Interaction Effect on Laterally Loaded Piles in Cohesionless Deposit

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Abstract Pile is the only solution to transfer the vertical and lateral loads to deeper strata in high-rise buildings. Here, an attempt has been made on laboratory model single pile and pile groups to investigate lateral resistance of the piles. However, this paper puts up the results of lateral static load tests executed on model steel and wooden single pile and pile groups, in cohesion-less deposit about 1 m deep at varying sand density and length to diameter ratio keeping the spacing constant. Load is applied using turn-buckle and measured by a spring balance. Dial gauges are installed to investigate the average displacement. The effects of embedded length to diameter ratio, sand density, configuration of piles, material of piles and group efficiency are studied and explored. The test results are substantiated theoretically by GEO5 software for both single pile and pile groups considering the properties in aligned with that of experimental studies.

Keywords Efficiency · Pile–soil–pile interaction · Lateral load · Pile groups · Load settlement · Turn-buckle

1 Introduction

In general, pile foundations are subjected to lateral loads due to earth pressure, wind action, wave action, earthquake, impact of ships and so on, which are claimed to be found in the range of 10–15% of the vertical loads in case of onshore structures and 25–30% in case of coastal and offshore structures (Gandhi and Selvam 1997). In many situations, piles are constructed in groups to support the structure which differs in behaviour substantially as compared to that in single pile. The pile–soil–pile interactions as observed cause pile groups to deflect more in significant to the single

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pile for the same average load applied on both. The bending moment, also, in case of group of piles is significantly more than that in single pile due to weakening of soil resistance (Brown et al. 1988). It is because of the ability to represent the nonlinear behaviour of soil, versatility and simplicity, the p–y curve method is broadly used in the design among the different methods available for analysis of lateral loaded piles. In 1988, Brown et al. proposed the concept of p-multipliers to reduce p–y curve of a single pile to obtain p–y curves for piles in group for incorporating group interaction effects. Previous research studies on group of piles in sand include full field tests and centrifuge model tests (Brown et al. 1988; Poulos and Davis 1980; Rollins et al. 2005).

Piles are seldom isolated but are usually arranged in a manner of pile groups in order to strengthen the load resistance. Although a pile group strengthens the overall lateral load resistance, the soil–structure interaction effect weakens the individual pile response of the piles in the group (Poulos 1971b). The overall lateral load is divided among each of the piles in the group. Each pile pushes against the soil behind it creating a shear zone in the soil (Phanikanth et al. 2010). These shear zones begin to enlarge and overlap as the lateral load increases (Broms 1964; Poulos 1971a). More overlapping occurs as the piles are spaced very closely together in the group arrangement. The overlapping occurring in between two piles along the same row is referred as “edge effects” and that in different rows is referred as “shadowing effects” (Rollins et al. 1998). All of these “group interaction effects” result in less lateral resistance per pile in the pile group.

However, the majority of the reported field tests on groups have been carried out at different spacing and single to two, three L/D ratios. Lateral load tests on pile groups with most efficient spacing of 3.5D diameters and of two materials are insufficient (Walsh 2005). Effects of pile group configuration and pile spacing in the direction perpendicular to loading were not comprehensively investigated. In this study, an extensive experimental procedure has been opted to perform tests on the model pile group embedded in sand subjected to lateral loads. The density of sand that has been used is obtained at two heights, that is, 45 and 65 cm by rainfall method technique. Also, the mechanism of providing the load and measuring it has never been used in the past to provide the smooth lateral loading. The effects of number of piles, arrangement of piles and different materials of the piles have been studied effectively.

2 Materials Used

2.1 Sand

The sand collected from Kharkai River, located near Jamshedpur city (India), is used in the present study. The direct shear test was performed on the sample of air dried sand. Relative density test was performed at three heights 25, 45 and 65 cm at which

Table 1 Index properties of soil

S. no.	Description	Value
1	Uniformity coefficient, C_u	2.7
2	Coefficient of curvature C_c	1.0
3	Fineness modulus of sand	3.34
4	Modulus of elasticity of sand	1.7 kg/cm^2
5	Specific gravity	2.76
6	Maximum dry density	1.71 g/cc
7	Minimum dry density	g/cc

the densities obtained were 58, 72 and 85%, respectively. The present study is done on 45 and 65 cm height of rainfall. The sand is classified as course sand in zone II by performing fineness modulus test depicting a value of 3.34, which lies in the range of 2.9–3.7 for coarser sand. Dry sieve analysis is also done to ensure the particle size distribution of the sand used (Table 1).

