Study on Piles Subjected to Axial and Lateral Loading

V. K. Stalin, A. Priyadharshini, P. Deepan, and A. Abudaheer

Abstract Piles are often subjected to combination of vertical and lateral loading in places like bridge piers, offshore structures, retaining walls, etc. The behaviour of piles under biaxial loading is much more complex when piles are embedded in layered soil system. In this paper, an attempt is made to study behaviour of pile subjected to vertical and lateral loading for varying soil layers. Model pile load tests have been conducted in a model tank filled with sand, clay and clay–sand medium to examine the behaviour of single pile and pile group under vertical and lateral loading. Both single and pile group (2 × 2) have been subjected to axial compressive loads and lateral loads, for varying type of soil medium, combinations of loading, number of pile and L/D ratio. Result indicated that the vertical load capacity of pile increases with L/D ratio and number of piles at any given settlement, but however, the vertical capacity of sand medium is always higher compared to clay or clay–sand medium. Similar trend is observed on the lateral load capacity also. At the given deflection, lateral capacity increases with L/D ratio and number of piles relatively on the higher magnitude for sand medium but less noticed for clay and clay–sand bed. Under the influence of ultimate vertical load, the lateral capacity of pile is much lower than the lateral capacity of pile without vertical load, for single pile irrespective of the settlement and for pile group at specified settlement values.

Keywords Pile foundation · Combined loading · L/D ratio

1 Introduction

Normally, vertical piles are used to carry vertical compression loads coming from super structures such as tall buildings, bridges, etc. Piles used in tall chimneys, hill

V. K. Stalin · A. Priyadharshini · P. Deepan (✉) · A. Abudaheer
Department of Civil Engineering, College of Engineering, Anna University, Chennai 600025, India
e-mail: deepangeotech95@gmail.com

A. Priyadharshini
e-mail: priyavanaja606@gmail.com

S. Patel et al. (eds.), *Proceedings of the Indian Geotechnical Conference 2019*,
Lecture Notes in Civil Engineering 133,
https://doi.org/10.1007/978-981-33-6346-5_46

retaining wall, high-rise buildings, offshore structures, etc. are normally subjected by high lateral load. The piles are commonly used to carry vertical compressive load to resist uplift also as to resist lateral and inclined load. These piles are used to support vertical loads, lateral loads and combinations of vertical and lateral loads. However, in view of the complexity involved in analysing the piles under combined loading, the current practice is to analyse the piles independently for vertical loads to determine their bearing capacity and settlement and for the lateral load to determine their flexural behaviour. Since the piles are not often adequately designed to resist lateral loads, the response of piles under lateral load in the presence of vertical loads is more critical and interesting for the design engineers. Zhang and Small [5] presented a method of analysis for a ground and cap supported by piles embedded in a layered soil and subjected to horizontal and vertical loads. Rajagopal and Karthigeyan [3] analysed the pile behaviour subjected to combined vertical and lateral loads. It is concluded that the presence of a vertical load marginally reduces the lateral load capacity of piles in clayey soils for vertical load level up to 0.6Vult and by as much as 20% for higher vertical load level. Karthigeyan and Rajagopal [1] presented some numerical results on the effect of vertical load over the lateral capacity of 2 × 2 pile group in homogeneous sand. Miyamoto [2] carried out dynamic centrifuge tests performed on a four-pile group foundation model embedded in saturated fine sand layers. It is concluded that the proposed model well represented the pile foundation response in liquefied soil. Zamri et al. [4] carried out 3D finite element analysis of the behaviour of single pile under pure lateral and combined loading with different water table elevations. They found that dry soil condition yielded higher lateral resistance than fully saturated soil condition. The present investigation focuses on the effect of L/D ratio, number of piles and various soil types on the load carrying capacity of pile and pile groups under vertical and lateral loading combination.

