layers of each of 150mm thick. Sand was rained from a pre calibrated height of 20 mm and each layer of sand was given 25 blows by using the heavy compaction tamping rod, such that the required density of tank was achieved.

B. Testing phase

Single pile and group of pile was modeled for testing under two cases.

Case 1 : Pile cap bottom resting on the surface of soil medium

Case 2 : Pile cap provided 25 mm above ground level

The vertical and lateral load tests are conducted on pile raft as per procedure recommended by IS 2911 (Part 4). The proving ring and two LVDT(Linear Variable Differential transformer) are placed in position over the pile cap. Axial load is applied in increments by means of 50kN proving ring over the pile cap. Each increment of loading is maintained until the pile settlement become less than 0.02mm/min. The vertical deflection of the pile is measured by LVDT corresponding to the load, when the deflection of the pile ceases, the next load increment is applied. The test is proceeded until the pile achieves its ultimate axial capacity for the corresponding failure load. In case of lateral loading, the same procedure is followed and the load-settlement curve is plotted for vertical and lateral loading cases.

C. Vertical loading

Case 1 : Vertical loading were applied when the pile cap is resting on ground

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Case 2 : Vertical loading were applied when the pile cap is placed 25 mm above the ground

The vertical load was applied using hydraulic jack and it was measured by 50kN proving ring. Continuous measurement of vertical displacement was carried out using LVDT with ± 25mm travel. Tests were carried out until punching shear failure occurs in the foundation medium. 3 types of pile was used single, four and nine pile group. Results were given in the form of load vs. settlement curve.

Fig. 3 Vertical loading setup

D. Lateral loading

Case 1 : Lateral loading were applied when the pile cap is resting on ground

Case 2 : Lateral loading were applied when the pile cap is placed 25 mm above the ground

Hydraulic jack is used to put on the lateral load through a load cell which has capacity of 2kN and load indicator is used to measure the applied load. Testing the pile and pile groups we find out Horizontal deflection was measured by using LVDT sensors same used in vertical load test, Tests were continued up to the permissible deflection and the results are discussed. Same setup was used for two cases, pile on the bed and pile cap above the bed.

Fig. 4 Lateral loading setup

E. Combined loading

In case of combined loading, **two third of the final vertical load at which the total displacement attains a value of 12 mm of ultimate vertical load was kept constant** and then the lateral load was varied till the deflection of permissible limit was occurred. Testing was done for two cases, pile loading arrangements were also carried out for combined loading conditions. Two LVDTs were used to measure the lateral deflection and then results were interpreted from the load vs. settlement curve.

5. RESULTS AND DISCUSSIONS

A. Vertical loading test results

Vertical loading tests were carried out for all two cases. the results are compared and presented.

TABLE 3: Corresponding load carrying capacity and settlement for vertical loading

Position of pile cap	Load (KN)	Settlement (mm)
Single pile cap on bed	0.72	26.92
Single pile cap above bed	0.12	20
4 pile cap on bed	1.92	28.33
4 pile cap above bed	0.54	29.07
9 pile cap on bed	5.58	26.11
9 pile cap above bed	2.82	29.39

