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Bearing capacity of 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 was varied. Based on the model test results a preliminary outline for estimation of the ultimate bearing capacity is presented.

1 INTRODUCTION

The results of a number of studies which relate to the determination of the ultimate bearing capacity of shallow foundations supported by geogrid-reinforced sand are presently available in the literature (e.g., Guido et al. 1986, 1987; Khing et al. 1992; Omar et al. 1993). However, similar published studies for foundations on saturated clays are very limited. Shin et al. (1993) published the results of their laboratory model tests for bearing capacity of strip foundations on geogrid-reinforced saturated clay. The present paper is an extension of that work in which the bearing capacity of a strip foundation located on the top of a clay slope has been experimentally investigated.

2 STATEMENT OF THE PROBLEM

The problem investigated in this study is schematically shown in Fig. 1. The geogrid-reinorced clay slope has a height H and makes an angle β with the horizontal. The unit weight and the undrained shear strength of the clay are γ and c_u respectively. A strip foundation of width B is located at a distance d from the edge of the foundation. There are n layers of geogrid reinforcement–the first one located at a depth u from the bottom of the foundation. The depth of reinforcement D can be given as

$$D = u + (n - 1)h \qquad (1)$$

where h = vertical spacing between consecutive layers of geogrid.

The width, b, of each geogrid layer can be given as

$$b = b'_1 + B + b'_2 \qquad (2)$$

It was concluded from the study of Shin et al. (1993) that, for horizontal ground (i.e., $\beta = 0$), for mobilization of the maximum ultimate bearing capacity, $b'_1 = b'_2 = 2B$. For that reason, in this study b'_1 was assumed to be $2B$. However b'_2 can be equal to or less than $2B$ depending on the the slope angle and the depth of the reinforcement layer from the bottom of the foundation.

3 LABORATORY MODEL TESTS

Laboratory model tests were conducted in a natural clay with a biaxial geogrid as reinforcement. Details of the clay soil and the geogrid are given in Table 1.

Laboratory model were conducted in a box having inside dimensions of 1.22 m (length) × 152.4 mm (width) × 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 the 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, t). 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

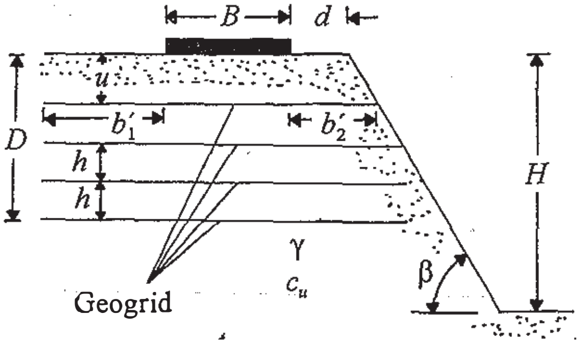

Fig.1 Strip foundation on geogrid-reinforced clay slope

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.

For performing the tests, the moist soil was placed in the test box and compacted in 25.4-mm thick layers using a flat-bottomed hammer. The geogrid reinforcement layers having a $b = 5B$ were placed at desired values of u/B and h/B. After compaction was complete, 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 2.

Table 1. Details of the soil and geogrid

Item for the clay	Quantity	Item for the geogrid	Quantity
Passing 0.075 opening	98%	Structure	Punctured sheet drawn
Less than 0.002 mm size	21%	Polymer	PP/HDPE co-polymer
Liquid limit	44%	Junction	Unitized
Plasticity index	20%	Aperture size (MD/XMD)	25.4 mm/33.0 mm
Average unit weight during test	18.25 kN/m^3	Nominal rib thickness	0.76 mm
Average moisture content during test	35.8%	Nominal junction thickness	2.29mm
Average degree of saturation during test	98%		
Average undrained vane shear strength	9.1 kN/m^2 (± 6%)		

Table 2. Sequence of model tests

Series	β (deg)	d/B	n	u/B	h/B	Remarks
I	35, 40, 45, 50	0, 1, 2	—	—	—	Unreinforced clay, $H = 0.533$ m
II	45	1	3	0.25, 0.4, 0.6, 0.8, 1.0	0.333	Reinforced clay, $H = 0.533$ m
III	0, 35, 40, 45, 50	0, 1, 2	1, 2, 3, 4, 5, 6	0.4	0.333	Reinforced clay, $H = 0.533$ m
IV	45	1	2, 3, 4, 5	0.4	1.332, 0.666, 0.444, 0.333	Reinforced clay, $H = 0.533$ m