2 Materials

River sand collected from nearby site is washed and air-dried before the same is used for laboratory testing. The river sand has coarse sand, medium sand and fine sand of 14%, 65% and 21%, respectively. Based on the Cc and Cu values, the sand is classified as poorly graded sand (SP). Natural clay is collected from west Tambaram, Chennai, Tamil Nadu. The soil is having clay, silt and fine sand of 64%, 20% and 16%, respectively. As per Indian Standard of Classification, the soil is classified as clay of high plasticity (CH). Model hollow aluminium piles with an outer diameter of 10 mm, inner diameter of 4 mm and thickness of 3 mm plugged at both ends are used. The length-to-diameter ratio (L/D ratio) of the piles of 12 and 24 is selected to study the short rigid piles and long flexible piles based on the stiffness factor, T of the pile system as per IS 2911 (Part 1/Sec1), 2010. Aluminium plate of 5 mm thickness and size 45 mm × 45 mm is used as pile cap. For 2 × 2 pile group, the pile cap is welded on the top of the piles with 3D centre - centre spacing between the piles. Steel square tank of 500 mm × 500 mm of breath and width and height 700 mm is used

Table 1 Index properties of sand

Properties	Value
Maximum dry unit weight, Υ_{dmax}	17.24 kN/m^3
Minimum dry unit weight, Υ_{dmin}	15.50 kN/m^3
Maximum void ratio, e_{max}	0.65
Minimum void ratio, e_{min}	0.58
Specific gravity, Gs	2.67
Coarse sand	14%
Medium sand	65%
Fine sand	21%
Coefficient of uniformity, Cu	4.55
Coefficient of curvature, Cc	1.32
Soil classification	Poorly graded sand (SP)

Table 2 Index properties of clay

Properties	Value
Clay	64%
Silt	20%
Fine sand	16%
Liquid limit, W_L	77%
Plastic limit, W_P	33%
Plasticity index, I_P	45%
Shrinkage limit, Ws	8%
Specific gravity, Gs	2.68
Free swell index	100%
Soil classification	Clay of high plasticity (CH)

in the experiments. These dimensions are arrived based on significant depth (0.1q) for pile foundation, which is sufficiently large enough to avoid boundary effect. The test tank contains a pulley with frame attached at the side of the tank to apply lateral load using loading frame hinged using string (Tables 1 and 2).

3 Methods

3.1 Model Tank

The schematic view of the model tank along with provisions for applying vertical load and lateral load is shown in Fig. 1. A steel square tank of 500 mm $\times$ 500 mm of breath and width and height 700 mm is used in the experiments. Figure 2 shows

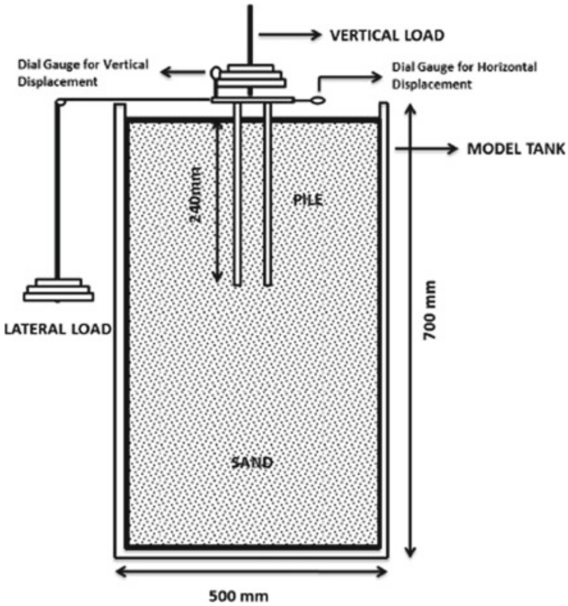

Fig. 1 Schematic view of vertical and lateral load test in model tank

Fig. 2 View of model tank with provision apply vertical and lateral load

the photographic view of model load test setup. The dial gauges used for taking measurement of lateral deflection and vertical measurement have the least count of 0.002 mm.

3.2 Vertical Load Test on Pile

There is a provision to apply static vertical load on the top of the pile head, see Fig. 1, and corresponding settlement. The load is applied to estimate load settlement curve, until the failure load is reached in both single-pile and four-pile group (2 × 2). The vertical load test is conducted for varying L/D ratio, soil medium and number of piles. This ultimate failure load is used as a reference to apply lateral load. The vertical load is varied as 0.3, 0.5 and 0.8 times of ultimate failure load to analyse lateral load capacity of model piles. IS 2911 (part 4), 1985 Section 6.2. Maintained Load Method was followed with regard to application of load increment.

