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ORIGINAL PAPER

Behaviour of Cyclic Laterally Loaded Pile Group in Soft Clay

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Abstract The capacity of laterally loaded piles is mainly governed by the strength of soil at the proximity of top level of the piles. In coastal areas, the topsoil mostly comprises of soft clay and they extend for a considerable depth, offering low resistance against lateral loads. In addition to static loads, the piles are subjected to cyclic loads. Experimental study of single pile and pile group for varying *L*/*D* ratios, number of piles in a group and spacing between the piles under static and cyclic lateral load is studied. Cyclic lateral load tests were conducted for *L*/*D* ratios of 12, 18 and 24 under cyclic load ratio of 0.6. Cyclic load tests were performed by embedding the piles in a clay bed of consistency 0.2. The experimental results showed that for pile of *L*/*D* ratios the 12, 18 and 24 displacement at pile head becomes nearly constant after 300 hundred cycles. From the pattern of displacement versus number of cycles, it is observed that shorter piles exhibit higher magnitudes of displacement compared to longer piles upon cyclic loading. However, longer piles show higher rate of increase in displacement with number of cycles compared to shorter piles.

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Keywords Static lateral load · Cyclic lateral load · *L*/*D* ratio · Number of piles in a group · Pile spacing

Introduction

The structural members are often subjected to considerable lateral forces such as wind loads in hurricane-prone areas, earthquake loads in seismic areas and wave loads in offshore environments. Lateral load is also due to impact of ship, during berthing and wave action in the case of offshore structures. Pile supported foundation of earth retaining and transmission tower structure is also subject to lateral loads. Soil–structure interaction is the mechanism that governs pile response behaviour and capacity of the structure to the applied loads. The behaviour of static laterally loaded pile in horizontal ground is well studied by subgrade reaction method, elasto-plastic method, *p*-*y* curve method and elastic continuum method. Out of which *p*-*y* curve method is used widely.

The study of static laterally loaded pile is initially studied by Brom's [1] and proposed that the ultimate resistance of cohesionless soil is equal to three times the Rankines passive pressure. Matlock [2] proposed the classic *p*-*y* curve method for both cohesion and cohesionless soil under static and cyclic lateral load. Poulos [3] studied the behaviour through elastic theory to analyse the displacements, rotation and moments in a pile subjected to horizontal load and moment.

The study of cyclic laterally loaded pile was triggered with emerge of offshore structures. Pile foundations of marine structures viz., offshore platforms and jetties, are subjected to significant amount of cyclic lateral loads. Poulos [4] analysed and presented an elastic-based analysis of a statically loaded pile, which used total stress approach to incorporate the effects of cyclic loading. He observed that the ultimate load capacity and cyclic stiffness decrease with increase in number of cycles '*N*' and with increasing cyclic load level.

Brown et al. [5] conducted static cyclic lateral load tests for pile group in large scale. The soil resistance due to static and cyclic loading was found. Under two-way cyclic loading, the failure of piles was mainly due to degradation of skin friction. The amount of degradation due to cyclic loading depends on the cyclic displacement, the number of cycles, the soil type and type of pile [6]. From a series of full-scale test by Todd et al. [7], the threshold deflection below which cyclic soil degradation would not occur was observed for cyclic lateral load for varying diameter. The degradation was caused by the gap formation, which is intensified by hydraulic scour.

Under cyclic loading of rigid piles, cyclic load levels greater than 50% of static lateral capacity, deflection to increase enormously with number of cycles. They reported that the post-cyclic behaviour under static load could improve for cyclic load levels less than 40% of static lateral capacity [8]. The deterioration of soil–pile interaction under lateral cyclic loading [9], the quasi-static nature of loading induces considerable deterioration in the interactive performance of soil–pile system. With increase in cyclic load level and cyclic displacement level, the degradation factor was observed to decrease nonlinearly.

A full-scale test followed by 3D FEM analysis revealed that the lateral load-carrying capacity of the single and group pile reduces when it is subjected to cyclic loading compared to static loading due to degradation of soil stiffness [10]. The critical spacing between the pile in a group under cyclic loading which depends upon its configuration is found to be 7D, and the deflection of closely spaced pile groups is five times more than the widely spaced pile group [11].

The failure mechanism of pile under static lateral load was studied widely and behaviour of cyclic lateral load for single and group pile is less. Hence an study was attempted to understand the influence of embedded length and number of piles in a group subjected to static, cyclic and post cyclic- static lateral load for single and group pile.

Experimental Investigation

Soil sample collected from Siruseri, Chennai, India, was used in all the experiments. An open pit was dug in the site, and bulk sample was collected. The collected sample was then air-dried, powdered and passed through sieve to carry out respective experiments.

