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Strip foundation on geogrid-reinforced clay slope

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ABSTRACT: Results for the ultimate bearing capacity of a surface strip foundation on a saturated clay slope reinforced with layers of geogrid are presented. Only one type of biaxial geogrid was used for the tests. The location of the top geogrid layer, center-to-center spacing of the geogrid layer, and depth of geogrid reinforcement were varied. Based on the model test results a preliminary outline for estimating the ultimate bearing capacity is presented.

1 INTRODUCTION

During the last ten years, bearing capacity of shallow foundations supported by geogrid-reinforced sand were studied by several investigators such as Guido et al. (1986, 1987), Khing et al. (1992), Omar et al. (1993). Shin et al. (1993) also determined the ultimate and allowable bearing capacities of surface strip foundations supported by geogrid-reinforced saturated clay soil. Results of practicably all studies related to bearing capacity of foundations available at the present time were determined from small-scale laboratory model studies. These studies show that, in general, the ultimate bearing capacity of shallow foundations can be improved by incorporating geogrid reinforcement. The present paper is an extension of the work of Shin et al. (1993) in which the bearing capacity of a strip foundation located at the top of a clay slope has been experimentally investigated in the laboratory.

2 GEOMETRIC PARAMETERS

The geometric parameters of the bearing capacity study reported here are shown in Fig. 1. The saturated clay slope shown has a height H and makes an angle β with the horizontal. The undrained shear strength and saturated unit weight of the clay are c_u and γ respectively. There are n layers of geogrid reinforcement with the first layer located at a depth u below the bottom of the foundation. Thus the total depth, D, of reinforcement measured below the foundation can be given as

$$D = u + (n - 1)h \tag{1}$$

where h = vertical spacing between consecutive layers of geogrid.

The geogrid-reinforced clay slope supports a surface strip foundation of width B. The distance between the edge of the strip foundation and the edge of the slope is d.

It is important to point out that the width, b, of the reinforcing geogrid layers can be given as

$$b = b_1 + B + b_2 \tag{2}$$

Shin et al. (1993) showed that, for horizontal ground surface (i.e., $\beta = 0$), for mobilization of the maximum ultimate bearing capacity

$$b_1 = b_2 \approx 2B \tag{3}$$

Therefore, in this study, b_1/B was kept at 2 for all tests. However, depending on the magnitude of D/B and the slope angle β, b_2 can be equal to or less than $2B$.

3 LABORATORY MODEL TESTS

Laboratory model tests were conducted using a natural clayey soil. A biaxial geogrid was used as reinforcement. Details of the clayey soil and geogrid are given in Tables 1 and 2, respectively.

Model tests were conducted in a box having inside dimensions of 1.22 m (length) × 152.4 mm (width) ×

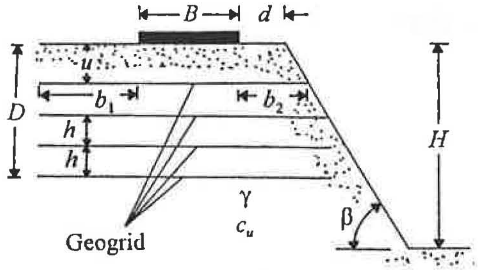

Fig. 1 Geometric parameters for a surface strip foundation on geogrid-reinforced clay slope

Table 1. Details of the clayey soil used for model tests

Item	Quantity
Passing 0.075 opening	98%
Less than 0.002 mm size	21%
Liquid limit	44%
Plasticity index	20%
Average unit weight during test	18.25 kN/m^3
Average moisture content during test	35.8%
Average degree of saturation during tests	98%
Average undrained vane shear strength	9.1 kN/m^2 (± 6%)

Table 2. Details of the geogrid used for reinforcement

Item	Quantity
Structure	Punctured sheet drawn
Polymer	PP/HDPE co-polymer
Junction	Unitized
Aperture size (MX/XMD)	25.4 mm/33.0 mm
Nominal rib thickness	0.76 mm
Nominal junction thickness	2.29 mm

610 mm (depth). The sides of the box were braced with angle irons to prevent yielding during soil compaction and application of load to the model foundation. The inside of the box was made as smooth as possible to minimize friction with the edges of the model foundation during load application. The model foundation was made from hard wood with dimensions of 76.2 mm (B) × 152.4 mm (length) × 38.1 mm (thickness). To ensure rigidity, an aluminum plate of the same width as the model foundation was mounted on its top. The base of the model foundation was made rough by cementing a thin layer of sand to it with epoxy glue. A hole was made on the top of the foundation to ensure that the applied centric load remained vertical during the tests.

