Uplift Capacity of Rectangular Foundations in Sand

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Laboratory model test results for the net ultimate uplift capacity of rectangular foundations in sand are presented. The length-to-width ratios of the rectangular foundations were varied from 1 to 5. Tests were conducted in loose, medium, and dense sands. For square foundations, the critical embedment ratio increases with the degree of compaction of sand and is approximately the same as that proposed by Meyerhof and Adams. For a given degree of sand compaction, the critical embedment ratio increases with the length-to-width ratio of the foundation. A procedure for the estimation of the uplift factor, and thus the net ultimate pullout load for deep foundations, is presented.

During the past 15-20 years, a number of studies, both experimental and theoretical, have been carried out for the determination of the ultimate uplift capacity of anchors and foundations in cohesionless soils [e.g., Baker and Kondner (1), Balla (2), Esquivel-Diaz (3), Meyerhof and Adams (4), Sutherland (5), and Vesić (6)]. An excellent review of these works is given by Vesić (6). Most of the experimental studies mentioned above, either the small-scale laboratory model tests or the large-scale field tests, have been made on horizontal circular anchors and foundations that have the vertical uplifting force being applied through a rigid shaft attached at the center. The purpose of this paper is to present some laboratory model test results for the ultimate uplift capacity of horizontal foundations (Figure 1) that have the uplifting force being applied centrally through a rigid shaft. Some of the preliminary results of this study were presented by Das and Seeley (7). To the best of our knowledge, no other detailed experimental study on this subject is currently available in the literature. Results of a similar study in saturated medium and stiff clays have been presented by Das (8,9).

THEORETICAL EXPRESSION FOR ULTIMATE UPLIFT CAPACITY

A review of existing literature shows that a number of theoretical expressions for the ultimate foundation uplift capacity of axially symmetric cases (circular) have been proposed by investigators like Balla (2), Vesić (6), and Mariupol'skii (10). However, the only analytical expression currently available for the determination of the ultimate uplift capacity of rectangular foundations is given by Meyerhof and Adams (4). For foundations at shallow depths, their relation can be expressed as follows:

$$Q_u = \gamma D^2(2SB + L - B)K_u \tan\phi + W + W_a \quad (1)$$

where

Q_u = gross ultimate uplift capacity,
γ = unit weight of soil,
D = depth of embedment,
S = shape factor,
B = width of foundation,
L = length of foundation,
K_u = uplift coefficient,
ϕ = soil friction angle,
W = effective weight of soil immediately above the foundation, and
W_a = effective weight of the foundation.

As proposed by Meyerhof and Adams, the theoretical values of the uplift coefficient (K_u) for various friction angles of sand are shown in Figure 2 (4). For shallow foundations, the shape factor (S) increases linearly (4) with the embedment ratio (D/B), i.e.,

$$S = 1 + m(D/B) \quad (2)$$

where m is the shape-factor coefficient.

The variation of m with ϕ is shown in Figure 3 (4). It needs to be pointed out that the values of m suggested by Meyerhof and Adams were ϕ = 20°, 25°, 30°, 35°, 40°, and 45°. In order to interpolate the values for intermediate friction angles, we have joined the points by a line.

Although Equation 1 was proposed about 12 years ago, adequate experimental work has not been undertaken to verify it. It appears that the above relation (Equation 1) may be expressed in a more convenient form, i.e., in terms of a nondimensional uplift factor (N_q). This can be done in the following manner.

For an uplift capacity test, the net ultimate uplift load may be given by the expression:

$$Q_o = Q_u - W_a \quad (3)$$

where Q_o is the net ultimate uplift load. Also, the expression for W in Equation 1 is of the form:

$$W = D\,B\,L\,\gamma \quad (4)$$

The uplift factor may be defined as

$$N_q = Q_o/(\gamma\,A\,D) \quad (5)$$

where A is the area of the foundation = B x L.

A combination of Equations 1-5 and some rearrangement yields the following:

$$N_q = (D/B)K_u \tan\phi \left\{[1 + 2m(D/B)]\,(B/L) + 1\right\} + 1 \quad (6)$$

In general, for a given foundation, N_q increases with the embedment ratio D/B (general shear failure in soil) up to a certain maximum value, and after that it remains constant (local shear failure in soil). The embedment ratio at which the uplift factor (N_q) reaches a maximum value is referred to

Figure 1. Parameter for ultimate uplift capacity of rectangular foundations.

