Bearing capacity of shallow strip foundation on geogrid-reinforced sand

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ABSTRACT: Small-scale laboratory model test results conducted to determine the ultimate bearing capacity of a shallow strip foundation supported by sand reinforced with multiple layers of geogrid are presented. The depth of the foundation was varied from zero to 0.75 times the width of the foundation. Only one type of geogrid was used for reinforcement with sand compacted at two different relative densities. Based on the model test results it appears that, when the depth of embedment is greater than zero, the bearing capacity ratio for reinforced sand is higher than that obtained for surface foundation condition.

1 INTRODUCTION

Since about 1985, results have been reported on small-scale laboratory model tests conducted to determine the ultimate bearing capacity of shallow foundations supported by sand and cohesive soils reinforced by multiple layers of geotextile, geogrid, rope fibers, and wire mesh. In practically all of these studies, the tests were conducted for surface foundation condition (that is, depth of foundation, D_f = 0). The improvement in the ultimate bearing capacity due to the inclusion of reinforcement layers is represented in the literature by a nondimensional quantity called the *bearing capacity ratio* (*BCR*), or

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

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

In practical cases, the bases of all shallow foundations are constructed at a certain depth below the ground surface (that is, $D_f \neq 0$). The purpose of this paper is to report some recent laboratory model test results on the ultimate bearing capacity of a strip foundation supported by sand with multi-layer geogrid reinforcement. The tests were conducted at two relative densities of sand, and the embedment ratio, D_f/B (B = width of the foundation), was varied from zero to 0.75.

2 STATEMENT OF THE PROBLEM

Figure 1 shows a shallow strip foundation of width B supported by a sand with geogrid reinforcement. The depth of embedment of the foundation is D_f. There are N layers of geogrid, each of width b. The first layer of geogrid is located at a depth u below the bottom of the foundation. The vertical distance between consecutive layers of geogrid is h. Thus, the depth of reinforcement below the bottom of the foundation,

$$d = u + (N - 1)h \tag{2}$$

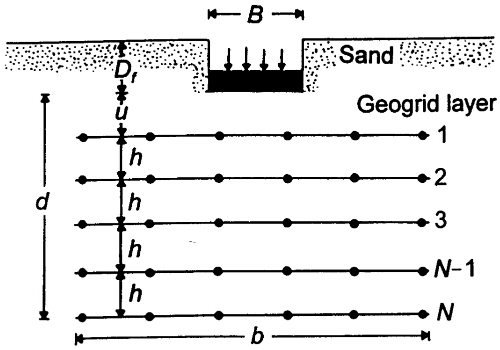

Figure 1. Shallow strip foundation on geogrid-reinforced sand

For vertical loading, the theoretical ultimate bearing capacity, $q_{u(D_f/B)}$, of a strip foundation on unreinforced sand with an embedment ratio of D_f/B can be expressed as

$$q_{u(D_f/B)} = qN_q F_{qd} + \frac{1}{2}\gamma B N_\gamma F_{\gamma d} \tag{3}$$

where $q = \gamma D_f$; γ = unit weight of sand; N_q and N_γ = bearing capacity factors; F_{qd} and $F_{\gamma d}$ = depth factors

According to Hanson (1970), for $D_f/B \le 1$

$$F_{\gamma d} = 1 \tag{4}$$

and

$$F_{qd} = 1 + 2\tan\phi(1-\sin\phi)^2 \frac{D_f}{B} \tag{5}$$

where φ = soil friction angle

Thus

$$q_{u(D_f/B)} = qN_q F_{qd} + \frac{1}{2}\gamma B N_\gamma \tag{6}$$

Similarly, the ultimate bearing capacity of a strip foundation (at an embedment ratio of D_f/B) on geogrid-reinforced sand [$q_{u(R)(D_f/B)}$] subjected to vertical load can be assumed as

