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# Behaviour of 2 × 2 Pile Group under Static and Cyclic Lateral Loading

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## Introduction

Pile foundations are often used to support structures such as offshore platforms, bridges, high-rise buildings, transmission towers, wind farms, and variety of units in industrial plants which are subjected to significant amount of lateral loads. Lateral loads on piles occur due to earth pressure, earthquake, wave action, impact of berthing ships, wind force, operating machineries, traction of braking vehicles, cable tension, etc. Mechanics of the behaviour of the group of laterally loaded piles is more complex than those of the axially loaded pile group (Reese et al. 2006). Piles in the group subjected to lateral loading are influenced by the existence of similarly loaded nearby piles due to pile–soil-pile interaction, leading to reduction in lateral load capacity of the pile group. Lateral loading on pile foundations due to wave and earthquake loadings are cyclic in nature, which bring additional complexity to the soil-structure interaction problem. Pile group behaviour under cyclic lateral loading is nonlinear and involves complicated group interaction. Cyclic loading in clay under undrained condition leads to degradation of stiffness and reduction in shear strength. Formation of gap at pile-soil interface, buildup of excess pore pressure and remoulding of clay under cyclic lateral loading, lead to higher deflections and higher bending moments than static loading.

## Brief Review of Literature

The analysis of single pile and pile groups under static lateral loading could be categorized into: Limit state method (Broms 1964), Subgrade reaction method using finite difference (Matlock and Reese 1960), Elastic continuum method (Poulos 1979), p-y curve method (Brown et al. 1988) and Finite element method ( Karthigeyan et al. 2007). The behaviour of single pile and pile groups under cyclic lateral loading was analysed using Elastic continuum method (Poulos 1982), p-y Curve method (Georgiadis et al. 1992; Rollins et al. 2006b), Discrete element method (Grashuis et al. 1990) and Finite element method (Rajashree and Sundaravadivelu 1996).

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Rollins et al. (1998) investigated the behaviour of full scale pile group with three diameter spacing driven in clay and subjected to static lateral loading. It was observed that the pile group deflected over two times more than the single pile under same average load. The results also indicated that the piles in trailing rows carried significantly less load than the piles in leading row due to shadowing effect. Narasimha Rao et al. (1998) studied the behaviour of laterally loaded model pile groups embedded in marine clay. They have shown that the behaviour of pile group depends mainly on critical spacing of the piles, which is a function of both the embedment length of piles and arrangement of piles. Ilyas et al. (2004) carried out centrifuge model tests on laterally loaded pile groups in clay. It was observed that the centre pile carries much less load and bending moment than those of the outer piles in the same row.

Brown et al. (1987) investigated the behaviour of large scale pile group with three diameter spacing in stiff clay under two-way cyclic lateral loading. It was shown that the maximum soil resistance for the piles in group is greatly reduced as compared to single pile due to cyclic loading. Rollins et al. (2006a) performed series of full scale cyclic lateral load tests on pile groups with various spacing to study the effect of pile spacing on the behaviour of pile group. It was observed that the group interaction effects decreased considerably as spacing increased from 3.3 to 5.65 times the diameter of pile. Ramakrishna (1997) conducted one-way cyclic lateral load tests on model pile groups embedded in clay consisting of two piles arranged in series and parallel configuration. It was shown that capacities of piles weaken at cyclic load levels exceeding 60% of the static capacities. Moss et al. (1998) studied the behaviour of closely spaced model linear pile group embedded in clay, subjected to two- way cyclic lateral loading. It was observed that the magnitude of maximum bending moment increases and location of maximum moment moving down the pile length with increasing numbers of cycles of loading. Peng et al. (2006) summarized various devices used for applying cyclic lateral load to model piles.

## Need of the Present Investigation

It is evident from the literature review and also observed by Reese et al. (2006), the experimental data on the behaviour of pile groups in clay under lateral loads are limited. The effects of spacing and cyclic load level on pile-soil-pile interaction of pile group under cyclic loading have not previously been studied extensively. Previous experimental studies mainly concentrated on single spacing. Moreover only a few tests have been carried out using two-way cyclic lateral loading on piles. Available methods for analysis of pile groups subjected to cyclic loading use group interaction factors derived from static tests. Hence a comprehensive test programme was planned and carried out to study the behaviour of pile groups in clay under static and cyclic lateral loading.

## Objectives / Scope

The objectives of the present investigation are

> To study the effects of pile spacing, cyclic load ratio and number of cycles on pile group behaviour.

> To study the pile-soil- pile interaction effects in clay under static and cyclic lateral loads.

> To estimate the pattern of load distribution in the pile group under lateral loads.

> To estimate pile group efficiency under lateral load for different spacing

> To bring out the effects of gap formation and pore pressure build up on cyclic lateral behaviour of pile groups

> To bring out the combined effect of cyclic loading and group interaction

> To estimate the critical spacing and critical load level under cyclic lateral loading

The scope of the present investigation is to carry out static and two-way cyclic lateral load tests on 2 $\times$ 2 model rigid pile groups with spacing of 3D to 9D embedded in soft clay under free head condition.

## Materials Used

### Soil

The clay used in the present study was collected from Siruseri, Chennai. The properties of soil are given in Table 1.

**Table 1 Properties of Clay**

| *Property* | *Value* |
|---|---|
| Liquid limit ($w_L$) | 67% |
| Plastic limit ($w_P$) | 28% |
| Plasticity index ($I_P$) | 39% |
| Free swell index | 35% |
| Specific gravity ($G_s$) | 2.58 |
| Soil classification | CH |
| Undrained shear strength ($c_u$) ($I_c$ = 0.38) | 11.0 kPa |

### Pile

Similitude laws are adhered to in selecting model pile material and dimensions. Prototype pile is 550 mm diameter solid section made of reinforced cement concrete of $M_{25}$ grade. Scaling law (Wood et al. 2002) used in this study is given below:

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

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.