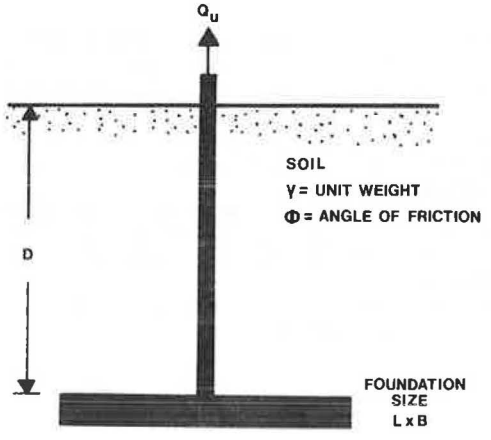


Figure 2. Theoretical value of uplift coefficient.

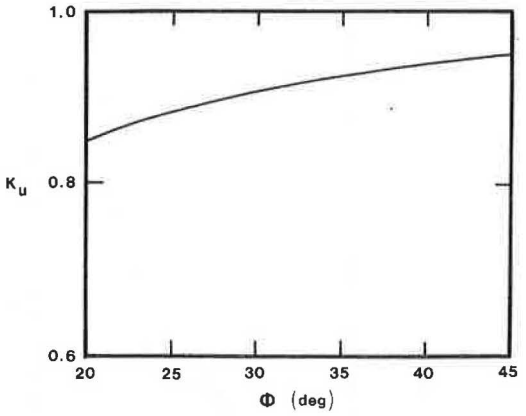


Figure 3. Variation of shape-factor coefficient with angle of friction of soil.

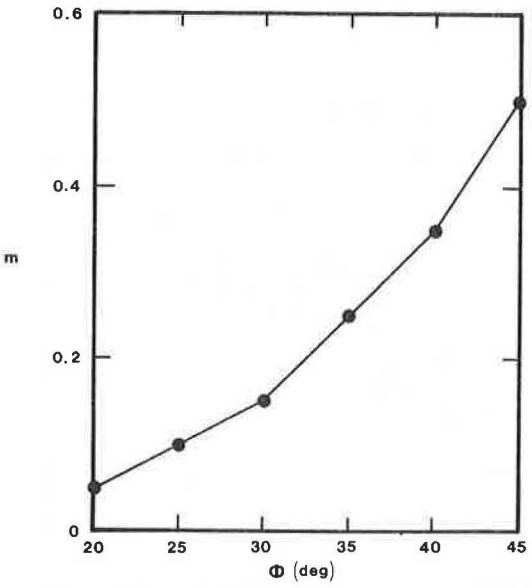
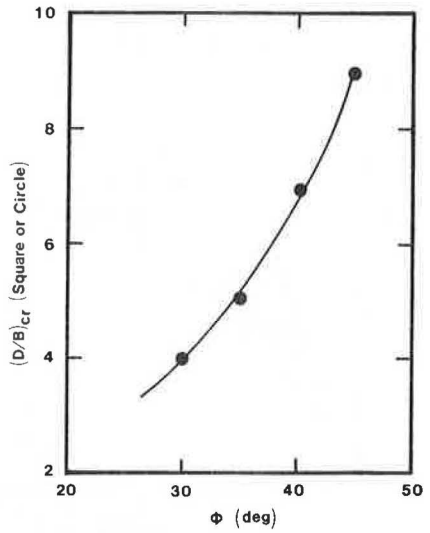


Figure 4. Variation of critical embedment ratio for circular or square foundations.



here as the critical embedment ratio $(D/B)_{cr}$. Foundations with $D/B \leq (D/B)_{cr}$ are referred to as shallow foundations, and those with $D/B > (D/B)_{cr}$ are called deep foundations.

Figure 4 shows the values of critical embedment ratios for circular foundations as recommended by Meyerhof and Adams. They were obtained after observation of several model tests. It may be assumed that similar values will be applicable for square foundations.

LABORATORY MODEL TESTS

Laboratory model tests for the uplift capacity of horizontal foundations were conducted in a box that measured 0.6x0.6x0.6 m. A silica sand was used for these tests. The grain-size distribution of the sand is shown in Figure 5.

