TECHNICAL NOTES

MODEL PILE GROUP SUBJECTED TO CYCLIC LATERAL LOAD

ALAM SINGH* and SHAMSHER PRAKASH**

ABSTRACT

A 4-pile group of vertical, flexible piles embedded in dense sand was subjected to cyclic lateral load, with and without vertical load acting on cap. Conditions of free rotation and no rotation of the cap were imposed. A single pile was also tested. Effect of cyclic load on horizontal deflection, rotation of cap and moments induced in the piles has been investigated. The deflection, rotation and moment were observed to increase at a decreasing rate with cyclic loading. Cap restraint reduced the corresponding changes. Effect of vertical load was not of significance.

Key words: model test, pile group, repeated loading, sand

IGC: E2/E4

INTRODUCTION

Horizontal forces may form a major part of the loading system for structures supported on pile groups, such as bridge abutments, piers, fenders, dolphins, quays, anchorages for water-front structures and retaining walls. These forces may often be repetitive or cyclic in nature, and include forces due to earthquake shocks and those due to traffic and wind in case of bridges and the ones caused by the impact of ships during berthing, and by wave, wind and current pressures. A study of pile groups subjected to cyclic, lateral load is, therefore, of significance for the design of such structures.

Prakash (1962) tested a 4-pile group of instrumented, aluminium model piles in loose sand under cyclic lateral load applied at the ground line. The group was free to undergo rotation at the cap level. In actual problems, the interaction of super-structure with the foundation may introduce head restraint. Also, a vertical load may simultaneously act with the lateral load. Murthy (1964) studied the effect of cyclic, lateral load on instrumented pile bents. Chandrasekaran (1967) and Prakash and Chandrasekaran (1970) tested 4-pile groups of vertical and batter model piles. The spacing of the piles at the

* Professor & Head of Civil Engineering Department, University of Jodhpur, Jodhpur, (Rajasthan), India.

** Professor of Soil Dynamics, University of Roorkee, Roorkee (U.P.), India.

bottom of the cap was 3 times the pile width. The piles were, however, not instrumented and only deflection and rotation of the cap could be measured at the ground surface.

The investigations reported herein envisaged an experimental study of the behaviour of a 4-pile group of flexible, vertical piles under cyclic, lateral load applied to the cap situated at the ground line. The effects of vertical load and cap-restraint were also studied. The piles were instrumented with electric resistance strain gauges. A single pile was also tested for comparative purposes. All tests were performed in dense sand.

MATERIALS AND APPARATUS

Clean coarse-medium sand with the following characteristics was used as the soil medium: coarse fraction (1.18 mm — 600 micron) = 43 %, medium fraction (600 micron — 212 micron) = 51 %, fine fraction (212 micron — 75 micron) = 6 %, effective size = 0.27 mm, uniformity coefficient = 2.4, coefficient of curvature = 0.9, maximum voids ratio = 0.67, minimum voids ratio = 0.44, relative density = 80 %, angle of shearing resistance = 46 degrees.

The model pile consisted of extruded, aluminium alloy tubing, 12.7 mm square in section with 1.6 mm thick wall and flexural stiffness (EI) as $10.42 \times 10^4 \text{ kg-cm}^2$. The piles were fully embedded to a depth of 61 cm, which corresponded to a non-dimensional depth coefficient greater than 5, and made the piles behave as flexible, infinitely long ones (Davisson, 1960). Four piles, fixed to a rigid cast aluminium plate, at a centre to centre pile spacing equal to 4 times the pile width (B) and arranged in a square pattern, formed the test group. One of the front corner piles (which may be designated as F_1) and its rear corner pile (R_1) and the single reference pile were instrumented with electric resistance strain gauges at a close spacing of 3 cm centre to centre on both the front and back faces, normal to the plane of lateral loading. The gauges had the following specifications; type SA-10 flat grid, gauge factor $2.06 \pm 2\%$, resistance 119.1 — 0.2 ohms, overall size $24 \times 12 \text{ cm}$ and gauge length $10 \times 5 \text{ cm}$. The line of action of the lateral load was kept parallel to the sides of the pile group and passed centrally through the cap.