The clay soil was well pulverized in the laboratory and then thoroughly mixed with water. In order to ensure uniform moisture distribution, the moist soil was then placed in several plastic bags and cured for about a week before use.

In starting the tests, the moist clayey soil was placed in the test box and compacted in 25.4-mm thick layers. The compaction was achieved using a flat bottom hammer. The geogrid reinforcement layers having b = $5B$ were placed at desired values of u/B and h/B. After completion of compaction, the slope was formed by trimming the compacted soil. For all tests, b_1 was kept at $2B$. As mentioned before, the magnitude of b_2 was less than or equal to $2B$. Once the slope was formed, the model foundation was placed at the top of the slope at a desired d/B. The model test box was then placed under a steel frame. Load to the model foundation was applied by a hydraulic jack. The load and corresponding settlement were measured by a proving ring and dial gauges, respectively. The undrained shear strength, c_u, of the compacted clay was determined at the end of each bearing capacity test with a hand-held vane shear device.

The ultimate load for each test was determined from the load-settlement curves using the procedure described by Vesic (1973). A total of 104 tests were conducted and the sequence of the model tests is summarized in Table 3.

4 MODEL TEST RESULTS

4.1 *Test Series A*

The bearing capacity tests conducted in this series were on unreinforced clay. Meyerhof (1957) provided the theory for the ultimate bearing capacity of a strip foundation on a clay slope (ϕ = 0 condition). According to this theory,

$$q_u = c_u N_{cq} \tag{4}$$

where q_u = ultimate bearing capacity on unreinforced clay; N_{cq} = bearing capacity factor.

Table 3. Sequence of model tests

Series	β (deg)	d/B	n	u/B	h/B	Remarks
A	35, 40, 45, 50	0, 1, 2	—	—	—	Unreinforced clay
B	0, 35, 40, 45, 50	0, 1, 2	1, 2, 3, 4, 5, 6	0.4	0.33	Reinforced clay
C	45	1	3	0.25, 0.4, 0.6, 0.8, 1.0	0.333	Reinforced clay
D	45	1	2, 3, 4, 5	0.4	1.332, 0.666, 0.444, 0.333	Reinforced clay

Note: For all tests, $H = 0.533$ m

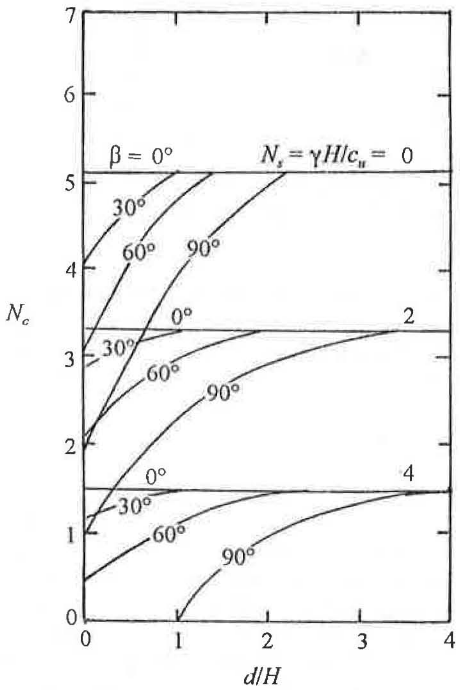

Figure 2. Meyerhof's bearing capacity factors for strip foundation on top of a purely cohesive slope