2.2 Pile

In this study, the scaling law is used to select the model pile material and its dimensions (Walsh 2005). Steel and wooden piles have been selected using the scale law. The length of the pile is 65 cm and diameter 4.4 cm. In case of steel pipe pile the wall thickness has been chosen as 0.25 cm. For wooden piles, solid wooden material of diameter and length same as that of steel is chosen. Pile cap in case of steel pile has been used of same material of thickness 4 mm having holes at required spacing so that the piles can be easily fixed by nut and screw mechanism. In case of wooden pile arrangement with the pile cap, two separate wooden plywood of thickness 15 mm are used, and the bottom plywood is having the hole while the top plywood has the head rest for the pile head. Fixity of the wooden pile cap to the wooden pile is done by the nut and bolt mechanism.

$$\frac{E_m I_m}{E_p I_p} = \frac{1}{n^5} \tag{1}$$

where E_m = modulus of elasticity of model pile; E_p = modulus of elasticity of prototype pile; I_m = moment of inertia of model pile; I_p = moment of inertia of prototype pile; and 1/n = scale factor for length. This is used to stimulate the prototype pile in software GEO5, of 1000 mm diameter of steel pipe pile in case of steel piles and wooden pile of same diameter for wooden case study. The other scaling factors used in the study are presented in the table. The pile cap was attached to the piles leaving 150 mm above the sand surface as a free standing length for the group. Screwing of top of the piles and providing a hole in pile cap for threading the bolts in the piles to fix them was done to ensure partial fixity (Table 2).

Table 2 Scaling factors used in the study

Variable	Scaling factor
Length	1/10
Density	1
Stiffness	1/10
Stress	1/10
Strain	1
Pile flexural rigidity	$1/10^5$
Pore fluid density	$1/10^3$

2.3 Turn-Buckle and Spring Balance

Turn-buckle is used to provide lateral load by rotating the central shaft of the turn-buckle. It is connected from one side to the pile cap and from another side to the spring balance which measures the load applied by the turn-buckle at any instant. Dial gauges have been installed on both sides of the turn-buckle to measure the average deflection of the pile cap.

3 Experimental Programme

3.1 Experimental Setup and Instrumentation

The schematic diagram of the test setup is shown in Fig. 1. Tests were conducted on model piles group embedded in the sand in rectangular steel testing chamber of 1.3 m × 1.3 m area and 0.90 m depth. Piles were placed at suitable depth from top of the tank to maintain the L/D ratios of 12 and 15, where L denotes the embedded length of the pile into the sand and D being the diameter of the pile. Rectangular plate of thickness 4 mm has been used as the pile cap.

Turn-buckle has been used to apply the load and a spring balance is attached to the turn-buckle for noting down the pull generated by the turn-buckle. Two dial gauges have been set on both sides of the turn-buckle to obtain the average displacement of the pile cap in the direction of the load.

3.2 Soil Bed Preparation and Pile Installation

In the present study, the sand bed was prepared similar to the procedure that was adopted by Rollins et al. (2005) in layers maintaining the uniformity throughout the tank. The collected sand from Kharkai River was air dried and sieved through 4.5 mm sieve to obtain a range of particle size less than 4.5 mm. Sand sample were placed at a

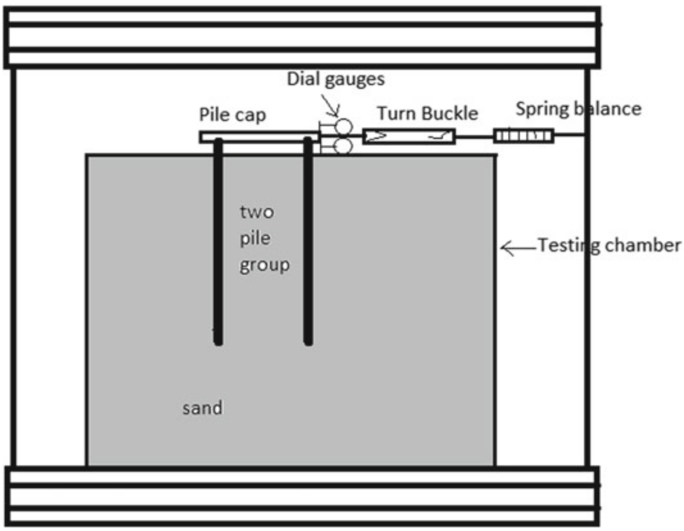

Fig. 1 Schematic diagram of the experimental setup

location where no moisture was entrapped into the sand. The pile has been placed at the desired depth, then sand was placed from a desired height uniformly throughout the tank with the help of aluminium box by rainfall method which was ensured to allow specific amount of sand uniformly through the hole provided for pouring the sand into the tank.

The uniformity of the sand was maintained by placing cans in each layer and calculating the density at the end of each test. In case the density did not simulate the required density of the sand, the test was repeated. The verticality of the pile has been done by placing spirit level on the head of the pile. In this case, the installation process simulates the bored pile condition. Model penetrometer test was conducted at each layer to ensure the uniform density all along. The density and un-drained shear strength were determined as per Bureau of Indian Standards BIS 2002. The un-drained shear strength of sand was measured by conducting tri-axial tests on the samples of 38-mm diameter and 76-mm height.

3.3 Test Procedure

Static lateral load was applied on the model piles by turn-buckle which was connected to the pile cap by nut and bolt mechanism at one end, the other being attached to the spring balance which was mounted on the horizontal rod parallel to the tank width movable at different heights. The loads were applied in increments and were maintained for a period of 30 min to allow the deflection to stabilize as per the Bureau of Indian Standards BIS 006b. During the application of static loads, the load

Fig. 2 Actual setup of dial gauges; turn-buckle, spring balance and pile attached with pile cap

transferred to the pile group was measured through the weighing balance and the deflection was measured by two dial gauges placed on the pile cap as shown in the schematic diagram (Fig. 2).