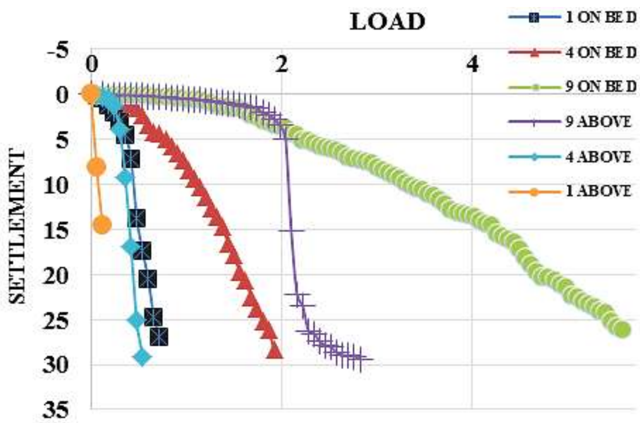

Fig. 5 Comparison of Load – Settlement Curve for Vertical Loading Cases

From the curve it is observed that during the initial stage, load settlement curve varies linearly which is mainly due to the uniform distribution of applied load to the pile cap. Nonlinear variation was observed suddenly due to the failure of surrounding soil by shearing action before the failure of pile occurs. When the pile cap is placed above the bed, the pile group of four pile and nine pile group capacity is 68% and 45% less than the group capacity of pile cap fixed on ground, the above values are for 12mm settlement. When the pile cap is in contact with the bed, the capacity of the single pile and pile group is 100% more than the free standing pile and pile group, the vertical load capacity of the pile group appears to be not in direct proportion of single pile capacity on bed. In case of four pile group for 5mm, 9mm, 12mm settlement, the four pile group capacity is 48%, 41%, 35%. less than the theoretical group capacity (no of pile X single pile capacity). When the same comparison is done for nine pile group the variation was found to be 35%, 20%, 13%. Such a behaviour understood through theoretical analysis only. Thus the load carrying capacity of group pile was varies irrespective of the no of piles in the group. Thus the load carrying capacity rises as the depth of the position of pile cap on the soil surface increased which is mainly due to increase in passive earth pressure around the pile and pile cap.

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B. Lateral loading test results

TABLE 4: Corresponding load carrying capacity and deflection for lateral loading

Position of pile	Load(KN)	Deflection(mm)
Single pile on bed	0.24	15.02
Single pile cap above bed	0.09	18.46
4 pile cap on bed	0.75	12
4 pile cap above bed	0.31	12.5
9 pile cap on bed	1.14	12.3
9 pile cap above bed	0.64	13.32

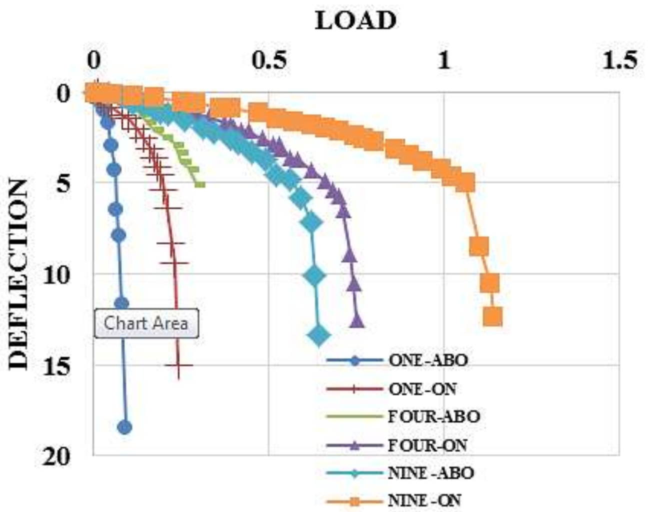

Fig. 6 Comparison of Load – Deflection Curve for lateral Loading Cases

Lateral load tests were carried out independently on the single pile and also on a group consisting of four and nine piles. Similar to vertical loading, for lateral loading also the load carrying capacity and cap resistance increased when the pile cap is placed on the soil surface. Fig.6 shows that the load carrying capacity and cap resistance increased as the depth of the position of pile cap increases when it placed on the soil surface. Free standing pile group of four and nine pile capacity was reduced to 58% 43% when it compared to pile cap resting on the ground, the above values for 12 mm settlement. Load carrying capacity of pile was increased when pile cap was resting on ground. Similarly capacity of single pile on bed was compared with group piles on bed for deflections of 5mm 9mm 12mm, For 4 pile group i was observed the variations of 15% 21% 22% less than the theoretical group pile capacity of single pile. For 9 pile group i observed the variations of 41% 45%47% which is less than the theoretical group pile capacity (no of pile X single pile capacity), the lateral load capacity of the pile group appears to be not in direct proportion of single pile capacity. It is also due to intensification in the confinement of soil with more pile – soil – pile cap interaction. Pile load carrying capacity will be increased with respect to number of piles.