Four model aluminum plates, which measured 50.8x50.8 mm, 50.8x101.6 mm, 50.8x152.4 mm, and 50.8x254 mm, were used for the tests. This gave length-to-width ratios (L/B) of 1, 2, 3, and 5, respectively. All of the aluminum plates were 3.18 mm thick.

For conducting the model tests, sand was compacted in layers of 25.4 mm thickness in the box for the desired height. Uplifting force to the plates was applied through a 6.35-mm-diameter steel rod attached rigidly at the center of each plate. The rod was connected to a lever arm that was fixed to the side of the test box. Step loads were applied at the other end of the lever arm. The lever-arm ratio was 1:10.

Three series of tests were conducted by changing the density of compaction of sand. The average unit weight of compaction for each series and the corresponding angle of friction, as determined from standard triaxial tests, are given in the table below:

Series	Nature of Compaction	Relative Density (%)	Unit Weight (kN/m^3)	Friction Angle (°)
1	Loose	21.7	14.81	31
2	Medium	47.6	15.79	34
3	Dense	72.9	16.88	40.5

For a given series, the ultimate uplift load for each plate was obtained for embedment ratios that varied from 1 to 10.

LABORATORY MODEL TEST RESULTS AND INTERPRETATION

The laboratory experimental results for the net ultimate uplift loads (Q_o) for the three series of tests are given in Figures 6, 7, and 8. By using these experimental values of net ultimate load and Equation 5, the experimental values of the uplift factor for all tests at various embedment ratios have been calculated and are shown by solid lines in Figures 9, 10, and 11. Note that the broken lines shown in these figures are calculated theoretical variations of the uplift factors based on Equation 6 and will be discussed later in this paper. As expected, for a given plate in a given series, the value of N_q increased with embedment ratio up to a certain maximum value and remained constant thereafter, thereby showing deep foundation behavior. From the best-fit experimental curves, the critical embedment ratios have been determined and are also shown in Figures 9, 10, and 11. Based on this, it may be seen that the critical embedment ratio for the square plates increased from about 4.8 in loose sand (series 1) to about 6.5 in the case of dense sand (series 3). With some variation that has to be expected, these are in good agreement with the sug-

Figure 5. Grain-size distribution of sand used in model tests.

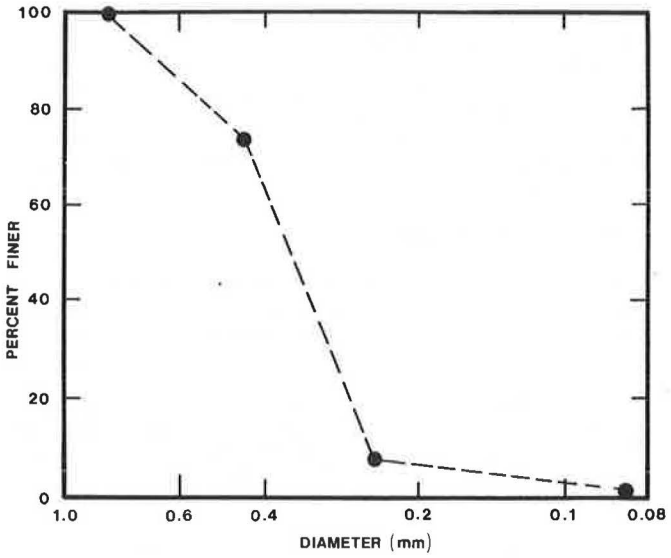


Figure 6. Plot of net ultimate uplift load versus embedment ratio (series 1).

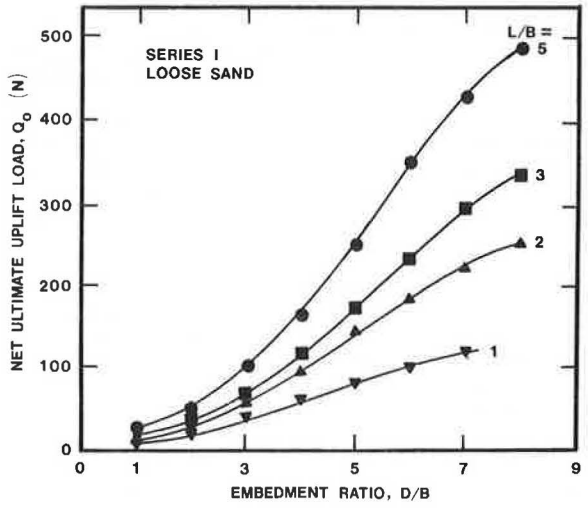


Figure 7. Plot of net ultimate uplift load versus embedment ratio (series 2).

