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Factors Influencing the Behaviour of Flexible Pile Groups Under Lateral Loading in Soft Clay

G. Kesavan[1] · S. S. Chandrasekaran[1]

Abstract Experimental investigation is carried out to study the lateral load–deflection and bending behaviour of model flexible pile groups embedded in soft clay. The effects of embedment length of pile, magnitude of applied lateral load, size of group, row and column wise position of piles in the group, cyclic loading and presence of vertical loading on lateral response of pile group are evaluated. Results from the tests reveal that flexible piles subjected to lateral load greater than about 60 % of ultimate lateral load cannot be considered as flexible. Maximum bending moment of front row pile of 3 × 3 group is about 16 % higher than that of middle row pile. Within the same row piles, corner pile has about 10 % higher bending moment than that of middle pile. Maximum bending moment in pile subjected to 15 cycles of loading is about 80 % higher than that for static loading. The lateral capacity of the 3 × 3 pile group with 60 % of ultimate vertical load is about 18 % less than that of the pile group with no vertical load.

Keywords Lateral load · Flexible · Pile group · Soft clay · Bending moment

Introduction

Pile foundations are used to support structures when the bearing capacity of the soil is low or magnitude of load on structure is high. Piles are used in groups in most of the industrial applications [5, 20, 24]. More than hundred piles are normally used in a group to support very heavy industrial structures like coke chamber in petroleum refinery. Lateral loading on piles are of active or passive type. The lateral response of pile groups is complex as it depends on various factors [7–9, 22, 23]. Few studies have been reported on the lateral behaviour of full scale pile groups in clay [4, 14, 21, 22]. Model tests carried out so far were of centrifuge model tests [10, 25] and 1-g model tests [5, 6, 20].

Studies on bending behaviour of pile groups in soft clay under lateral loading are very limited. Many studies report on the behaviour of either rigid or intermediate piles whereas majority of the piles in practice are flexible [18]. Studies on behaviour of flexible piles in group are scanty. In many practical applications, pile groups are often subjected to simultaneous vertical and lateral loads [1, 12, 13]. Experimental investigations on the influence of vertical loads on lateral response of pile groups in clay are sparse.

In the present experimental study, the effects of embedment length of pile, magnitude of applied lateral load, size of group, row and column wise position of piles in the group, cyclic loading and presence of vertical loading on lateral load–deflection and bending behaviour of flexible pile groups embedded in soft clay are investigated.

Experimental Programme

Properties of Soil

In the present experimental investigation, the clay sample collected from Kanchipuram near Vellore in Tamilnadu state of India is used. The properties of the clay are: liquid limit = 53 %, plastic limit = 24 %, plasticity index = 29 %

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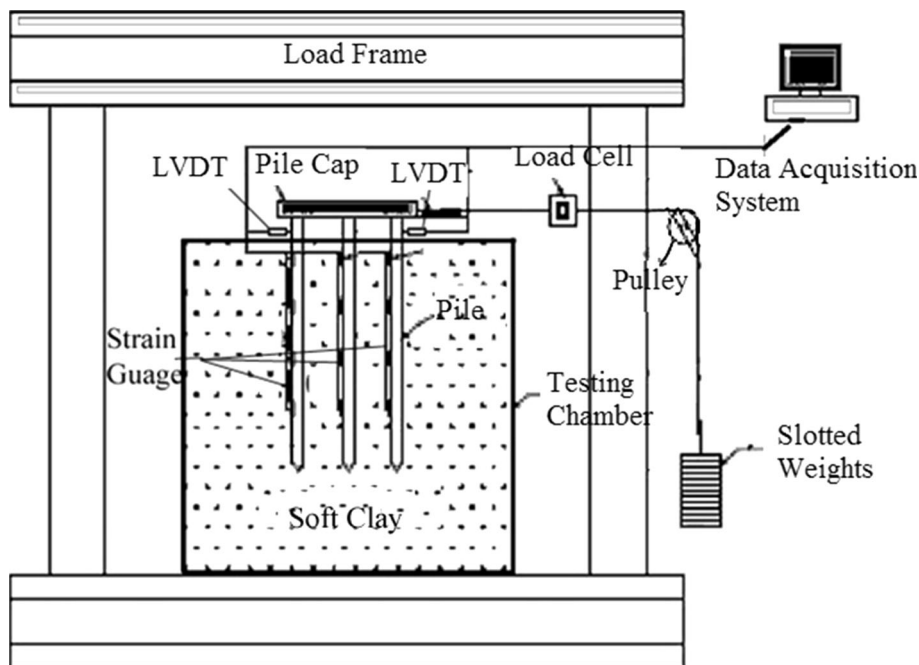
Fig. 1 Schematic diagram of the test arrangement

and undrained shear strength at soft consistency (consistency index of 0.32) = 8 kPa. As per Unified Soil Classification System, the soil is classified as fat clay (CH) [2]. Particle size distribution test by wet sieve analysis and sedimentation analysis were conducted. The percentage of the clay content is 46 %.

Model Pile

Model pile made of aluminium tube having outer diameter of 19.6 mm, wall thickness of 1.2 mm and internal diameter of 17.2 mm is used in the present study. This model pile with a length scaling factor [26] of 1/10 simulates a prototype pile of 350 mm diameter solid section made of reinforced cement concrete (RCC) having compressive strength of 30 N/mm² [11]. Scaling law proposed by Wood et al. [26] has been used to select model pile dimensions that simulate the prototype RCC pile having 350 mm diameter. The model pile is of hollow section made of aluminium having outer diameter (d_o) 19.6 mm and internal diameter (d_i) 17.2 mm. Scaling law (Wood et al. [26])

$$\frac{Em\ Im}{Ep\ Ip} = \frac{1}{10^5} \qquad (1)$$

where Em = Young's modulus of model pile (70 Gpa), Im = Moment of inertia of model pile ($\pi/64\ (do^4 - di^4) = 2948\ mm^4$), Ep = Young's modulus prototype pile = $5000\ \sqrt{f_{ck}} = 27{,}386\ N/mm^2$ (compressive strength of concrete $f_{ck} = 30\ N/mm^2$), Ip = Moment of inertia of prototype pile.

Aluminum plate of 10 mm thick is attached at the pile top located 100 mm above ground surface. Tests are conducted with free head condition of pile.

