Ultimate Bearing Capacity of Strip Foundation on Geogrid-Reinforced Clayey Soil

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요 지

여러층의 지오그리드로 보강된 포화된 점토질지반에 띠기초의 극한 지지력에 대한 실내모형실험결과를 제시하였다. 최대 극한지지력을 유발하는데 필요한 최적 보강길이와 보강심도, 첫번째층의 지오그리드 보강심도를 도출하였다. 모형실험결과를 바탕으로 극한 지지력을 도출할 수 있는 준경험방정식을 제시하였다.

Abstract

Laboratory model test results for the ultimate bearing capacity of a surface strip foundation supported by a near-saturated clayey soil reinforced with layers of geogrid have been presented. The optimum values for the width of the reinforcement layers, the depth of reinforcement, and the location of the first layer of geogrid for mobilization of maximum bearing capacity have been determined. Based on the model test results, an empirical procedure to estimate the ultimate bearing capacity has been developed.

Keywords : Geogrid, Reinforcement, Clayey soil, Ultimate bearing capacity

1. Introduction

During the past fifteen to twenty years, geogrids have been used extensively to reinforce slopes and embankments as well as in the backfill of retaining walls. In the past eight to ten years, results of several laboratory model tests relating to the ultimate and allowable bearing capacities of shallow foundations supported by sand reinforced with multiple layers of geogrid have been reported in the literature(e.g., Guido et al., 1986; Khing et al., 1993; Yetimoglu et al. , 1994). These studies were primarily conducted to evaluate the following parameters in a nondimensional form, where the most beneficial effect from the soil

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reinforced with respect to the ultimate bearing capacity will be derived: (a) distance of the top layer of reinforcement measured from the bottom of the foundation, u; (b) total depth of reinforcement, $d=u+(N-1)h$; and (c) width of each reinforcement layer, b (Fig.1). The improvement in the ultimate bearing capacity has generally been expressed in a nondimensional form as

$$BCR_u=\frac{q_{u(R)}}{q_u} \tag{1}$$

where $q_{u(R)}$=the ultimate bearing capacity with geogrid reinforcement and q_u=the ultimate bearing capacity without the reinforcement.

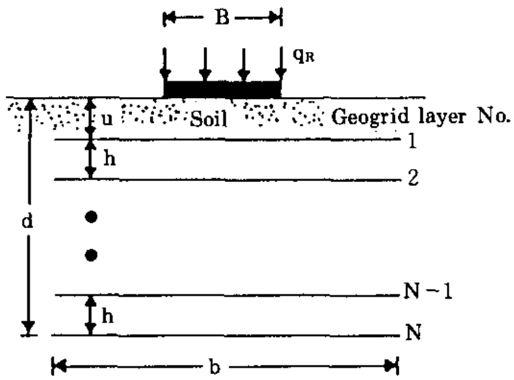

Fig.1 Geometric parameters for a strip foundation supported by geogrid-reinforced clay

A review of the existing literature shows that, unlike the bearing capacity studies on reinforced sand, theoretical and/or experimental studies relating to the ultimate and allowable bearing capacities of shallow foundations supported by geogrid-reinforced saturated clayey soil are somewhat scarce. Limited information on the topic of geosyntheics-reinforced clay can be found in the works of Ingold and Miler(1982), Milligan and Love (1984), Dawson and Lee(1988), Mandal and Sah(1992).

The purpose of this paper is to report some recent model test results to determine the ultimate bearing capacity of a surface strip foundation supported by geogrid-reinforced saturated clay. For the tests the nondimensional parameters u/B, h/B, and d/B were varied(B=foundation width, h=distance between consecutive geogrid layers, and d=depth of geogrid reinforcement). Only one clayey soil and one type of geogrid were used for the tests. Based on the results of these model tests, the following will be discussed:(1) the optimum values of u/B, b/B, and d/B for mobilization of the maximum ultimate bearing capacity for a given clay-geogrid system, and (2) an empirical procedure to estimate the ultimate bearing capacity for a given value of u/B, h/B, and d/B.