C. Combined loading test results

In case of combined loading, an increase in load carrying capacity was found when the axial load was applied constantly to the pile cap is placed on the soil surface.

TABLE 5: Corresponding load carrying capacity and deflection for combined loading

Position of pile	Load (KN)	Deflection (mm)
Single pile on bed	0.28	14.01
Single pile cap above bed	0.15	17.46
4 pile cap on bed	1.125	12
4 pile cap above bed	0.42	12.5
9 pile cap on bed	1.71	12.9
9 pile cap above bed	0.96	12.55

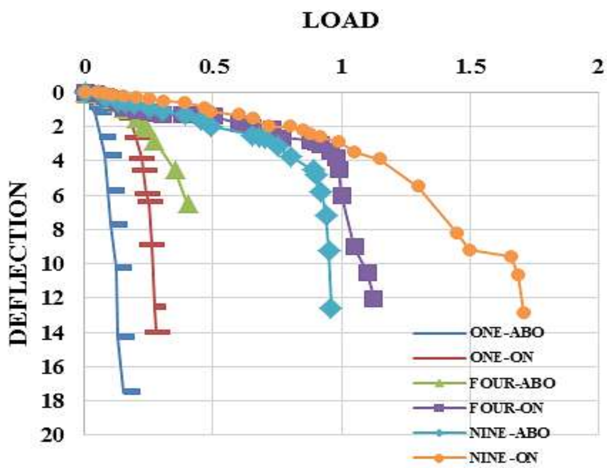

Fig. 7 Comparison of Load – Deflection Curve for combined Loading Cases

Load carrying capacity of Free headed four pile and nine pile groups was found to be 55% and 42% less than the capacity of pile groups placed on bed. Then the theoretical analysis was done by the capacity of single pile compared with group of piles four and nine piles, the variations observed that the four pile group capacity 23% 18% and 15% less than the theoretical group capacity of a single pile, similarly for the nine pile group variations are observed 45% 38% and 33%, the above values are for 5mm, 9mm, 12mm deflections. Increase in lateral load capacity of a pile is mainly due to increase in axial capacity of pile along with increased passive earth pressure on the sides of pile and pile cap. It is mainly due to confinement of soil particles. Combined loading was attain a more load than vertical and horizontal loading, it is mainly due to the axial load on the pile cap.

6. CONCLUSION

The following conclusions were made based on the experimental observations and theoretical analysis. This work aims at understanding the loading behavior under various circumstances.

1. For vertical loading free standing nine pile group is 42% less than the group pile capacity when it is fixed to ground, similarly for lateral and combined loading, the load carrying capacity was reduced to 43% and 42%., nine pile group placed above bed attains a lesser variation than single pile and four pile group placed above bed.

2. When the pile cap is in contact with the bed the capacity of the single pile and pile group is 100% more than the free standing pile and pile group.

3. In case of vertical loading, minimum variation of load carrying capacity to be observed as 13 % at 12mm settlement for the nine pile group, similarly for the lateral and combined loading minimum variation of pile load capacity was observed as 15% for the four pile group at 5mm and 12mm settlement respectively.

4. From the theoretical analysis the loading capacity of the pile group appears to be not in direct proportion of the single pile capacity (no of pile X single pile capacity).

5. In the case single pile and pile group, there is an increase in load carrying capacity when the piles are tested under combined loading this due to confining stress which increase the shear strength of soil at different depths.

6. The passive earth pressure and length of pile plays a dynamic role in the lateral resistance of pile.

7. Load carrying capacity and the cap resistance can be increased by accumulating the number of piles and also by altering the piles arrangement with regard to the loading direction.

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