The model piles are instrumented with electrical resistance strain gauges along their length to study the bending behaviour. Foil type electrical strain gauges having resistance of 120 Ω are used in quarter bridge arrangement along the pile length. The strain gauges were placed in the tension face of the pile and the strain has been measured in the same direction where the strain gauges placed. The suitable locations for strain measurement were marked on the cleaned surface of the model pile. The strain gauges were fixed at the marked locations using adhesive (HBM-Z70). Lead wires were attached to the strain gauges using printed circuit boards. The resistance of strain gauges before and after pasting to the pile is checked using multimeter. Thin coating of viscous putty (HBM-AK22) was applied over strain gauges to make it water proof.

Experimental Setup and Procedure

The schematic sketch of the test setup is shown in Fig. 1. Tests are conducted on pile groups embedded in clay in rectangular test chamber of 1.2 m length, 0.7 m breadth and 1.2 m height. Clay bed is prepared as per the procedure adopted by Chandrasekaran et al. [5]. The clay was mixed in separate chamber with required amount of water (water content w = 43.5 %) to get the required consistency (Ic = w_L − w/Ip = 32 %) of clay. The soil was allowed to saturate for 2 days. After placing the model pile in the centre
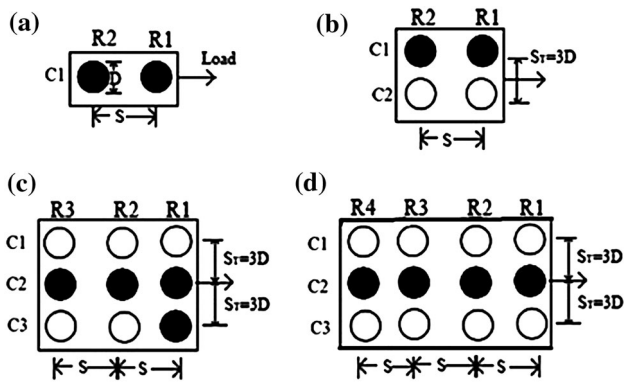
Fig. 2 Configuration of pile groups: a 1 × 2 group, b 2 × 2 group, c 3 × 3 group and d 3 × 4 group. *Filled circles* instrumented pile. S, spacing of piles in the direction of loading; D, diameter of piles; S_t, transverse spacing

of the test chamber using template, uniformly mixed clay was placed and packed in the chamber in layers of 100 mm thickness and tamped with template in order to remove entrapped air to ensure homogeneous condition. Clay samples were taken at various depths. The water content, density, undrained shear (vane shear test) strength tests were conducted on the collected soil samples. The results obtained from the tests confirm the homogeneity of the prepared clay bed.

Static lateral load tests are conducted on single piles and pile groups (1 × 2, 2 × 2, 3 × 3, 3 × 4 groups). The configuration of pile groups is depicted in Fig. 2. Embedded length to diameter (L/D) ratio of the pile is varied from 15 to 40. Spacing in the direction of loading to diameter (S/D) ratio is varied from 3 to 7. Spacing in the direction perpendicular to loading is kept as 3D. All the tests are conducted at soft consistency of clay (I_c = 0.32). Based on the relative stiffness factor [16], piles having L/D ratio of 15 and 20 are rigid piles, L/D ratio of 30 are intermediate and L/D ratio of 40 are flexible piles.

Static lateral loads are applied on pile cap in increments (Fig. 1). Each increment of load is maintained for 30 min. A load cell attached between the pile cap and rope is used to measure the load carried by the pile group. Pile head and ground line deflections are measured using linear variable displacement transducers (LVDT). Bending Strain is measured along the embedded length of the pile from strain gauges pasted on the piles at various depths. The bending moment is calculated using the following expression

$$M = EI\varepsilon/r \qquad (2)$$

where E = Young's modulus of the model pile material, I = Moment of inertia of the model pile, ε = Measured bending strain and r = Horizontal distance between strain gauge position (outside side surface of the pile) and neutral axis.

A 24 channel data acquisition system is used in the present study to monitor and store the data automatically.
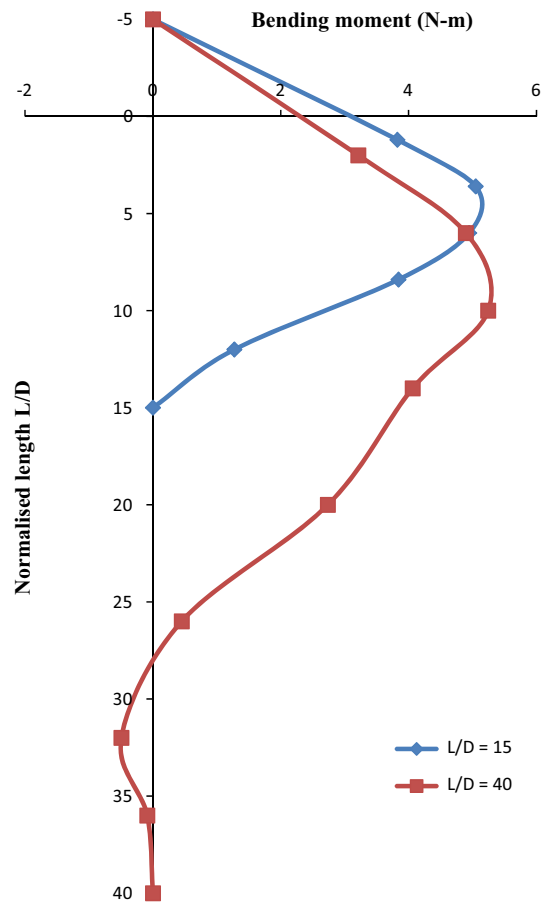

Fig. 3 Bending moment profiles of single piles

The data acquisition system consists of a digital carrier frequency amplifier system of HBM make MGC plus (Model: AB 22A) with 24 channels. It is used to amplify the signals received from transducers. This amplifier system is connected to personal computer using communication processor with USB interface. CATMAN Professional software is used to acquire and analyse and data received from various types of transducers through the amplifier system.