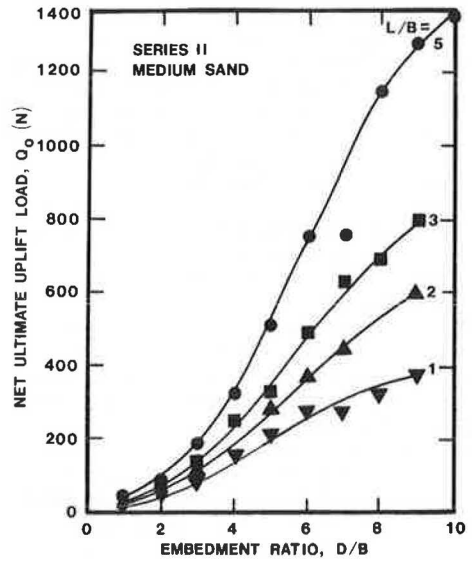


Figure 8. Plot of net ultimate uplift load versus embedment ratio (series 3).

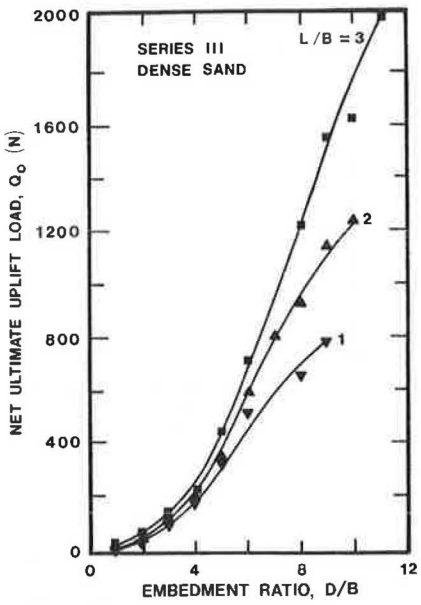


Figure 9. Plot of N_q versus embedment ratio (series 1).

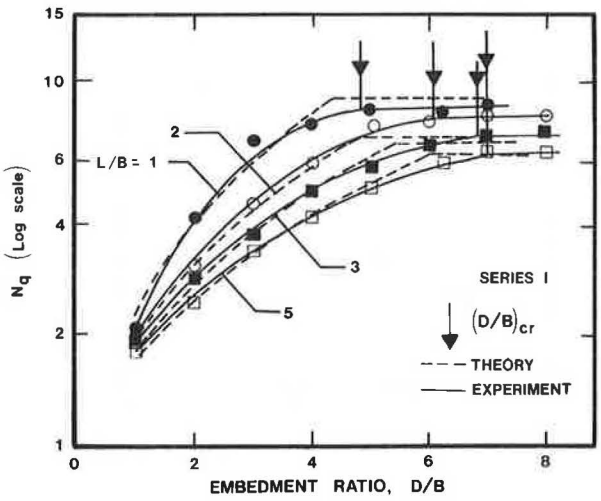


Figure 10. Plot of N_q versus embedment ratio (series 2).

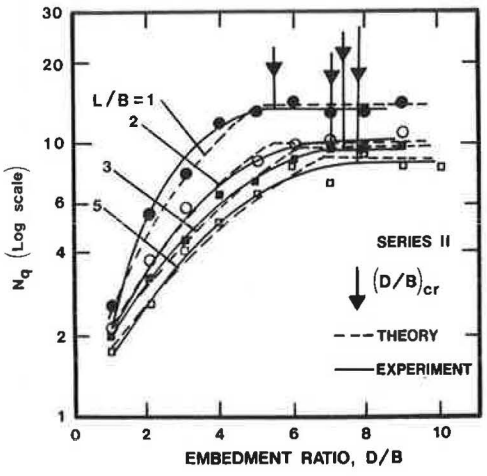


Figure 11. Plot of N_q versus embedment ratio (series 3).