2. Laboratory Model Tests

For the present model tests, a natural clayey soil was used. The soil had 98% finer than U.S. No. 200 sieve(0.075mm opening) and 23% finer than 0.002mm. Other physical properties of the soil were: liquid limit=44% and plasticity index=20%. The clayey soil obtained from the field was pulverized in the laboratory and mixed with water so that the degree of saturation would be greater than 95% in the compacted condition. For uniform moisture distribution, the moist soil was then placed in plastic bags and cured for about a week before use.

A biaxial geogrid(TENSAR BX1100) was used as reinforcing material. The physical properties of the geogrid were: structure-punctured sheet drawn, polymer-PP/HDPE co-polymer, junction method-unitized: aperture size (MD /XMD)-25.4mm/33.02mm, rib thickness-0.76mm, and junction thickness -2.29mm.

The model foundation measured 76.2mm(B)×304.8mm and was made from an aluminum plate. The model test box measured 1.09m(length)×304.8mm(width)×0.91m(height). The sides of the box were braced with angle irons to avoid yielding during soil compaction and the model tests. The ends of the model foundation and the sides of the test box were made as smooth as possible to reduce friction during the tests.

For the laboratory tests, the moist soil was placed in the box and compacted in 25.4mm thick layers by a flat-bottom hammer. The geogrid layers were placed in the clayey soil at desired values of u/B and h/B. The model foundation was placed on the surface of the compacted clayey soil bed. Load to the model foundation was applied by a hydraulic jack. The load and corresponding settlement were measured by a proving ring and two dial gauges placed on each side of the center line of the foundation. The undrained shear

Table 1. Laboratory model tests

Series	u/B	N	h/B	b/B	Average c_u (kN/m^2)
A	—	—	—	—	3.14
B	—	—	—	—	6.02
C	—	—	—	—	5.93
D	0.25	4	0.333	2-10	3.14
E	0.4	4	0.333	2-10	3.14
F	0.6	4	0.333	2-10	3.14
G	0.8	4	0.333	2-10	3.14
H	0.9,1.0	4	0.333	8	3.14
I	0.4	1-6	0.333	4	3.14
J	0.4	1-6	0.333	4	6.02
K	0.4	2-5	1.332-0.333	5	5.93

Note : 1. Series A, B, and C are tests without reinforcement
2. N=number of geogrid layers

Table 2. Physical properties of the clayey soil at varying moisture contents

Test series	Average moisture content, w (%)	Average moist unit weight, γ (kN/m^3)	Average degree of saturation, S_r (%)	Average c_u (kN/m^2)
A, D-I	42.50	17.40	97	3.14
C, J	38.02	17.90	98	5.93
B, K	37.70	18.10	98	6.02

strength, c_u, of the compacted clayey soil was determined at the end of each bearing capacity test using a hand vane shear device. Several attempts were initially made to collect specimens of compacted clayey soil from the model test box by pushing thin-walled tubes and subjecting them to UU triaxial tests. This procedure was not fully satisfactory, since obtaining specimens of very soft clayey soil is not simple and they can be disturbed to a great extent. The difference in c_u obtained from the triaxial tests and the vane shear tests was less than $\pm 8\%$. For that reason it was considered more practical to continue the vane shear tests. The results presented in the present study are based on BCR_u, which is a ratio. It is anticipated that the error(s) introduced in determing c_u will not affect the final result. Table 1 gives the details of the tests conducted under this program. The average physical properties of the compacted moist clay in the test box are given in Table 2.