3.4 Testing Phases

Static lateral load tests were conducted on model single piles and pile groups embedded in sand. Experimental loading test was done at first and then the software analysis was done to substantiate the test results obtained experimentally. Tests were conducted in the following sequence:

1. Single steel and single wooden pile with embedment length to diameter L/D ratios of 12;
2. 1*2 and 2*2 steel and wooden pile groups with L/D ratio of 12 and 15 keeping S/D ratio 3.4.
3. Single steel and wooden pile in GEO5 software following the scaling factor and keeping the L/D ratio of 12 and 15 and S/D ratio 3.4.
4. 1*2 and 2*2 steel and wooden pile groups in GEO5 software following the same scaling factor and keeping L/D ratio of 12 and 15 and S/D ratio of 3.4.

The spacing in the direction perpendicular to the direction of loading S_T was kept constant as 3.4D for 1×2 and 2×2 pile groups. The deflection in the GEO5 software is calculated and compared with the deflection observed in experimental results. The configurations of pile groups are shown in Fig. 3.

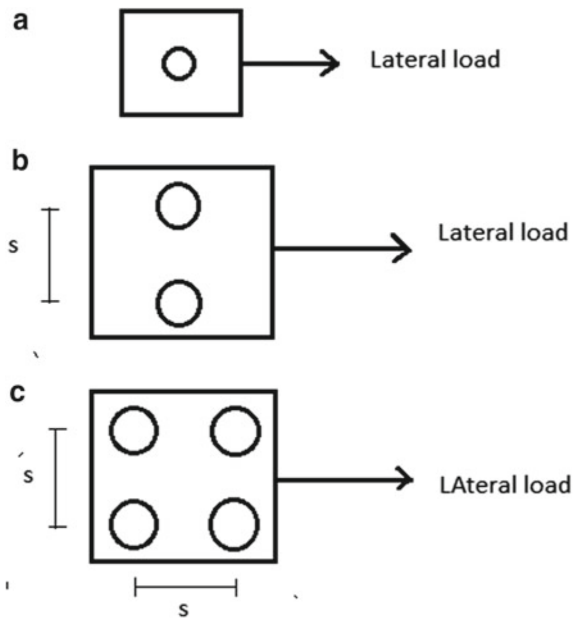

Fig. 3 Configuration of pile groups used in the study: **a** 1 × 1, **b** 1 × 2, **c** 2 × 2

The piles are classified as rigid or flexible based on the relative stiffness factor K_{rc} (Poulos and Davis 1980).

$$K_{rc} = \frac{E_P I_P}{E_S L^4} \tag{2}$$

where E_P = modulus of elasticity of model pile material; I_P = moment of inertia of pile section; E_S = secant modulus of soil; and L = embedded length of pile. The pile is said to be rigid if K_{rc} is greater than 10^{-2} and flexible if K_{rc} is less than 10^{-2} (Poulos and Davis 1980).

4 Results and Discussion

4.1 Group Efficiency

Pile group interaction effect is also studied by calculating the group efficiency and is given as

$$\eta = \frac{Q_G}{\eta_g Q_S} \tag{3}$$

Table 3 Group efficiency of steel pile experimental

Length/diameter (L/D)	Pile group	Spacing/diameter S/D	Group efficiency
12	1 × 2	3.4	1.25
	2 × 2	3.4	0.875
15	1 × 2	3.4	1.19
	2 × 2	3.4	0.84

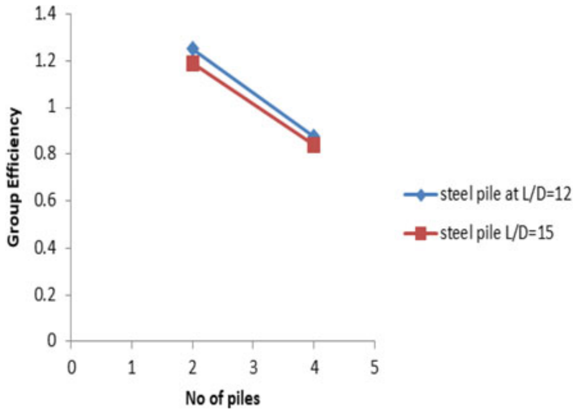

Fig. 4 Group efficiency versus number of piles

where Q_G = lateral load capacity of the group corresponding to a deflection of 0.2D; Q_S = lateral load capacity of the single pile corresponding to a deflection of 2.2D; and η_g = number of piles in the group. Group efficiencies of the single pile and group of piles have been shown in Table 3 corresponding to a deflection of 0.23 D (Fig. 4).

4.2 *Effect of Number of Piles*

To evaluate the effect of number of piles on the behaviour of pile groups at 3.4D spacing with L/D ratios of 12 and 15, the average load-pile head deflection curves for groups with varying number of piles are presented in Fig. 5. At larger pile head deflections, the average pile group response shows softer curve than that obtained in the case of single pile.

