Model Uplift Tests on Pile Groups in Sand

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ABSTRACT

Laboratory model test results for determination of the efficiency of group piles embedded in sand and subjected to uplifting load are presented. The tests have been conducted in loose and dense sand. For the pile groups tested, it appears that in loose sand the group efficiency of piles reaches approximately 100 percent at center-to-center pile spacings of about six pile diameters. In dense sand, the group efficiency increases almost linearly with the increase of pile spacing. At a pile spacing of 6D, the group efficiency is substantially lower than 100 percent. For any given pile configuration and center-to-center spacing, the group efficiency is lower in dense sand than that obtained from tests in loose sand.

The ultimate load-carrying capacity and efficiency of group piles embedded in sand and subjected to vertical compressive loads have been the subject of investigation by several authors in the past. Some of the experimental results can be found in the works of Kezdi (1), Vesic (2,3), Kishida (4), Tejchman (5), Hanna (6), Lo (7), Press (8), Cambefort (9), and Kishida and Meyerhof (10). An excellent review of most of the works has been given by O'Neill (11). Most of these investigations have been conducted by driving the piles into sand. For such cases, the pile group efficiencies were equal to, or larger than, one at all center-to-center pile spacings because of the densification of sand due to pile driving.

In contrast, relatively little information is currently available in the literature about a closely related problem, that is, the ultimate load-carrying capacity of group piles subjected to uplifting load (Figure 1). Some laboratory and field test results on the uplift capacity of single piles in sand have been presented by Das and Seeley (12), Meyerhof (13,14), Ireland (15), Esquivel-Diaz (16), Meyerhof and Adams (17), Macdonald (18), and Das and Rozendal (19). Laboratory and field test results for the uplift capacity of single piles in clay have been provided by Das and Seeley (20), Meyerhof and Adams (17), Turner (21), Sowa (22), Mohan and Chandra (23), Patterson and Urie (24), Bhatnagar (25), and Ali (26).

The purpose of this paper is to present some small-scale laboratory model test results on the uplift efficiency of group piles embedded in sand. In recent years, it has become increasingly clear that quantitative information obtained from small-scale laboratory model tests conducted under ordinary conditions may be somewhat questionable. However, it is expected that the study will provide some qualitative information that is not presently available.

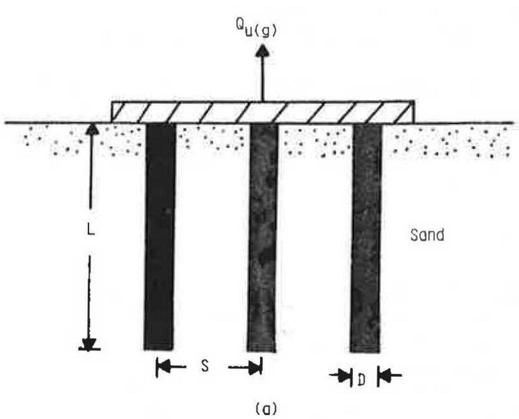

FIGURE 1 Group pile subjected to uplifting load.

LABORATORY MODEL TESTS

Laboratory model tests were conducted in a wooden box measuring 1.07 m x 1.07 m x 0.915 m (height). The sides of the box were heavily braced to avoid any lateral yielding.

A poorly-graded silica sand was used to conduct the model tests. The sand had a 99-percent passing rate for No. 20 sieve, a 55-percent passing rate for No. 40 sieve, and a 0-percent passing rate for No. 200 sieve.

Wooden model piles having diameters of 25.4 mm and lengths of 508 mm were used for the tests. The piles were not tapered. The outside surface of the piles was made rough by applying glue over it and then rolling it over the sand used for the tests. The piles were allowed to dry for several days before use.

For conducting the tests, single piles or pile groups were centrally located in the test box. Sand was poured into the box in 25.4- to 50.8-mm-thick layers and compacted to desired unit weights. For all tests, the length of embedment of piles was 381 mm.