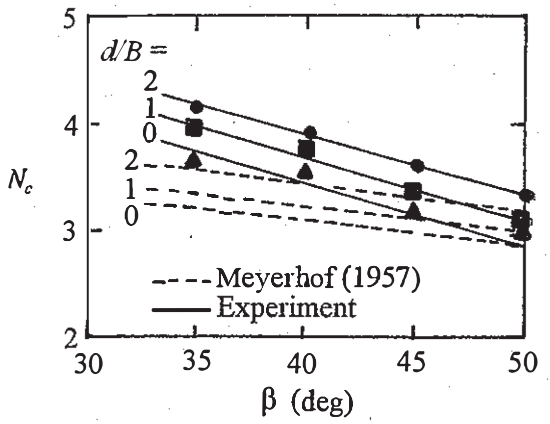

Fig.2 Variation of N_c with β and d/B–Series I

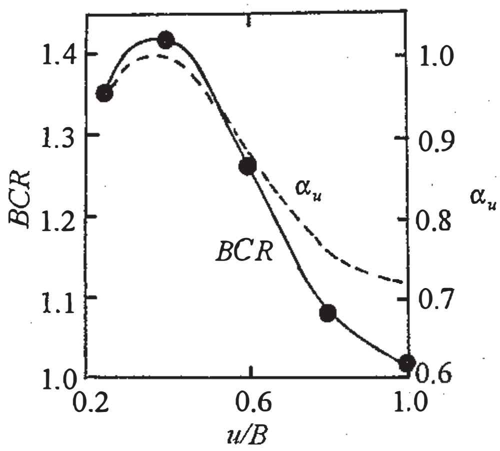

Fig.3 Plot of BCR vs. u/B–Series II ($\beta = 45°$, $n = 3$, $d/B = 1$, $h/B = 0.333$)

4 MODEL TEST RESULTS

4.1 *Bearing capacity factor in unreinforced clay (Series I)*

The bearing capacity factor, N_c, for a surface foundation on an unreinforced clay slope can be determined as

$$N_c = \frac{q_u}{c_u} \tag{3}$$

where q_u = ultimate bearing capacity for unreinforced clay

The experimentally-derived bearing capacity factors from tests conducted in Series I for various values of d/B and slope angle (β) are shown in Fig. 2 along with the theoretical variation as predicted by Meyerhof (1957). The comparison shows that, for β less than 50°, the experimental values are higher than those predicted by theory.

4.2 *Reinforced clay slope–determination of $(u/B)_{cr}$ Series II*

The tests in Series II 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). The ultimate bearing capacity can be expressed in a nondimensional form as

$$BCR = \frac{q_{u(R)}}{q_u} \tag{4}$$

where BCR = bearing capacity ratio, $q_{u(R)}$, q_u = ultimate bearing capacities on reinforced and unreinforced slopes, respectively

In test Series II 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. 3. 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. For a given geometric configuration the BCR obtained at $(u/B)_{cr}$ may be designated as BCR'. The plot of $\alpha_u = BCR/BCR'$ is also shown in Fig. 3.

4.3 *Reinforced clay slope–determination of $(D/B)_{cr}$ (Series III)*

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 4 shows the experimental variation of $BCR = BCR'$ 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. 4, for all cases irrespective of β and d/B, the value of $(D/B)_{cr}$ is about 1.72.

Figure 5 shows a plot of $BCR'_{(D/B)cr\text{-}\beta}/BCR'_{(D/B)cr\text{-}\beta=0}$ with d/B for various values of β. It can be seen that, for $d/B \geq 3$, the slope angle has no effect on the bearing capacity ratio.

For a given β, u/B and h/B, the ultimate bearing capacity varies with depth of reinforcement (D/B).