This points it out the reduction in stiffness of piles in the group. It can now be interpreted from Fig. 5 that the degree of nonlinearity in the response of piles in the group tends to increase with the size of the pile group. This happening of increase in the nonlinearity occurs due to the interaction effect of the piles in the group. Also their combined load bearing zone into the sand strata comes out as a reason for such nonlinearity.

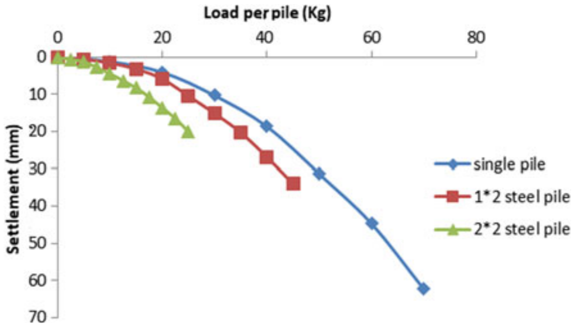

Fig. 5 Load settlement behaviour of steel piles with L/D = 12 and RD = 70%

This interaction zone under the soil of the pile in the pile group is solely responsible for the increase in the nonlinearity and reduction in the stiffness of the pile group. The percentage reduction in lateral capacity, corresponding to a deflection of 0.23D, has been computed and been presented in graphs.

This provides a route to the conclusion that there is an increase in the percentage reduction of the lateral capacity of the pile groups as compared to that is single pile with increase in the number of piles in the group. Also, the fact that a single pile shows less deflection at the applied load as compared to that applied to the pile group is considered as another reason for reduction in lateral capacity. There occurs an increase in overlapping of stress zone due to increased number of piles in the group which leads to a sharp reduction in the lateral capacity.

4.3 Effect of Embedment Length

The lateral capacity of 1 × 2 groups at 3.4D spacing increases with embedment length, as shown in Table 2, due to the additional passive resistance developed along the increased embedment length (Figs. 6 and 7).

4.4 Effect of Sand Density

Sand density affects the load capacity of piles in sand. With more dense sand, the load capacity of the pile decreases. Two densities of sand have been obtained at 45 cm rainfall and 65 cm rainfall. At these two, the settlement behaviour of piles has been studied. Owing to increase in density, the load carrying capacity increases due to more firm soil strata to withhold the piles. Corresponding to same settlement value of 0.23D, the load carrying capacity of pile shows the inverse pattern with the increase in number of piles (Figs. 8 and 9).