When pullout tests were conducted on single piles, the uplifting load was applied at the pile head by means of a steel rod having a diameter of 6.35 mm. The steel rod was, in turn, attached to a lever arm type arrangement. A steel frame containing the lever arm was attached rigidly to the top of the test box. The lever arm ratio was 1:1.5. For tests on a group of piles, an aluminum plate 6.35 mm thick was used as the pile cap. The piles were attached to the pile cap by means of screws. The uplift force to the pile group was applied centrally by means of a steel rod, one end of which was attached to the pile cap and the other end was attached to the lever arm type of loading device. In all tests, step loads were applied at the end of the lever arm and the deflection was recorded by a dial gauge.

All tests were conducted at two relative densities of compaction. Other details of the test parameters of the sand are given in Table 1. Figure 2 shows the arrangement of the pile groups tested. The center-to-center spacing of the piles in each group was varied from 2D to 6D (D = pile diameter) during the test.

TABLE 1 Details of the Test Parameters for the Soil

Test Series Number[a]	State of Compaction of Soil	Unit Weight of Compaction (kg/m^3)	Relative Density of Compaction (%)	Triaxial Angle of Friction, ϕ (degrees)
A-1 to A-4	Loose	1510	21.7	31
B-1 to B-4	Dense	1721	72.9	40.5

[a]For configuration of piles in each series, see Figure 2.

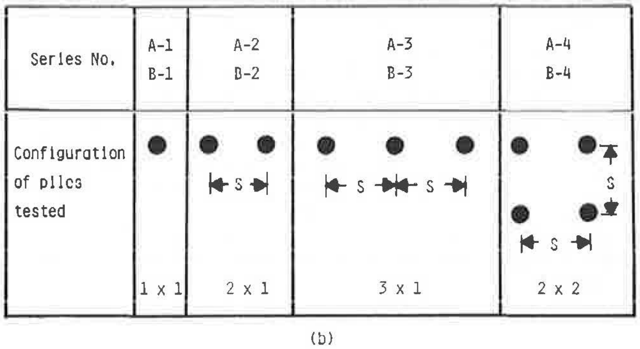

FIGURE 2 Configuration and series number of piles under test.

MODEL TEST RESULTS

The net ultimate uplift capacity of single piles can be written as:

$$Q_{un} = Q_{ug} - W \quad (1)$$

where Q_{un} and Q_{ug} represent net and gross uplifting loads, respectively, and W represents weight of the pile.

In a similar manner, the net $[Q_{un(g)}]$ and gross $[Q_{ug(g)}]$ ultimate uplifting loads for a group pile can be expressed as

$$Q_{un(g)} = Q_{ug(g)} - W_g \quad (2)$$

where W_g represents weight of the piles in the group and the pile cap.

In the conventional manner, the group uplift efficiency E is equal to

$$E = Q_{un(g)}/n\, Q_{un} \quad (3)$$

where n represents the number of piles in a given group.

The uplift capacity tests on single piles (Series A-1 and B-1) were repeated three times in loose and dense sand. The average value of the net ultimate uplift capacity (Q_{un}) in loose sand (A-1) was 3.39 kg, and that in dense sand (B-1) was 29.11 kg with a variation of less than 10 percent. The average skin friction, f_{av}, during uplift for a straight-shafted circular pile can be calculated as

$$f_{av} = Q_{un}/\pi DL \quad (4)$$

where L represents the pile length.