3. Model Test Results

Test Series A, B, and C

These tests were conducted on unreinforced clay. The plots of the load per unit area of the foundation, q, obtained from the tests are shown in Fig. 2. From these plots, the magnitudes of the ultimate bearing capacities can be determined. For a strip surface foundation

$$q_u = c_u N_c \tag{2}$$

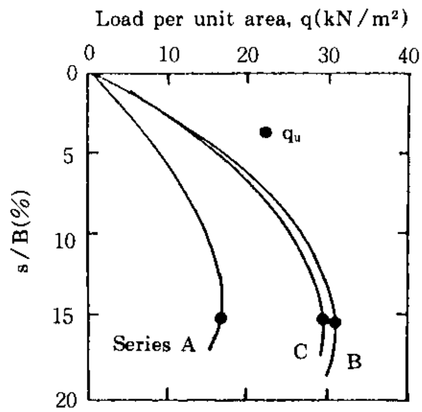

Fig.2 Plot of q versus s/B-unreinforced clay (Series A, B, and C)

where N_c=bearing capacity factor.

The experimental ultimate bearing capacities(q_u) determined from Fig. 2 are 16.3kN/m², 31.0kN/m², and 30.3kN/m² for Series A, B, and C, respectively. Using these experimental values of the undrained cohesion given in Table 2 and Eq. (2), the value of N_c can be determined to be 5.2, 5.15, and 5.1, respectively, for tests in Series A, B, and C. These values of N_c are in good agreement with the theoretical value of 5.14(Meyerhof, 1951).

Test Series D, E, F, G, and H

These tests were conducted to evaluate the variation of BCR_u with u/B, b/B. For all tests the number of geogrid layers was kept at 4 and the spacing between the layers was equal to B/3. Fig. 3 shows the plots of q_R(load per unit area of the foundation) versus s/B (s=foundation settlement) for Test Series D, in which the magnitude of u/B was 0.25. It needs to be pointed out that practically all q_R versus s/B plots obtained from tests with geogrid reinforcement did not show a peak value of q_R(for ultimate bearing capacity) even at a large settlement level. The ultimate bearing capacities [q_R] for these tests were determined to be the points at which $\Delta q_R/\Delta s$ became minimum(Vesic, 1973). The plots of q_R versus s/B for Series E, F, G, and H were similar in nature. The magnitudes of the settlement at ultimate load were practically the same, that is, ranged from 16% to 20% of the width of the foundation, B.

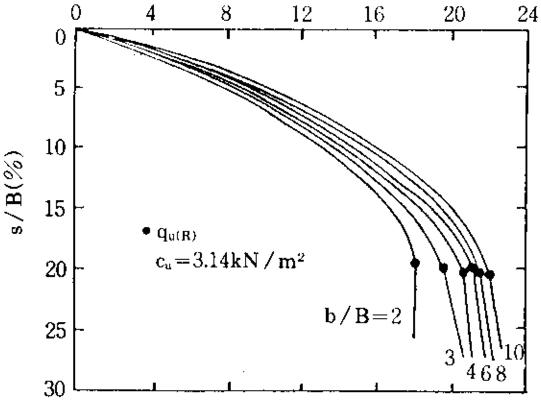

Fig.3 Plot of q_R versus s/B−Series D (N=4, h/B=1/3, u/B=0.25)

Using the experiment value of q_u obtained from Series A and those of $q_{u(R)}$ from tests in Series D, E, F, and G, the variation of BCR_u for various u/B ratio was calculated by using Eq. (1) and is shown in Fig. 4. In a similar manner, the bearing capacity ratios obtained for u/B varing from 0.25 to 1.0 with h/B=0.333, b/B=8, N=4, and c_u=3.14kN/m² obtained from Series D, E, F, G, and H are plotted in Fig 5. Based on these Figures, the following observation can be made.