3.3 Lateral Load Test on Pile

In the model load test setup, see Fig. 1, there is a provision to apply lateral load and to measure the corresponding deflection. For a given vertical load, the static lateral load is also applied until the failure load is reached, to analyse the lateral capacity of pile and pile groups.

3.4 Experimental Procedure Adopted to Carry Out Vertical and Lateral Load Capacity of Piles'

The tank of 500 mm × 500 mm × 700 mm is filled with sand layer for several layers; see Fig. 1. Sand layer is approximately 500 mm thickness and tamped with flat plate to achieve 60% relative density. In the case of clay bed, the hand remoulded clay sample is carefully placed at an initial moisture content of 68% and corresponding consistency of 0.2. During filling the tank with either sand bed or clay bed and clay–sand bed, the aluminium model piles (2 Nos. or 4 Nos.) are placed as the approximate location and soil layers are placed surrounding the model piles. After filling the tank completely with sand or clay bed to a embedded length 700 mm, a free head of 20 mm is provided in all medium. To facilitate lateral loading, pile is connected to loading frame using high-tension wire. The vertical or lateral load and pile head displacement are recorded at regular interval up to failure for both vertical and laterally loaded pile and pile group using dial gauge. For each test, separate soil bed is prepared. For clay–sand layer bed, clay is filled up to the L/2 of the embedded length of the pile used followed by sand till the bottom of the model tank. In the analysis of vertical and laterally loaded piles, the main parameters involved are ultimate pile capacity and displacement. Herein, the vertical and lateral load capacity are arrived for known settlement of 2 mm, 4 mm and 6 mm in case of vertical loaded piles and deflection of 1.5 mm, 3 mm and 4.5 mm for lateral loaded piles.

4 Results and Discussions

4.1 Vertical Load Carrying Capacity of Pile

The vertical load capacities of pile for L/D ratio 12 and 24 for single- and 2 × 2 pile group are analysed for varying soil medium. Similarly, for a given soil medium, the effect of L/D ratio and number of pile on the vertical capacity of pile are also analysed in this section.

Effect of soil medium. Figures 3 and 4 present the vertical load—settlement behaviour of single pile for varying soil medium and L/D ratio. These curves are not showing a typical parabolic shape with single peak. Hence, the vertical load capacity is arrived for a known settlement of 2 mm, 4 mm and 6 mm.

Similar trend of vertical load settlement curve, see Figs. 3 and 4, has been observed in case of 2 × 2 pile group subjected to a pure vertical load.

at 6 mm settlement

Effect of L/D ratio. The results indicate that, from Figs. 5 and 6 and Table 3, it is thus inferred that for a single pile in sand, clay and clay–sand medium, when L/D ratio increases the vertical load capacity also increases irrespective of settlement. Similarly, in the case of four pile group, the vertical load capacity increases with increase in L/D ratio for any known settlement value of 2 mm, 4 mm and 6 mm.

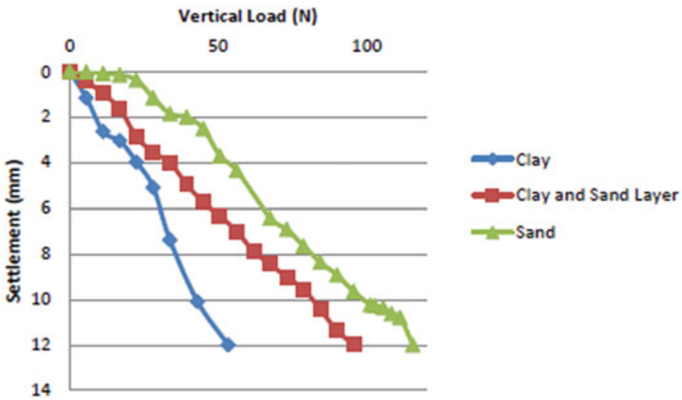

Fig. 3 Vertical load—Settlement curve of single pile for varying soil medium for L/D ratio 12