Results and Discussion

Effect of Embedment Length of Pile

Figure 3 depicts the bending moment profiles of rigid (L/D of 15) and flexible (L/D of 40) single piles subjected to same magnitude (32 N) of lateral load. It can be observed from the figure that the rigid pile (L/D of 15) has significant bending moments of same sign throughout the entire embedded length. It has maximum bending moment of 5 N m occurring at a depth of 5D from the ground surface. In contrast, the flexible pile (L/D of 40) has significant
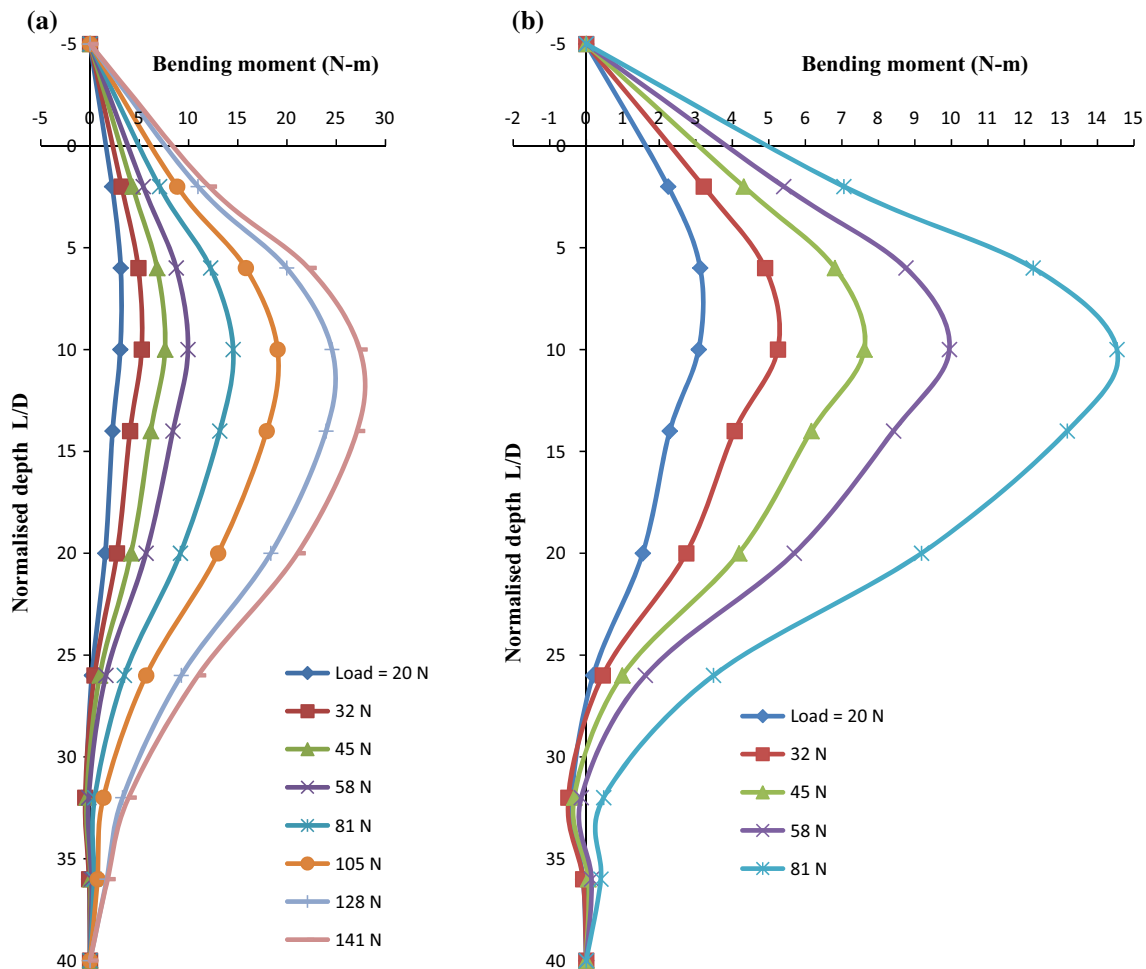
Fig. 4 Bending moment behaviour of single piles. **a** Variation of bending moment with magnitude of lateral load and **b** effect of magnitude of load on flexible behaviour

bending moments only up to a certain depth (23D) and bending moment changes sign along the depth. It has maximum bending moment of 5.3 N m which is only marginally higher (6 %) than that of the rigid pile. The maximum bending moment of the flexible pile occurs at a depth of 10D, which is 100 % deeper than that for the rigid pile. The zero bending moment (point of contraflexure) occurs at a depth of 27D for the flexible pile. The above observations reiterate that in flexible pile (L/D of 40) the deflections and bending moments are confined to the upper part of the pile and the overall length of the pile does not significantly affect the response of the pile. The above observation is consistent with the results of Randolph [18] and Rollins et al. [22].

Effect of Magnitude of Lateral Load

The bending moment profiles of flexible (L/D of 40) single pile for various magnitudes of applied lateral loads are

shown in Fig. 4a, b.The bending moment of pile below ground surface increases with depth and reaches a maximum value at a certain depth. It shows a decreasing trend below that depth, have a point of contraflexure and changes sign. The magnitude of maximum bending moment (Fig. 5a) and its depth of occurrence (Fig. 5b) increase significantly with the increase in the magnitude of lateral load. This result matches well the results reported by Rao et al. [20] and Rollins et al. [21]. The depth of maximum bending moment varies from 8D to 12D (Fig. 5b). The depth of point of contraflexure also increases (from 27D to 32D) when the magnitude of applied lateral load increases from 20 to 58 N (Fig. 4b). It is important to note from the Fig. 4b, when the load is increased beyond 58 N (64 % of ultimate lateral load), the pile is not showing any point of contraflexure. Thus, flexible piles cannot be considered as flexible (length independent) beyond certain value of ultimate lateral load (64 % in present study). The observation is the same for pile group also. This observation is consistent with the results of Rollins et al. [21, 22].
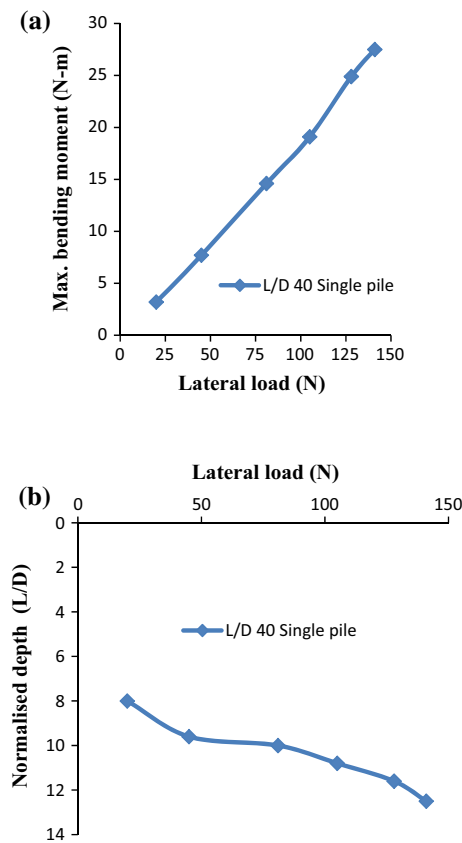
(a)

(b)

Fig. 5 Maximum bending moment of single pile: **a** variation of maximum bending moment with lateral load and **b** location of maximum bending moment versus magnitude of lateral load

Ultimate load in the present study is taken as the load corresponding to deflection equal to 20 % of pile diameter (i.e. 3.92 mm) as per Broms [3] criterion. The ultimate load for single pile is 90 N and 40 N for 3 × 3 pile group. As can be observed from Fig. 4b for single pile and (Fig. 6b) 3 × 3 pile group, flexible piles subjected to lateral load greater than about 60 % of ultimate lateral load cannot be considered as flexible. This observation is very important in structural design of piles particularly in deciding upon curtailment of flexural reinforcement.