Aluminium tube of outer diameter 25.6 mm and inner diameter 18.6 mm is selected with length scaling factor of 1/10. The other scaling factors used in the study are presented in Table 2.

Aluminium plates of 20 mm thick were used as pile caps. The study reported here is a part of experimental investigation programme on laterally loaded pile groups in clay under static, cyclic and dynamic loading. Static and cyclic test results will be compared with the results of dynamic experiments. Minimum 150 mm above the ground surface is required to fix the electro dynamic exciter. Besides deflections at pile head level, deflections were also measured at ground level to calculate the rotation of pile group. Tests were conducted with free head condition. Pile caps were attached at the top of piles leaving 150 mm above the ground surface as a free standing length for the group.

**Table 2 Scaling Factors Adopted in the Study**

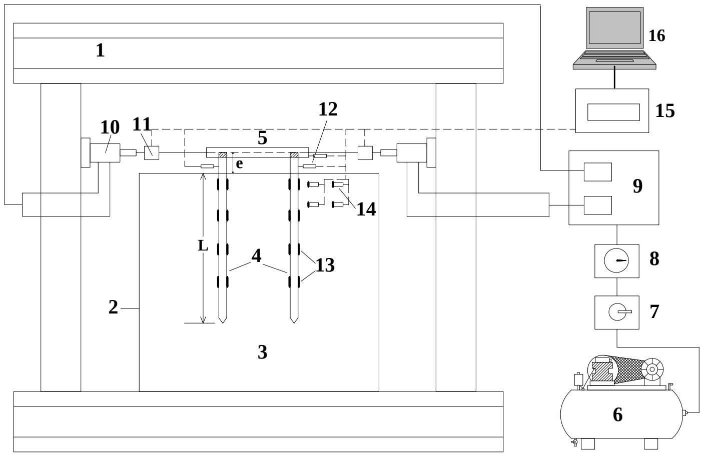
| *Variable* | *Scaling Factor* |
|---|---|
| Length | 1/10 |
| Density | 1 |
| Stiffness | 1/10 |
| Stress | 1/10 |
| Strain | 1 |
| Pile Flexural Rigidity | $1/10^5$ |
| Mass | $1/10^3$ |
| Pore Fluid Density | 1 |
| Force | $1/10^3$ |

# Experimental Programme

## Experimental Setup and Instrumentation

Experimental setup used for cyclic lateral load test on pile group is shown in Figure 1**.** Cyclic lateral load tests were conducted on model pile groups embedded in clay in steel testing chamber of size 1.5 m diameter and 1.3 m height which was sufficiently large enough to avoid side effects. Two-way cyclic lateral loading was applied on model piles using two pneumatic power cylinders attached on the loading frame on both sides of the pile cap and connected to pile cap with wire rope. Filtered compressed air was regulated through the precision pressure regulator which is used to control the cyclic load level. Electronic timer is used to control the period of loading. Two solenoid valves used to supply the compressed air to one cylinder during half of the period while cutting the supply to other cylinder and vice versa which in turn move the pistons back and forth and enabling two-way cyclic lateral load application to the pile cap.

Piles were instrumented with electrical resistance strain gauges along the length to study the bending behaviour. The strain gauges have resistance of 120 ohms, gauge factor of 2.02 and connected in a quarter bridge arrangement. Load carried by pile cap and individual piles were measured using strain gauge type load cells of nominal capacity of 5000N. Pile head and ground line deflections were measured using probe type inductive Linear Variable Displacement Transducers (LVDTs) with nominal displacement range of 50mm. Miniature pore pressure transducers embedded at various depths were used to record the excess pore pressure generation. The pore pressure transducers are of integrated silicon strain gauge bridge type having operating pressure range of 350 mbar. A 40 channel data acquisition system comprising HBM make MGC Plus carrier frequency amplifier system and SPIDER8 with Catman Professional software was used to monitor and store the data automatically.




| | | | | | |
|---|---|---|---|---|---|
| 1 | Loading Frame | 7 | Pressure Regulator | 12 | LVDT |
| 2 | Steel Tank | 8 | Electronic Timer | 13 | Strain Gauges |
| 3 | Clay | 9 | Solenoid Valves | 14 | Pore Pressure Transducer |
| 4 | Pile | 10 | Pneumatic Power cylinder | 15 | Amplifier (MGC+, Spider8) |
| 5 | Pile Cap | 11 | Load Cell | 16 | DAS |
| 6 | Air Compressor | | | | |

**Fig. 1 Schematic of Cyclic Lateral Load Test Setup**

## Test Procedure

### *Clay Bed Preparation*

In the present study, the clay was mixed in a separate mixing tank with required amount of water to get the soft consistency (consistency index, $I_c$ of 0.38). After fixing the pile/piles in the centre of the test tank, uniformly mixed clay was placed and hand packed in the test tank in several layers each of 15 cm thickness in order to remove entrapped air and to ensure homogenous packing. Because of high water content, there was no difficulty in placing the soil and a fairly homogeneous deposit was formed. Water content, density and undrained shear strength tests carried out at various depths of the soil bed confirmed the homogeneity of the clay bed prepared.