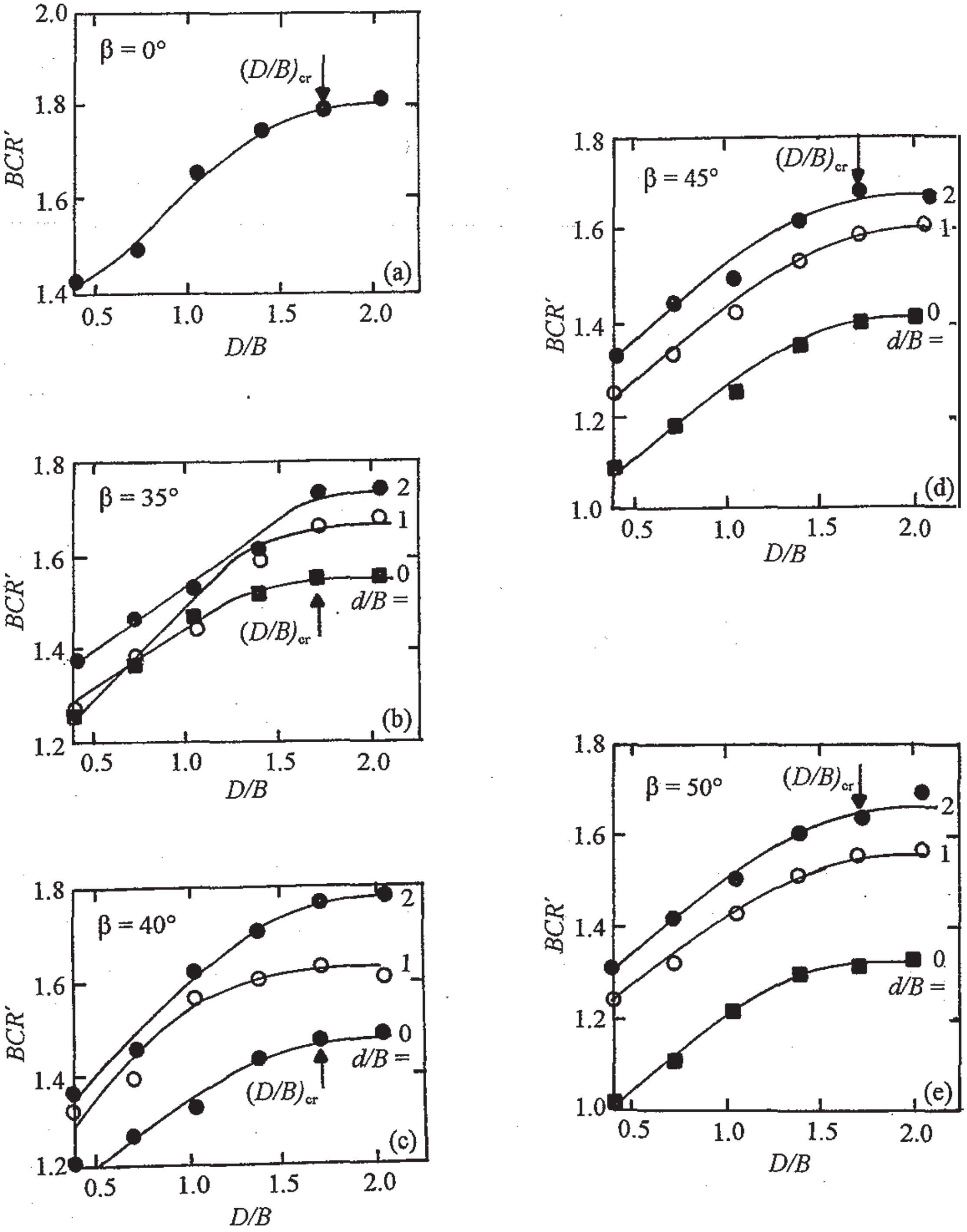

Fig. 4 Plot of *BCR′* vs. *D/B*–Series III ($u/B = 0.4$, $h/B = 0.333$, $N = 1, 2, 3, 4, 5, 6$)

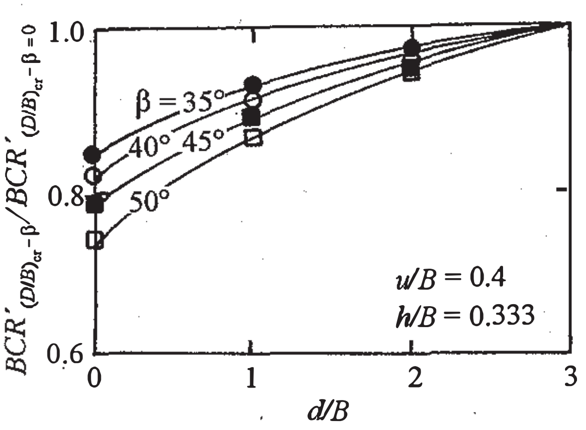

Fig. 5 Variation of $BCR'_{(D/B)cr-\beta}/BCR'_{(D/B)cr-\beta=0}$ with d/B–Series III

