Ultimate Uplift Capacity of Circular Anchors in Layered Soil

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요 지

단단한 모래층 하부에 위치한 연약점토층에 설치된 수평 원형 앵커들의 극한 상향 인발력에 대한 실내모형실험 결과들을 제시하였다. 점토층의 한계매립비에 대한 효과를 평가하였다. 순극한상향인발력을 도출할 수 있는 단순화한 방법을 제시하였다.

ABSTRACT

Laboratory model test results for ultimate uplift capacity of horizontal circular anchors embedded in soft clay overlain by dense sand are presented. The effect of the critical embedment ratio on the thickness of the clay layer was evaluated. An approximate procedure for estimating the net ultimate capacity is presented.

Keywords : Circular anchor, Critical embedment ratio, Dense sand, Layered soil, Soft clay, Uplift capacity

1. Introduction

Horizontal anchors are used for mooring purposes and several offshore construction works. A number of papers concerning to the ultimate uplift capacity of horizontal anchors embedded in clay and also in sand have been published during the last 25 years. These publications are based on small-and large-scale model tests using centrifuge, and also limited field tests. A review of literature shows that, at this time, practically no information is available for the

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estimation of the uplift capacity of horizontal anchors embedded in layered soil. The purpose of this paper is to provide progress report on some laboratory model tests conducted to evaluate the uplift capacity of a circular anchor embedded in a soft saturated clay overlain by a dense sand.

2. Geometric Parameters and Parametric Relationships

Figure 1 shows a circular anchor plate embedded in a soft saturated clay. The diameter of the anchor plate is B. The thickness of the soft clay layer above the anchor plate is H_c. The unit weight and the undrained cohesion($\phi = 0$ concept) of the clay are γ_c and c_u, respectively. A dense sand layer having a thickness of H_s is located above the soft clay layer. The dry unit weight and the angle of friction of the sand are γ_s and ϕ_s, respectively. Thus, the total thickness of the soil located above the bottom of the anchor plate is

$$H = H_s + H_c \tag{1}$$

The gross ultimate pullout resistance of the anchor is equal to Q_u. The net ultimate pullout resistance Q_0, of the anchor can be given as

$$Q_0 = Q_u - W' \tag{2}$$

where W' is the effective self weight of the anchor.

If $H_c = 0$ then $H = Hs$ and at ultimate pullout load, the failure surface in soil located above the anchor will be entirely in the sand. The net ultimate uplift capacity of the anchor can be expressed in a nondimensional form called breakout factor, F_q(Meyerhof and Adams, 1968, Das and Seeley, 1975). This was summarized by Das(1990), or

$$F_q = \frac{Q_0}{\gamma_s A H_s} = 1 + 2[1 + m\left(\frac{H_s}{B}\right)]\frac{H_s}{B} K_u \tan\phi_s \tag{3}$$

where A = area of the anchor plate = $\frac{\pi}{4}B^2$

m = a coefficient which is a function of soil friction angle, ϕ_s

K_u = nominal uplift coefficient which is also a function of ϕ_s

Based on the theory and the experimental parameters provided by Meyerhof and Adams (1968), Figure 2 gives the variation of F_q with H_s/B and ϕ_s for a circular anchor plate. It is important to note that, for a given friction angle ϕ_s, F_q increases with H_s/B and remains constant thereafter. For $H_s/B > (H_s/B)_{cr}$ it is referred to as a deep anchor.

If H_s is equal to zero, then $H = H_c$. Therefore the failure surface in soil at ultlmate load will be entirely located in clay. In that case