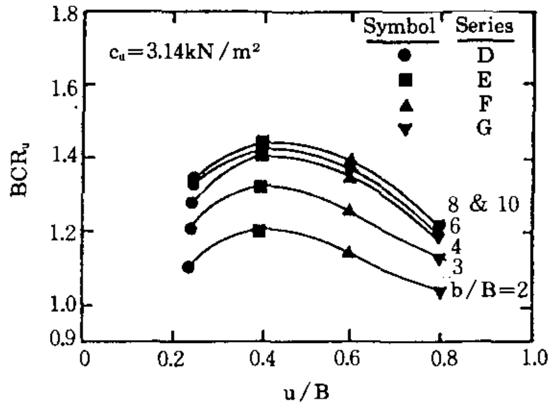

Fig.4 Variation of BCR_u versus u/B—Series D, E, F, and G

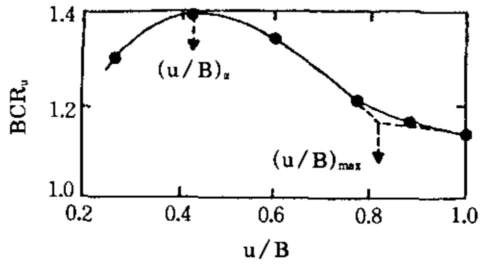

Fig.5 Variation of BCR_u with u/B (h/B=1/3, b/B=8, N=4, c_u=3.14kN/m²)

1. For a given b/B, the bearing capacity ratio increases with u/B and reaches a maximum at $u/B=(u/B)_{cr}\simeq 0.4$.
2. For $u/B>(u/B)_{cr}$, the magnitude of BCR_u decreases, reaching approximately a minimum at $u/B=(u/B)_{max}\simeq 0.8$. When u/B increases, BCR_u will be ultimately equal to 1.0. This implies that the failure surface in soil is located entirely above the first layer of geogrid(Binquet and Lee, 1975). From Fig. 4, for a given value of b/B, one can plot the variation of $BCR_{u-(u/B)}/BCR_{u-(u/B)cr}=\alpha_u$ with u/B, as shown in Fig. 6. It appears that, taking into consideration the scattering that occurs in experimental work, α_u has a unique relationship with u/B(for a given value of h/B) irrespective of the magnitude of b/B.

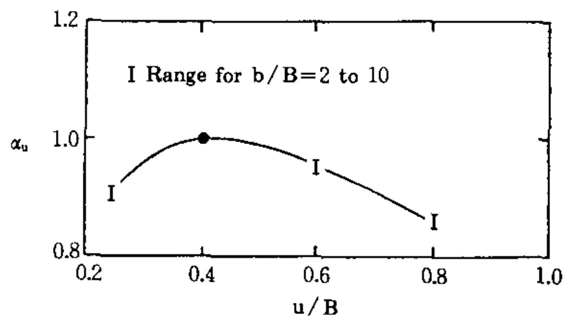

Fig.6 Plot of α_u with u/B(h/B=1/3)

Again using the experimental results from these four test series(D, E, F, and G), the variation of BCR_u with b/B for various ratios of u/B are plotted in Fig. 7.a. For any given u/B ratio, the bearing capacity ratio, BCR_u, increase with b/B in practically two linear segments, the initial one being steeper than the latter. The magnitude of b/B at the point of intersection of these two segments may refer to the critical width ratio, $(b/B)_{cr}$. The significance of the critical width ratio is that the effectiveness of the geogrid layers in increasing the load-bearing capacity of foundations decreases for $b/B>(b/B)_{cr}$. Based on Fig. 7a, $(b/B)_{cr}$) is about 4. The results of Fig. 7a can be expressed in a nondimensional form (for a given h/B) as $\alpha_b=BCR_{u-(b/B)}/BCR_{u-(b/B)cr}$ (Fig. 7b). In spite of some scatter the actural value of α_b can be expressed as (for h/B=0.333)

$$\alpha_b=0.0625(b/B)+0.75 \quad (3)$$

Test Series I and J

The tests in these series were conducted to determine the optimum depth of reinforcement required to obtain the maximum bearing capacity ratio. For all tests, the width of reinforcement was kept at 4B since this was the critical requirement, b_{cr}, for ultimate load consideration. The h/B ratio for all tests was 1/3; however, the number of reinforcement layers was varied. Using the experimental load-settlement diagrams, the variations of BCR_u were calculated and plotted in Fig. 8a. It can be seen from the figure that, irrespective of the undrained shear strength c_u, the magnitude of $d/B=(d/B)_{cr}$ at which the bearing capacity ratio reaches an approximate maximum value is about 1.75. The results shown in Fig. 8a can be expressed in a more general form as $\alpha_d=BCR_{u\ (d/B)}/BCR_{u-(d/B)cr}$(Fig. 8b). The average plot can be expressed as