### *Static Lateral Load Test*

Static lateral load tests on model single piles and pile groups were carried out as per Indian Standard (IS 2911: Part 4 – 1985). The static lateral load was applied by placing weights on a hanger connected to a flexible steel rope strung over a pulley supported by a loading frame using the same experimental setup used for cyclic lateral load test (Figure 1). The loads were applied in increments of approximately 1/5$^{th}$ of safe load till the rate of deflection less than 0.01 mm per 30 minutes before applying the next increment.

### *Cyclic Lateral Load Test*

Two-way cyclic lateral loading representing wave and earthquake loadings were applied to the model single piles and pile groups at different cyclic load ratios. The Cyclic Load Ratio (CLR) is defined as the ratio of magnitude of cyclic lateral load to static ultimate lateral capacity of the pile (Poulos 1982).

### *Wave Loading*

The different magnitudes of cyclic lateral load corresponding to CLR of 0.35, 0.5, 0.65 and 0.8 representing wave loading (Brown et al. 1987; Ramakrishna1997; Peng et al. 2006) were applied to the pile group. The period of cyclic loading is kept as ten seconds to simulate wave loading typical of storm waves in east coast region of India. A typical cyclic loading pattern is shown in Figure 2. The cyclic load was applied for number of cycles and the loading was stopped around 300 cycles.

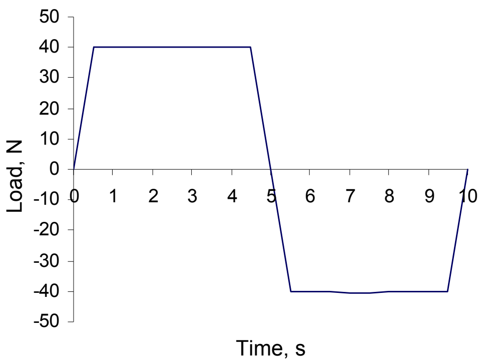



**Fig. 2 Typical Cyclic Loading Pattern**

### *Earthquake loading*

During an earthquake, a structure and its foundation will experience forces at some peak level (Moss et al. 1998). Seed et al. (1975) suggest that seismic loading can be expressed in terms of cyclic shear stresses and given number of stress cycles, at amplitude of 65% of peak cyclic shear stress that would produce an increase in pore pressure equivalent to that of the irregular time history for various magnitudes of earthquake. In the present study, cyclic lateral loading equal to CLR of 0.65 (65% of static ultimate lateral capacity of pile group) was applied on pile group for 10 cycles to simulate a cyclic loading typical of a M 6.0 earthquake (Seed et al 1975).

## Test Programme

Figure 3 shows the arrangement of piles in 2 × 2 pile group used in this study. The transverse spacing is kept constant as 3D, whereas the spacing in the direction of loading is varied. All the tests are conducted at consistency index $I_C$ of 0.38, which represents typical soft clay. The details of the model tests conducted are given in Table 3.

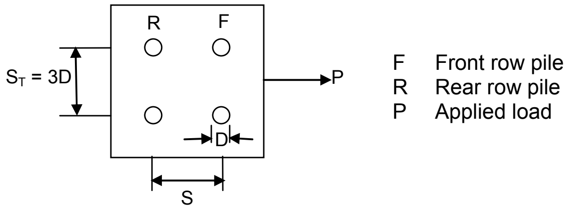



**Fig. 3 2 × 2 Pile Group**

In Table 3, the following notations are used: $I_C$ = Consistency index of clay, L = Embedded length of pile, D = Diameter of pile, S = Centre to centre spacing of piles in the direction of loading, $S_T$ = Transverse spacing (Centre to centre), L/D = Embedded length to diameter ratio, S/D = Spacing to diameter ratio and CLR = Cyclic load ratio.

**Table 3 Testing Programme**

| *Static Lateral Load Tests* | | *Cyclic Lateral Load Tests* | |
|---|---|---|---|
| Single Pile | 2 x 2 Pile Group | Single Pile | 2 x 2 Pile Group |
| $I_C$ = 0.38<br>L/D = 15 | $I_C$ = 0.38<br>L/D = 15<br>S/D = 3, 5, 7, 9<br>$S_T$ = 3D (Constant) | $I_C$ = 0.38<br>L/D = 15<br>CLR = 0.35, 0.50, 0.65, 0.80 | $I_C$ = 0.38<br>L/D = 15<br>S/D = 3, 5, 7, 9<br>$S_T$ = 3D (Constant)<br>CLR = 0.35, 0.50, 0.65, 0.80 |

Poulos and Davis (1980) defined the relative stiffness factor ($K_{rc}$) as

$$K_{rc} = \frac{E_p I_p}{E_s L^4} \tag{2}$$

Where $E_P$ = Modulus of elasticity of pile material (70 GPa), $I_P$ = Moment of inertia of pile section, $E_S$ = Secant modulus of soil (= 55 $c_u$), $c_u$ = Undrained shear strength of clay, and L = Embedded length of pile = 0.375 m (for L/D = 15). For the L/D ratio of 15 adopted in this study, $K_{rc}$ is obtained as 0.09. The pile can be classified as rigid pile as $K_{rc}$ value is greater than $10^{-2}$. The stress – strain behaviour of soil is nonlinear which is represented by p-y curves in the analysis of laterally loaded piles. The secant modulus approach is used in the p-y curve method. Lambe and Whitman (1969) observed that elastic modulus for a soil is usually the secant modulus from zero to one –half of peak deviator stress. Soil strain parameter $E_{50}$ which is used in p-y method corresponds to 50% of the maximum stress. Established correlations of secant modulus with undrained shear strength are based on load – deflection measurements of full scale piles. Hence in the present study the secant modulus is used.