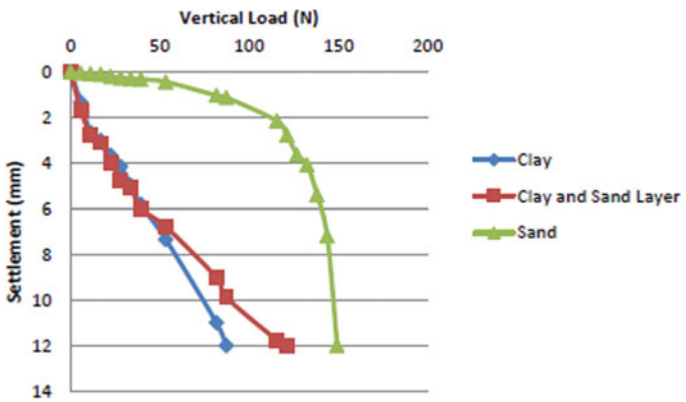

Fig. 4 Vertical load—Settlement curve of single pile for varying soil medium for L/D ratio 24

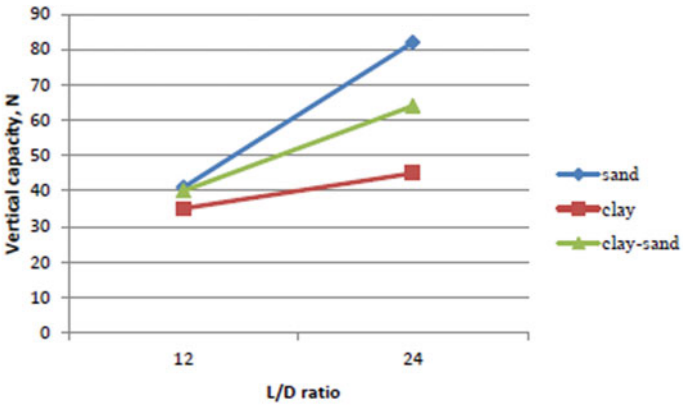

Fig. 5 Vertical Load—L/D Ratio variation of single pile for different soil medium at 6 mm settlement

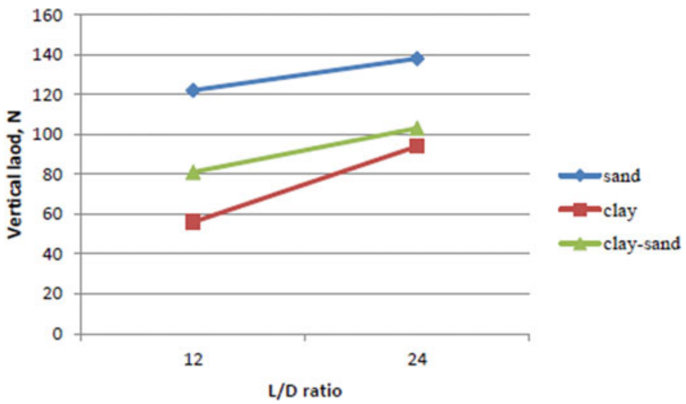

Fig. 6 Vertical Load—L/D Ratio variation of 2 × 2 pile group for different soil medium

Table 3 Vertical load capacity of single pile and 2 × 2 pile group for varying settlement

Soil medium	L/D ratio	Load, N					
		Single pile			2 × 2 pile group		
		2 mm	4 mm	6 mm	2 mm	4 mm	6 mm
Sand bed	12	22	24	41	47	96	122
	24	35	51	82	115	127	138
Clay bed	12	6	23	35	17	35	56
	24	13	51	45	34	65	94
Clay–sand layer	12	11	23	40	23	39	81
	24	22	28	64	36	89	103

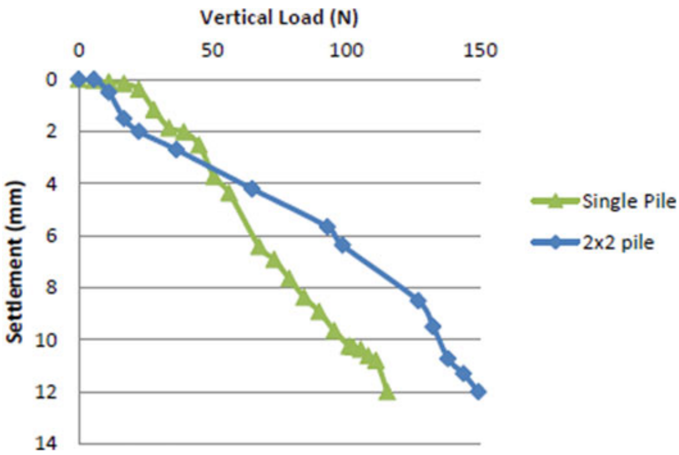

Fig. 7 Vertical load—Settlement curve for number of piles (L/D Ratio = 12) in Sand

Effect of number of pile. Figures 7, 8, 9 and 10 show the vertical capacity of pile for single-pile and four-pile group for varying settlement for sand, clay and clay–sand medium. It is observed that the pile capacity increases with number of piles irrespective of soil medium and L/D ratio, but the influence of number of pile is very significant in sand medium. Almost three times increase is found on vertical capacity of four pile group compared to single pile; refer Table 3.