Effect of Size of the Pile Group

For comparing the performance of pile group with that of single pile, the average load per pile is calculated by dividing the total load on the pile group by number of piles in the group. Figure 7, presents average load-pile head deflection of closely spaced (S/D of 3) flexible (L/D of 40) 1 × 2, 2 × 2, 3 × 3 and 3 × 4 pile groups. At relatively low pile head deflections, the average loads carried by piles in the group are similar to that of the single pile. It can be observed from the Fig. 7, with increase in deflections, the average load carried by each pile in the group is

considerably lesser than that of the single pile. The lateral capacity of pile group is less than an individual pile because of "group interaction" effect. In the closely spaced pile groups (S/D of 3) investigated in the present study, piles are influenced by adjacent piles due to overlapping of stress zones (pile–soil–pile interaction), leading to reduction in lateral capacity of the pile group. The percentage reduction in lateral capacity of the pile groups in comparison to the single pile increases with the number of piles in the group due to corresponding increase in the overlapping of stress zones. Similar results were reported by Ilyas et al. [10].

For given average load per pile of 60 N, the deflection of single pile is 2.1 mm and that of 1 × 2, 2 × 2, 3 × 3 and 3 × 4 pile groups are 2.7, 5, 7.1 and 9.5 mm respectively. It is significant to note that for same average load per pile, the deflection of 3 × 3 and 3 × 4 pile groups are 3.4 and 4.5 times respectively more than that of the single pile. The larger deflection of closely spaced pile groups is due to pile-soil-pile interaction effect. These results are in consistent with Rao et al. [20], Rollins et al. [21], Rollins et al. [22] and Illyas et al. [10].Ultimate lateral capacities of pile groups obtained corresponding to 4 mm (0.2D) deflection are 77, 50, 42 and 38 N for 1 × 2, 2 × 2, 3 × 3 and 3 × 4 pile groups respectively. The percentage reductions of lateral capacities compared to that of the single pile are 53 and 58 for 3 × 3 and 3 × 4 pile groups respectively.

Effect of Row Position on Load and Moment Distribution in Pile Groups

Lateral load is applied at the pile cap and measured using load cell (Fig. 1). Deflections are measured at two levels-at pile cap (same elevation of applied load) and deflection of rear and front row piles at ground level (top of clay bed) using LVDTs. Average load per pile is calculated by dividing the total load on the pile group by the number of piles in the group. Figure 8 depicts average load per pile–ground line deflection of 2 × 2 and 3 × 3 pile groups (L/D of 40) respectively in Fig. 8a, b. It can be observed from the Fig. 8a, b that the load distribution in pile groups is not uniform among the piles but it depends on the position of row with respect to the direction of applied lateral load (Fig. 2). For the same average load per pile, deflection of rear row (R2) pile of 2 × 2 group is substantially more than that of the front row (R1) pile (Fig. 8a). Rear row (R2) pile deflects about 25 % more than that of front row (R1) pile for the same average load per pile of 60 N (Fig. 8a). Similarly in 3 × 3 group, deflection of rear row (R3) pile is about 33 % more than that of front row (R1) pile for the same average load per pile of 60 N Fig. 8b. For a given deflection of 3.2 mm, front row (R1) pile of 2 × 2 group
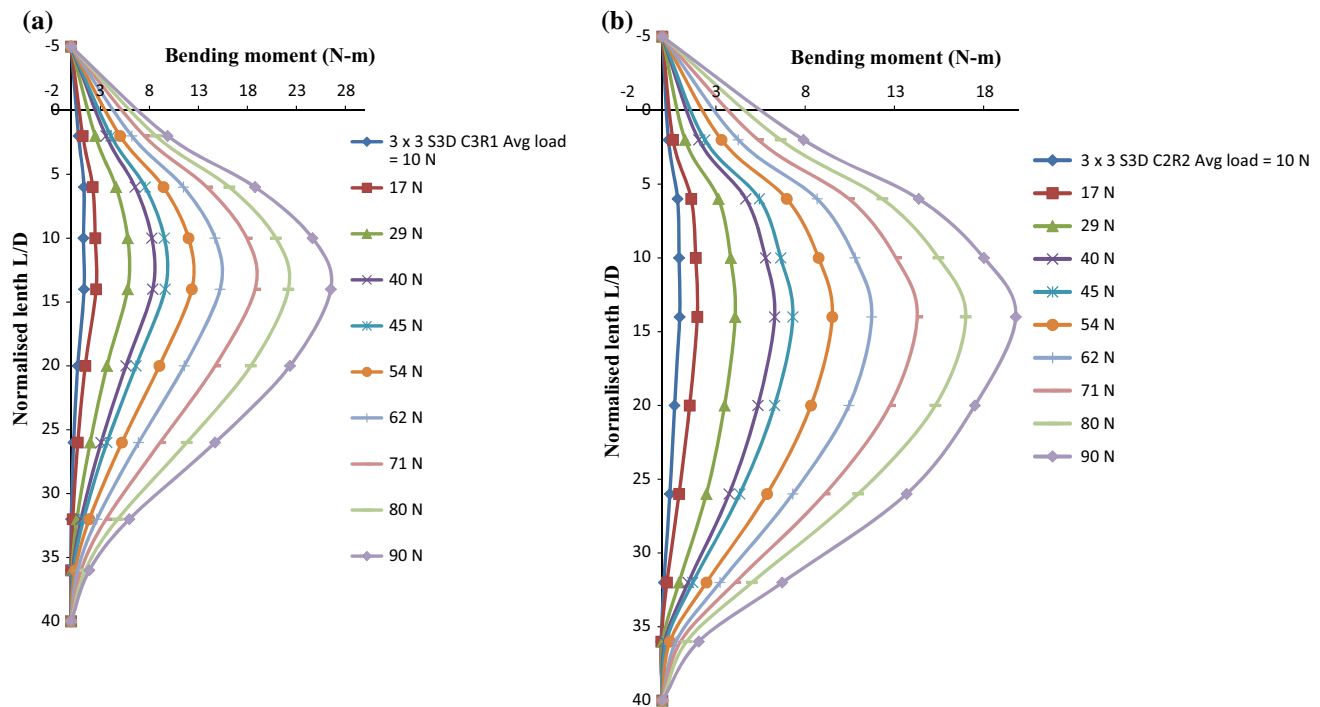
Fig. 6 Bending moment profiles of piles in 3 × 3 group: **a** leading row pile and **b** middle row pile