Properties of Soil

To characterize the soil, various experiments are conducted and it comprises of 30% sand, 26% silt and 44% clay. The soil exhibits liquid limit of 60%, plastic limit of 28.6% and plasticity index of 31.4%. As per ASTM-2487 [12] soil classification system, the soil is classified as clay of high plasticity (CH). The soil posses shear strength of 5 kPa at soft soil consistency of say 0.2, and this soft consistency was maintained throughout the experiments.

Experimental Programme

1 g model test was carried out in laboratory to study the behaviour of static and cyclic lateral load of single and group pile embedded in soft clay [13]. The effect of embedded pile length, number of piles in a group and spacing between the piles are the varied parameters involved in this study. Table 1 summaries the variables considered in the present study.

Experimental Set-up and Preparation of Clay Bed

A steel circular tank of diameter 400 mm and height 500 mm was used in the experiments which are free from side wall effects. Hollow aluminium piles with an outer diameter (*D*) of 18 mm and thickness of 1 mm plugged at the end was used. The length to diameter ratio (*L*/*D*) of the piles of 12, 18 and 24 was selected to understand the behaviour of both short rigid piles, intermediate piles and long flexible piles [1].

A steel pile cap of 6 mm thickness with 18 mm (diameter of pile) hole is drilled to fix the pile to ensure the fixity condition in its head, and the lateral load is applied in a direction perpendicular to the line joining the piles, and it is known as parallel arrangement [14]. For pile group of 2.5D, 4D and 6D spacing, pile group length is 81mm, 108mm and 144 mm, respectively.

Experiments were conducted in a homogeneous clay bed of consistency 0.2. The required quantity of air-dried clayey soil was blended with the predetermined water content to achieve the consistency of 0.2. After conditioning the required quantity of soil, it was kept for 2 days before placing in the tank to test. Enough care was taken to control the moisture at the desired consistency in all cases. The conditioned soil was mixed thoroughly and filled in the tank in layers from the bottom of the tank up to the desired elevation by adopting kneading compaction technique. The pile was then placed vertically in position, and preparation of clay bed was continued till the top level of the tank, which represents non-displacement pile.

Table 1 Parametric study with notations

Parameter	Variable
Embedded length (*L*/*D*)	12(*P*1),18(*P*2) and 24(*P*3)
Number of piles	Single, two(*G*1) and four(*G*2) group
Spacing between piles	2.5D (*S*1), 4D (*S*2) and 6D (*S*3)

L Length of the pile, *D* Diameter of the pile

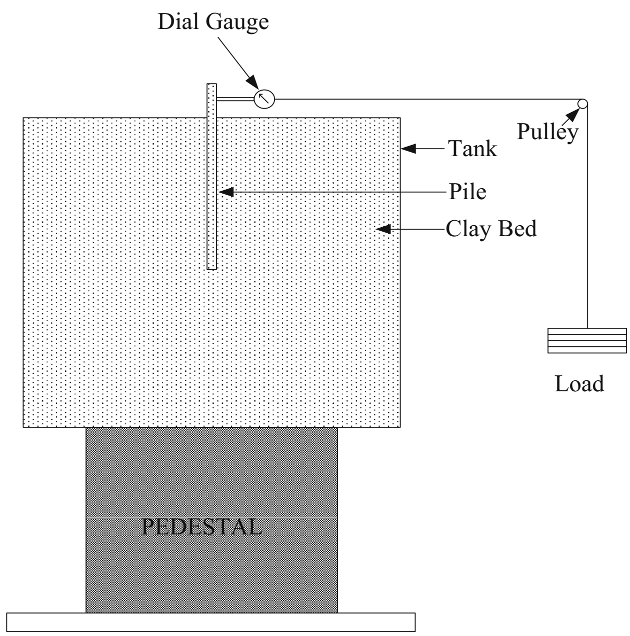

Fig. 1 Schematic representation of static lateral load experimental set-up

Loading System

Static Loading

Figure 1 shows the schematic representation of static lateral load test. The pile was connected to loading frame using high-tension wire through a pulley arrangement. A dial was fixed at the pile head to measure the deflection. Once the pile is fixed, it was loaded laterally at equal load increments. After each loading, the lateral displacement of pile was measured. Each increments load was maintained constant until the rate of displacement is less than 0.002 mm in 10 min or until 30 min has elapsed, whichever occur first. The load at which the load–displacement curve becomes asymmetric to displacement axis is taken as ultimate lateral load [15].