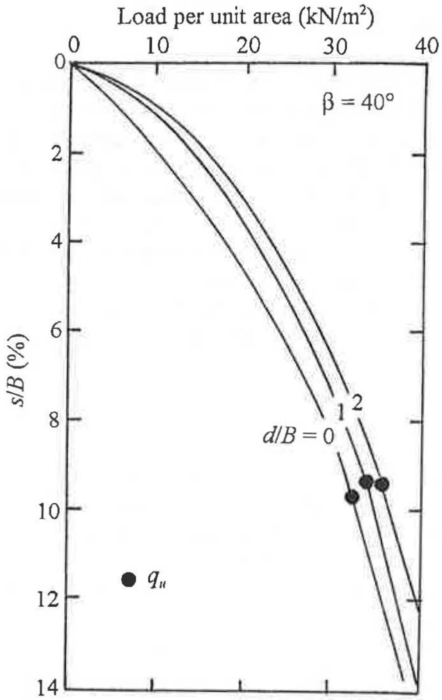

Figure 3. Typical plots of load per unit area vs. s/B– tests on unreinforced slope (Series A)

For surface foundations, $N_{cq} = N_c$. Hence

$$N_c = \frac{q_u}{c_u} \text{ (for depth of foundation, } D_f = 0) \quad (5)$$

Figure 2 shows the theoretical variation of N_c against d/H obtained by Meyerhof (1957). Figure 3 shows typical plots of s/B (s = foundation settlement) versus load per unit area of the foundation along with the ultimate bearing capacity, q_u.

The experimentally-derived bearing capacity factors from tests conducted in Series A for various values of d/B and slope angle (β) are shown in Fig. 4 along with the theoretical variation predicted by Meyerhof. The comparison shows that, for β less than 50°, the experimental values are higher than those predicted by theory.

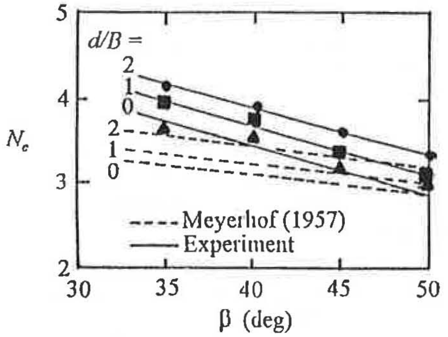

Figure 4. Comparison between the theory and experimental values of N_c (Series A)

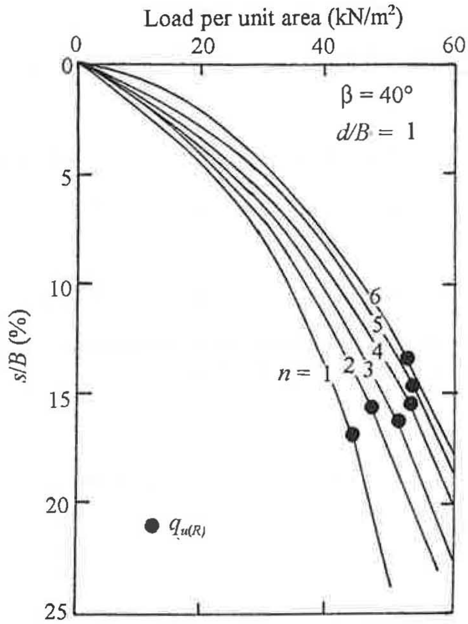

Figure 5. Typical plots of load per unit area vs. s/B –tests on reinforced slope (Series B)

4.2 *Test Series B*

The tests in this series were conducted to determine the critical depth of reinforcement, $D/B = (D/B)_{cr}$, beyond which the contribution of reinforcement to the improvement of the bearing capacity is practically negligible. All tests were conducted at $u/B = 0.4$ and $h/B = 0.333$. Figure 5 shows typical plots of s/B vs. load per unit area on the foundation (for $\beta = 40°$ and $d/B = 1$) along with ultimate bearing capacity on reinforced clay slope, $q_{u(R)}$. For similar values of β, d/B and H/B, the ultimate bearing capacity can be expressed in a nondimensional form as

$$BCR = \frac{q_{u(R)}}{q_u} \tag{6}$$

Figure 6 shows the experimental variations of BCR for $\beta = 0°$ to $50°$ and $d/B = 0$ to 2. In all cases BCR increases with D/B up to an approximate value and remains constant thereafter. Hence as shown in Fig. 6, for all cases irrespective of β and d/B, the value of $(D/B)_{cr}$ is about 1.72.