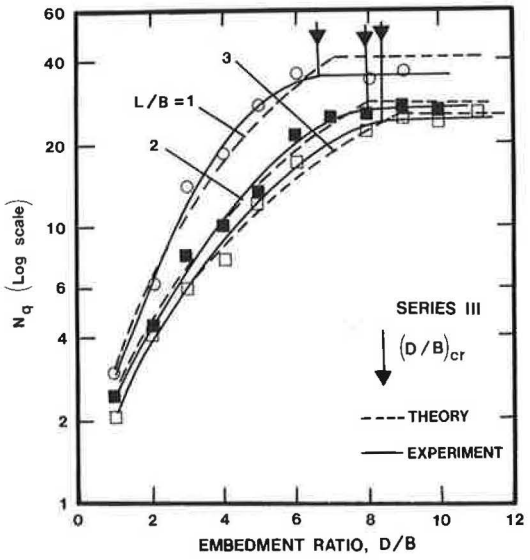
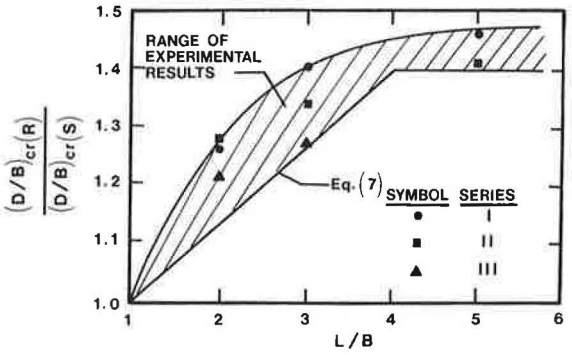


Figure 12. Variation of critical embedment ratio with plate size.



gested values that are shown in Figure 4. However, one important factor that needs to be pointed out is that, for a given series of tests, the critical embedment ratio generally increased with the length-to-width ratio of the plate. Figure 12 shows the variation of the ratio of the critical embedment ratio of rectangular plates $[(D/B)_{cr(R)}]$ to that for square plates $[(D/B)_{cr(S)}]$. Although this shows the general trend, the limited number of experimental data points and their wide scattering make it difficult to draw a definite conclusion. However, a conservative estimate may be given by the following equation:

$$(D/B)_{cr(R)} = (D/B)_{cr(S)}[0.133(L/B) + 0.867] \leq 1.4\,(D/B)_{cr(S)} \quad (7)$$

In order to compare the experimental uplift factors with theory, the following procedure has been adopted:

1. By using the soil friction angle (ϕ), the critical embedment ratio for square foundations $[(D/B)_{cr(S)}]$ was determined from Figure 4.
2. By using the value for $(D/B)_{cr(S)}$ determined in step 1 and Equation 7, the critical embedment ratio of rectangular foundations was determined.
3. For $D/B \leq (D/B)_{cr(R)}$ (as determined in step 2), the uplift factor (N_q) at various embedment ratios was calculated from Equation 6 as follows:

$$N_q = (D/B)\,K_u \tan\phi \left\{[1 + 2m(D/B)_R](B/L) + 1\right\} + 1 \quad (8)$$

4. For $D/B \geq (D/B)_{cr(R)}$ (as determined in step 2), N_q was calculated as follows:

$$N_q = (D/B)_{cr(R)}\,K_u \tan\phi \left\{[1 + 2m(D/B)_{cr(R)}](B/L) + 1\right\} + 1 \quad (9)$$

The uplift factors, as determined from steps 3 and 4, have been plotted in Figures 9, 10, and 11. The comparison shows a generally good agreement between experiment and theory for shallow foundation conditions $[D/B < (D/B)_{cr}]$. For deep foundation conditions, the theoretical uplift factor sometimes overestimates the experimental values up to a maximum of about 10 percent. However, for a preliminary estimation of the ultimate capacity, this appears to be generally satisfactory.

CONCLUSIONS

Based on the model test results for the ultimate uplift capacity of foundations reported herein, the following conclusions can be drawn:

1. The critical embedment ratio of foundations increases with the degree of compaction of sand. The general range of the values of $(D/B)_{cr(S)}$ observed in this test program is generally consistent with that recommended by Meyerhof and Adams (4).
2. The degree of compaction of soil remaining constant, for horizontal foundations the critical embedment ratio increases with the increase of the length-to-width ratio of the plate. A conservative equation for $(D/B)_{cr(R)}$ has been proposed (Equation 7).
3. The uplift factor for shallow foundations derived from the basic equation of Meyerhof and Adams (4) compares reasonably well with the experimental results.
4. A procedure for obtaining the uplift factor and thus the net ultimate load for deep rectangular foundations has been proposed.

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