4.2 Lateral Load Capacity of Pile

Lateral pile load test for single-pile and four-pile group (2 × 2) was conducted for varying soil medium (sand, clay and clay–sand bed), L/D ratio and number of piles.

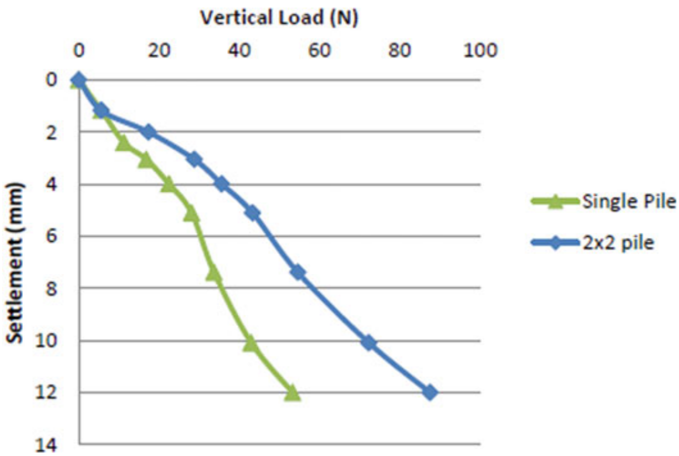

Fig. 8 Vertical load—Settlement curve for number of piles (L/D Ratio = 12) in Sand

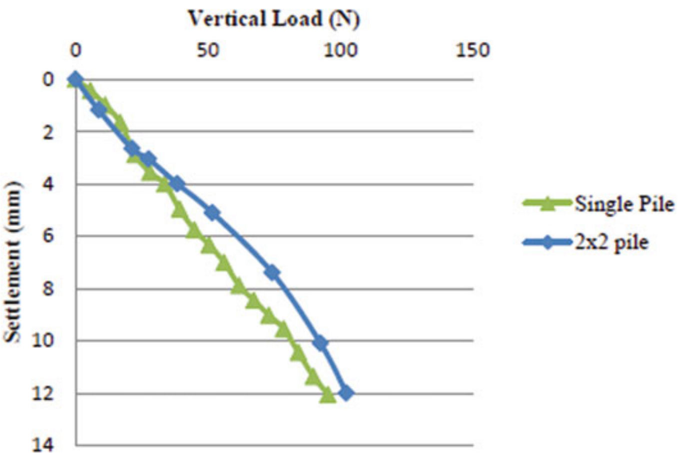

Fig. 9 Vertical load—Settlement curve for number of piles (L/D Ratio = 12) in Clay- Sand Bed

The lateral load is applied independently without vertical load on model pile head, and results are discussed below.

Effect of soil medium. The variation of lateral load capacity with deflection of pile is without any vertical load for varying L/D ratio 12 and 24 for single-pile and four-pile group. The lateral load–deflection curve also did not show a typical parabolic shape with single peak; see Figs. 11 and 12. Hence, the lateral load capacity of pile is considered corresponding to the known deflection of 1.5 mm, 3 mm and 4.5 mm for analysis.

Similar trend of lateral load and deflection curve as shown in Figs. 11 and 12 has been observed in case of clay and clay–sand bed subjected to a pure lateral load.