A plot of $BCR_{(D/B)_{cr}-\beta}/BCR_{(D/B)_{cr}-\beta=0}$ with d/B for various values of β obtained from Fig. 6 is shown in Fig. 7.. From this figure it can be seen that, for $d/B > 3$, the slope angle β has no effect on the bearing capacity ratio.

4.3 *Test Series C*

The tests in Series C were conducted to determine the critical values of u/B [i.e., $(u/B)_{cr}$] for mobilization of maximum ultimate bearing capacity (for similar values of β, c_u and d/B). In this test series, for $\beta = 45°$, $d/B = 1$, $h/B = 0.333$ and $n = 3$, the magnitude of u/B was varied. The experimental bearing capacity ratios (BCR) obtained are shown in Fig. 8. Note that the BCR increases from $u/B = 0.25$ and reaches a maximum value at $u/B = 0.4$. Thus, the critical u/B [i.e., $(u/B)_{cr}$] is about 0.4.

4.4 *Test Series D*

Tests in this series were conducted to determine the effect of h/B on BCR. In conducting the tests, $u/B = (u/B)_{cr} = 0.4$, $d/B = 1$, $D/B = (D/B)_{cr}$, and $\beta = 45°$ were kept constant; however, h/B was varied by changing the number of reinforcement layers (n). Based on the experimental results, the variation of BCR with h/B is shown in Fig. 9. From this figure it appears that, for all practical purposes, the effect of reinforcement on BCR is negligible for $h/B >$ about 0.8.

5 TENTATIVE PROCEDURE TO ESTIMATE ULTIMATE BEARING CAPACITY

Based on the present tests, a preliminary procedure to estimate the ultimate bearing capacity of a strip foundation on geogrid-reinforced saturated clay can be developed as follows. This procedure is valid only for stability number $N = \gamma H/c_u$ greater than zero and slope