$$Q_0 = A(\gamma_c H_c + F_c c_u) \tag{4}$$

where F_c = breakout factor which is a function of embedment ratio, H_c/B

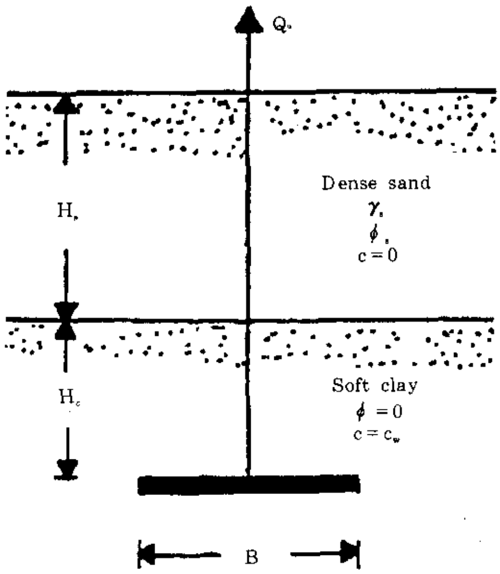


Fig.1 Geometric parameters for a circular anchor

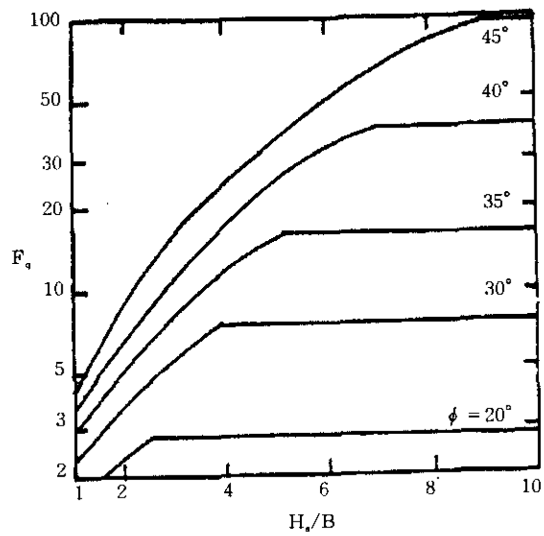


Fig.2 Variation of F_q with H_s/B and ϕ_s

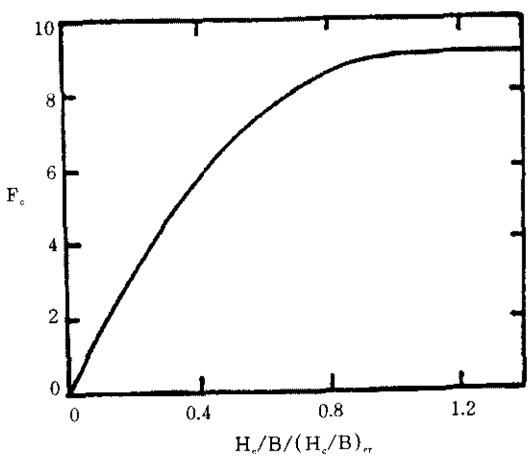


Fig.3 Variation of F_c with H_c/B

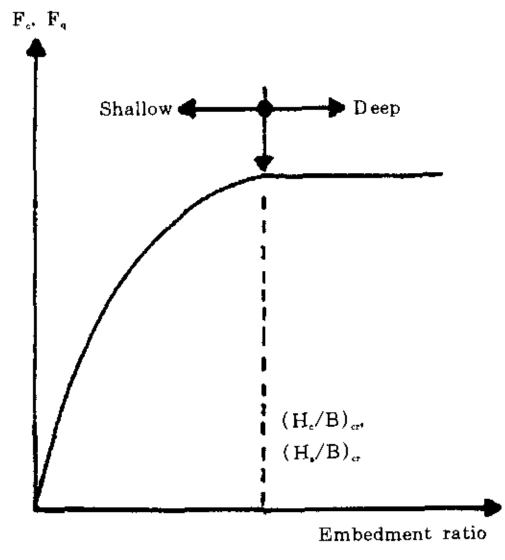


Fig.4 General nature of variation of F_q and F_s with embedment ratio

For a given c_u, the breakout factor increases with H_c/B(shallow anchor condition) up to a maximum at the critical embedment ratio, $(H_c/B)_{cr}$, and remains constant thereafter(deep anchor condition). According to Das(1978)

$$\left(\frac{H_c}{B}\right)_{cr} = 0.107c_u + 2.5 \leq 7 \tag{5}$$

where c_u is in kN/m^2

At $(H_c/B)_{cr}$, the magnitude of $F_c \approx 9$. Based on several model test results, Das(1980) proposed a variation of F_c with H_c/B, and this variation is shown in Figure 3. Thus, in homogeneous soil, the nature of variation of F_q and F_c with H/B will be as shown in Figure 4.