Cyclic Loading

In order to facilitate cyclic loading, the cyclic load ratio was found.

$$\text{Cyclic load ratio(CLR)} = \frac{\text{Cyclic load}}{\text{Static load}}$$

The cyclic load ratio is taken as 0.6 in all experiments. Static load is taken as the ultimate load from load–displacement curve and the cyclic load was found. A time-controlled motor was used to stimulate five cycles (two-way cyclic loading) per minute.

The following step by step procedure discusses the cyclic loading pattern,

Step 1: Initially, the pile was loaded equally on both the hangers using high-tension wire by hanging it inside the empty bucket (1 and 2), which had a motor inside. As load on hangers were same and they were hanging in air, the net load acting on the pile was zero.

Step 2: Both the buckets (1 and 2) were partially filled with water so that the hangers were not immersed, maintaining the step 1 loading condition.

Step 3: Once the circuit was switched on, the motor in bucket 2 sucks the water from the bucket 1 and delivers to the bucket 2 by a pipe connected between the buckets in bottom for about 6 s. This leads the hanger in bucket 2 is immersed in water and buoyant force reduces the load on this hanger. In this condition, the net lateral load acting on the pile is equal to the buoyant force and pile moves laterally towards the hanger loaded in air simulating one-way cyclic load (Fig. 2a).

Step 4: After the sixth second, the motor in bucket 1 sucks the water from bucket 2 and delivers the water to bucket 1 for another 6 s. This makes the hanger, which was immersed in water hangs in air, and the other side is immersed in water; now the net lateral force acting on the pile is equal to buoyant force. The pile deflects laterally towards the hanger loaded in air, which is in opposite direction compared to the previous direction of deflection (Fig. 2b). To complete one two-way cyclic loading time required was 12 s and pile was subjected to five cycles of loading in a minute.

Step 5: Step 3 and 4 were repeated several times to subject the pile to require number of cycles of lateral load. Under each loading, the deflection at the pile head was noted using dial gauge at predetermined time intervals.