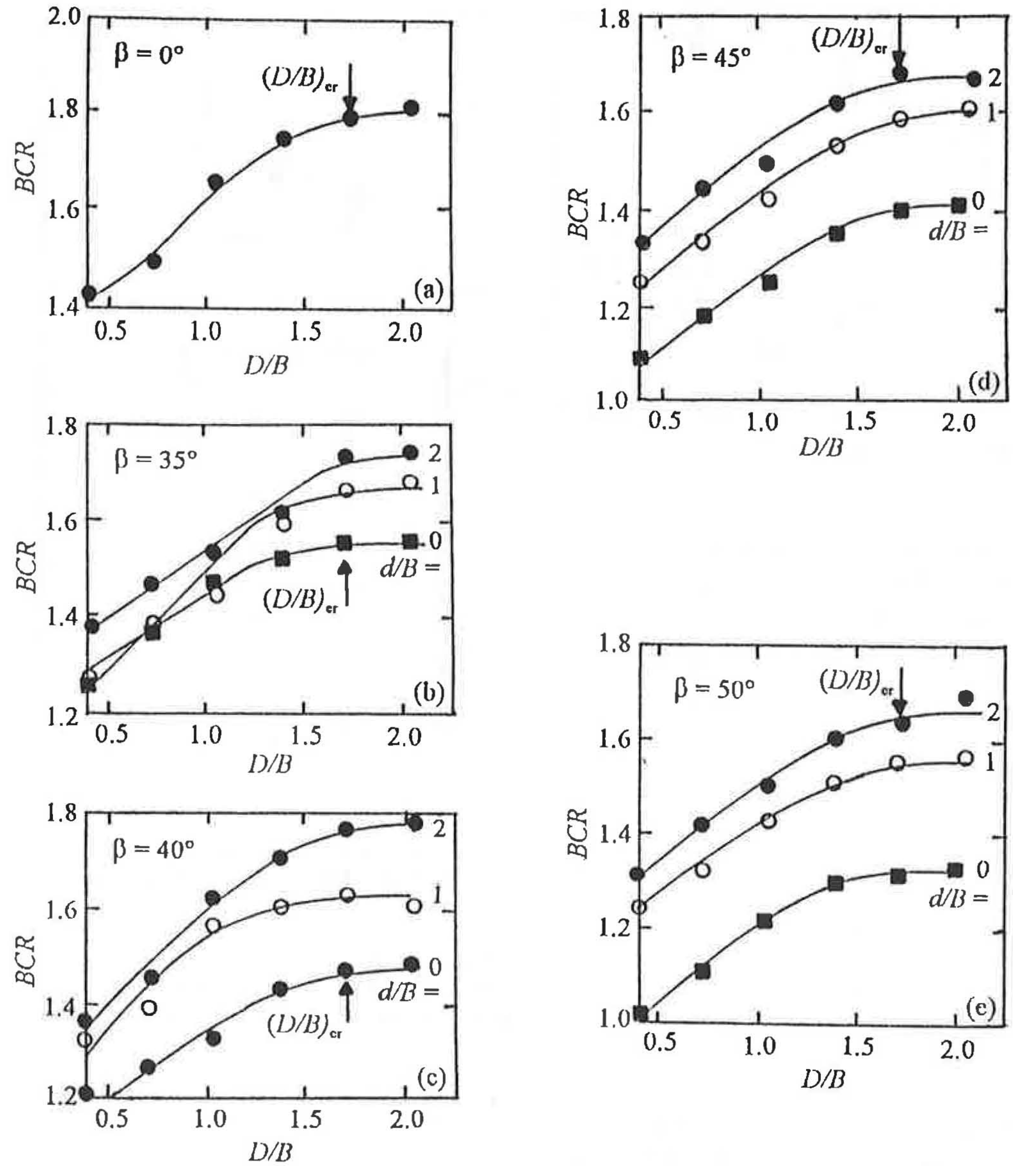

Figure 6. Variation of bearing capacity ratio with D/B and d/B–$\beta = 0°$, 35°, 40°, 45°, and 50° (Series B)

angle $\beta = 35°$ to 50° (the range of the present tests). Thus

$$q_{u(R)} = c_u N_{c(R)} + \gamma D_f \tag{7}$$

where $N_{c(R)}$ = the modified bearing capacity factor which is a function of d/B, D/B, u/B and h/B; and D_f = depth of foundation. It will be shown below that $N_{c(R)}$ can be expressed as

$$N_{c(R)} = N_c \alpha_D \alpha_u \alpha_h BCR'_{(D/B)_{cr}-\beta} \tag{8}$$

where N_c = bearing capacity factor for unreinforced slope with $D_f/B = 0$ (Fig. 2), α_D = reinforcement depth factor, α_h = spacing factor, α_u = location factor for the first layer of geogrid, $BCR'_{(D/B)_{cr}-\beta}$ = bearing capacity for a slope angle β with $h/B = 1/3$, $u/B = 0.4$ and $D/B = (D/B)_{cr} = 1.72$.

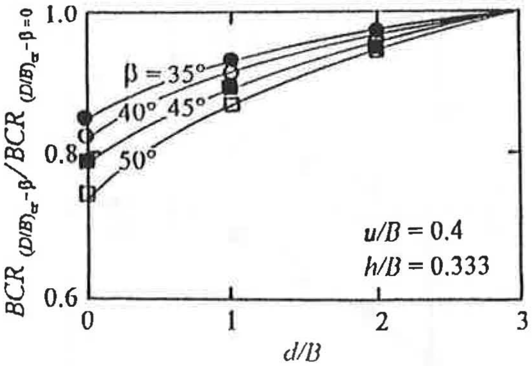

Fig. 7. Plot of $BCR_{(D/B)_{cr}-\beta}/BCR_{(D/B)_{cr}-\beta=0}$ based on the results shown in Fig.6.