## Static Lateral Behaviour

### Load-deflection Behaviour of Single Pile

Figure 4 shows the load-deflection curve for the single pile tested for static loading with L/D ratio of 15. Ultimate lateral capacity of a pile is usually obtained from load tests based on deflection criteria or point of intersection of tangents (double tangent method). As per Broms (1964), ultimate capacity is taken as the load corresponding to a deflection equal to 20% of the diameter of pile. Meyerhoff (1980) suggested that ultimate lateral capacity is the one at which the portion of load deflection curve becomes straight. The criteria based on deflection is well established and recommended by many previous researchers (Poulos 1980, Narasimha Rao et al. 1996, Rollins et al. 1998, Ilyas et al. 2004) for comparison of pile group behaviour with that of the single pile. Hence, in the present study ultimate lateral capacity of single pile and pile groups is estimated using deflection criteria suggested by Broms. The lateral capacity of pile is 60 N for the L/D ratio of 15. This particular static lateral load test was performed on single pile to provide comparison to the pile group tests.

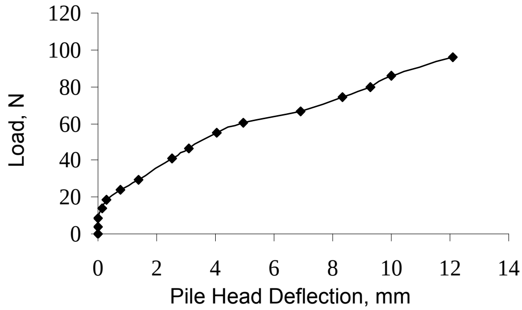



**Fig. 4 Load-Deflection Curve for Single Pile**

### Group Interaction Effect and Group Efficiency

Figure 5 shows load-deflection curves for 2×2 pile group with L/D ratio of 15 for various S/D ratios. The lateral capacities of pile groups are estimated using the same approach which used for single pile. They are: 174 N, 213 N, 236 N and 282 N for plies with S/D ratio of 3, 5, 7 and 9 respectively. It is noted that the lateral capacity of pile group at closer spacing is low and improves as the spacing between the piles increases. From Figure 5 it is noticed that the lateral capacities are lesser for S/D ratios of 3 and 5 which is attributed to the overlap of stress bulbs of individual piles causing loss of passive resistance. It is observed that due to group interaction effect, the deflection of the pile group with

S/D ratio of 3 is about two times more than that of the pile group with S/D ratio of 7 for the same magnitude of load.

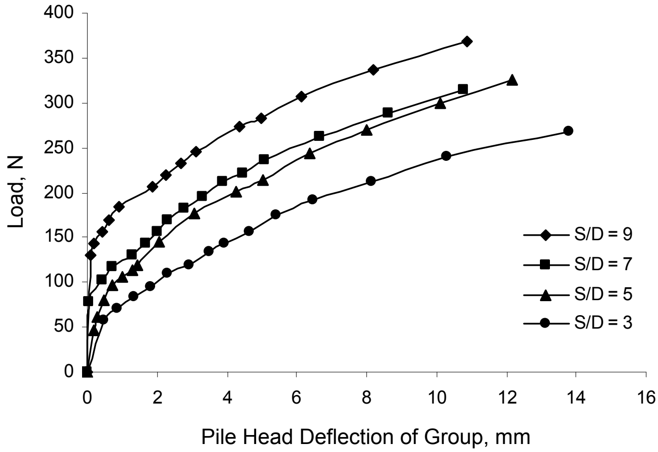



**Fig. 5 Load – Deflection Curves for 2 × 2 Pile Group under Static Loading**

Group interaction effect is also studied by calculating the group efficiency.

Group Efficiency $(\eta)=\dfrac{Q_G}{n_g\ Q_S}$ (3)

where $Q_G$ = Ultimate lateral load capacity of group, $Q_S$ = Ultimate lateral load capacity of single pile, and $n_g$ = Number of piles in the group.

The group efficiency obtained from experiments is shown in Figure 6.

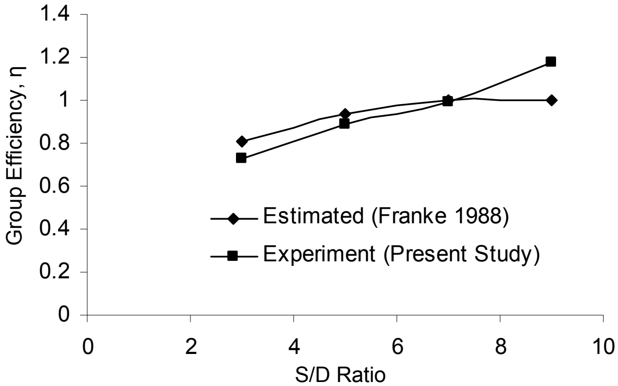



**Fig. 6 Comparison of Group Efficiency of the Pile Group under Static Load**

The group efficiency of closely spaced pile groups is less due to group interaction caused by shadowing effect. The group efficiency for S/D ratio of 3 is 0.73 and it agrees well with the experimental results of Ramakrishna (1997) and Ilyas et al. (2004) for similar pile groups in clay. The group efficiency improves with the spacing and approach to unity for S/D ratio of 7 and more than 1 for S/D ratio of 9. The spacing at which the group efficiency equal to one is referred as critical spacing and hence in the present study the critical spacing corresponds to S/D = 7. The group efficiency based on ultimate load obtained using double tangent method matches very well with that calculated based on Broms criteria.