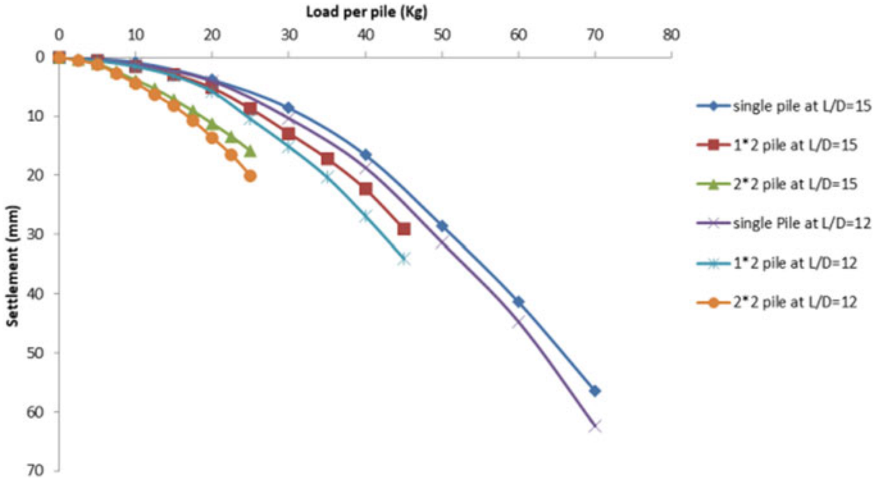

Fig. 6 Load settlement behaviour of steel pile at RD = 70%

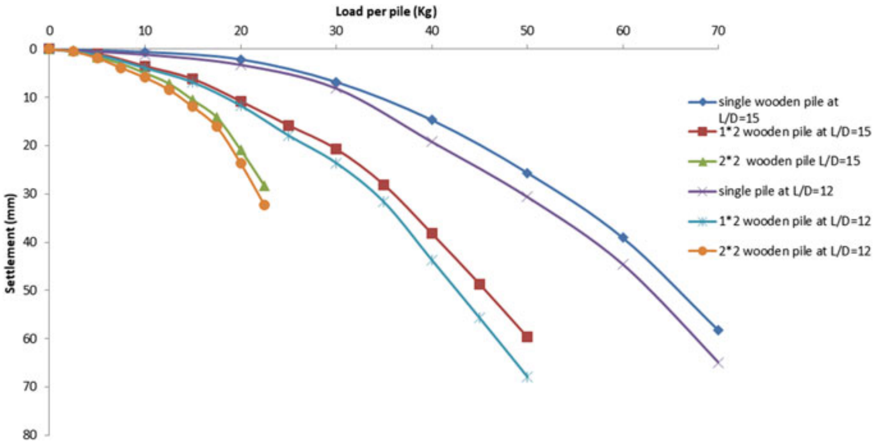

Fig. 7 Load settlement behaviour of wooden pile at RD = 70%

4.5 Effect of Pile Material

Pile material has different effect on the loading capacity of the pile group. Steel and wooden piles have been compared based on their loading capacity. At different L/D ratio and at different sand density, a comparative study is done to show that steel pile has more load carrying capacity. Behaviour of 1 × 2 and 2 × 2 pile group configurations has been shown for both wooden pile and steel pile. The difference in the load carrying capacity of pile group in both the configurations is due to more interaction

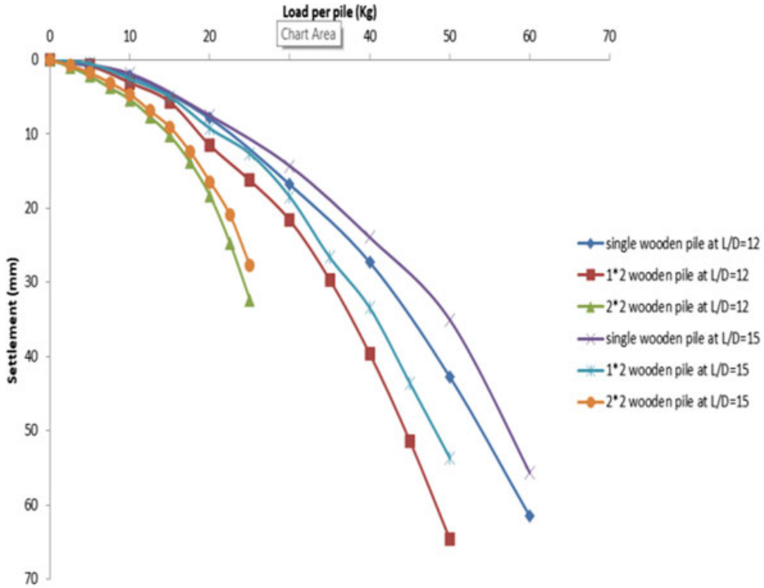

Fig. 8 Load settlement behaviour of wooden pile at RD = 85%

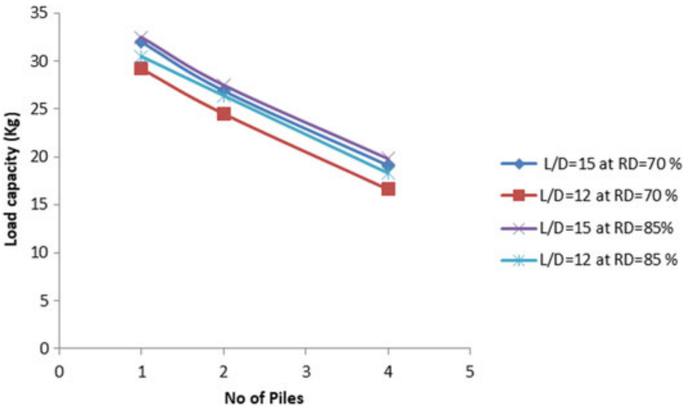

Fig. 9 Load capacity at different relative density and different L/D ratio

in case of 2 × 2 pile group configuration as compared to 1 × 2 configuration. This interaction occurring in both directions in case of 2 × 2 configuration causes it to deflect less as compared to that in case of 1 × 2 pile configuration in which only one side interaction occurs (Figs. 10 and 11).