However it appears that BCR' and D/B can be represented by a single nondimensional plot. In order to do that, let (for a given u/B, h/B, d/B and β)

$$\alpha_d = \frac{BCR'_{(D/B)-\beta}}{BCR'_{(D/B)_{cr}-\beta}} \qquad (5)$$

Figure 6 shows the average plot of α_d with D/B (along with the range for various values of β and d/B) obtained from the experimental values given in Fig. 4 ($u/B = 0.4$, $h/B = 0.333$). In spite of some scatter, for all values of β

$$\alpha_d \approx 0.179(D/B) + 0.72 \text{ (for } D/B \le 1.4) \qquad (6)$$

$$\alpha_d \approx 0.094(D/B) + 0.94$$

$$\text{(for } 1.4 \le D/B \le 1.72) \qquad (7)$$

4.4 *Reinforced clay slope–variation of BCR′ with h/B (Series IV)*

Tests in this series were conducted to determine the effect of h/B on $BCR = BCR'$. In conducting the tests, $u/B = 0.4$, $d/B = 1$ and $D/B = (D/B)_{cr}$ 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. 7. From the experimental plot it appears that, for $h/B \le 0.8$,

$$\alpha_h = \frac{BCR'_{(h/B)}}{BCR'_{(h/B=0.333)}} \approx 1.3 - 0.9(h/B)$$

$$\text{(for } h/B \le 0.8) \qquad (8)$$

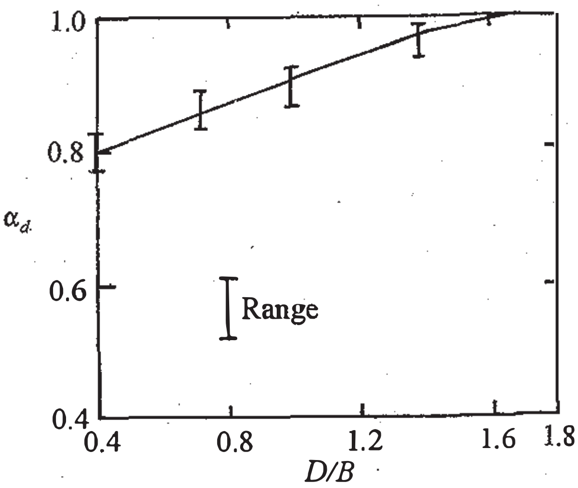

Fig. 6 Variation of α_d vs. D/B–Series III

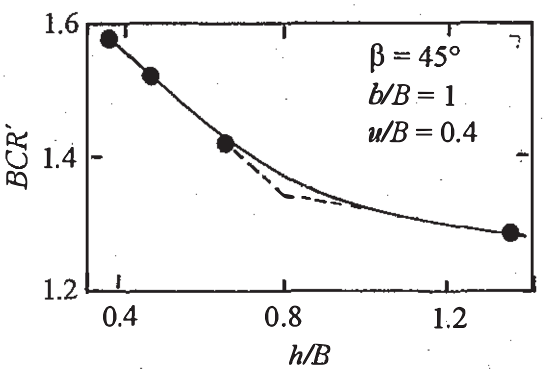

Fig. 7 Change of BCR' with h/B–Series IV

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_s greater than zero, slope angle β = 35° to 50° (the range of the present tests), $b'_1/B = 2$, $b'_2/B \le 2$ (which is a function of β and the depth of reinforcement). Thus

$$q_{u(R)} = c_u N_{c(R)} + \gamma D_f \qquad (9)$$

where $N_{c(R)}$ = modified bearing capacity factor which is a function of b/B, and D_f = depth of foundation

The modified bearing capacity factor can be expressed as

$$N_{c(R)} = N_c \, \alpha_d \, \alpha_u \, \alpha_h \, BCR'_{(D/B)_{cr}-\beta} \qquad (10)$$

where N_c = bearing capacity factor for unreinforced slope (with $N_s > 0$, $D_f/B = 0$) which is a function of d/B and β as determined from the theory of Meyerhof (1957), $BCR'_{(D/B)cr\text{-}\beta}$ = bearing capacity ratio for $D_f/B = 0$, $u/B = 0.4$, $h/B = 1/3$ and $n = 5$.

The magnitudes of α_d and α_h can be determined from Eqs. (6), (7), and (8). The magnitude of $BCR'_{(D/B)cr\text{-}\beta}$ 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 $BCR'_{(D/B)cr\text{-}\beta}$ is to conduct a laboratory test with one layer of geogrid ($n = 1$) and desired d/B with $D_f/B = 0$, $u/B = 0.4$, $b'_1/B = 2$, $b'_2/B \leq 2$. From the results of the test, $BCR'_{(D/B)cr\text{-}\beta}$ can be determined by using Eq. (6), or

$$BCR'_{(D/B)\text{-}\beta} = \frac{BCR'_{(\text{test})}}{(0.179)(D/B) + 0.72} = \frac{BCR'_{(\text{test})}}{(0.179)(0.4) + 0.72} = \frac{BCR'_{(\text{test})}}{0.79} \qquad (11)$$

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 bearing capacity of strip foundations.

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