The tests were performed in a model tank 120 cm by 120 cm in plan and 120 cm in depth. The working of the model tank and its various fittings have been reported elsewhere (Singh, 1970). The lateral loads were applied to the single pile and the pile group at the ground level by means of a flexible wire rope passing over aluminium pulleys provided with ball bearings. The lower end of the wire rope carried the load pan. The vertical load could be applied centrally on top of the group from a loading head through a calibrated proving ring. The head restraint for controlling rotation of the cap could be applied by means of a balancing couple through a system of couple arms with front and rear load pans (Singh, 1970). Fig. 1 shows the set-up for lateral and vertical loading. Fig. 2a and 2b show the set-up for rotation control. By placing equal weights in the front and rear load pans (Fig. 2) a couple in the form of a pure moment could be transmitted to the pile cap through a system of ball bearing and pulleys. A sensitive bubble-

Fig. 1. Set-up for Lateral and Vertical Loading

Fig. 2a & 2b. Set-up for Rotation Control

tube level accurate to 1×10^{-4} radians per division was kept to check the horizontal position of the cap and as soon as a slight tilt was observed the couple was increased.

The horizontal displacement of the pile cap was measured by a dial gauge fixed in contact with the rear face of the cap. Two dial gauges mounted on top of the cap in the plane of lateral loading were used for measuring rotation when the cap was free to rotate.

TESTS PERFORMED

The following four types of tests were performed:

Test 1: The test was performed on the single pile by increasing the horizontal load in increments of 2, 3.5 and 6 kg. This constituted the first application of the load. The

horizontal deflection of the cap was measured for all the three load increments, but the strains were measured for the 6 kg load only. The load was removed in the same order and re-applied. The deflection of the cap was measured. The procedure was repeated upto 5 cycles, after which the application or removal of the 6 kg load was done as a single load. The pile was subjected to one hundred cyclic applications of the 6 kg load. The deflection of the cap was measured at 10, 25, 50, 75 and 100 cycles and the strains were measured at 25, 50, 75 and 100 cycles. The maximum limit of 6 kg load for cycling loading was decided after a preliminary sustained load—deflection test on the single pile. Fig. 3 shows the static sustained load test curve for the single pile. It was anticipated that the cyclic load of 6 kg would be low enough in comparison with the failure load so as not to extend the behaviour of the pile-soil system to the plastic range on repetitive loading. Fig. 3 shows also the sustained load-deflection curves for the 4-pile group under free-rotation and zero-rotation conditions of the cap. For plotting the load-deflection curves for the group, the total horizontal load on the group has been divided by the number of piles, i.e., four, to get the average load per pile so that the behaviour of the group and the single pile may be plotted on common axes in the same figure for comparison purposes.

Fig. 3. Sustained Load Versus Deflection

Test 2: The test was performed on the 4-pile group with the cyclic-application of 24 kg horizontal load, i.e., 4 times the load on the single pile. Upto 3 cycles, the load was increased and removed in increments at 8, 14 and 24 kg and the deflection and rotation of the cap were measured. For subsequent cycles upto 100, the load was applied or removed as one lot by lifting the load platform manually. Deflections and rotations were recorded for 4, 5, 10, 25, 50, 75 and 100 cycles and strains were measured for the first cycle and for 25, 50, 75 and 100 cycles.

Test 3: As a first part of the test, the pile group was loaded to a constant vertical load

of 164 kg and the initial strains were recorded. It was then subjected to the cyclic application of the 24 kg horizontal load in a manner similar to that of Test 2.

The vertical load for the group was selected on the basis of vertical load—settlement tests on the single pile and the group (Singh, 1969). These tests indicated the ultimate bearing capacity of the single pile as about 50 kg, which was very much lower than the theoretical buckling load of about 900 kg according to Davisson (1960). By adopting the average pile load as 41 kg, the group was loaded to 164 kg. Tests had also indicated the bearing capacity of the group much higher than that of the single pile and the group was able to sustain the load of 164 kg at a settlement not exceeding 4×10^{-2} cm (Singh, 1969).