By using Equation 4, the values of f_{av} for single model piles in loose and dense sand were determined to be 83.63 kg/m^2 and 718.12 kg/m^2, respectively. Das and Rozendal (19) have provided a review of the existing theoretical and semiempirical relations for estimation of the ultimate uplift capacity of single piles in sand. In that study, Das and Rozendal (19) have proposed a set of equations to obtain the net ultimate capacity of buried piles as:

$$Q_{un} = \int_0^L f\, p\, dz \quad (5)$$

where f represents the unit skin friction at a depth z, and p represents the pile perimeter. Although the details are beyond the scope of this abridgment, according to this procedure:

$$Q_{un} = 1/2\, \pi D\gamma L_{cr}^2 K_u \tan\delta + \pi D\gamma L_{cr} K_u (L - L_{cr}) \tan\delta$$
$$\text{(for circular piles and } L > L_{cr}) \quad (6)$$

where

γ = unit weight of soil,
L_{cr} = critical embedment,
K_u = uplift coefficient as proposed by Meyerhof (13), and
δ = soil-pile friction angle.

The magnitude of δ is a function of the soil friction angle, ϕ, and the relative density of compaction, D_r. Similarly, L_{cr} is a function of D_r, or

$$L_{cr} = D(0.138D_r + 4.5) \quad (\text{for } D_r \leq 80\%) \quad (7)$$

In the preceding equation, D_r is in percent. By using this procedure (with $\delta \simeq 0.55\phi$ for loose sand and $\delta \simeq \phi$ for dense sand), the magnitudes of Q_{un} for the piles under consideration can be estimated to be about 3.97 kg and 37.7 kg for loose and dense sand, respectively. These values are somewhat higher than the experimental values.

The net ultimate uplifting loads for group piles (Series A-2, A-3, A-4, B-2, B-3, and B-4) as determined from the laboratory tests are shown in Figure 3. As expected, the value of $Q_{un(g)}$ gradually increased with the increase of center-to-center spacing of piles in a given group.

By using Equation 3 and the experimental values of Q_{un} and $Q_{un(g)}$, the group efficiencies for each series have been calculated and are shown in Figure 4. From these plots, the following observations can be made:

1. For any given pile configuration and center-to-center spacing, the group efficiency in dense sand is lower than for those conducted in loose sand.
2. The group efficiency at any given center-to-center pile spacing and state of compaction of sand decreases with the number of piles in the group.
3. For tests in loose sand, pile groups of 2 x 1 and 3 x 1 reached a group efficiency of approximately 100 percent at a pile spacing of 5 to 6D. However, this was not the case for the four-pile group with a 2 x 2 configuration. At a pile spacing of about 6D, a group efficiency of about 95 percent was observed.
4. For tests in dense sand, the group efficiency for any given series increased almost linearly with the center-to-center pile spacing. However, the value of E was never 100 percent within the limits of the test.

CONCLUSIONS

A number of laboratory model tests for uplift capacity of pile groups in sand have been presented. For a given pile configuration and center-to-center spacing, the group efficiency is substantially lower in dense sand as compared to that in loose sand. For the tests conducted, the group efficiency approaches approximately 100 percent in loose sand at pile

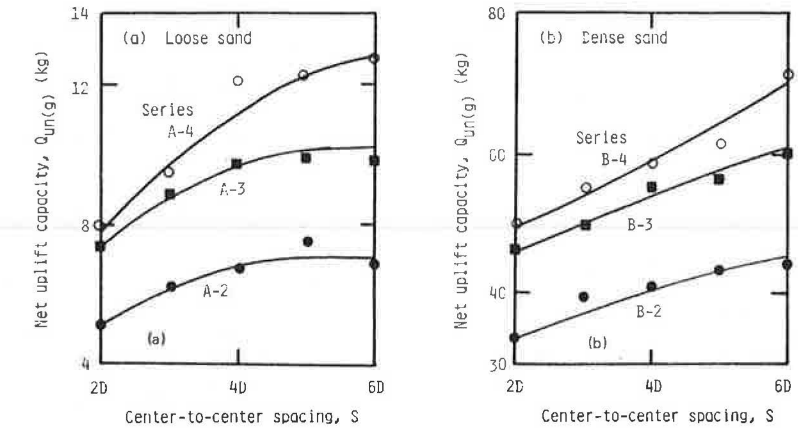

FIGURE 3 Net uplift capacity of group piles in (a) loose sand (test series A2, A3, and A4) and (b) dense sand (test series B2, B3, and B4).