The present study is primarily directed to evaluate the magnitude of $(H/B)_{cr}$ and Q_0 in layered soil, that is, for the condition of $H_c/B \geq 0$. For these tests only one type of clay and one type of sand were used. Based on the limited number of tests, a preliminary evaluation of the anchor holding capacity and the critical embedment ratio where the shallow anchor condition changes to deep anchor condition will be discussed.

3. Laboratory Model Tests

Laboratory model tests were conducted by using a plate anchor made of Plexiglas. The model anchor had a diameter (B) of 76.2mm and a thickness of 13mm. The clay and sand used for the study had the following properties:

Clay:

Percent finer than No. 20 U.S. sieve(0.075mm opening) = 98%

Percent finer than 0.002mm = 25%

Liquid limit = 43%

Plastic limit = 23%

Plasticity index = 20%

Sand:

Percent passing No. 20 U.S. sieve(0.85mm opening) = 100%

Percent passing No. 60 U.S. sieve(0.25mm opening) = 0%

In order to conduct a model test, the clay soil collected from the field was pulverized in the laboratory. It was then mixed with water. To achieve uniform moisture distribution, the moist soil was then placed in several plastic bags and stored in a moist curing room for several days before use. Figure 5 shows a schematic diagram of the model test arrangement in the labortory.

The tests were conducted in a tank measuring 500mm in diameter and 850mm in height. For conducting a test, the model anchor was placed over a Plexiglas pipe to vent the bottom of the anchor plate, thereby eliminating any possible mud suction force. A rigid shaft with a diameter of 6mm was attached to the model anchor. Moist clay soil was placed in the test tank and compacted to 25-mm-thick layers by using a flat bottomed hammer up to the desired

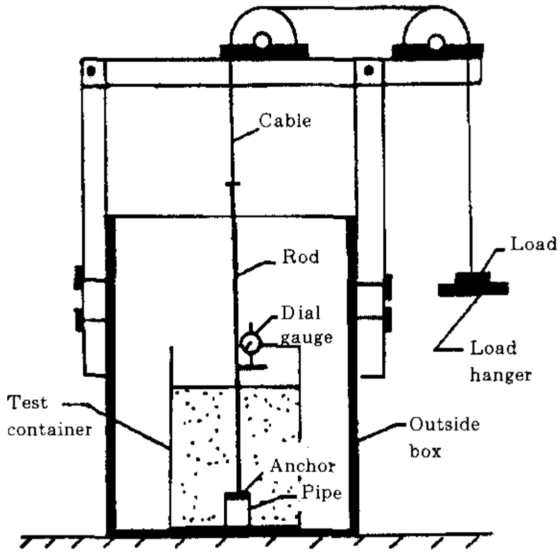


Fig.5 Schematic diagram of the model test arrangement

height(that is, H_c). A thin coat of petroleum jelly was placed over the compacted clay layer to prevent moisture migration from the moist clay to the sand layer. After that, sand of thickness H_s was poured into the tank by using a raining technique. After completing the clay and sand layers, the test tank with soil was kept 24hours to be consolidated before testing. The consolidated clayey soil was not overconsolidated. The top of the rigid shaft was attached to a cable that passed over two pulleys affixed to a rigid frame. A load hanger was attached to the other end of the cable, on which step loads could be placed. A dial gauge was used to measure the anchor movement corresponding to a given load. The undrained shear strength of the soil, c_u, was measured by a hand vane shear test device. The internal soil friction angle of sand was determined by using the direct shear test with the relative density of 70%. Table 1 gives the average properties of the sand and clay in the compacted condition. The sequence of the laboratory test conducted in the present program is given in Table 2.