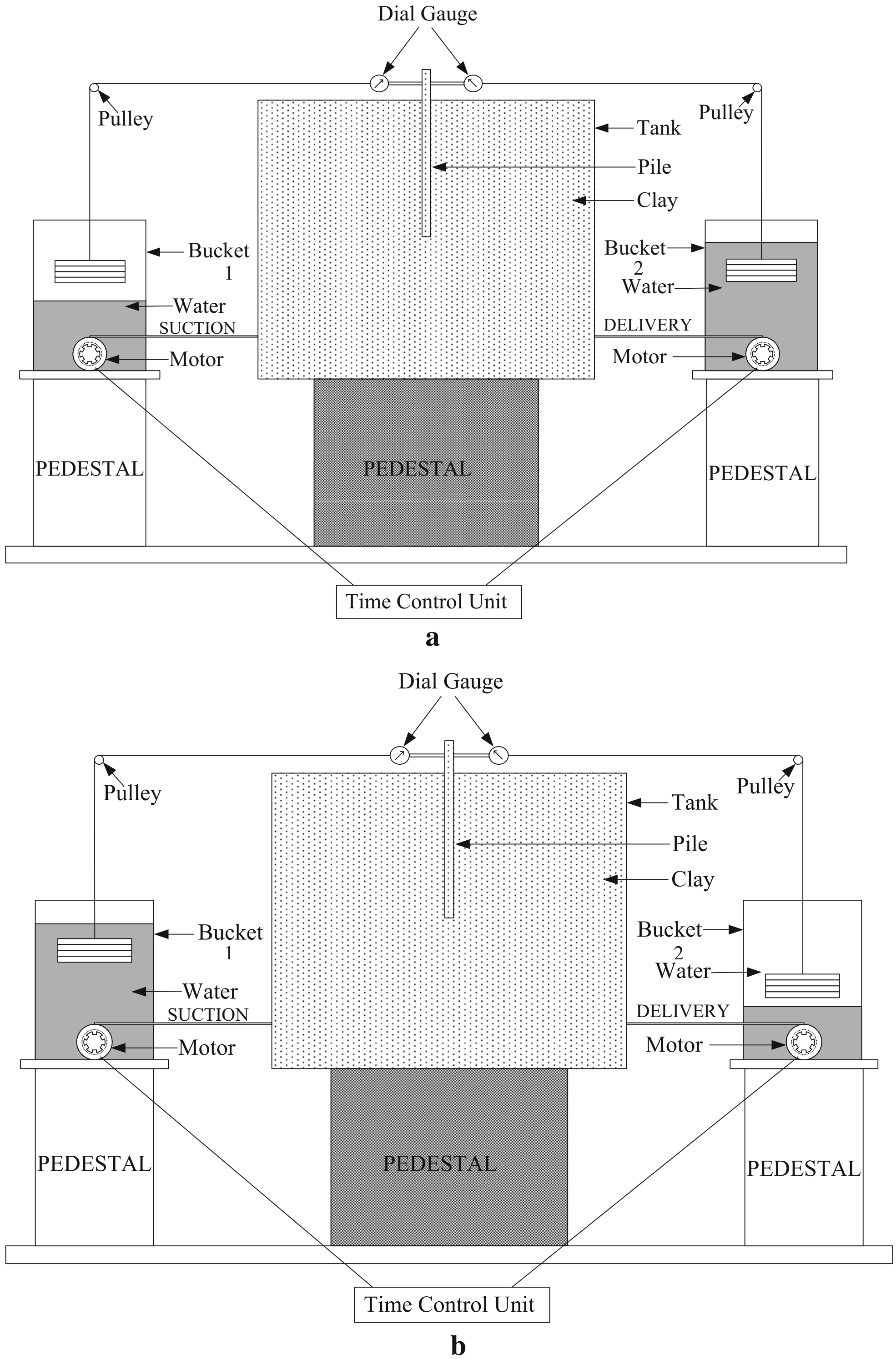

Fig. 2 Schematic representation of cyclic loading system. **a** Step 3, **b** Step 4

Results and Discussion

Effect of *L/D* Ratio

Initially, static lateral load tests were performed to find the ultimate lateral load of single and group pile. Ultimate capacity for different *L/D* ratios and different pile group is presented in Table 2. It is observed that, with increase in *L/D* ratio for single pile, the lateral load capacity of single pile increases linearly (Fig. 3). This is mainly due to behaviour of pile from short rigid to long flexible pile.

For a pile of *L/D* ratio 12, the static pile capacity is 47.2 N. Cyclic load corresponds to CLR of 0.6 is 28.32 N and for *L/D* = 18 and 24, it was 39.24 and 48.9 N, respectively [16]. Figure 4 plots the displacement at pile head for two-way cyclic loading. The displacement of pile at every 25 cycles was noted, the pile deflects in the direction of loading and a gap is formed behind the pile extending to some depth. When the direction of loading is reversed there is a considerable reduction in resistance. Because of this, the deflection of the pile is slightly increased for subsequent loading. For cyclic load ratio of 0.6, the major portions of the displacement are observed as elastic and hence there is only slight reduction in resistance during cyclic loading. Because of this, the deflection is observed to become constant after three hundred cycles. In Table 3, the maximum displacements of single and group pile are listed.

The post-cyclic static behaviour of the pile was found after 400 cycles of loading, in which the static load is applied in increment and the corresponding displacement at pile head is measured. Same criterion as that for static loading is followed in this case as well to apply the next load increment. Table 4 shows the post-static cyclic lateral load for various conditions. The post-cyclic static response of pile is in Fig. 5. For the single pile of *L/D* ratio 12 the post-cyclic static capacity is 1.34 times as that of static capacity. For pile *L/D* ratio 18 and 24 the post-cyclic static capacity is 1.10 and 1.15 times as that of static capacity. It is also observed that with increase in embedment length the displacement reduces.

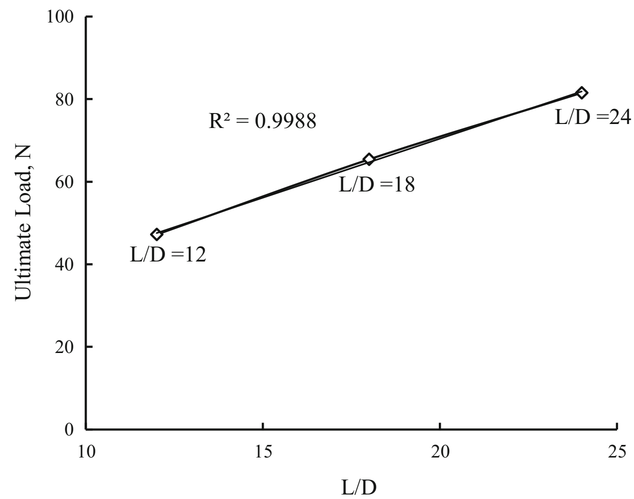

Fig. 3 Variation of static ultimate lateral load of pile with varying *L/D* ratios

Effect of Spacing

Under static loading, with increase in spacing the lateral load carried by the pile increases (Fig. 6). The capacity of pile with *L/D* = 12 increases about 9.23%, 30.59% and 36.64% for pile group of 2 with 2.5D, 4D and 6D spacing, respectively, when compared with single pile: it gets narrowed with increase in *L/D* ratio. The increase in capacity of pile group with increase in spacing is because of the shadowing effect [17].

