(2) It is ascertained by comparing with the exactly computed results that the probability of failure and the optimum design alternative determined by the approximate method is accurate enough in engineering practice.

(3) Some examples of the optimization of improvement of a clay layer by sand compaction piles are shown. The method of choosing the best design from different kinds of construction methods are also discussed based on the numerical examples.

REFERENCE

A PROCEDURE FOR ESTIMATION OF UPLIFT CAPACITY OF ROUGH PILES

BRAJA M. DAS

ABSTRACT
The model test results for the ultimate uplift capacity of piles of Das, Seeley and Pfeifle (1977) have been extended. Based on the model test results, it has been found that the unit skin friction at the soil-pile interface increases linearly with depth up to a critical embedment ratio. The critical embedment ratio is dependent on the relative density of the soil. Based on the laboratory experimental results, a tentative procedure for estimation of the ultimate uplift capacity of piles has been presented.

Key words: bearing capacity, model test, pile, sand, static, tension (IGC : E 4)

INTRODUCTION
In a previous paper of Das, Seeley and Pfeifle (1977), some laboratory model test results for the ultimate uplift capacity of rough rigid piles in sand were presented. The model tests were conducted with a wooden pile 0.61 m long and 25.4 mm in

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Manuscript was received for review on November 29, 1982.
capacity of the same pile in the same sand as presented by Das, et al. (1977) have now been extended up to an embedment ratio of $L/D=24$. The purpose of this paper is to present the extended model test results and to propose a tentative procedure for the estimation of the uplift capacity of piles in sand.

**MODEL TESTS**

The grain-size analysis of the sand used in the tests, the procedure for making the surface of the 25.4 mm diameter piles rough, model test equipment and the test procedures have been described by Das, et al. (1977) and will not be repeated here. A summary of

<table>
<thead>
<tr>
<th>Series No.</th>
<th>Unit weight of compaction of sand, $\gamma$ (kN/m$^3$)</th>
<th>Angle of friction of sand, $\phi$ (deg)</th>
<th>Relative density of compaction, $D_r$ (%)</th>
<th>Range of $L/D$ for all the tests</th>
<th>Diameter of pile (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>14.81</td>
<td>31</td>
<td>21.7</td>
<td>4 to 24</td>
<td>25.4</td>
</tr>
<tr>
<td>II</td>
<td>15.79</td>
<td>34</td>
<td>47.6</td>
<td>4 to 24</td>
<td>25.4</td>
</tr>
<tr>
<td>III</td>
<td>16.88</td>
<td>40.5</td>
<td>72.9</td>
<td>4 to 24</td>
<td>25.4</td>
</tr>
</tbody>
</table>

**Fig. 1.** (a) Variation of uplifting coefficient with soil friction angle (after Meyerhof, 1973); (b) variation of $\delta/\phi$ with relative density of compaction (after Das, et al., 1977).

\[ Q_0 = \rho L \bar{f} \]  

where $\rho =$ perimeter of the piles and $\bar{f} =$ average frictional resistance per unit area of soil-pile interface. The average frictional resistance, $\bar{f}$, can be expressed as,

\[ \bar{f} = \frac{1}{2} K_u T L \tan \delta \]  

where $K_u =$ uplift coefficient and $\delta =$ soil-pile friction angle.

The variation of $K_u$ with the soil friction angle as proposed by Meyerhof (1973) is shown in Fig. 1(a). The angle $\delta$ is a function of the soil friction angle $\phi$ and the relative density of compaction ($D_r$). The variation of $\delta/\phi$ with $D_r$ as experimentally determined by Das, Seeley and Pfeifle (1977) is shown in Fig. 1(b).

The model tests for the ultimate uplift

**Fig. 2.** Variation of net ultimate uplift capacity with embedment ratio
all the model tests conducted for the ultimate uplift capacity determination is given in Table 1. The experimental net ultimate uplifting loads at various embedment ratios as determined from the laboratory are shown in Figs. 2(a) and (b).

**Analysis of Model Test Results**

The skin friction during pullout per unit area of the soil-pile interface at a depth $z = \frac{L_0 + L_1}{2}$ can be approximately obtained as,

$$f = \frac{Q_0(z=L_1) - Q_0(z=L_0)}{\pi D(L_0 - L_1)} \quad (3)$$

The skin friction $f$ determined from the experimental results [Fig. 2(a) and (b)] by using Eq. (3) with $L_0 - L_1 = 2D$ have been plotted in Fig. 3(a) and (b) for all three series of tests. It can be seen from these figures that, for any given series of tests, the unit skin friction increases almost linearly with depth up to a certain critical $L/D$ ratio and remains constant thereafter.

Esquivel-Diaz (1967) also conducted some limited number of laboratory tests with rough piles having a diameter of 76.2 mm. The tests were conducted in loose and dense sand. For comparison purposes, the variation of $f$ with $L/D$ as determined from his test results using Eq. (3) has also been shown in Fig. 3(a) and (b).

Based on Fig. 3(a) and (b), it can be seen that the critical embedment ratio $L/D = (L/D)_{cr}$ up to which the unit skin friction increases linearly with depth depends on the relative density of compaction of sand. The variation of the experimentally determined critical embedment ratios has been plotted against the corresponding relative densities of compaction of sand in Fig. 4. It may be noted that the critical embedment ratio for the tests conducted by Esquivel-Diaz in dense sand could not be determined since they were not conducted far enough down. Based on the experimental results shown in Fig. 4, the critical embedment ratio can be expressed as,

$$(L/D)_{cr} = 0.156 D_r + 3.58 \quad (\text{for } D_r \leq 70\%)$$

(4)

and

$$(L/D)_{cr} = 14.5 \quad (\text{for } D_r \geq 70\%)$$

(5)

It can also be seen from Fig. 3 that, for $L/D \leq (L/D)_{cr}$, the unit skin friction can be expressed as,
A SUGGESTED PROCEDURE FOR ESTIMATION OF ULTIMATE UPLIFT CAPACITY

Published literature regarding the uplift capacity of piles is rather scarce at this time. Based on the present model test results, following is a step-by-step tentative procedure for estimation of uplift capacity of piles in sand.