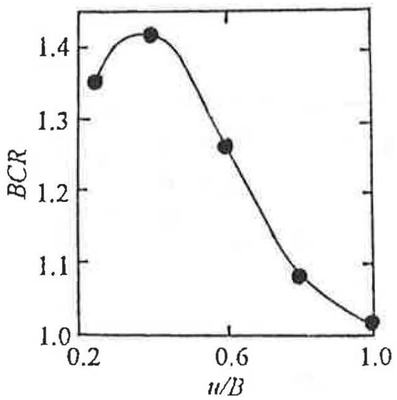

Fig. 8. Plot of BCR vs. u/B–$\beta = 45°$, $d/B = 1$, $h/B = 1/3$, $n = 3$ (Series C)

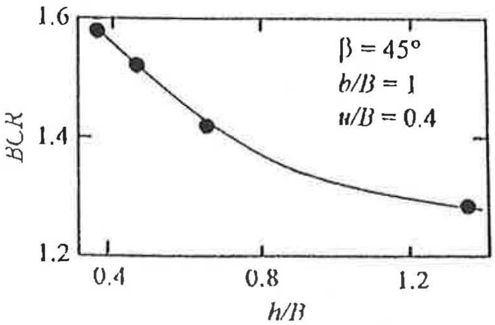

Fig. 9. Plot of BCR vs. h/B (Test Series D)

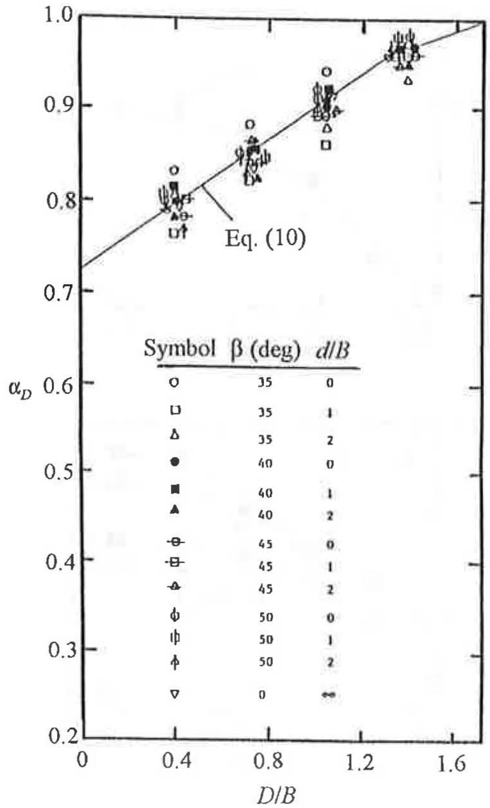

Fig. 10. Plot of α_D vs. D/B for various values of β and d/B obtained from Fig. 6 (Test Series B)

Figure 10 shows a plot of α_D vs. D/B for various values of β and d/B. The parameter α_D can be expressed as (for a given u/B, h/B, d/B and β)

$$\alpha_D = \frac{BCR_{(D/B)-\beta}}{BCR_{(D/B)_{cr}-\beta}} \tag{9}$$

The plots of α_D shown in Fig. 10 were obtained from the experimental values of BCR shown in Fig. 6 (Series B tests). In spite of some scatter it appears that, for all values of β and d/B.

$$\alpha_D \approx 0.179(D/B) + 0.72 \quad (\text{for } D/B \le 1.4) \tag{10}$$

$$\alpha_D \approx 0.094(D/B) + 0.94 \quad (\text{for } 1.4 \le D/B \le 1.72) \tag{11}$$