Single pile with all varying *L/D* ratios; show the maximum displacement at pile head during cyclic loading. There is decrease in displacement in the pile head with increase in spacing between the piles in the group. The main reason behind this reduction is the reduction in passive force that results in creating a gap between the pile and the soil that leads to increase in pile group displacement. The formation of gap decreases with increase in spacing; which in turn reduces the displacement of pile group (Fig. 7).

The post-cyclic static behaviour of pile shows increase in lateral load with increase in spacing (Fig. 8). Increase in

Table 2 Ultimate lateral load for different *L/D* of various pile group and spacing

L/D	Ultimate lateral load (N)						
	Single	Two-pile group			Four-pile group		
		2.5D	4D	6D	2.5D	4D	6D
12	47.2	52	68	74.5	107.2	117	131.4
18	65.4	85	105.8	113.26	150	166.7	179
24	81.5	101.5	129.34	150	168	186	229

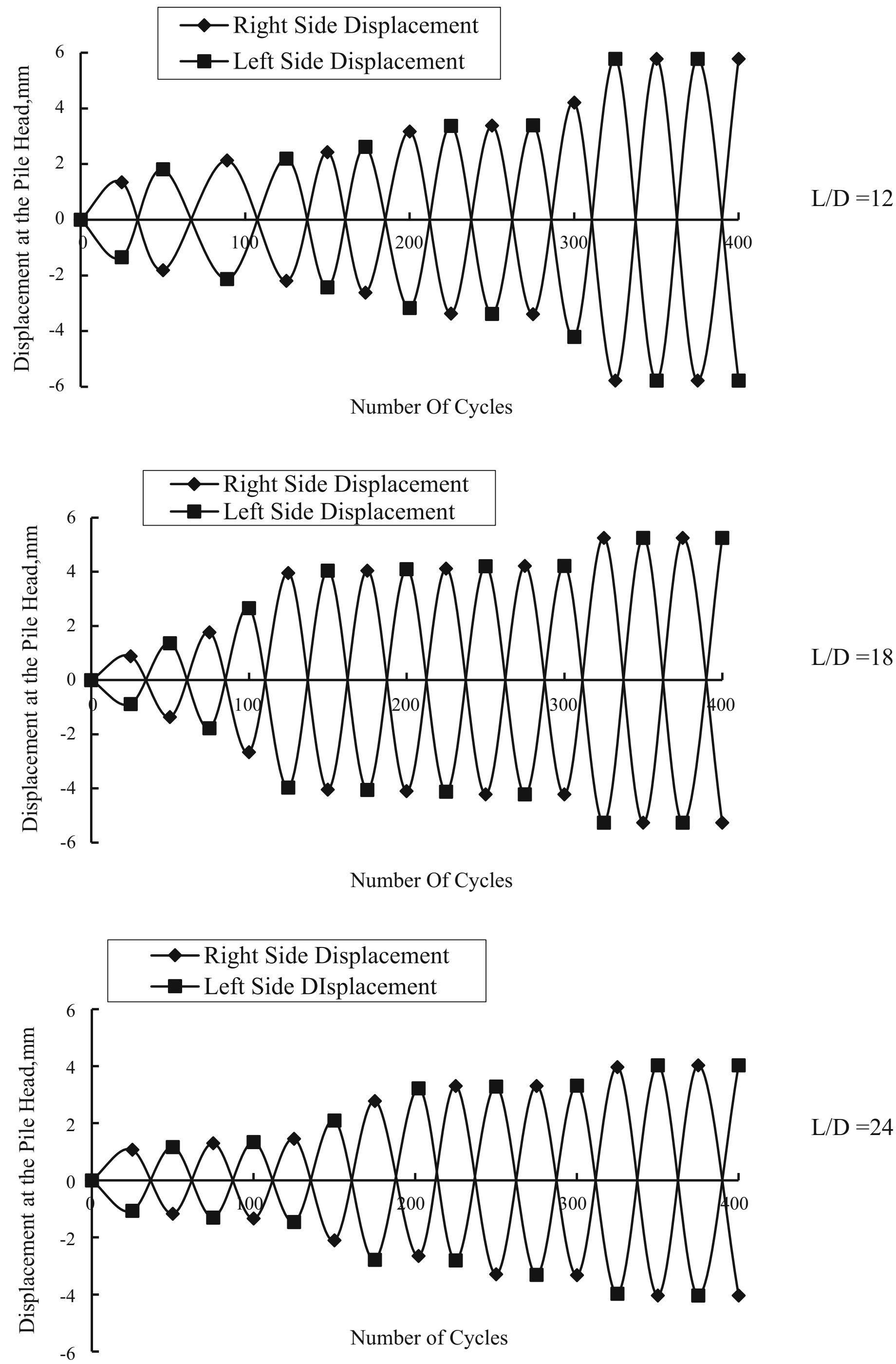

Fig. 4 Displacement of single pile under cyclic load for different *L*/*D* ratios

spacing results in increase in capacity till 6D spacing even in post-cyclic loading (Fig. 9).