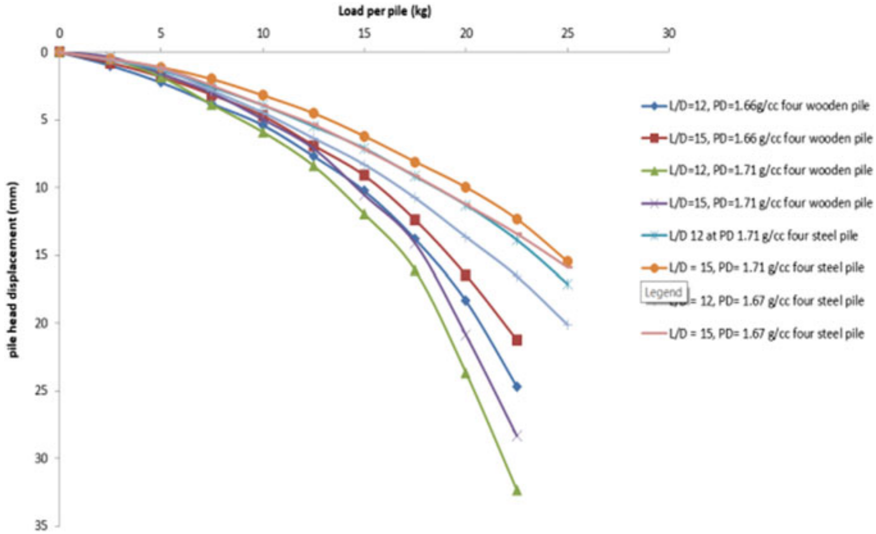

Fig. 10 Load displacement behaviour of 2*2 steel and wooden pile groups

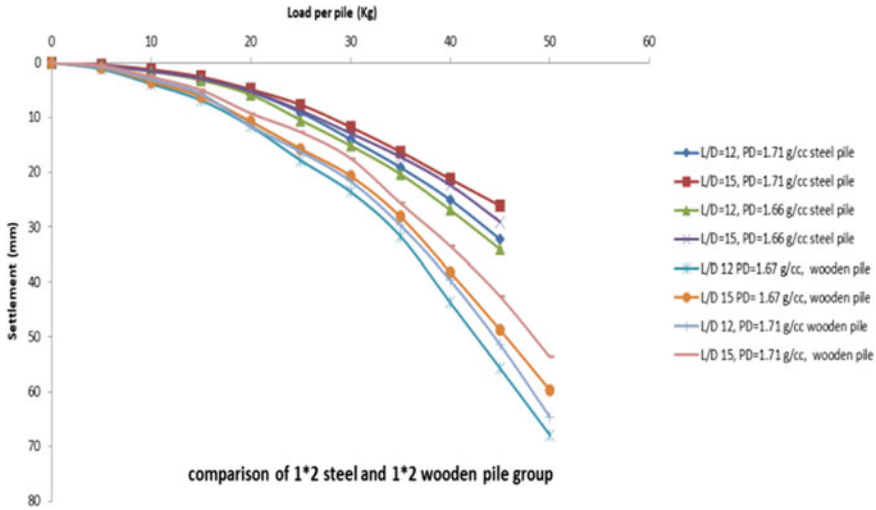

Fig. 11 Load displacement behaviour of 1*2 steel and wooden pile groups

4.6 Loading Capacity of Piles in Group

Piles in group show the decreasing efficiency with number of piles. Single pile shows maximum loading capacity as compared to piles in group due to interaction effect of piles in group. The piles have been studied for their capacity corresponding to the

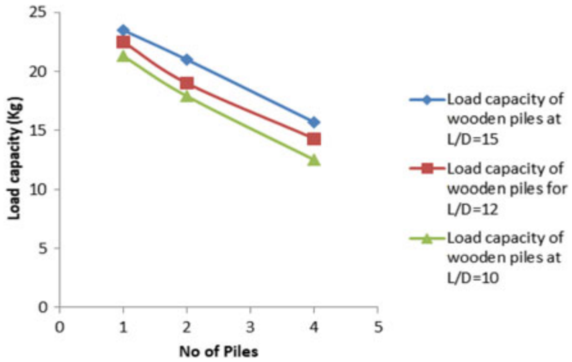

Fig. 12 Load capacity of wooden piles versus number of piles

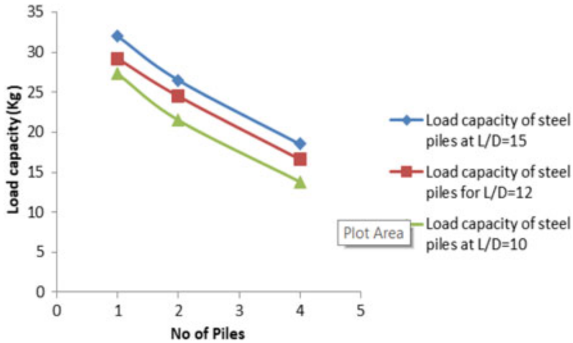

Fig. 13 Load capacity of steel piles versus number of piles

settlement of 0.23D for single as well as group of piles. Both the steel and wooden piles show the decreasing pattern of load carrying capacity with increase of number of piles. This behaviour of load carrying capacity occurs due to the interaction effect of piles. For a single pile, the load carrying capacity corresponding to 0.23D settlement is greater as compared to that of 2 pile or 4 pile group at the same settlement amount (Figs. 12 and 13).

Comparison curve is shown in Fig. 14 with previous study of Gandhi and Selvam (1997). The comparison curve is drawn on the dimensionless quantity to compare the test results effectively.

5 Software Test Results

5.1 Pile Head Displacements

Pile head displacements that have been obtained in the case of single steel and single wooden pile are analogous to that of experimentally obtained test results.

