TECHNICAL NOTE

UPLIFT CAPACITY OF RIGID STEEL PILE GROUPS
IN CLAY

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ABSTRACT

Laboratory model test results for the ultimate uplift capacity of group piles embedded in clay have been presented. The length-to-diameter ratios of the group piles tested under this program have been kept at 12 and 15. The group uplift efficiency varies with the embedment ratio, number of piles in the group, and the center-to-center spacing of the piles. For the present tests, a group efficiency of about 100% is reached at a center-to-center spacing of 6 to 7 pile diameters.

Key words : cohesion, clay, pile group, uplift capacity (IGC : E 4)

INTRODUCTION

The net ultimate uplift capacity of a single pile embedded in saturated clay (Fig.1) can be expressed in the form

$$Q_u = Q_u' - W_p = p L \alpha c_u \quad (1)$$

where Q_u' = gross ultimate uplift capacity, Q_u = net ultimate uplift capacity, W_p = weight of the pile, p = perimeter of the pile cross-section, L = length of embedment, c_u = undrained cohesion of the clay, and α = adhesion factor.

In a previous paper, Das and Seeley (1982) have presented a number of laboratory model test results for the ultimate uplift capacity of single piles embedded in clay along with

other existing results presently available in literature.

In many circumstances, however, piles are used in groups. A limited number of experimental results for the ultimate uplift capacity of group piles embedded in sand are presently available in the works of investigators such as Chaudhuri, Ghataora, and Symons (1982), Das, Seeley, and Smith (1976), and Meyerhof and Adams (1968). In contrast to that, except for a few model test results by Meyerhof and Adams (1968), published works relating to the ultimate uplift capacity of group piles embedded in clay are practically nonexistent.

The purpose of this paper is to present

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Fig. 1. Geometric parameter for a pile embedded in clay and subjected to uplift load

the results of some recent laboratory model tests on group uplift capacity of piles in clay. The present study is limited to pile embedment ratios varying from 10 to 18. Also, the maximum number of piles used in a group is limited to six for the present study.

LABORATORY MODEL TESTS

Laboratory model tests were conducted with a total of six model steel piles. Each of these piles had a diameter of 25.4 mm and a length of 0.457 m. For conducting tests on group piles at various center-to-center-spacing-to-diameter ratios, the piles were attached to an aluminum cap having dimensions of 0.457 m $\times$ 0.457 m. The aluminum cap was made out of a plate having a thickness of 9.53 mm. Holes were drilled through the pile cap at various spacings, and also at the top of each model pile. The piles were attached to the cap in various configurations by means of screws.

Model tests were conducted in a box measuring 1 m $\times$ 1 m $\times$ 0.8 m (height). The sides of the box were heavily braced to avoid

lateral yielding.

The clay used for the model tests had 88% passing No. 40 U.S. sieve (0.425 mm), 80% passing No. 60 U.S. sieve (0.25 mm), and 59.7% passing No. 200 U.S. Sieve (0.075 mm). The liquid and plastic limits of the soil were 32% and 18%, respectively. A large amount of pulverized clay was mixed with the required amount of water and mixed thoroughly. The moist soil was stored in sealed plastic bags for a week in a moist, humid room before use.

For conducting the model tests, the moist soil was poured into the test box in batches and compacted in layers about 50.8 mm thick. The compaction was done by means of a flat-bottomed rammer. After the compaction, the piles with the desired configurations attached to the cap were pushed into the clay by means of a hydraulic jack using a guided sleeve. A steel cable was attached to the top of the pile cap, and the cable passed over two pulleys. A load hanger was attached to the other end of the cable. Step loads were applied to the load hanger, and a time lapse of 5 to 8 minutes was allowed between each step load. The vertical displacement of the pile groups after each step load application was measured by a dial gauge. Fig. 2 shows a schematic diagram of the laboratory test arrangement.

The plans of the configuration of group piles tested under this program are shown in Fig. 3. Other details of the laboratory

Fig. 2. Schematic diagram of the laboratory model test arrangement for ultimate uplift capacity of group piles

Fig. 3. Configurations of group piles tested

model tests are given in Table 1.

MODEL TEST RESULTS

The net ultimate pullout loads (Q_u) as

determined from the laboratory for tests on single piles (1x1 configuration) are shown in Fig. 4 as a function of the embedment ratio, L/D . As expected, the ultimate pull-out load in a given type of soil (i.e., a given c_u) increased with the embedment ratio of the model pile.

According to Eq. (1), the adhesion factor

$$\alpha = \frac{Q_u}{pLc_u} \quad (2)$$

By using the preceding equation and the experimental values of Q_u (Fig. 4), p , L , and c_u , the adhesion factors for each test (No. 1 through 12) have been calculated and these are shown in Fig. 5. Also shown in this figure are the range of α values obtained from the laboratory model tests of Bhatnagar (1969), Ali (1968), and Das and Seeley (1982). As can be seen from this plot, the present experimental values are in the general range. The average values of α obtained from the present tests are given below.

c_u (kN/m ²)	Average α
9.97	0.45
16	0.407
26.2	0.234

Hedegus and Khosla (1984) have recently presented the field pullout test results of H-piles in stiff clays. The deduced values of α from these field tests are as follows:

Table 1. Details of laboratory uplift tests on group piles

Test No.	Average c_u^* (kN/m ²)	Embedment ratio, L/D	Group configuration**	Average unit weight of compaction of soil, γ (kN/m ³)	Average moisture content (%)	Average degree of saturation (%)
1, 2, 3, 4	9.97	10, 12, 15, 18	1x1	18.92	29.2	98
5, 6, 7, 8	16.0	10, 12, 15, 18	1x1	19.83	21.6	94
9, 10, 11, 12	26.2	10, 12, 15, 18	1x1	20.63	18.0	95.2
13-18	9.97	12	2x1	18.92	29.2	98
19-22	9.97	12	3x1	18.92	29.2	98
23-27	9.97	12	2x2	18.92	29.2	98
28-31	9.97	12	3x2	18.92	29.2	98
32-36	9.97	15	2x1	18.92	29.2	98
37-41	9.97	15	2x2	18.92	29.2	98

* Determined from unconsolidated-undrained triaxial tests

** Refers to Fig. 3

D =pile diameter

Fig. 4. Plot of Q_u vs. L/D for single piles (1x1 configuration)

Fig. 5. Plot of adhesion factor vs. L/D

Undrained cohesion, c_u (kN/m ²)	α	
	Assuming soil plug develops between flanges	Assuming actual pile surface
196.5	0.25	0.21
134.1	0.17	0.15

The preceding values are in the general range shown in Fig. 5.

The net ultimate uplift capacity of group piles can be expressed as

$$Q_{ug} = Q_{ug}' - W_{pg} \quad (3)$$

Fig. 6. Variation of Q_{ug} against S/D

where Q_{ug}' = gross ultimate capacity of a group of piles, Q_{ug} = net ultimate capacity of a group of piles, and W_{pg} = weight of piles in the group and cap.

By using the preceding equation, the net ultimate uplift capacities of group piles tested under this program (Tests No. 13 through 41) have been determined and are plotted in Fig. 6 (i. e., Q_{ug} vs. S/D ; where S = center-to-center spacing of the piles in the group). According to the conventional definition of group efficiency, η

$$\eta = \frac{Q_{ug}}{nQ_u} \quad (4)$$

where n = number of piles in a group.

Using the experimental values of Q_{ug} given in Fig. 6 and the experimental values of Q_u given in Fig. 4 [Note: for $c_u = 9.97$ kN/m², $L/D = 12$, $Q_u = 117.42$ N (test No. 3); and for $c_u = 9.97$ kN/m², $L/D = 15$, $Q_u = 127.2$ N (test No. 4)], the variations of η with S/D have been calculated. These are shown in Fig. 7. From this plot, the following observations may be made:

1. For a given pile configuration, the group efficiency increases approximately linearly with the S/D ratio until it reaches 100%. This is similar to that observed for pile groups in clay subjected to compressive loading (for example, Whitaker, 1957). It needs to be pointed out, however, that the

Fig. 7. Variation of group efficiency with S/D for various pile group configurations

model tests conducted by Whitaker were push-in tests. The present tests are pullout tests for piles. For the present pullout tests, the S/D ratio at which the group efficiency of 100% is reached appears to depend upon the embedment ratio (L/D) and is independent of the number of piles present in a group. For pile groups with $L/D=12$, the value of $(S/D)_{\eta=100\%}$ is about 6. Similarly, for pile groups with $L/D=15$, the values of $(S/D)_{\eta=100\%}$ is about 7.5. Thus, $(S/D)_{\eta=100\%} \approx 1/2 (L/D)$.

2. For a given type of soil (i.e., c_u) and S/D , the efficiency η generally decreases with the increase in number of piles in the group. This fact is demonstrated in Fig. 8 which shows a plot of group efficiency against number of piles in a group (for $L/D=12$ and 15) at $S/D=2$ and 4. It needs to be pointed out that, for pile groups with $L/D=15$, only two actual data points are available for each S/D (i.e., 2 and 4). For that reason, discontinuous curves have been plotted.

Fig. 8. Variation of group efficiency with the number of piles in the group and S/D

3. For a given type of soil and S/D and number of piles in a group, the group efficiency appears to decrease with the increase of the embedment ratio. For $S/D < 6$, the difference ranges from between one to about 5%.

The present tests have been conducted for embedment ratios of 12 to 15. For comparison purposes, the laboratory model test results of Meyerhof and Adams (1968) with a group pile configuration of 2×1 and $L/D=20$ are also shown in Fig. 7. The trend appears to be similar to that observed in the present tests. The results presented in Fig. 7 show that, at a S/D ratio of about 6 to 7, the group efficiency reaches a magnitude of about 100%.

CONCLUSIONS

A number of laboratory model test results for the ultimate uplift capacity of pile groups embedded in clay have been presented. More laboratory and field test results are necessary in the future to develop a rational method of estimation of group efficiency of piles under uplifting load. However, based on the present tests, the following general conclusions can be drawn.

1) The variation of the adhesion factor,

α , as obtained from the present tests, falls in the general range of values obtained by previous investigators.

2) For similar soil, embedment ratio, and group pile configuration, the group efficiency increases linearly with S/D . The magnitude of η reaches a value of about 100% at $S/D \approx 6$ to 7. Other quantities remaining the same, group efficiency decreases with the increase of number of piles in the group and also the embedment ratio (L/D).

NOTATIONS

c_u =undrained cohesion
 D =pile diameter
 L =embedment length
 n =number of piles in a group
 p =perimeter of pile section
 Q_u =net ultimate uplift capacity of single piles
 Q_u' =gross ultimate uplift capacity of single piles
 Q_{ug} =net ultimate uplift capacity of pile group
 Q_{ug}' =gross ultimate uplift capacity of pile group
 W_p =weight of single pile
 W_{pg} =weight of group piles
 α =adhesion factor
 γ =unit weight of soil

η =group efficiency

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