Table 1. Average properties of the sand and clay in compacted condition

Item	Quantity
Clay:	
Moisture content	31%
Undrained shear strength, c_u	$18kN/m^2$
Moist unit weight, γ	$18.95kN/m^3$
Sand:	
Dry unit weight, γ_s	$17.14kN/m^3$
Relative density	70%
Angle of friction(from direct shear test)	40.3°

Table 2. Sequence of laboratory tests

Seroes	type of soil	H/B
A	Sand only	1 to 9 ($H/B = H_s/B$)
B	Clay only	1 to 6 ($H/B = H_c/B$)
C	Sand over clay	$H_c/B = 1$, $H_s/B = 1, 2, 3, 4, 5, 6$
D	Sand over clay	$H_c/B = 2$, $H_s/B = 1, 2, 3, 4$
E	Sand over clay	$H_c/B = 3$, $H_s/B = 1, 2, 3$
F	Sand over clay	$H_c/B = 4$, $H_s/B = 1, 2$

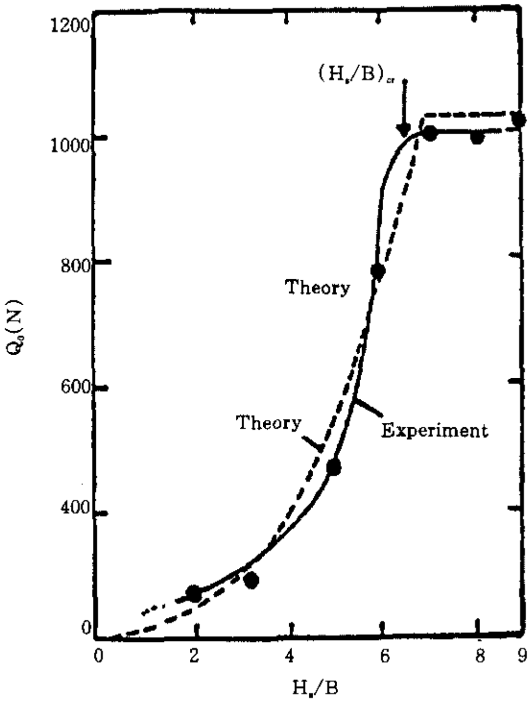


Fig.6 Variation of Q_0 with H_s/B – Series A

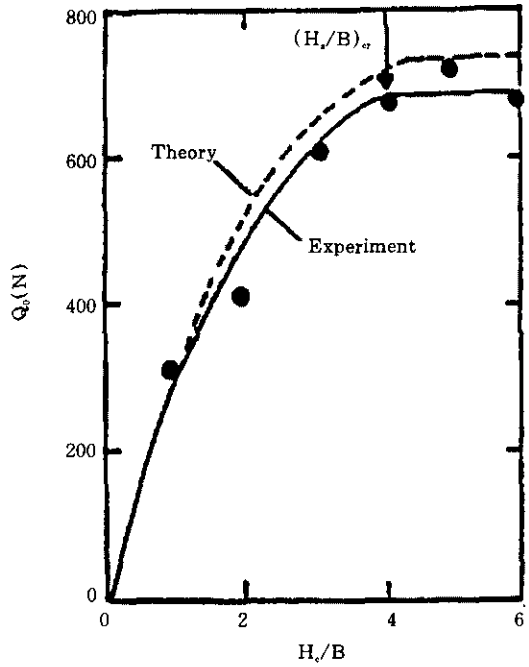


Fig.7 Variation of Q_0 with H_c/B – Series B

4. Model Test Results

Series A

These tests were conducted in sand only. Figure 6 shows the variation of the net ultimate load with the embedment ratio $H_s/B(=H/B)$ for the test conducted in this series. The magnitude of Q_0 gradually increased with H_s/B and reached a maximum at approximately $H_s/B \approx 6.5$. Also shown in this figure is the theoretical variation of Q_0 obtained from Figure 2. The general agreement between the theory and experiment appears to be reasonably good.

Series B

These tests were conducted in clay only. The variation of the experimental net ultimate pullout resistance with $H_c/B(=H/B)$ is shown in Figure 7. It can be seen that, for these tests, $(H_c/B)_{cr} \approx 4$. Also shown in this figure is the theoretical variation of Q obtained by using Eqs. (4) and (5), Figure 3, and Fc at $(H/B)_{cr}=9$.