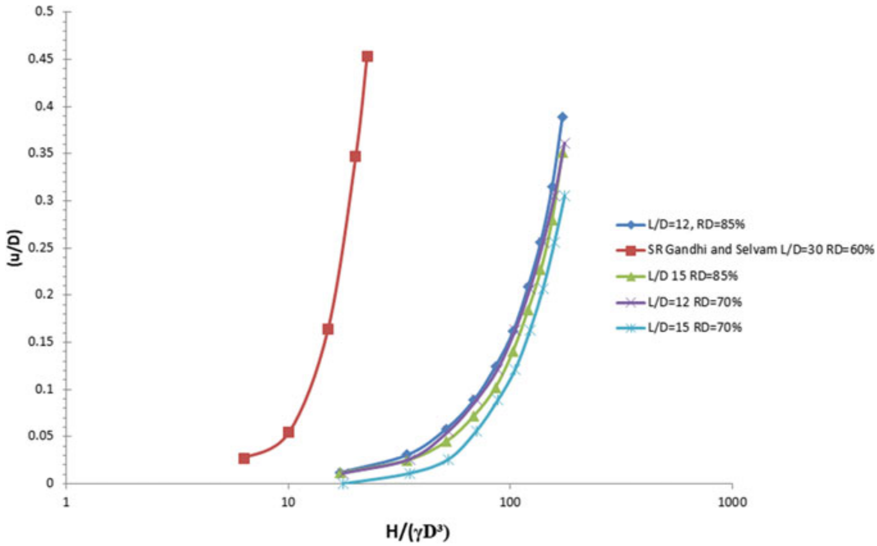

Fig. 14 Comparison of four steel pile groups

The soil properties in the case of the software analysis were kept the same as that of during the experimental tests. The pile head displacements in case of software analysis are somewhat greater as compared to that of load displacements obtained in experimental tests. Displacement behaviour of prototype pile in software analysis for each configuration has been depicted in subsequent figures. The difference in the displacement occurs due to change in the site condition, presumed analysis values in software and also due to the change of pile dimension and other factors (Figs. 15, 16 and 17).

Figure 18 shows the pile head displacements of single steel and single wooden pile with increase in the embedded length into sand layer. For the lesser embedded depth of the pile in the sand, the difference in the pile head displacements is larger as compared to that in case of larger embedded length of the pile into the sand. This occurs due to more resistant behaviour of the sand in larger embedded length of the pile in the sand. A comparative study of the steel and wooden pile can also be interpreted by the graph as for wooden piles the pile head displacements are greater as compared to that for steel pile due to its rigidity and larger modulus of elasticity as compared to wooden piles.

5.2 *Moment Distribution Trends*

The curve in Fig. 19 shows the trend analysis of moment distribution curve in the laterally loaded piles in sand. The comparison curve has been drawn with the results

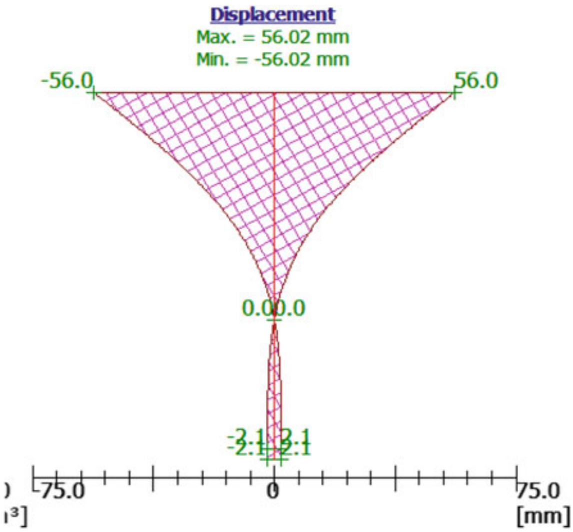

Fig. 15 Load pile head displacement of single steel pile at L/D = 12 at 70% RD

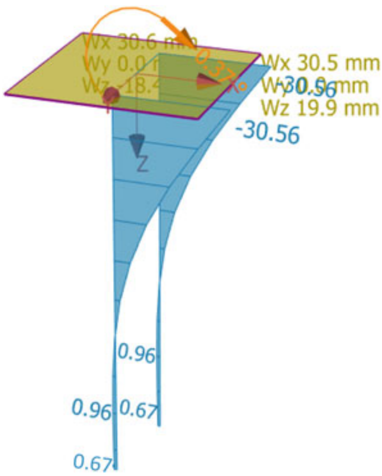

Fig. 16 Horizontal pile head displacements of two pile groups in prototype L/D = 12 and RD of 70%

of Poulos and Davis (1969). The results shown here have been converted into non-dimensional form to show the exact comparison study of laterally loaded piles.

6 Conclusion

Based on the results of the present experimental work on model pile groups embedded in sand, the following conclusions are drawn:

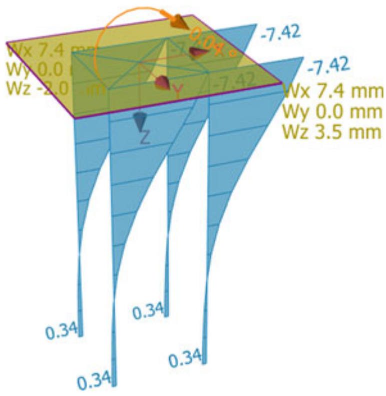

Fig. 17 Horizontal displacements of pile groups in prototype L/D = 12 and RD of 70%