The group efficiency is also estimated by accounting the following group interaction factors ($\alpha$) proposed by Franke (1988):

In the direction of loading:

For leading row pile ($\alpha_{LL}$) = 1; For rear row pile ($\alpha_{LR}$) = 0.25 + 0.125 (S/D) ≤ 1.0

In the direction perpendicular to loading:

For end pile ($\alpha_{QA}$) = 0.7 + 0.1 ($S_T$/D) ≤ 1.0.

The group efficiency is estimated by the following expression:

$$\text{Group efficiency } (\eta) = \frac{\sum \alpha Q_s}{n_g Q_s} \tag{4}$$

where $\sum \alpha$ = Sum of the interaction factors for all piles in the group.

The estimated and experimental group efficiencies are shown in Figure 6 and it is seen that there is a good agreement for the S/D values of 3, 5 and 7.

## Load Distribution in Pile Group and Comparison with Single Pile

Figure 7 shows average pile load versus ground line deflection of individual piles of the pile group under static loading with S/D = 3. Average load on individual pile is computed by dividing the total load on the pile group by the number of piles. It is noted from the figure that the load distribution in the pile group is not uniform but it depends on the row position. For a given deflection, the front row piles carry about 15 % more load than the rear row piles. This is attributed to the shadowing effect due to group interaction. The rear row piles carry lesser load because of stress overlap with front row piles and subsequent reduction in the passive resistance.

The load deflection behaviour of single piles is also shown in Figure 7. At relatively smaller displacements, the average load carried by piles in the group is similar to that of the single pile. However, with increase in deflection, the average load carried by each pile in the group is significantly less than the single pile. The deflection of piles occurred in the group and single pile under static loading is given in Table 4.

For the same average pile load, front row piles deflect about 1.7 times more than that of the single pile, whereas the rear row piles deflect about 2 times more than that of the single pile. This is due to overlap of stress zones in the closely spaced pile group thereby reducing the lateral resistance. These results are in concordance with the observations made based on the full scale test of pile group carried out by Rollins et al. (1998) and centrifuge model studies by Ilyas et al. (2004).

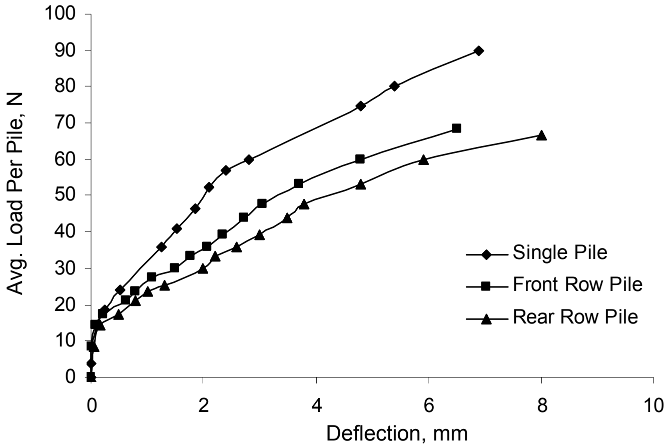



**Fig. 7 Average Load per Pile Vs. Deflection of Individual Piles of the Group: Static Loading (S/D = 3)**

**Table 4 Ground Line Deflection of Single Pile and Piles in the Group (S/D = 3) Under Static Loading**

| Average Load on Pile (N) | Deflection of Individual Single Pile (mm) | Deflection of Piles in Front Row of the Group (mm) | Deflection of Piles in Rear Row of the Group (mm) |
|---|---|---|---|
| 24 | 0.52 | 0.8 | 1.00 |
| 36 | 1.26 | 2.07 | 2.60 |
| 47 | 1.85 | 3.06 | 3.8 |
| 60 | 2.8 | 4.8 | 5.9 |

## Cyclic Lateral Behaviour

### Formation of Gap and its Progression

When the pile group is subjected to two-way cyclic lateral loading, separation and formation of gap occurred at pile-soil interface, which is shown in Figure 8. During half-cycle of the cyclic loading, the pile is pulled one side, forcing separation at rear side of the pile-soil interface thereby releasing stress and clay expands. It gets repeated on the other side during other half-cycle of the loading. As the stresses are developing on contact surfaces only, initially cracks are developed at the surface and then gaps occurred during subsequent cycles. The width and depth of the gap increased progressively as depicted in the figure. With increase in number of cycles of loading and remoulding of clay under repeated loading, the reduction in shear strength and degradation of stiffness is occurred. The size of gap formed depends on cyclic load ratio and number of cycles. The gap widened as large as about 10 mm (0.4 times the pile diameter) and penetrated up to a depth of 130 mm (5 times the pile diameter) at the end of cyclic loading with CLR of 0.8. In addition, heaving of clay has also occurred at the surface on both sides of the piles.

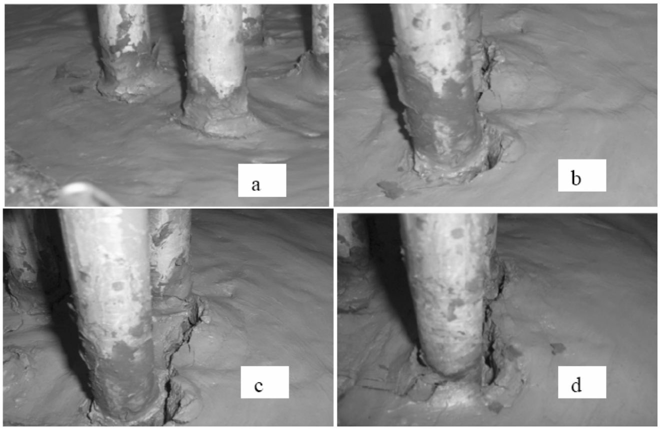



**Fig. 8 Formation of Gap and its Progression (S/D = 3, CLR = 0.8)**

## Buildup of Excess Pore Pressure

Typical pore pressure response measured using miniature pore pressure transducer embedded in clay at a depth of 150 mm (6D) and at a distance of 50 mm (2D) in front of the front row piles in the direction of loading is shown in Figure 9.