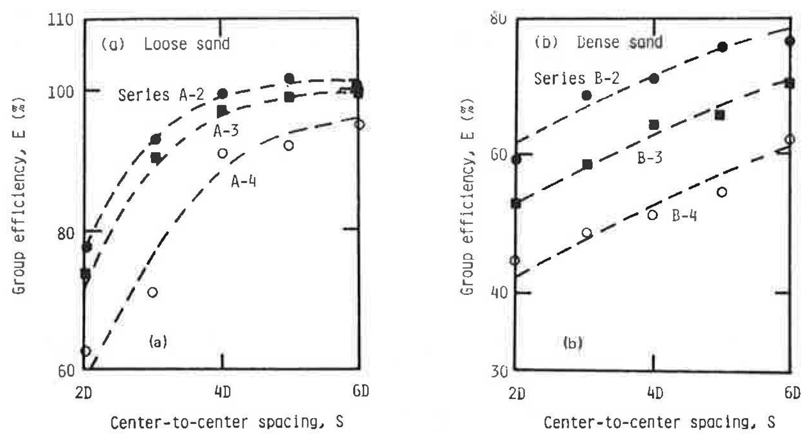

FIGURE 4 Group efficiency of piles in (a) loose sand and (b) dense sand.

spacing of about 6D but is substantially lower than 100 percent for dense sand.

It needs to be pointed out, however, that the present model tests have been conducted on rough buried piles. In the field, a majority of the piles are driven. The process of pile driving has an effect of densification on the soil surrounding the pile, particularly in loose sand. The procedure and the compaction technique used in the present model tests does not reflect the pile driving effect at all, which is a limitation of the study.

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Bearing Capacity of Eccentrically Loaded Continuous Foundations on Layered Sand

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ABSTRACT

Laboratory model test results on the ultimate bearing capacity of continuous rough foundations resting on a layered sand are presented. For this study, the top layer of sand is a dense sand that is underlain by a loose sand at a limited depth. The eccentricity ratio for load application has been varied from zero to 0.25. The laboratory model test results have been compared with the theory presented by Meyerhof and Hanna, which has been modified to take into account the effective area concept for eccentrically loaded foundations. The agreement between the theory and the model test results is satisfactory up to an eccentricity ratio of 0.25.

The bearing capacity of shallow foundations has been the subject of intense study for the past 40 years since the pioneering work of Terzaghi (1). Most of these studies are related to foundations resting on homogeneous soil layers extending to great depths. However, the published literature on the bearing capacity of shallow foundations on layered soils is relatively scarce (2-8). Meyerhof and Hanna (5) have more recently published a generalized ultimate bearing capacity theory for shallow foundations on layered soils subjected to inclined loading.

At this time, a survey of literature indicates that experimental works relating to the ultimate bearing capacity of eccentrically loaded foundations on layered sands have not yet been attempted. The purpose of this paper is to present some recent laboratory model test results for the bearing capacity of an eccentrically loaded continuous foundation resting on a dense sand layer underlain by a loose sand extending to a great depth.

THEORETICAL SOLUTION FOR CENTRALLY LOADED CONTINUOUS FOUNDATION

To evaluate the ultimate bearing capacity of a continuous foundation resting on a stronger sand layer (unit weight = γ_1 and angle of friction = ϕ_1) underlain by a weaker sand layer (unit weight = γ_2 and angle of friction = ϕ_2), Meyerhof and Hanna (5) proposed a failure mechanism according to which a punching shear failure takes place in the top stronger sand layer, followed by a typical bearing capacity failure in the weaker soil layer located below the stronger soil. This is shown in Figure 1. According to this mechanism,

$$q_u = q_{u(2)} + \gamma_1 Z^2 [1 + D_f/Z] K_s \tan \phi_1/B - \gamma_1 Z \leq q_{u(1)} \quad (1)$$