$$\alpha_d=0.2(d/B)+0.7(\text{for } d/B\le 1.4) \quad (4)$$

$$\alpha_d=0.057(d/B)+0.9\ [\text{for } 1.4\le d/B\le (d/B)_{cr}] \quad (5)$$

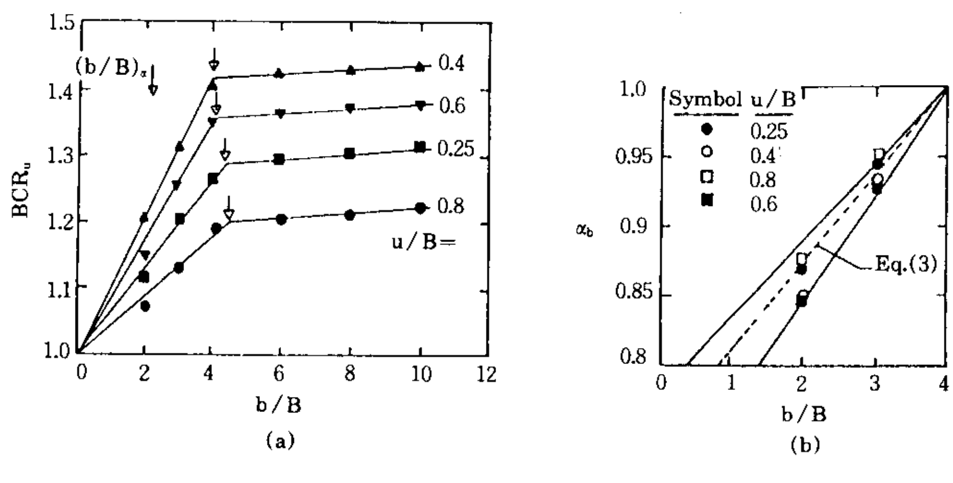

Fig.7 Plot of (a) BCR_u versus b/B: (b) α_b versus b/B—Series D, E, F and G ($N=4$, $h/B=1/3$, $c_u=3.14kN/m^2$)

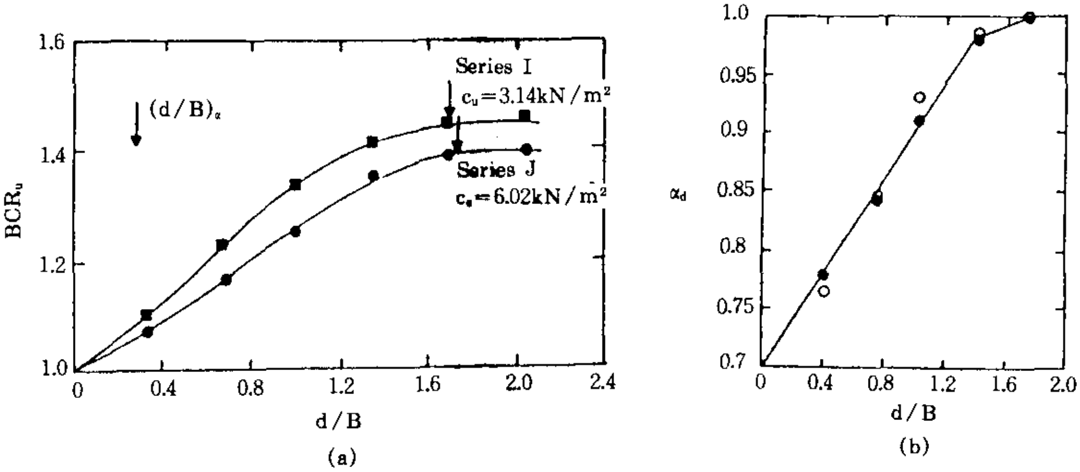

Fig.8 Plot of (a) BCR_u versus d/B; (b) α_d versus d/B—Series I and J (N=4, u/B=0.4, h/B=1/3)