carry about 18 % more load than that of rear row (R2) pile. In 3 × 3 group, the rear row pile (R3) carry about 15 % less load than the leading row (R1) pile for same deflection of 3.9 mm. It is clear from the above observations that the front row piles carry more load than that of the trailing row piles. This is in agreement with the studies of Brown et al. [4], Ilyas et al. [10] and Rollins et al. [22]. This is due to group interaction effect [5, 21, 22].

Figure 9 depicts the bending moment profiles of various row piles of 3 × 3 pile group (L/D of 40) for the average load per pile of 42 N. The piles are from middle column (C2) of the group Fig. 2. The bending profile of single pile for the same load is also presented in the Fig. 9 for comparison. Variation of maximum bending moment of piles in group with increasing magnitudes of lateral load is depicted in Fig. 10 along with that of the single pile. Significant observations from the figures (Figs. 9, 10) are bending moment distribution among the piles in the group depends on row position. In the middle column (C2) piles, the maximum bending moment of the front row (C2R1) piles is substantially higher than that of the trailing row piles (C2R2 and C2R3). The middle row pile (C2R2) has least maximum bending moment among all the rows. Maximum bending moment of front row (C2R1) pile is about 7 % higher than that of rear row (C2R3) pile and about 16 % higher than that of middle row (C2R2) pile (Figs. 9, 10). At deeper depths, the trailing row piles (C2R2 and C2R3) carry higher moments than that of front row (C2R1) pile.

Within the same row (R1) piles, corner pile (C3R1) has about 10 % higher maximum bending moment than that of middle pile (C2R1) (Figs. 9, 10). The middle column piles (C2R1, C2R2 and C2R3) carry substantially higher moments than that of outer column pile (C3R1) at deeper depths (Fig. 9). Though the single pile exhibit flexible bending behaviour (Fig. 9) with change in sign of bending moment along the depth, the piles in 3 × 3 group do not exhibit flexible behaviour (Fig. 9) due to strong group interaction effects. These observations are of prime importance in structural design of pile groups and in deciding upon flexural reinforcement and its curtailment.

Effect of Cyclic Loading

In order to investigate the effect of nature of loading, two-way cyclic lateral load was applied to 3 × 3 pile group (L/D of 40).

The experimental set up of cyclic lateral load test is depicted in Fig. 11. Two-way symmetric cyclic lateral load is applied on model piles using two pneumatic power cylinders attached to the loading frame on both sides of the pile cap by a wire rope. Compressed air is regulated through the pressure regulator which is used to control the cyclic load level. Electronic timer is used to control the period of loading. Lateral load applied to the pile group during both half of the loading cycle is measured using two load cells. Pile head and ground line deflections are
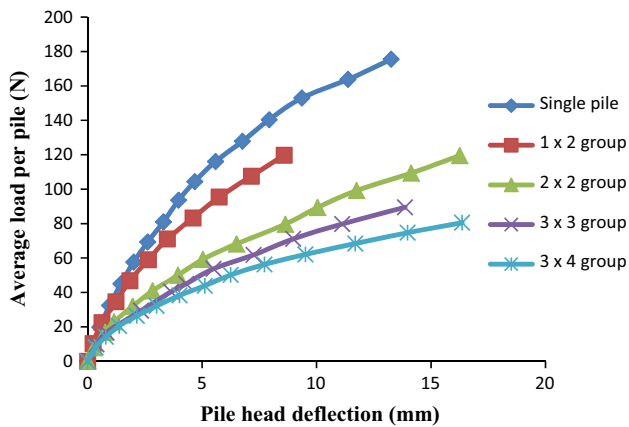
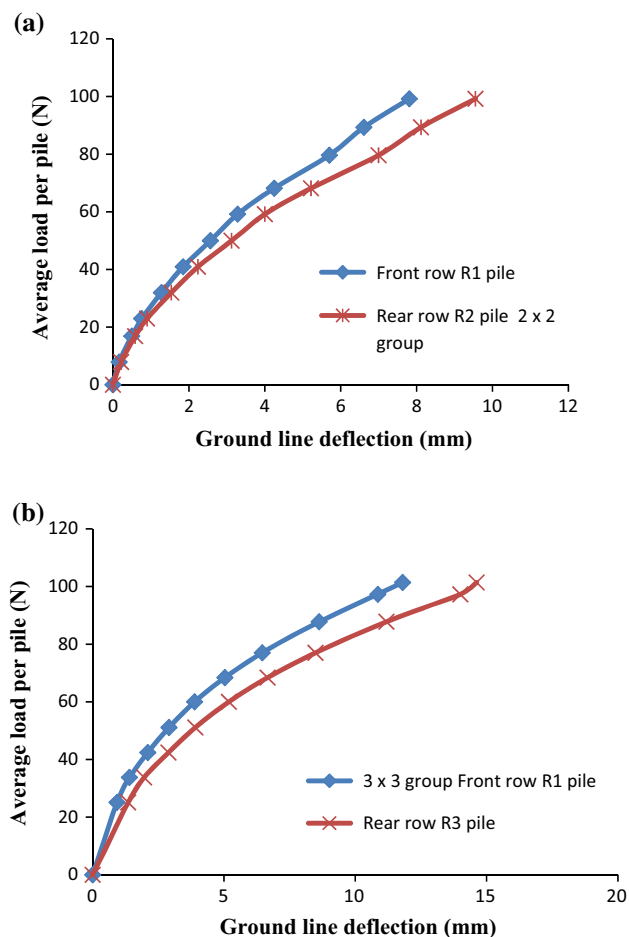Fig. 7 Load–deflection behaviour of pile groups

(a)

(b)

Fig. 8 Load–deflection behaviour of different row pies: **a** 2 × 2 group and **b** 3 × 3 group

measured using LVDTs. The clay bed is in saturated state during cyclic loading test and having consistency index of 0.32 as in the case of static loading. Miniature pore

pressure transducers embedded in the clay bed were used to measure the pore pressure response.