Test 4: The test was performed in the same manner as Test 2, but with the difference that the pile cap was maintained horizontal.

TEST RESULTS AND DISCUSSION

The flexural strains measured for the instrumented piles of the group (F_1 and R_1) and the single pile were converted into moment curves by data processing on an IBM-7044 digital computer. Deflection versus depth curves for the single pile were also obtained.

Horizontal Deflection and Rotation

The curves of cyclic load versus horizontal deflection at ground line for the single pile (Test 1) and the 4-pile group (Tests 2, 3 & 4) are plotted in Fig. 4. Horizontal deflec-

Fig. 4. Cyclic Load Versus Deflection

tion versus number of cycles of load repetition for all the four tests are given in Fig. 5. Fig. 6 shows the curves of depth versus deflection for the single pile at different cycles of loading. The variation of rotation with number of cycles is shown in Fig. 7. Typical values of deflection and rotation, expressed as percentages of the respective values for the first cycle, are tabulated in Table 1.

Fig. 5. Deflection Versus Cycles

Fig. 6. Depth Versus Deflection for Single Pile

Fig. 7. Rotation Versus Cycles

Table 1. Effect of Cyclic Load on Horizontal Deflection and Rotation
(The deflection and rotation for the various cycles are expressed as percentages of the corresponding values for the first cycle).

(a) Deflection y_g					(b) Rotation θ_g		
Cycle	Test 1	Test 2	Test 3	Test 4	Cycle	Test 2	Test 3
1	100	100	100	100	1	100	100
10	133	130	132	123	10	137	124
25	155	155	159	142	25	174	152
50	171	173	184	154	50	186	172
75	182	183	194	164	75	198	186
100	189	190	206	172	100	208	297

A study of the curves of Figs. 4 to 7 and tabulated data of Table 1 lead to the following inferences:

(i) Both the horizontal deflection (y_g) and rotation (θ_g) of the cap at ground level increase, at a decreasing rate, under cyclic loading. The maximum increase is observed to be about 100% of the value at the first cycle (Table 1). About one-third of the total increase occurs at 10 cycles and one-half at 25 cycles. The increase in the values of y_g and θ_g is relatively very small in the cyclic range from 75 to 100 in each case. The pile-soil system thus tends to become progressively more elastic with the increase of number of cycles. This typical behaviour can, however, be expected only when the magnitude of the cyclic load is small in comparison with the failure load.

A comparison of the percentage increase in deflection (y_g) over deflection at sustained load level with number of cycles with test data of Prakash and Chandrasekaran (1970) is shown in Fig. 8. In their tests the pile size was 15 mm diameter with 2.5 mm wall thickness and the cyclic load level was 24 kg, but the spacing of the piles was 3-dia centre to centre. A fair tally of the two results has been obtained because of the non-dimensional nature of the plot.

Fig. 8. Comparison of Author's Data with those of Prakash and Chandrasekaran (1970)

(ii) The behaviour of a single pile and a 4-pile group at pile spacing 4 times the pile width and under free rotation condition of the cap seems to be very much similar so far as the percentage increase in deflection is concerned. Such a coincidence was also observed in the sustained load-deflection behaviour (Fig. 3).

(iii) The vertical load, subject to the limitations of the magnitude used in the tests, does not appear to influence the percentage increase in deflection and rotation.

(iv) A restraint to the rotation of the pile cap reduces not only the deflection under sustained loading (Fig. 3) but also appears to be significant in lowering the percentage increase in deflection on cyclic loading (Test 4).

(v) The deflection tends to extend to greater depths of the pile with increased cycles of loading (Fig. 6, Test 1). The maximum depth affected by deflection is observed to correspond to 75–100 cycles in Test 1.

Bending Moment

The moment curves for the 4 tests are plotted in Fig. 9 and 10 and the typical percentage

Table 2. Effect of Cyclic Load on the Maximum Positive Moment (+ M) and the Negative Moment (– M). (The Moments for the various cycles are expressed as percentage of the values for the first cycle).