For a given slope angle β, h/B, d/B and D/B, the term α_u can be defined as

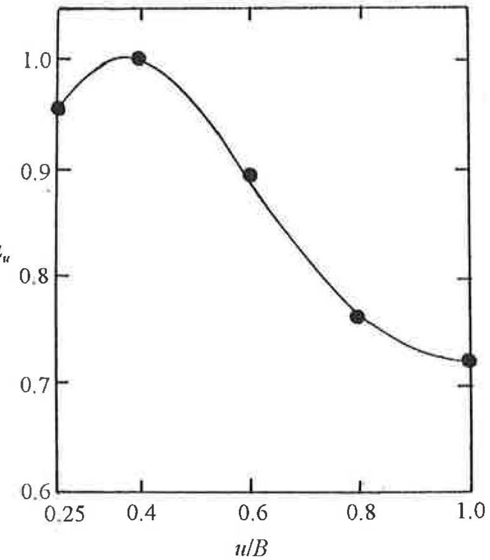

Fig. 11. Plot of α_u vs. u/B from Fig. 8 (Series C)

$$\alpha_u = \frac{BCR_{(u/B)-\beta}}{BCR_{(u/B)_{cr}-\beta}} \tag{12}$$

The variation of α_u with u/B derived from the experimental values shown in Fig. 8 is given in Fig. 11.

Again, for a given slope angle β, D/B, u/B and d/B, the spacing factor α_h can be written as,

$$\alpha_h = \frac{BCR_{(h/B)}}{BCR_{(h/B=0.333)}} \tag{13}$$

Figure 12 shows the plot of α_h versus h/B based on the results shown in Fig. 9. From the plot it appears that

$$\alpha_h \approx 1.3 - 0.9(h/B) \quad (\text{for } h/B < 0.8) \tag{14}$$

In order to calculate $q_{u(R)}$ using Eqs. (7) and (8), $BCR'_{(D/B)_{cr}-\beta}$ needs to be calculated. The magnitude of $BCR'_{(D/B)_{cr}-\beta}$ is a function of c_u, d/B, β and the physical properties of the geogrid. This is to be assumed or experimentally determined. One way of estimating $BCR'_{(D/B)_{cr}-\beta}$ is to conduct a laboratory

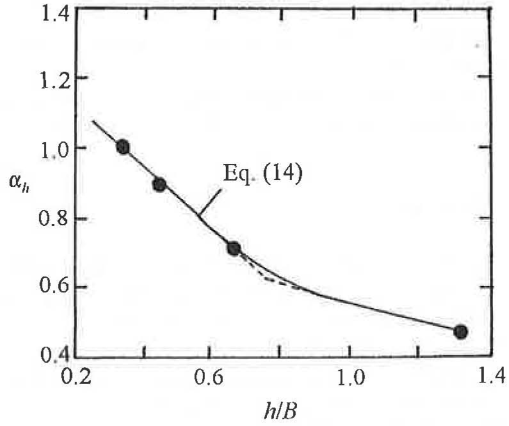

Fig. 12. Plot of α_h vs. h/B based on Fig. 9 (Series B)

test with one layer of geogrid ($n = 1$) and desired d/B with $D_f/B = 0$, $u/B = 0.4$, $b_1 = 2$ and $b_2/B \le 2$. From the results of the test, $BCR'_{(D/B)_{cr}-\beta}$ can be determined by using Eq. (10), or

$$BCR'_{(D/B)-\beta} = \frac{BCR'_{(\text{test})}}{(0.179)(D/B)+0.72} = \frac{BCR'_{(\text{test})}}{(0.179)(0.4)+0.72} = \frac{BCR'_{(\text{test})}}{0.79} \tag{15}$$

The magnitudes of α_D and α_h can be determined from Eqs. (10), (11) and (14). The magnitude of α_u can be estimated from Fig. 7.

6 CONCLUSIONS

The results of a number of bearing capacity tests for a model strip foundation supported by a geogrid-reinforced clay slope were presented. Based on these results, the following conclusions can be drawn.

1. Other conditions remaining the same, the first layer of geogrid should be located at a depth of 0.4B below the foundation for maximum increase in the ultimate bearing capacity derived from reinforcement.

2. The maximum depth of reinforcement which contributes to the bearing capacity improvement is about 1.72B.

3. A tentative procedure is suggested for estimating the ultimate baring capacity of strip foundations.

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