The magnitudes of cyclic lateral loads correspond to 25, 45, 65 and 85 % of static ultimate lateral load [4, 6, 15, 17, 19].The duration of cyclic load is 12 s typical of storm waves in Bay of Bengal.

Cyclic lateral load–deflection behaviour of 3 × 3 pile group is depicted in Fig. 12a for different number of cycles (N) of loading. Static load–deflection behaviour of the pile group is also plotted in the Fig. 12a for comparison.

Cyclic load–deflection curves (Fig. 12a) present strong nonlinear response. At low load levels (25 %) cyclic behaviour is similar to the static loading. Cyclic loading >45 % produce deflections much higher than that of the static loading. Deflection of pile group increases with increase in numbers of cycles of loading. Deflection of 3 × 3 pile group subjected to 50 cycles of loading of 28 N (65 % of static ultimate lateral load) is about 60 % higher than that under same magnitude static loading. This is due to the buildup of pore water pressure in clay with increase in number of cycles of loading (Fig. 12b). The pore pressure is measured using miniature pore pressure transducers embedded in clay bed at a depth of 100 mm (5D) and at a distance of 40 mm (2D) in front of C2R1pile of the pile group in the direction of loading. The generation and buildup of pore pressure in clay bed in undrained condition reduce the shear strength of clay.
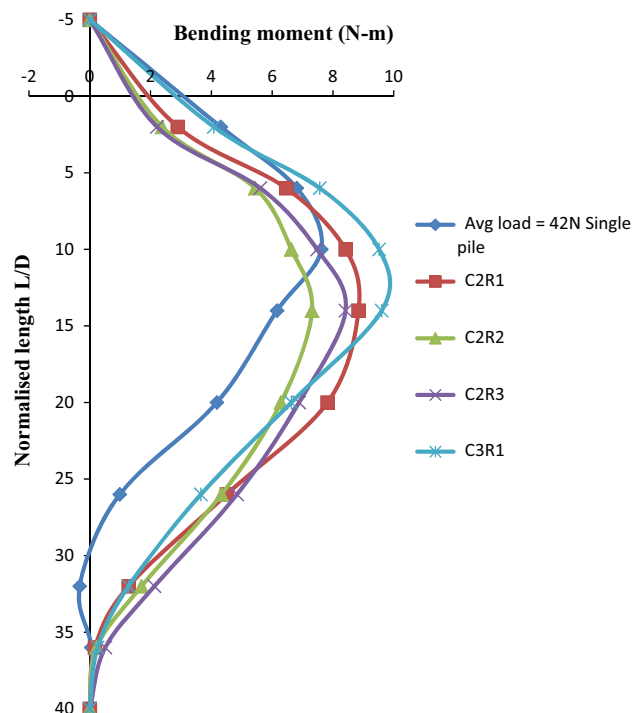

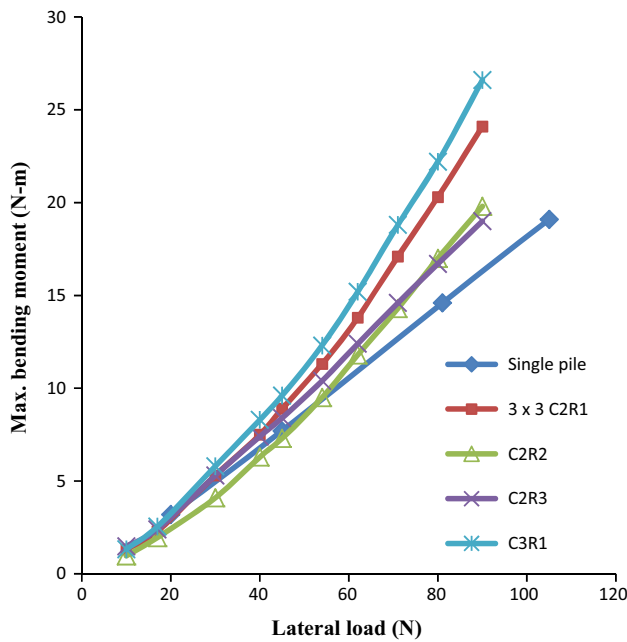Fig. 9 Bending moment profiles of piles in 3 × 3 group

Fig. 10 Variation of magnitude of maximum bending moment of 3 × 3 group with applied lateral load

Fig. 13. As can be noted from the figure, maximum bending moment under cyclic loading is about 80 % higher than that for static loading. Development of pore pressure and reduction in shear strength of clay lead to softening of soil resistance to pile group. This results in higher bending moment in pile. The depth of occurrence of maximum bending moment under cyclic loading is 14D which is about 25 % deeper than that for static loading (11D). The above experimental results are following the trends as reported by with Rollins et al. [22] and Chandrasekaran et al. [6]. This is due to formation of gap at pile–soil interface.

Effect of Vertical Load

In most cases of practical applications, vertical loads act upon pile groups in addition to lateral loads [1, 12, 13]. Vertical compressive load test is carried out on 3 × 3 pile group (L/D of 15).

The vertical loading arrangement is shown in Fig. 14. Piles are screwed into threads provided in the pile cap to enable the pile cap to carry the vertical loads. The pile cap is attached with a wider steel plate. The vertical compressive loads are applied in increments and vertical settlement of the pile cap is measured. Vertical load is applied by carefully placing dead weights using concrete cubes of required numbers on top of the attached steel plate. The stability of dead weights is ensured. The settlement of the pile group is measured using four numbers of dial gauges fixed at corners of the steel plate.