Series C, D, E, and F

These tests were conducted in layered soil with sand overlying clay. Figure 8 shows the mobilized net load (Q_{0mob}) versus upward displacement of the anchor for the tests conducted in Series C. In this case $H_c/B=1$ and $H_s/B=1$, 2, 3, 4, 5, and 6, thus giving $H/B=(H_c+H_s)/B=2$, 3, 4, 5, 6, and 7. The net ultimate loads(Q_o) obtained from each test are also shown as points in Figure 8. By using a similar procedure, the variation of Q_0 with H/B for the tests conducted in Series D, E, and F were obtained. Figure 9 shows the plot of Q_0 with H/B for $H_c/B=1$,2,3, and 4. From this figure the following observations can be made.

1. When H_c/B is less than the experimental value of $(H_c/B)_{cr}$ as obtained from the tests in Series B, the magnitude of Q_0 increases with H/B up to a maximum and remains practically constant thereafter. This is the case for tests conducted in Series C, D, and E. The embedment ratio at which Q_0 reached maximum can be called the critical embedment ratio [that is, $(H/B)_{cr}$] for the layered soil.

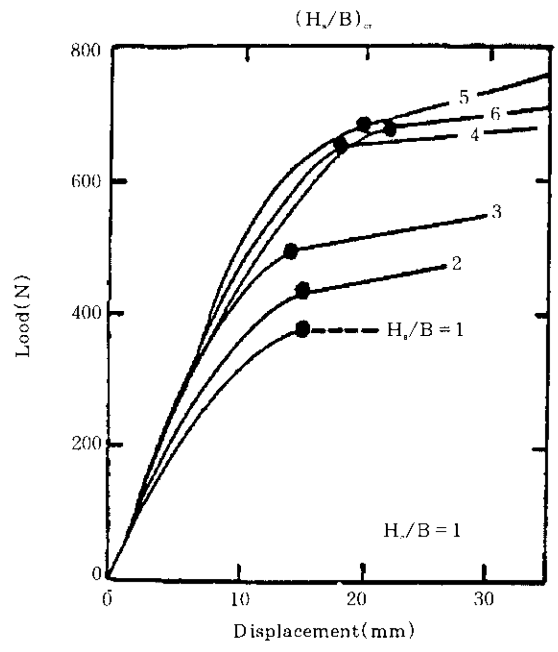
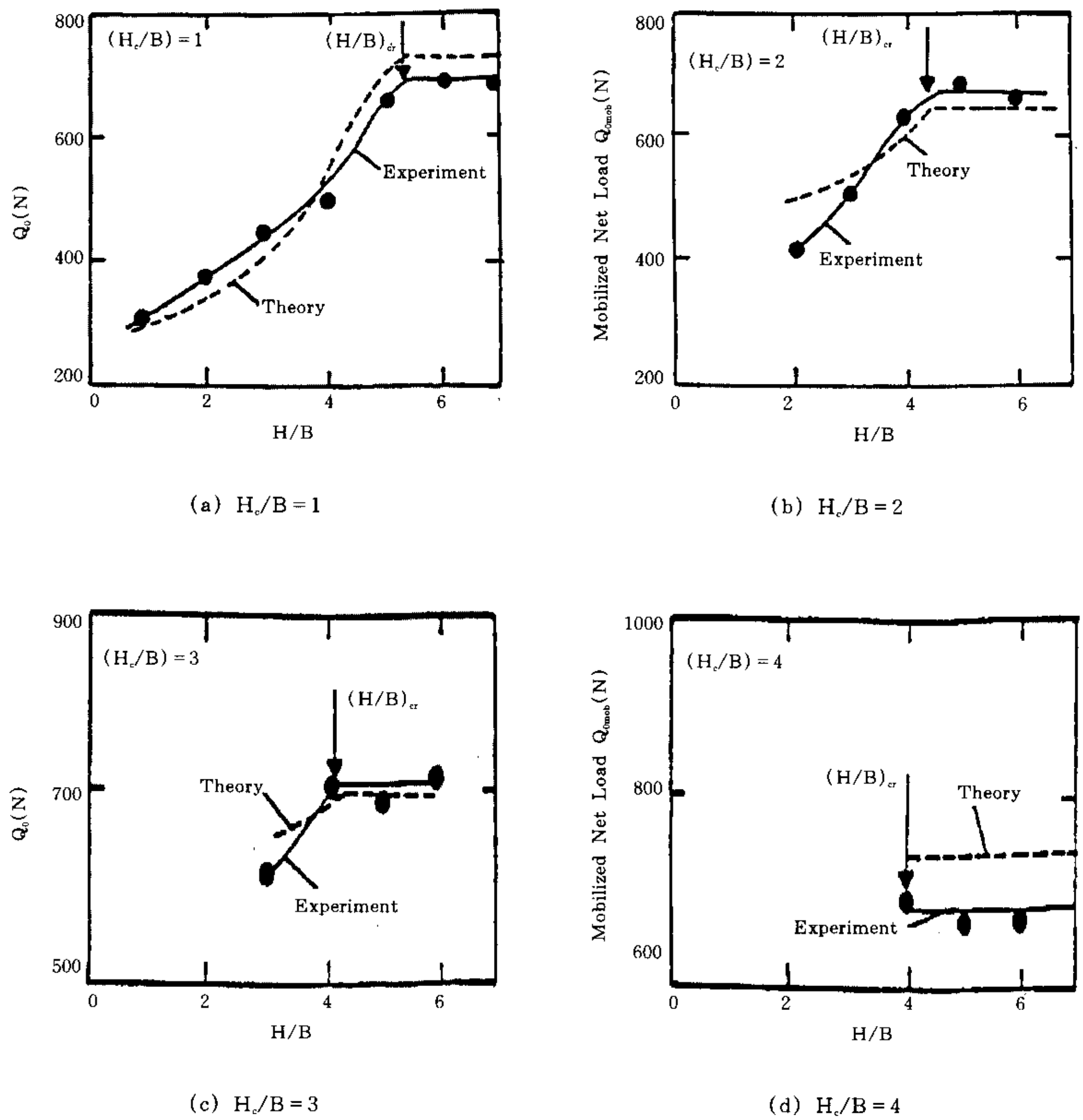