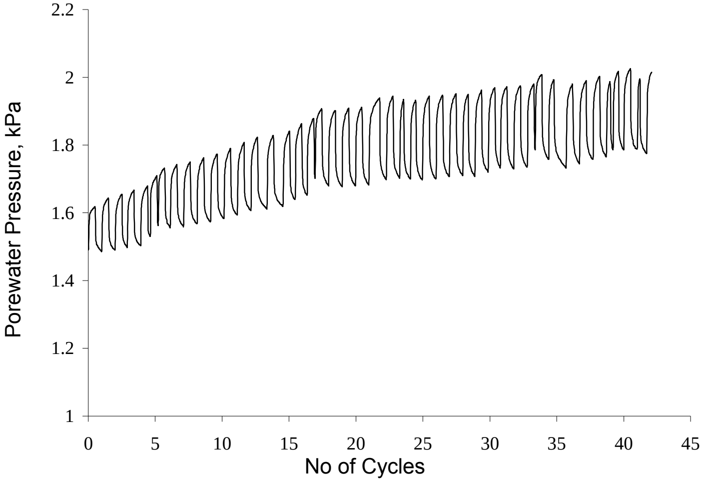



**Fig. 9 Typical Porewater Pressure Buildup in Soil (2 × 2 Group; S/D = 9; CLR = 0.65)**

During half-cycle of the cyclic loading pile moves and pushes the clay in front thereby increasing the passive earth pressure and subsequently generates excess pore pressure under undrained condition. During other half-cycle of the loading, soil expands causing reduction in pore pressure. The cumulative effect of repeated loading leads to increase in excess pore pressure with number of cycles of loading. This results in reduction of the shear strength of clay.

## Cyclic Response of Pile Group

### *Effect of Cyclic Load Ratio (CLR) on Pile Head Deflection*

Figure 10 shows the pile head deflection for a closely spaced 2 $\times$ 2 pile group under different magnitudes of cyclic loading i.e. for different values of CLR. It can be seen from the figure that at low magnitude of loading (CLR $<$ 0.5), the pile head deflection increases gradually with number of cycles but nonlinearly up to a certain number of cycles and then practically becomes constant irrespective of the increase in the number of cycles. But, at high magnitude of cyclic loading (CLR $>$ 0.5), as shown in Figure 10, there is a steep rise in deflection within a few number of cycles and it gradually increases with the increase in the number of cycles. The sudden steep rise of deflection is mainly due to the formation of gap around the piles up to a depth of five times the pile diameter from the surface which leads to reduction of passive resistance of the soil. Poulos (1982) defined *Critical Cyclic Load Level* as the cyclic load at which a dramatic increase in deflection occurs. In the present study, the critical cyclic load level is corresponding to CLR of 0.65. For 100 cycles of loading, the deflection at CLR of 0.65 is about 4.4 times that for CLR of 0.35 for the closely spaced pile group as shown in Figure 10. A similar behaviour is observed for the groups with S/D ratios of 5, 7 and 9.

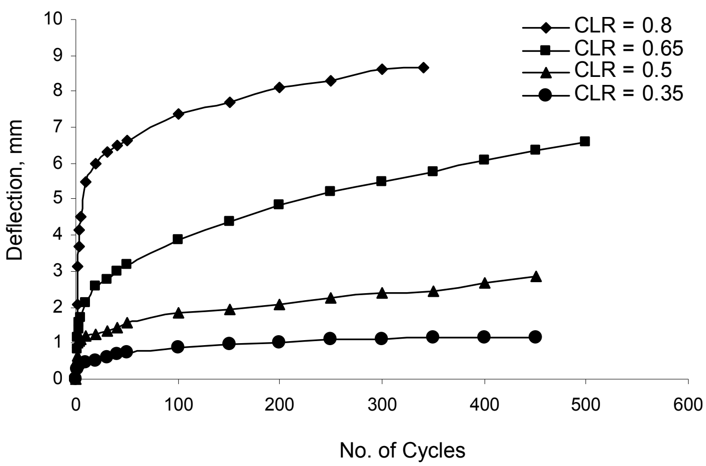



**Fig. 10 Deflection Vs. Number of Cycles for the Pile Group (S/D = 3)**

### *Effect of Number of Cycles of Loading on Load Deflection Behaviour*

The load-deflection behaviour of 2 × 2 pile group (S/D = 3) at different number of cycles of loading is shown in Figure 11. The nature of load-deflection curves at different cycles of loading indicates nonlinear behaviour of pile group. It can be easily noticed from Figure 11 that the degree of nonlinearity increases with increase in the number of cycles of loading. At low number of cycles, the nonlinear behaviour is related to degradation of stiffness of the soil due to pore pressure buildup as shown in Figure 9. But at higher number of cycles, the strong nonlinear behaviour of the pile group is related to both the formation of gaps around the piles up to a certain depth and degradation of stiffness of the soil due to pore pressure. It can be found from Figure 11 that the deflections of the pile group subjected to very high magnitude of cyclic load (CLR = 0.80) are: 2.09, 4.53, 5.48, 6.62 and 8.6 mm corresponding to 1, 5, 10, 50 and 300 cycles of loading. This clearly indicates that the deflection at 300 cycles of loading is about 4 times more than that at first cycle. But a major portion of increase in deflection occurs in the first 50 cycles of loading − 3 times more than that at first cycle (75% of total deflection at 300 cycles). Moreover, the first 10 cycles of loading are very much critical accounting for more than 2 times increase over that at first cycle (50% of total deflection at 300 cycles). Within the first few cycles of loading, the gap is formed and extends width and depth-wise with the number of cycles. During subsequent cycles of loading, the piles encountered reduced resistance in the softened zone produced by previous loading. After large number of cycles of loading, the soil gets stiffened, causing reduction in the rate of increase of deflection.