The ultimate vertical load carrying capacity of 3 × 3 pile group (L/D of 15) is found to be 840 N. In order to study the effect of vertical load on lateral capacity of the pile group, lateral load tests are carried on 3 × 3 pile group (L/D of 15) with vertical loads. The resulting behaviour is
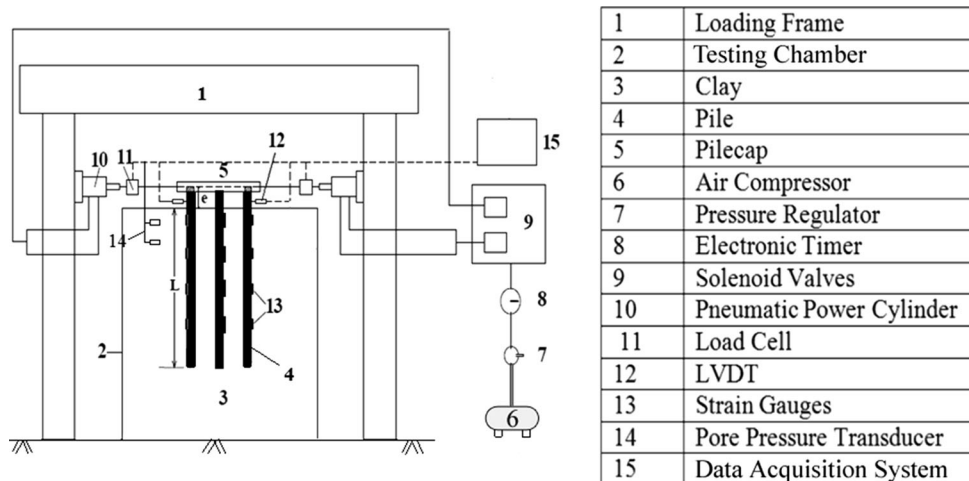
Cracks develop and form as gap (Fig. 12c) at the pile–soil interface during subsequent cycles of loading due to stress development at contact surface. Gap of width of about 8 mm (0.4D) and depth of about 100 mm (5D) develops for higher magnitudes of cyclic loading (Fig. 12c). As the cyclic loading is of two-way, gap develops at both sides of pile along with heaving of soil at surface. Hence, deflection of pile group under cyclic loading is significantly higher than that for static loading.

Bending moment profile of front row (C3R1) pile of 3 × 3 pile group (L/D of 40) under 15 cycles of loading of 28 N (65 % of static ultimate lateral load) is shown in

Fig. 11 Cyclic lateral load test setup

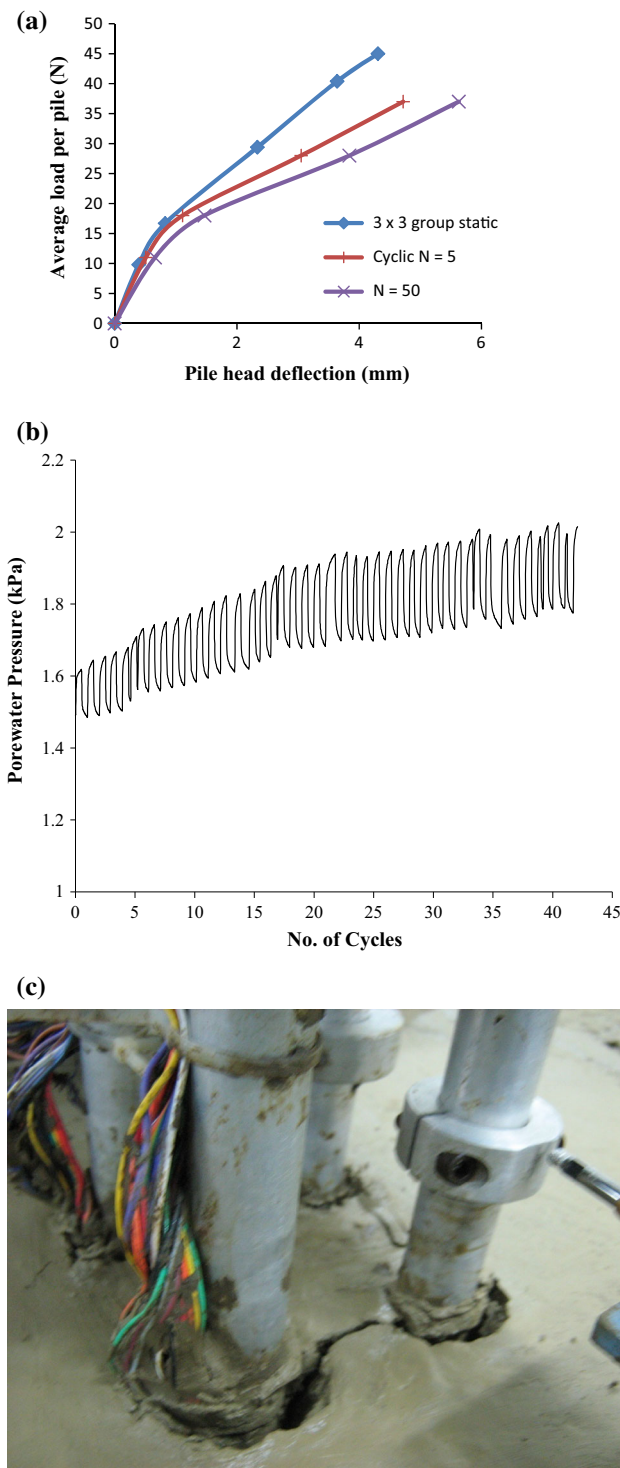| 1 | Loading Frame |
2	Testing Chamber
3	Clay
4	Pile
5	Pilecap
6	Air Compressor
7	Pressure Regulator
8	Electronic Timer
9	Solenoid Valves
10	Pneumatic Power Cylinder
11	Load Cell
12	LVDT
13	Strain Gauges
14	Pore Pressure Transducer
15	Data Acquisition System

(a)

(b)

(c)

Fig. 12 Cyclic lateral behaviour: **a** load–deflection curves, **b** pore pressure response and **c** formation of gap

Fig. 13 Cyclic bending behaviour of pile in 3 × 3 group

compared with that of lateral load tests on the pile group with no vertical load. As can be observed from Fig. 15a, at low vertical load level of 250 N (<30 % of ultimate load), lateral load test on pile group with vertical load show
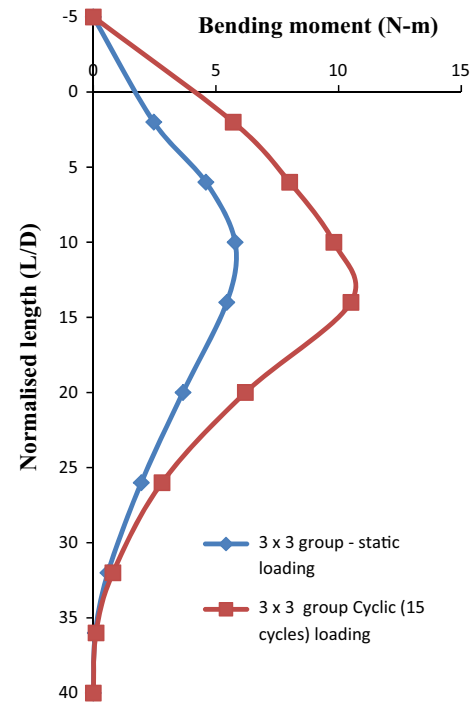
improved performance over that of pile group with no vertical load. The lateral capacity is more at low vertical load levels. This is attributed to confining effect developed by the vertical load.