Effect of Number of Piles

With increase in number of piles from single to four piles in a group, the capacity almost increases linearly (Fig. 10). From Fig. 11, it is observed that the average load carried by each pile in the pile group was lower than that of single pile for the same deflection [18]. However, in the laboratory tests, no special arrangement was made to measure the individual load-carrying capacity of pile in a group to show the individual load-carrying capacity of a pile in group. Group efficiency of the pile decreases with increase in number of piles and *L*/*D* ratio in a group (Fig. 12).

Similarly, cyclic lateral load tests were also carried out for the similar parameters. The displacement of single pile

Table 3 Displacement at the pile head under cyclic loading

L/*D*	Displacement at the pile head (mm)						
	Single	Two-pile group			Four-pile group		
		2.5D	4D	6D	2.5D	4D	6D
12	5.78	2.34	2.02	1.78	1.57	0.75	0.2
18	5.26	1.78	1.51	1.1	1.21	0.42	0.18
24	4.03	1.02	1.24	0.842	0.75	–	–

Table 4 Post-cyclic static capacity of the pile

L/*D*	Post-cyclic static lateral load capacity (N)						
	Single	Two-pile group			Four-pile group		
		2.5D	4D	6D	2.5D	4D	6D
12	63.44	89	92.34	128.72	123.62	132.18	147.87
18	72.16	130.56	135	149	138	148.48	178
24	93.78	144.16	149.34	154	152	–	–

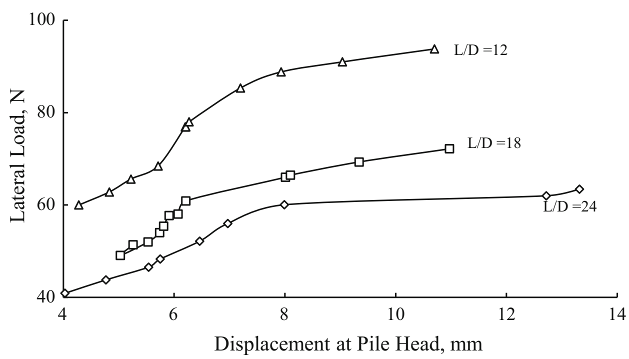

Fig. 5 Post-static cyclic load behaviour of single pile

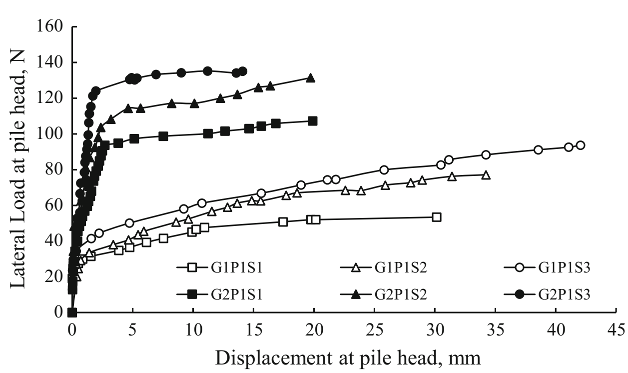

Fig. 6 Influence of pile spacing in static lateral load capacity of pile groups with *L*/*D* = 12

is higher than any other pile group of varying *L*/*D* ratios. When comparing the displacement of single pile with two-pile group, the decrease is about 65% on an average for *L*/

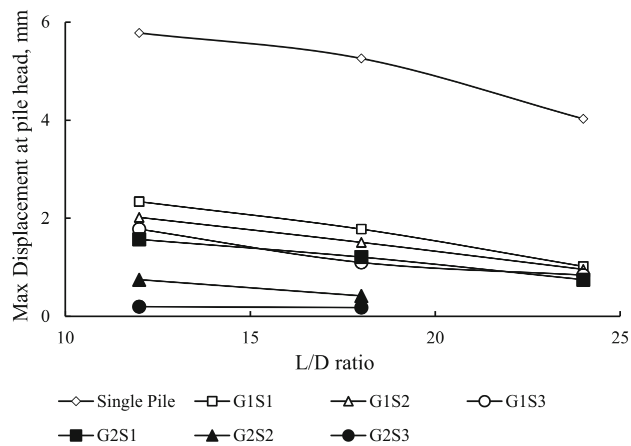

Fig. 7 Reduction in displacement due to increase in spacing between piles in a pile group