Fig.8 Plot of mobilized net load versus anchor displacement-Series C

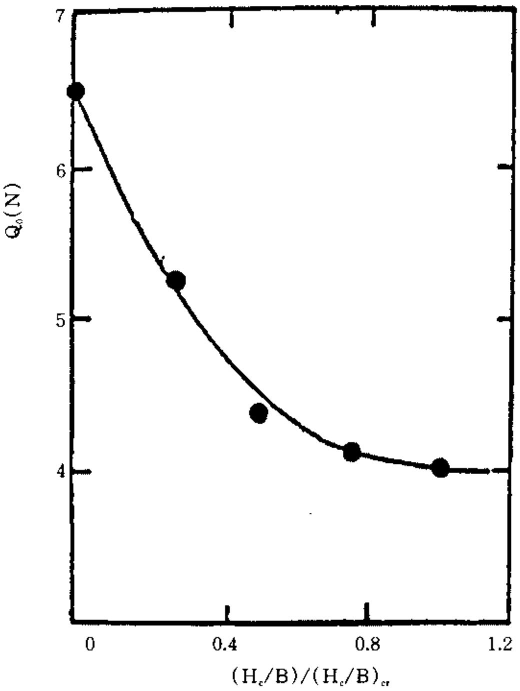
2. For tests in Series F, H_c/B was equal to $(H_c/B)_{cr}$. In this case, the magnitude of maximum Q_0 is practically the same irrespective of the value of H_s/B (and thus H/B). Figure 10 shows a plot of experimental $(H/B)_{cr}$ versus $(H_c/B)/(H_c/B)_{cr}$ obtained from Figures 5, 6, and 8. It generally shows that, as the thickness of the clay layer (H_c) increases, the effect of the sand layer gradually decreases.