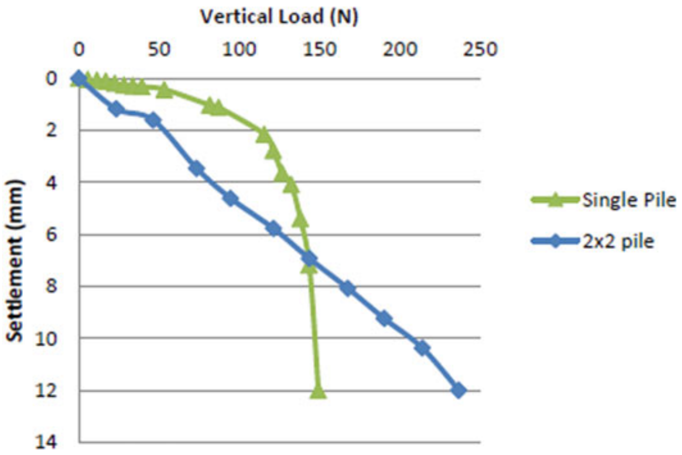

Fig. 10 Vertical load—Settlement curve for number of piles (L/D Ratio = 12)

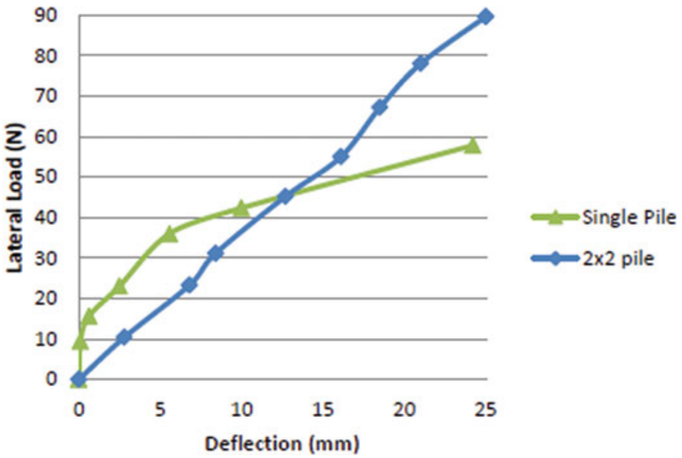

Fig. 11 Lateral load—Deflection curve for varying number of piles (L/D Ratio = 12) in Sand

From Table 4, it is seen that for any given deflection, the lateral load is always higher for sand bed compared to clay bed or clay–sand bed. For L/D = 24, the lateral load capacity of pile is 1.79, 2.3 and 1.4 times higher than that of L/D = 12, respectively for sand, clay and clay–sand medium. However, for single pile with either L/D = 12 or L/D = 24 in sand bed yielded higher lateral load capacity, but considering the rate of increase, in the lateral capacity is high for clay bed compared to sand or clay–sand bed. Similarly, for the four-pile group the lateral capacity of sand bed is always higher irrespective of deflection, L/D ratio and number of piles compared to clay or clay–sand bed.

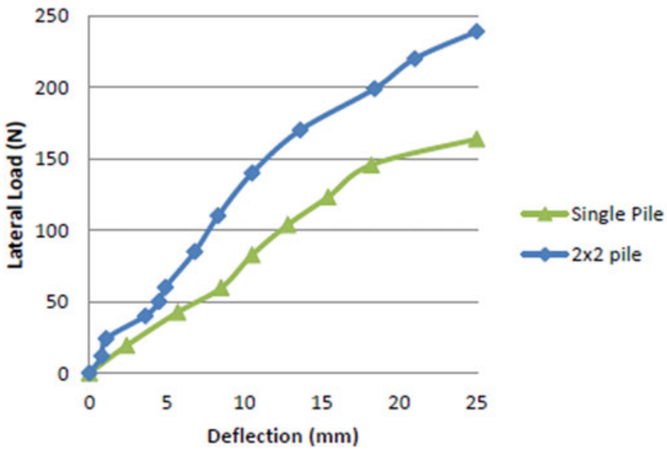

Fig. 12 Lateral load—Deflection curve for varying number of piles (L/D Ratio = 24) in Sand

Table 4 Lateral load capacity of single-pile and 2 × 2 pile group for varying deflection (without vertical load)

Soil medium	L/D ratio	Load, *N*					
		Single pile			2 × 2 pile group		
		1.5 mm	3 mm	4.5 mm	1.5 mm	3 mm	4.5 mm
Sand bed	12	16	25	34	9	13	19
	24	17	22	61	26	39	50
Clay bed	12	6	8	13	5	9	13
	24	14	26	30	15	29	38
Clay–sand layer	12	18	23	29	9	11	15
	24	16	33	42	13	29	41

Effect of number of pile. Table 4 shows the variation of lateral capacity for single-pile and four-pile group for deflection values of 1.5 mm, 3 mm and 4.5 mm with varying soil medium and inferred that the lateral load capacity decreases with number of piles. Similar trend is observed for clay–sand medium irrespective of deflection on L/D ratio. Figure 13 presents the variation of lateral load with number of piles for varying L/D ratio for 4.5 mm deflection. However, the lateral load capacity noted against 25 mm deflection showed a reverse trend; see Fig. 14.