But, when the vertical load on the pile group is increased to higher load levels (greater than 50 % of ultimate load) it shows the opposite behaviour. The lateral load–pile head deflection behaviour of 3 × 3 pile group (L/D of 15), with vertical compressive load of 504 N (60 % of ultimate vertical load), is compared with that of the pile group with no vertical load in Fig. 15a. For a given lateral load, the deflection of pile group with vertical load is higher than that of the pile group with no vertical load (Fig. 15a). At higher vertical load levels, shear stresses develop in the clay and nullify the benefit of confining stress, thus lead to higher deflections. Also it is attributed to failure of interface and reduction in lateral soil stresses [18]. The lateral capacity (18 N) of the 3 × 3 pile group with vertical load, corresponding to deflection of 4 mm (0.2D), is about 18 % less than that of the pile group with no vertical load (Fig. 15a). This result is in agreement with the observation of Karthigeyan et al. [12].

Similarly, 3 × 3 pile group (L/D of 15) with vertical load of 504 N and subjected to average lateral load per pile of 24 N exhibits higher bending moments when compared to that of the pile group with no vertical load (Fig. 15b). The maximum bending moment of the pile group with vertical load is about 50 % higher and occurs at a depth of
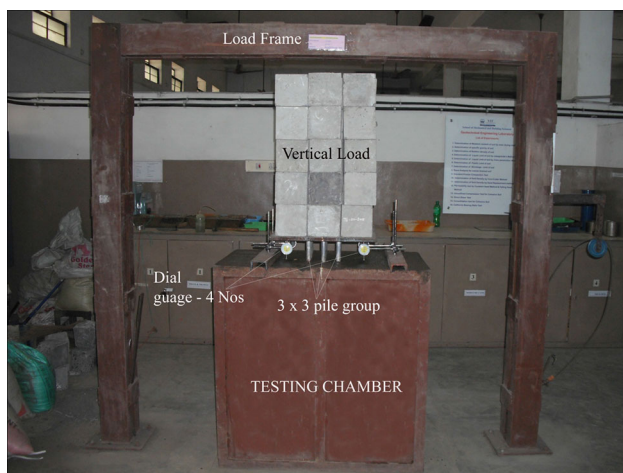
Fig. 14 Vertical load test setup

about 25 % deeper when compared to that of the pile group with no vertical load (Fig. 15b). This is attributed to softening of soil resistance to pile group under vertical load.

Conclusions

The following conclusions are drawn from the present experimental investigation on lateral response of pile groups in soft clay.

1. Flexible piles subjected to lateral load greater than about 60 % of ultimate lateral load cannot be considered as flexible (length independent). This observation is significant in structural design of piles particularly in deciding upon the curtailment of flexural reinforcement.

2. The load distribution in pile groups is not uniform among the piles but depends on the position of row with respect to the direction of applied lateral load. The front row piles carry more load than that of the trailing row piles due to group interaction effect. For a given deflection, front row (R1) pile of 2×2 group carries about 18 % more load than that of rear row (R2) pile. In 3×3 group, the rear row pile (R3) carries about 15 % less load than the leading row (R1) pile.

3. Though the single pile exhibit flexible bending behaviour, the piles in 3×3 group do not exhibit flexible behaviour due to strong group interaction effects.

4. Deflection of 3×3 pile group when subjected to 50 cycles of loading (65 % of static ultimate lateral load) is about 60 % higher than that under same magnitude of static loading.

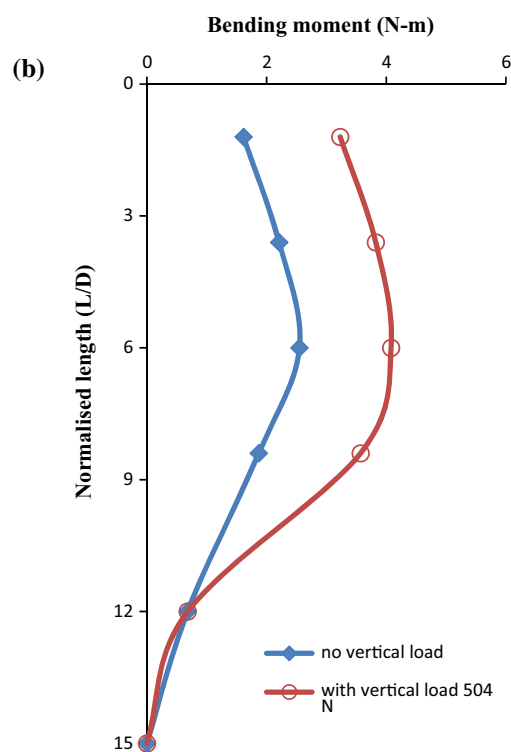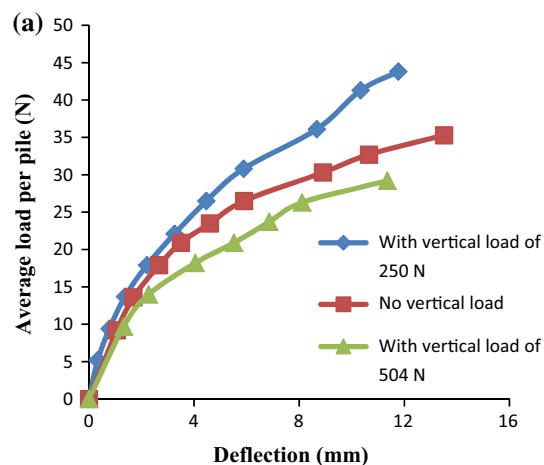5. Maximum bending moment under cyclic loading is about 80 % higher than that for static loading due to

Fig. 15 Effect of vertical load: a load–deflection behaviour and b bending moment profile

softening of soil resistance. Also the depth of occurrence of maximum bending moment under cyclic loading is about 25 % deeper than that for static loading.

6. The lateral capacity of the 3×3 pile group with vertical load (60 % of ultimate vertical load) is about 18 % less than that of the pile group with no vertical load. The maximum bending moment of the pile group with vertical load is about 50 % higher and occurs at a depth of about 25 % deeper when compared to that of the pile group with no vertical load.

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