Cycle	Test 1	Test 2			
		F_1		R_1	
		+ M	– M	+ M	– M
1	100	100	100	100	100
25	112	156	105	154	100
50	118	174	109	169	96
75	132	193	112	184	91
100	133	202	124	195	84

Cycles	Test 3				Test 4			
	F_1		R_1		F_1		R_1	
	+ M	– M	+ M	– M	+ M	– M	+ M	– M
1	100	100	100	100	100	100	100	100
25	153	107	138	97	124	119	117	109
50	176	117	154	95	130	125	122	118
75	184	134	162	76	137	125	126	120
100	193	137	169	75	139	129	128	120

increases are tabulated in Table 2. The maximum moments below the ground line have been designated as positive (+ M) in Table 2 and negative (– M) at the ground line. A study of these test data leads to the following inferences:

(i) The piles of the group are more sensitive to changes in moments due to cyclic loading than a single pile. Whereas the percentage increase in the maximum positive moment at 100 cycles for a single pile is only about 33%, it may be of the order of about 100% for the piles of a 4-pile group under free rotation.

(ii) The positive moments below the ground are affected to a greater extent than the negative moments at the ground line.

(iii) The presence of the vertical load does not appear to materially affect the percentage changes in the moments with increased cycles of loading (Table 2).

(iv) Cap restraint decreases the percentage changes in moments compared to free rotation condition.

Fig. 9. Moment Versus Depth, Tests 1 and 2

Fig. 10. Moment Versus Depth, Tests 3 and 4

CONCLUSIONS

The following conclusions may be drawn on the basis of the limited tests reported in this paper:

1. A cyclic, lateral load increases, in general, the deflection, rotation and bending moment of a single pile and the piles of a group. This increase occurs at a decreasing rate with the number of cycles, and the soil-pile system tends to become progressively more elastic after certain repetitions of load, provided the lateral load is not large enough to cause plastic failure.
2. A 4-pile group at pile spacing 4 times the pile width behaves similar to a single pile with respect to changes in horizontal deflection at the ground level. The piles of the group are, however, more sensitive to changes in moments compared to a single pile.
3. An average, vertical load per pile on the group upto an order of 4-5% of the theoretical buckling load for the single pile does not appear to materially affect the group behaviour.
4. A restraint to the rotation of the cap reduces the percentage increase in deflections and moments.

It may be worthwhile to study further the effect of greater vertical loads on the pile groups subjected to cyclic, lateral loading. Larger pile groups with different arrangements of piles deserve investigation in various types of soils.

ACKNOWLEDGEMENT

The work reported herein was carried out in the Department of Civil Engineering, University of Jodhpur. It formed part of a research scheme on "Investigations of Pile Groups under Lateral and Vertical Loads," financed by the University.

REFERENCES

- Chandrasekaran, V. (1967): "A Study of Behaviour of Battered Pile Groups under Lateral Cyclic Loads", M. E. Thesis, University of Roorkee, Roorkee.
- Davison, M. T. (1960): "Behaviour of Flexible Vertical Piles Subjected to Moment, Shear and Axial Load". Ph.D. Thesis, University of Illinois, Urbana.
- Murthy, V. N. S. (1964): "Behaviour of Batter Piles Subjected to Lateral Loads", Ph.D. Thesis, Indian Institute of Technology, Kharagpur.
- Prakash, S. (1962): "Behaviour of Pile Groups Subjected to Lateral Loads," Ph.D. Thesis, University of Illinois.
- Prakash, S. and Chandrasekaran V. (1970): "Deflections of Battered Pile Groups Under Cyclic Lateral Loads," Proc. Second South East Asian Regional Conference on Soil Engineering, June 11-15, Singapore.
- Singh, A. (1969): "Investigations of Pile Groups under Lateral and Vertical Loads", Ph.D. Thesis, University of Jodhpur, Jodhpur.
- Singh, A. (1970): "A Laboratory Model Tank for Testing Pile Groups," All India Convention on Instrumentation and Automation, Birla Institute of Technology, Ranchi, March, pp. 165-176.

(Received November 17, 1970)