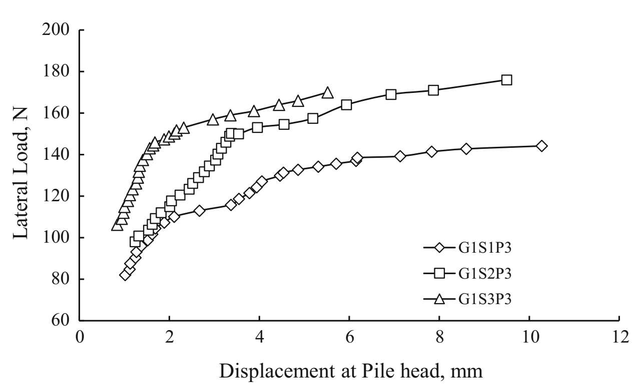

Fig. 8 Load–displacement behaviour of pile group during post-cyclic loading

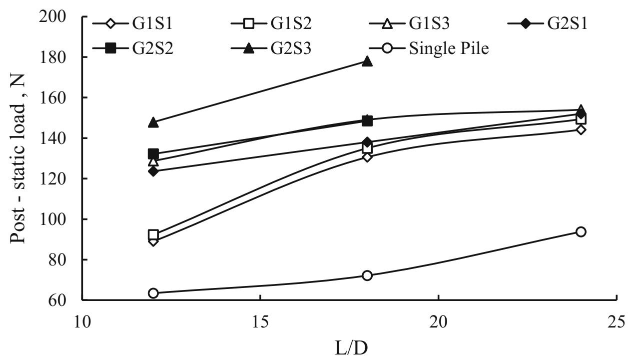

Fig. 9 Post-cyclic load for piles with different *L/D* ratios

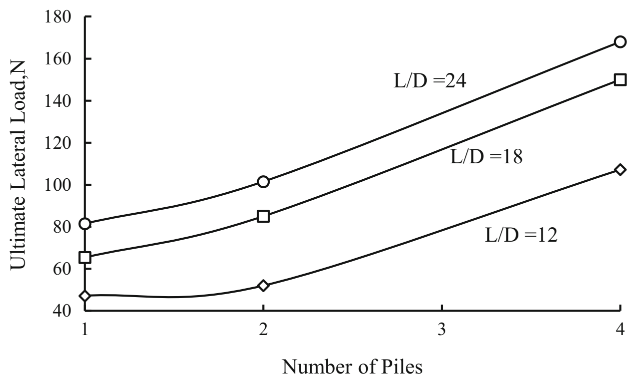

Fig. 10 Static lateral load with increase in number of piles (Spacing = 2.5D)

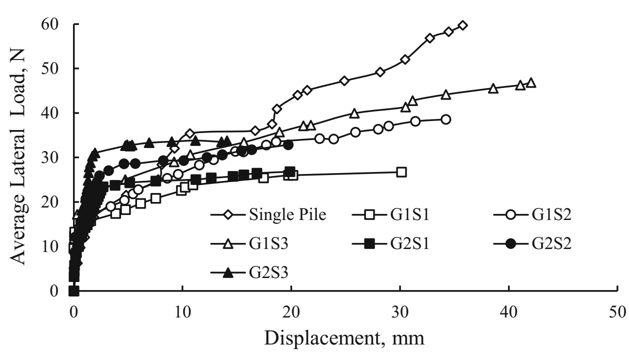

Fig. 11 Single and group pile behaviour (*L/D* = 12)

D ratio of 12; whereas the behaviour of intermediate and long pile, the increase in reduction is observed to be only 10% higher than the short pile. For a four pile group, the reduction in displacement is about 85% on average. The reduction in displacement is mainly due to increase in the inertial force. The inertial force is high for four piles when compared to two-pile group and single pile: this tends the single pile to displace more (Fig. 13). The same was inferred by Rollins and Ryan [19] that with increase in cyclic loading, the passive force degrades and this decrease in passive force leads the pile to displace more.