Test Series K

The tests in this series were conducted with u/B=0.4, b/B=5, and $d/B=1.73 \doteqdot (d/B)_{cr}$ to determine the variation of BCR_u with h/B. The plot of the experimental BCR_u with h/B is shown in Fig. 9. If we define a nondimensional term $\alpha_h = BCR_{u\ (h/B)} / BCR_{u-(h/B=1/3)}$, then the experimental variation shown in Fig. 9 can be expressed as

$$\alpha_h = 1.15 - 0.45(h/B) \quad (\text{for } 0.333 \le h/B \le 0.8) \tag{6}$$

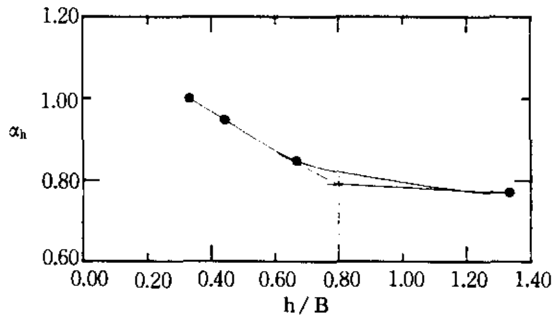

Fig.9 Plot of α_h versus h/B—Series K (u/B=0.4, b/B=5, d/B=1.73)

4. Estimation of $q_{u(R)}$

Based on the limited laboratory test results for given soil & geogrid and testing conditions, it appears that an estimation of the ultimate bearing capacity of a strip foundation supported by geogrid-reinforced saturated clayey soil can be made as

$$q_{u(R)}=c_u\, N_c(BCR'_u)\alpha_u\, \alpha_b\, \alpha_d\, \alpha_h+\gamma D_f \qquad (7)$$

where N_c=bearing capacity factor≃5.14; $BCR'_u=BCR_u$ for $u/B=(u/B)cr\simeq 0.4$, $h/B=1/3$, $d/B=(d/B)_{cr}\simeq 1.75$, and $b/B=(b/B)_{cr}\simeq 44$; γ=unit weight of soil; and D_f=depth of foundation.

The approximate relationships for α_u, α_b, α_d and α_h can be obtained from Fig. 4, Eq. 3, Eqs.(4) and (5), and Eq. (6), respectively. The magnitude of BCR'_u will be a function of c_u, the physical properties of the geogrid, and the interaction between the clayey soil and geogrid. That needs to be determined from a laboratory test conducted with the desired undrained shear strength of the clayer soil, b/B=4, u/B=0.4, and N=1. The bearing capacity ratio obtained from this test, and Eq. (4)(or Fig. 8a) may be used to estimate BCR'_u as

$$BCR'_u = \frac{BCR_u}{0.78} \qquad (8)$$

The authors realize that the above procedure is a rather impractical one for field engineers. However, when further test results on the subject are available, it may be possible to develop a better correlation between
BCR'_u, c_u and the type of geogrid.

5. Conclusions

The results of a number of laboratory bearing capacity tests for a surface strip foundation supported by a near-saturated clayer soil reinforced with layers of geogrid have been presented. Based on the laboratory test results, the following conclusions may be drawn:

1. The optimum values of the width b and depth d of the geogrid reinforcement for mobilization of maximum benefit in the bearing capacity improvement is about 4B and 1.75B.
2. For a given foundation-reinforcement system, the maximum benefit may be realized if the first layer of geogrid is located at a distance of 0.4B below the bottom of the foundation.
3. An empirical procedure to estimate the ultimate bearing capacity of clayey soil with geogrid reinforcement has been proposed.

There are several limitations to this study. For the present test program, only one type of soil and one type of geogrid were used. The scale effects for model studies of this type needs to be determined. Also, the effects of using full-scale geogrid for reinforcement along with a model foundation have not been explored. Further, theoretical and experimental studies will also be needed to develop a simple procedure to estimate BCR'_u.

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