In the case of L/D = 24, the rate of increase in lateral capacity of four pile group is 1.2 to 1.5 times higher than that of single pile and out of which higher value is obtained for sand bed and lower value for clay–sand bed; refer Table 4.

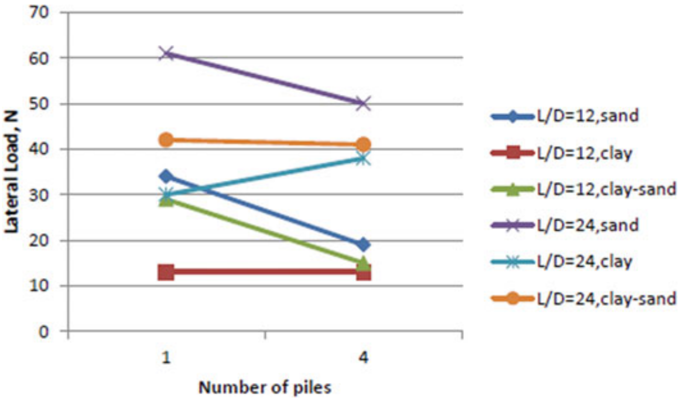

Fig. 13 Lateral Load—number of piles variation of piles for different soil medium and L/D ratio for 4.5 mm deflection

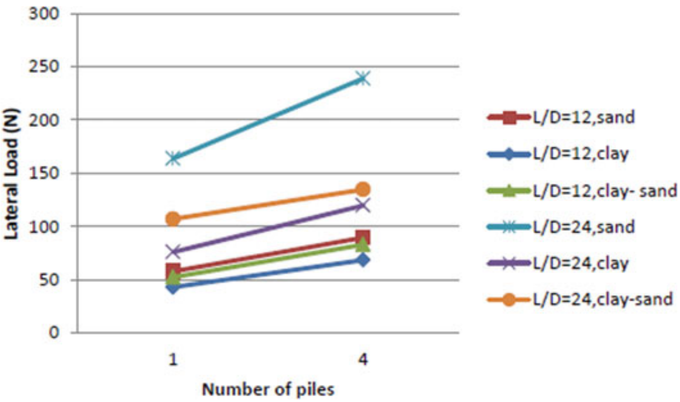

Fig. 14 Lateral Load—number of piles variation of piles for different soil medium and L/D ratio for 25 mm deflection

4.3 Lateral Load Capacity of Piles Under the Influence of Vertical Load

In order to find the influence of ultimate vertical load on the lateral load capacity, lateral load tests were conducted for varying L/D ratio, number of piles and soil medium, keeping the vertical load as that of ultimate vertical failure load. From Table 5, it is evident that, for single pile irrespective of soil medium, the lateral load increases with L/D ratio for any given deflection value, under the influence of ultimate vertical load. But, the lateral load decreases with increasing number of piles only for clay medium and that too for L/D = 24 at 4.5 mm deflection. Further, lateral load is almost higher for clay layer with number of piles for L/D = 12 at

Table 5 Lateral load capacity of single-pile and 2 × 2 pile group for varying deflection, L/D ratio and soil medium under the influence of vertical loading

Soil medium	L/D ratio	Load, *N*					
		Single pile			2 × 2 pile group		
		1.5 mm	3 mm	4.5 mm	1.5 mm	3 mm	4.5 mm
Sand bed	12	7	16	19	15	37	49
	24	25	29	41	22	43	52
Clay bed	12	12	17	23	9	11	24
	24	25	30	36	12	19	25
Clay–sand layer	12	7	14	18	9	22	36
	24	24	28	32	19	27	42