1. Obtain the diameter and the length of the pile and calculate the embedment ratio, \( L/D \).

2. Estimate the relative density of compaction, \( D_r \), of the sand.

3. Based on Eqs. (4) and (5), estimate the critical embedment ratio, \( (L/D)_{cr} \), and then \( L_{cr} \).

4. If the embedment ratio calculated in Step 1 is less than or equal to \( (L/D)_{cr} \), the net ultimate capacity can be given as,

\[
Q_0 = \int_{0}^{L} (p) (f) \, dz
\]

Combining Eqs. (6) and (7),

\[
Q_0 = \frac{1}{2} \eta L_{cr} K_u \tan \delta
\]

The value of \( K_u \) for a given soil friction angle can be obtained from Fig. 1(a). With known values of the relative density and friction angle of the soil, the angle \( \delta \) can be estimated from the average curve of Fig.1(b).

5. If the embedment ratio calculated in Step 1 is greater than \( (L/D)_{cr} \),

\[
Q_0 = \int_{0}^{L_{cr}} (p) (f) \, dz + pf_{(a1z=L_{cr})} (L - L_{cr})
\]

Combining Eqs. (6) and (9),

\[
Q_0 = \frac{1}{2} \eta L_{cr} K_u \tan \delta + \eta L_{cr} K_u \tan \delta (L - L_{cr})
\]

The value of \( L_{cr} \) can be obtained from Step 3.

6. The gross ultimate uplift capacity of the pile can now be given as,

\[
Q_u = Q_0 + W
\]

where \( W = \) self weight of the pile

COMPARISON WITH FIELD TEST RESULTS

It should be realized that Eqs. (8) and (10) are primarily based on Eqs. (4), (5), and (6), which are exclusively based on very small-scale laboratory tests. Large-scale field test results with all the relevant parameters are mostly nonexistent at this time for evaluation of the reliability of Eqs. (8) and (10). Vesic (1970) has reported a full scale uplift test on a driven pile along the banks of the Ogeechee River. The relevant data for this uplift tests are as follow:

- **Pile**: \( L = 15.02 \, \text{m}, \quad D = 0.457 \, \text{m} \)
- **Soil**: Classification—primarily SW to SP
- \( D_r = 87\% \)

Location of ground water table:
- Approximately 1.8 m below the ground surface
- Average saturated unit weight \( (\gamma_{sat}) = 19.96 \, \text{kN/m}^3 \)
- Average effective unit weight \( (\gamma') = 10.15 \, \text{kN/m}^3 \)

**Uplift capacity**: \( Q_0 = 1539 \, \text{kN} \)

The angle of friction of the sand was not determined. However, it can be estimated by the relation (Meyerhof, 1956; Bowles, 1977) as

\[
\phi = 30 + 0.15 D_r
\]

Using Eq. (12), for the sand under consideration with \( D_r = 87\% \), the value of \( \phi \) is equal
to 43 degrees. Referring to Fig.1, for $\phi = 43^\circ$, the value of $K_u \approx 3.35$ and $\delta \approx 43^\circ$. Also, from Eq. (5), $(L/D)_{cr} = 14.5$. Hence, $L_{cr} = (14.5)(0.457) = 6.63$ m. Also, assuming that the ground water table is coincident with the ground surface, Eq. (10) can be rewritten as,

$$Q_a = \frac{1}{2} \rho L_{cr} \delta K_u \tan \delta + \rho \gamma' L_{cr} K_u \tan (L - L_{cr})$$

(13)

Substitution of proper values of $\rho$, $\gamma'$, $L_{cr}$, $L$, $K_u$, and $\delta$ in Eq. (13) yields the value of $Q_a \approx 1250$ kN. This estimated value of $Q_a$ is about $18\sim 20\%$ less than the field test value of 1539 kN. They may considered to be in good agreement considering the fact that the angle of friction has been estimated in Eq. (13). Also, the pile under consideration was driven at the site, which can create densification of sand around it; thereby increasing the value of $\phi$.

CONCLUSIONS

Based on the experimental results obtained from laboratory model tests for the ultimate uplift capacity of piles, the following conclusions can be drawn.

1. The unit skin friction during uplift at the soil-pile interface increases linearly with depth up to a critical depth. Beyond the critical depth, the unit skin friction remains approximately constant.

2. The critical embedment ratio beyond which the unit skin friction remains constant increases with relative density of compaction.

3. A tentative procedure for estimation of the gross ultimate uplifting load has been proposed. More laboratory and field tests are needed to test the accuracy of the procedure.

NOTATION

- $D =$ pile diameter
- $D_r =$ relative density
- $f =$ unit skin friction per unit area
- $f' =$ average skin friction per unit area
- $K_u =$ uplift coefficient
- $L =$ length of embedment
- $p =$ perimeter of pile
- $Q_a =$ net ultimate uplift capacity
- $Q_u =$ gross ultimate uplift capacity
- $z =$ depth
- $\gamma =$ unit weight of soil
- $\gamma' =$ effective unit weight of soil
- $\delta =$ soil-pile friction angle
- $\phi =$ soil friction angle

REFERENCES