(a) $H_c/B = 1$ (b) $H_c/B = 2$

(c) $H_c/B = 3$ (d) $H_c/B = 4$

Fig. 9 Plot of Q_0 versus H/B



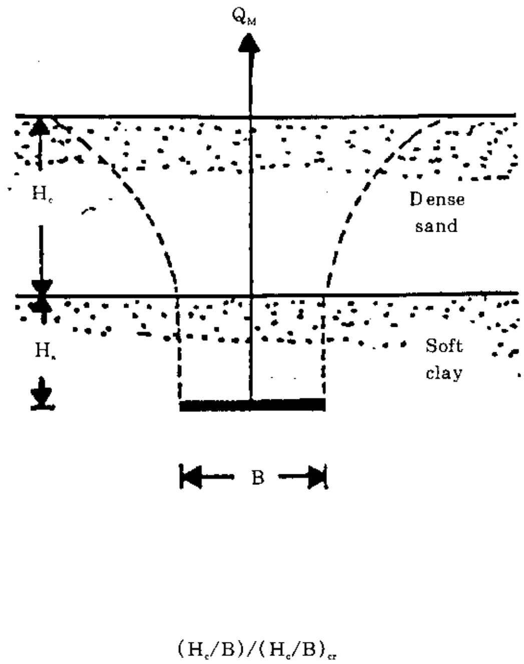


Fig.10 Variation of experimental $(H/B)_{cr}$ with $(H_c/B)/(H_c/B)_{cr}$

Fig.11 Assumed failure surface in soil at ultimate load for shallow anchor condition

5. Approximate Calculation of Net Ultimate Uplift Capacity

Figure 11 shows an approximate failure surface assumption in layered soil for net ultimate uplift capacity calculation. In soft clays the failure surface is vertical(Vesic, 1971) and, in dense sand, it is curved. Thus, for shallow anchor condition[that is, H_c/B $(H_c/B)_{cr}$], the net uplift capacity can be expressed as

Q_0 = contribution of clay layer, $Q_{0(c)}$ + contribution of sand layer, $Q_{0(s)}$ [for $H_c/B<(H_c/B)_{cr}$] (6)

From Eq. (4)

$$Q_{0(c)} = A[\gamma_c H_c + F_{c(H_c/B)} c_u] \quad (7)$$

From Eq. (3)

$$Q_{0(s)} = F_{q(H/B-Hc/B)}\ \gamma_s\ A\ (H-H_c) \quad (8)$$

The magnitude of Fc for an embedment ratio of H_c/B can obtained from Figure 3. Similarly the magnitude of F_q for an embedment ratio of $(H/B-H_c/B)$ can be obtained from Figure 2.

When H_c/B becomes greater than $(H_c/B)_{cr}$ the magnitude of Q_0 is equal to that obtained for the case of $H_c/B = (H_c/B)_{cr}$.

For $H_c/B \geq (H_c/B)_{cr}$, the sand layer has no influence on the net ultimate capacity. Thus

$$Q_0 = A[\gamma_c H_{c(cr)} + F_{c(H_c/B)cr} \cdot c_u] \tag{9}$$

Based on this concept, the theoretical values of the variation of Q_0 with H/B can be calculated in the following manner:

1. Determine $(H_c/B)_{cr}$ from Eq. (5).
2. Determine H_c/B and $(H_c/B)/(H_c/B)_{cr}$.
3. From Figure 9, by using the results of Step 2, obtain $(H/B)_{cr}$.
4. For $H/B \leq (H/B)_{cr}$, use Eqs. (6), (7), and (8) to calculate Q_0.
5. For $H/B \geq (H/B)_{cr}$, use Eq. (9) to calculate Q_0.

By using the above procedure, the variation of Q_0 was calculated and is shown in Figure 9. The deviation between the calculated and experimental ultimate uplift capacity is about ±20%.

6. Conclusions

A number of model test results to determine the ultimate uplift capacity of circular anchors embedded in a soft clay overlain by a dense sand is presented. Based on the model test results the following conclusions can be drawn.

1. When H_c/B is less than $(H_c/B)_{cr}$ the presence of the sand layer has an effect of increasing the net ultimate uplift capacity.
2. When H_c/B is equal to or greater than $(H_c/B)_{cr}$ the ultimate uplift capacity is the same as that in the clay alone.
3. An approximate method for calculating the uplift capacity in layered soil is presented. With further testing, some improvement to this procedure will be required.

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