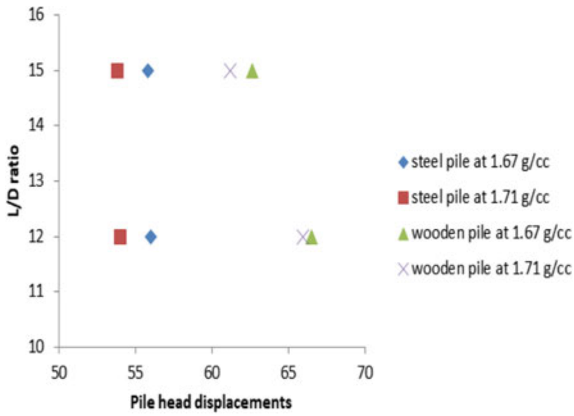

Fig. 18 Pile head displacements in computer analysis

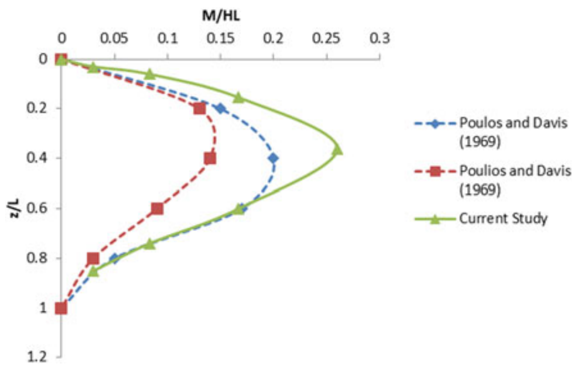

Fig. 19 Comparison study of moment distribution

1. Pile–soil–pile interaction leads to a considerable reduction in the lateral load capacity of piles in the groups as compared to the single pile. With the increase in number of piles in the pile group, the load capacity of the pile group increases significantly. For the same settlement value of 0.23D load taken up of 2*2 pile groups is more than single pile.
2. The density of sand affect the loading capacity of the pile groups and single as well. Increase in the density reduces the lateral load capacity of the pile group and single pile.
3. The embedment length is an important factor for the loading capacity and the interaction of the pile. With greater L/D ratio, the loading capacity of the group and single pile decreases. At L/D ratio of 15, the lateral loading capacity is 10–12% higher as compared to that at L/D ratio of 12 for steel piles and 14–18% for wooden piles.
4. Group efficiency decreases as the number of piles in the group increases due to the interaction effect. A reduction of 40% of efficiency has been obtained. Pile group efficiency decreases with the increase in the number of piles in the pile group. The efficiency obtained in case of pile group at the same S/D ratio has the decreasing order with change of L/D ratio and number of pile in the group. At the L/D ratio of 12, the difference in the efficiency that has been obtained for two pile group and four pile group is 42.85%. While for L/D ratio of 15, this difference in the efficiency obtained is 41.67%.
5. For 0.23D settlement value, the loading capacity of steel pile group increases by 14–18% for 1*2 configurations and 8–10% for 2*2 configurations.
6. The difference of the settlement of the single wooden pile and single steel pile has been observed up to 15–18% for the same average loading.

Notations:

The following symbols are used in this paper:

C_u	Uniformity coefficient
C_c	Coefficient of curvature
D	Diameter of the pile
E_m	Modulus of elasticity of model pile
E_p	Modulus of elasticity of prototype pile
E_S	Secant modulus of soil
I_m	Moment of inertia of model pile;
I_p	Moment of inertia of prototype pile;
K_{rc}	Relative stiffness factor
L	Length of the pile
P	Soil reaction
1/n	Scale factor for length
Q_G	Lateral load capacity of the group
Q_S	Lateral load capacity of the single pile
S	Spacing of pile in the direction of loading as well as in transverse to the loading
η_g	Number of piles in the group

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References

Broms B (1964) Lateral resistance of piles in cohesion less soil. J Soil Mech Found Eng 90(3):123–156

Brown DA, Morrison C, Reese LC (1988) Lateral load behaviour of pile group in sand. J Geotechn Eng ASCE 114(11):1261–1276

Gandhi S, Selvam S (1997) Group effect on driven piles under lateral load. J Geotech Geo-environmental Eng-123. https://doi.org/10.1061/(asce)1090-0241(1997)123:8(702)

Phanikanth VS, Choudhary D, Reddy CR (2010) Response of single pile under lateral loads in Cohesion-less soils. Electron J Geotech Eng 15:813–830

Poulos HG, Davis EH (1980) Pile foundation analysis and Design. Wiley, New York

Poulos HG (1971a) Behaviour of laterally loaded piles-single piles. Proc ASCE J Soil Mech Found Eng Div 97(SM5):711–731

Poulos HG (1971b) Behaviour of laterally loaded piles: Pile groups. Proc ASCE J Soil Mech Found Eng Div 97(SM5):733–751

Rollins KM, Peterson KT, Weaver TJ (1998) Lateral load behaviour of full scale pile group in clay. J Geotech Geoenviron Eng 124(6):468–474

Rollins KM, Lane JD, Gerber TM (2005) Measured and computed lateral response of a pile group in sand. J Geotech Geo-environmental Eng ASCE 131(1):103–114

Walsh JM (2005) Full scale lateral load test of a 3 x 5 pile group in sand. Department of Civil and Environmental Engineering, Brigham Young University