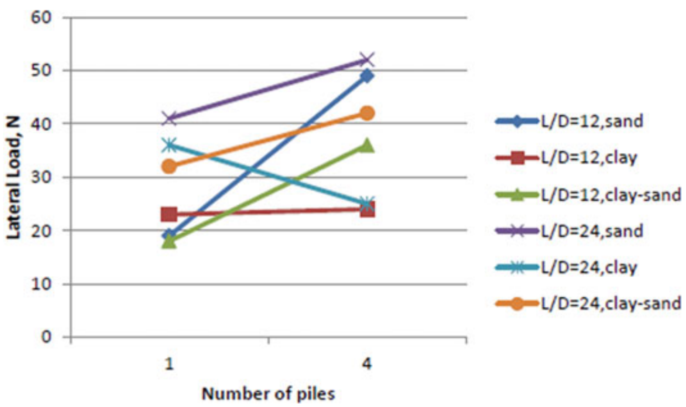

Fig. 15 Variation of Lateral Load – Number of piles for different soil medium and L/D ratio at 4.5 mm deflection

same deflection. But, in all the other cases, there is a considerable increase in lateral capacity irrespective of L/D ratio and soil medium. This could be due to the fact that the shaft resistance would have mobilized under the influence of vertical load and consequence of which the lateral load did not show progressive change on lateral capacity (Fig. 15).

4.4 *Comparison of Experimental and Theoretical Values of Ultimate Vertical Load Capacity of Single Pile in Sand, Clay and Clay–Sand Bed (for 12 mm Settlement)*

The theoretical ultimate vertical load capacities of single pile embedded in sand, clay and clay–sand bed computed based on IS 2911—part 1/ Section 1 (2010) clause

6.3.1.1 are 2.5 to 5 times lesser than that of experimental ultimate vertical load capacity of short pile and 1.5–5 times lesser than that of experimental ultimate vertical load capacity of long pile.

4.5 Comparison of Experimental and Theoretical Values of Lateral Load Capacity of Single Pile in Uniform Sand and Clay (for 1.5 mm, 3 mm and 4.5 mm Deflection)

The theoretical ultimate lateral load capacities of single pile embedded in sand bed computed based on Brom's (1965) method are 4–8.5 times lesser than that of experimental ultimate lateral load capacity for both short and long piles. Similarly, for clay bed the theoretical ultimate lateral capacity is 20 to 43 times lesser than that of experimental ultimate lateral load capacity for both short and long piles.

5 Conclusions

Based on the analysis of vertical, lateral and combination of vertical and lateral load test results of model piles for varying L/D ratio, number of piles and soil medium, the following general conclusions are drawn.

- Vertical load capacity of pile increases with number of piles, L/D ratio predominantly for sand bed compared to clay bed or clay-sand bed for a given settlement.
- Lateral load capacity of pile increases with L/D ratio irrespective of sand, clay and clay–sand medium for a known deflection. However, the lateral capacity decreases with number of piles when deflection is less than 4.5 mm and the same increases with number of piles corresponding to 25 mm deflection.
- The vertical and lateral load capacity of piles embedded in clay–sand layer gives 1.4–2.7 times higher than that of the vertical and lateral load carrying capacity of piles embedded in uniform clay bed.
- Under the influence of ultimate vertical load, the lateral capacity of single pile decreases compared to the case of lateral capacity of piles without any vertical load irrespective of settlement, whereas in case of pile group the lateral capacity decreases at specified settlement values.
- The effect of combined loading on lateral response of the piles is more pronounced in uniform clay bed rather than sand bed or clay–sand bed.

References

1. Karthigeyan, S., Rajagopal, K.: Lateral Response of 2 × 2 pile group under combined axial and lateral loading. In: International Geotechnical Conference, pp. 665–669 (2009)
2. Miyamoto, Y.: Pile response during earthquake and performance evaluation of pile foundation. Kobori Research Complex, Kajima Corporation, Tokyo, Japan, pp. 01–09 (2000)
3. Rajagopal, K., Karthigeyan, S.: Influence of combined vertical and lateral loading on the lateral response of piles. International Association for Computer Methods and Advances in Geomechanics (IACMAG), pp. 3272–3282 (2008)
4. Zamri, H., Chik, Jasim, M., Abbas, Taha, M.R.: Lateral behavior of single pile in cohesionless soil subjected to both vertical and horizontal loads. Eur. J. Sci. Res. **29**, 194–205 (Research Gate) (2009)
5. Zhang, H.H., Small, J.C.: Analysis of capped pile groups subjected to horizontal and vertical loads. Comput. Geotech. 01–21 (2000)