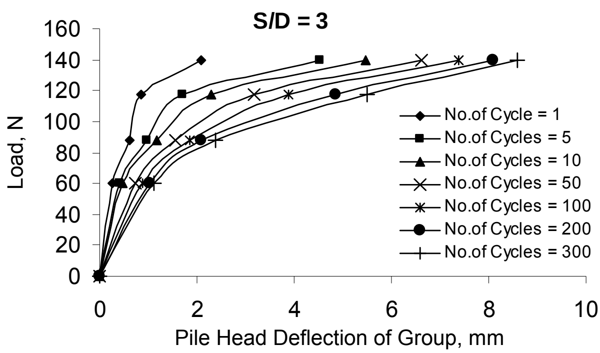



**Fig. 11 Load–Deflection Behaviour of Pile Group at Different Number of Cycles**

### *Effect of Pile Spacing on Load Deflection Behaviour*

The load-deflection curves obtained for 2 × 2 pile group with different pile spacing at 50 number of cycles of loading are shown in Figure 12. For a given load, the deflection at 50 cycles for groups with S/D ratios of 9 and 7 are less, whereas large deflections occur for groups with S/D ratios of 5 and 3. This is attributed to group interaction effect (i.e. shadowing effect) due to overlapping of stress zones. For the closely spaced pile groups (S/D = 3 and 5), when the piles are subjected to two-way cyclic loading, due to stress overlap, the entire soil column enclosed by the pile group moves as a single block in one direction during first half-cycle of the loading and in other direction during second half-cycle of the loading. This is depicted in Figure 13, where the clear shearing plane extending to full width of the pile group in the direction of loading is observed in addition to the gap at the pile–soil interface in front of the piles. Occurrence of block failure mode, under cyclic lateral loading for closely spaced pile groups remoulds and softens the soil column within the group thereby offering less resistance for subsequent cycles of loading, leading to very large deflections. As the spacing of piles in the group increased, the overlap of stress zones reduces.

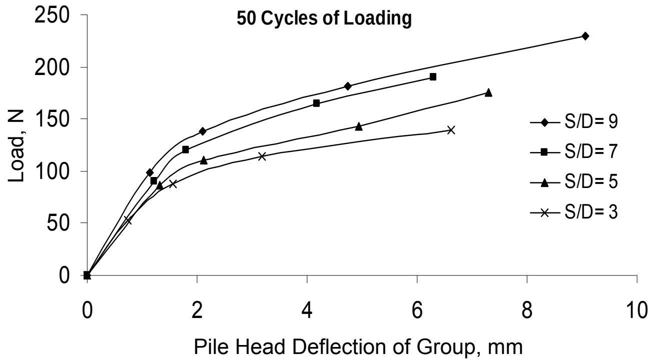



**Fig. 12 Effect of Pile Spacing on Load–Deflection Behaviour of 2 × 2 Group: Cyclic Loading**

**Fig. 13 Block Failure of Closely Spaced Pile Group (S/D = 3)**

For pile groups with S/D ratios of 7 and 9, both the gap formation and heaving occurred and soil near the pile (approximately 2D) gets softened but the remaining portion of the soil is relatively unaffected as depicted in Figure 14. When the spacing between the piles is reduced below 7D, a very large deflection is noticed as shown in Figure 12. For the 2 × 2 pile group considered in the present study, the critical spacing under cyclic lateral loading corresponds to S/D ratio of 7. The similar behaviour is observed for other number of cycles of loading, as evident from Figure 15.

**Fig. 14 Gap Formation and Heaving in Widely Spaced Pile Group (S/D =9)**

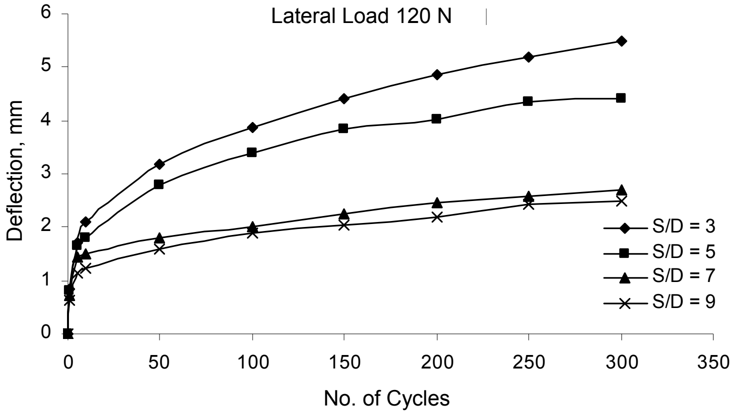



**Fig. 15 Effect of Number of Cycles on Pile Head Deflection of the Group**

For the same magnitude of load (120 N), which is 2 times the static capacity of single pile, the pile group deflections observed at 300 cycles are: 2.5, 2.71, 4.42 and 5.52 mm for S/D ratios of 9, 7, 5 and 3 respectively. This clearly demonstrates the occurrence of large deflections as the pile spacing reduces below the critical value of 7D. The deflection of the group with S/D = 3 is about 2 times more than that of the group with S/D = 7, which brings out the effect of group interaction.