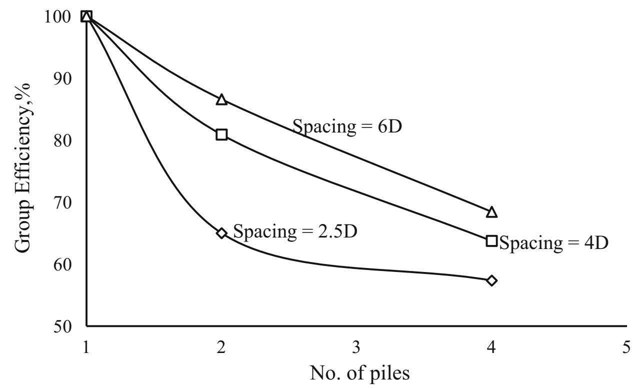

Fig. 12 Group efficiency for group pile (*L/D* = 18)

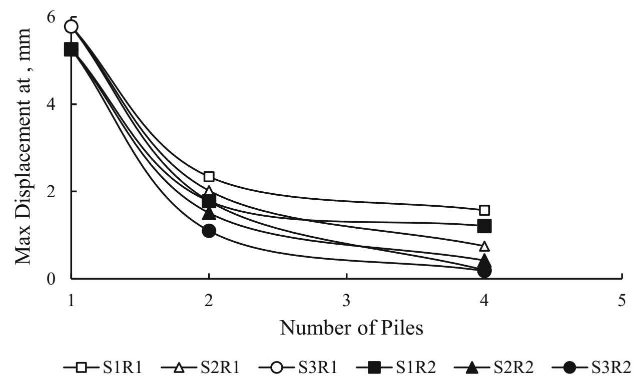

Fig. 13 Effect of increase in number of piles on displacement upon cyclic loading for *L/D* = 12 and 18

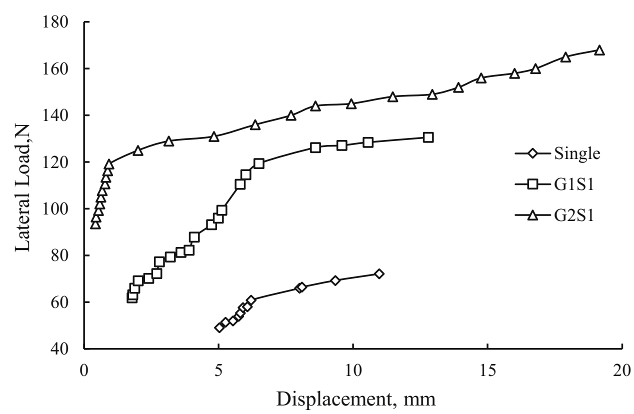

Fig. 14 Post-cyclic behaviour of single and pile group (*L/D* = 18)

In post-static testing, the load-carrying capacity of the pile group increases with increase in number of piles just like any other pile group behaviour under static loading (Fig. 14).

The overall graph between lateral load (static and post-cyclic static) and *L/D* ratio for various conditions is given in Fig. 15. It is observed that the post-static cyclic load is more than the static lateral loaded. For a two-pile group,

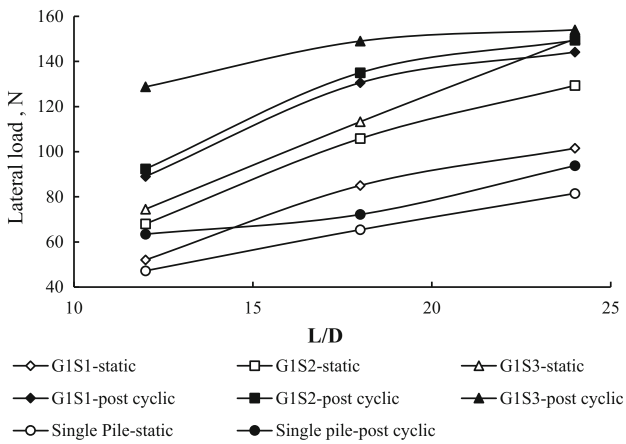

Fig. 15 Ultimate static versus post-cyclic load for different *L*/*D* ratios of piles

the capacity increases on average of 1.4 of static load and it is 1.02 times for four-pile group.

Conclusions

In the present study static, cyclic and post-cyclic static lateral loads tests were conducted in the laboratory by considering various parameters. The following inferences are made from the study,

1. With increase in *L*/*D* ratio from 12 to 24, the ultimate lateral load capacity of the pile increases linearly by 72.6%.
2. With increase in spacing and number of piles in a group, the lateral load capacity increases.
3. The group pile capacity increases greater for short piles due to the increase in stiffness when compared to long pile.
4. In cyclic loading, the displacement decreases with increase in *L*/*D* ratio, spacing and number of piles.
5. The static load-carrying capacity of pile after post-cyclic test, increases with increase in *L*/*D* ratio, number of piles and spacing.
6. In most cases, post-cyclic static capacity of pile group is higher than the static capacity of single and pile group.

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