## Comparison between Static and Cyclic Behaviour of Single Pile

The load–deflection curves of single pile subjected to static and cyclic loading are shown in Figure 16. Effect of cyclic loading is clearly observed as large deflections occurred due to the formation of gap, buildup of pore pressure and degradation of the stiffness of clay. It can be found from the figure that there is a significant reduction in the lateral capacity of the pile subjected to cyclic loading in comparison to the static loads. The ultimate lateral capacities of single pile under both the static and cyclic loading are given in Table 5. The static ultimate capacity of single pile, corresponding to a deflection of 20% pile diameter (5 mm), is 60 N, but the lateral capacity is 49 N under the cyclic loading at 50 cycles. It is clearly observed that the ultimate lateral capacity of single pile is reduced by about 20% due to 50 cycles of loading. This observation is in consistent with results of full scale test by Rollins et al (2006a).

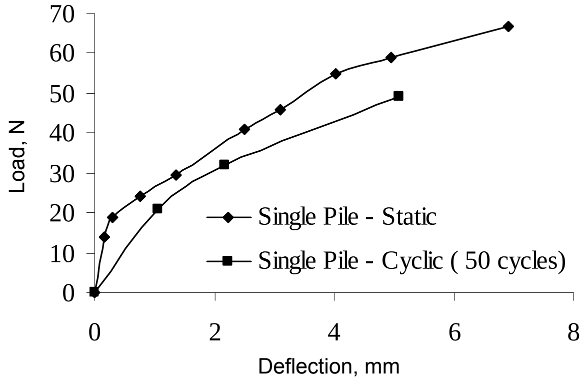



**Fig. 16 Load-Deflection Behaviour of Single Pile under Static and Cyclic Loading**

**Table 5 Ultimate Lateral Capacities of Single Pile and Pile Group**

| *Sl. No.* | *Pile Arrangement* | *S/D* | *Ultimate Lateral Capacity (N)* | |
|---|---|---|---|---|
| | | | *Static Loading* | *Cyclic Loading ( 50 Cycles)* |
| 1 | Single Pile | | 60 | 49 |
| 2 | Pile Group (2 × 2) | 3 | 174 | 120 |
| | | 5 | 213 | 150 |
| | | 7 | 236 | 180 |
| | | 9 | 282 | 195 |

## Combined Effect of Cyclic Loading and Group Interaction

The load–deflection curves of closely spaced pile group (S/D = 3) under static and cyclic loading are shown in Figure 17. At low levels of loading, pile group behaviour under both the static and cyclic loading follow similar pattern. But at higher load levels, the deflection of pile group under cyclic loading is much higher than that for static loading. The increasing effect of cyclic loading with increased load level on pile group behaviour is clearly depicted in the figure.

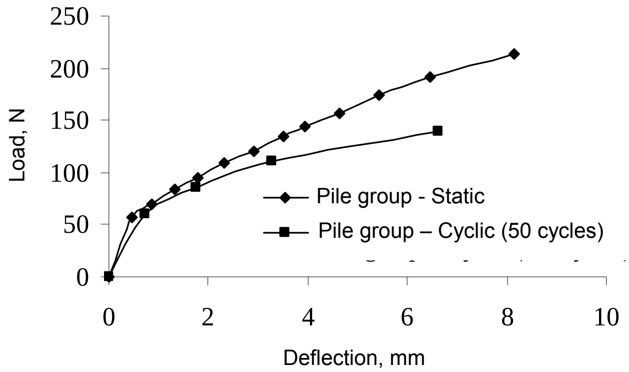



**Fig. 17 Load-Deflection Behaviour of Pile Group under Static and Cyclic Loading**

The ultimate lateral capacities of pile group, corresponding to a deflection of 20% of pile diameter (5 mm), for various spacing of piles under 50 cycles of loading is also given in Table 5. The table indicates that the lateral capacity of the closely spaced (S/D = 3) pile group under cyclic loading is 120 N, which is about 31% less than the static capacity. The percentage reduction in lateral capacity for pile group is higher than that for single pile which indicates the predominant effect of cyclic loading on the pile group than for the single pile. This observation is consistent with the results of full scale test by Brown et al.(1987). It is clearly noted from Table 5 and also clearly observed from Figure 12 that the lateral capacity of pile group with S/D =3 is about 40 % less than that for pile group with S/D =9 under 50 cycles of loading. It is clearly noted that the combined effect of cyclic loading and group interaction − the formation of gap, buildup of pore pressure and occurrence of block mode of failure, lead to the higher reduction in the ultimate capacity of the pile group.

## Conclusions

The following conclusions are drawn from the experimental study conducted on the model single piles and 2 × 2 pile group under static and cyclic lateral loading:

> Front row piles carry about 15% more load than rear row piles of the pile group for a given displacement under static lateral loading.

> The critical spacing in the direction of loading is about seven times the diameter of pile for the 2 × 2 pile group investigated in the present study.

> The critical cyclic load level is found to be corresponding to CLR of 0.65 and the corresponding deflection of the pile group is about four times higher than that at CLR of 0.35 for hundred cycles of loading.

> The deflection of the pile group increases with number of cycles of loading. The first ten cycles of loading is very much critical as it accounts for more than two times increase of deflection over that at first cycle.

> The lateral capacity of single piles under cyclic loading is about 20% less than the static case but the group capacity under cyclic loading is about 30% less than the static group capacity which indicates the predominant effect of cyclic loading on the pile group than for the single pile.

> Block mode of failure has occurred for closely spaced (S/D less than 5) pile groups under cyclic lateral loading.

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