$$q_{u(R)(D_f/B)} = q_{u(D_f/B)}(BCR) = qN_q F_{qd}(BCR_q) + \frac{1}{2}\gamma B N_\gamma (BCR_\gamma) \tag{7}$$

where BCR, BCR_q, and BCR_γ = bearing capacity factors

Hence, for any given D_f/B, and reinforcement condition (type of geogrid, u/B, h/B, d/B)

$$BCR = \frac{q_{u(R)(D_f/B)}}{q_{u(D_f/B)}} \tag{8}$$

For surface foundation condition, $D_f/B = 0$, and $q = 0$. So, from Eqs. 6 and 7

$$BCR = \frac{q_{u(R)(D_f/B=0)}}{q_{u(D_f/B=0)}} = BCR_\gamma \tag{9}$$

For $D_f/B > 0$, $q \neq 0$. So

$$BCR_q = \frac{q_{u(R)(D_f/B)} - q_{u(R)(D_f/B=0)}}{q_{u(D_f/B)} - q_{u(D_f/B=0)}} \tag{10}$$

For a given state of sand compaction and geogrid, the bearing capacity ratios (BCR, BCR_q, and BCR_γ) are likely to be functions of D_f/B, b/B, u/B, h/B, and d/B (that is, N). In this study, the laboratory variations of BCR, BCR_q, and BCR_γ with various values of D_f/B and d/B will be determined using Eqs. 8, 9, and 10 and compared. The laboratory tests were conducted at two relative densities of sands.

3 LABORATORY MODEL TESTS

Laboratory model tests were conducted in a metal box with inside dimensions of 1000 mm (length) × 174 mm (width) × 600 mm (height). One long side of the box was made of Plexiglas with a thickness of 20 mm. Contact® paper was attached to the inside of the other long side of the box to reduce friction between the edge of the model foundation and the box. Also, the edges of the model foundation were lightly coated with petroleum jelly. Angle irons were used to brace the outside of the test box to prevent yielding during soil compaction and bearing capacity tests.

The model foundation was made from wood and measured 172 mm (length) × 67 mm (width, B) × 77 mm (height). The base of the model foundation was made rough by cementing a layer of sand with epoxy glue. A poorly graded silica sand which had 100% passing 0.85 mm size sieve and 0% passing 0.25 mm size sieve was used for the tests. The uniformity coefficient and the coefficient of gradation of the sand were 1.51 and 1.1, respectively. A biaxial geogrid was used for soil reinforcement, and its physical properties are as follows:

Aperture size: 41 mm (MD) × 31 mm (XMD)
Maximum tensile strength: 14.5 kN/m (MD)
20.5 kN/m (XMD)
Tensile strength @ 5% strain: 5.5 kN/m (MD)
16.0 kN/m (XMD)

For the bearing capacity tests, sand was compacted in the test box in layers with thicknesses of 20 mm. Compaction was achieved by a flat-bottomed hammer. Accuracy of sand placement and consistency of relative density of sand were checked during compaction by placing small cans of known volumes at different locations. Geogrid reinforcement layers were placed at predetermined depths below the bottom of the model foundation. During the model tests, the geogrid layers had their machine directions parallel to the long side of the model test box. The model foundation was placed at

D_f/B values. All tests were conducted at average relative densities of compaction, D_r = 59% and 74%. For the sand, the maximum and minimum void ratios were 0.82 and 0.55, respectively. The peak soil friction angles determined at those relative densities (by direct shear tests) were 35° and 38°, respectively. Load to the model foundation was applied by an electric gear-controlled piston. The loading speed (piston movement) was kept at 2 mm/min. The load and corresponding foundation settlement were measured by a load cell and two dial gauges, respectively.

4 MODEL TEST RESULTS

In order to conduct the model tests with geogrid reinforcement in sand, it was important to decide the magnitude of u/B and b/B to derive maximum benefit in increasing the ultimate bearing capacity. By conducting model tests on surface foundations (D_f = 0) supported by sand with multiple layers of reinforcement, it was shown by several previous investigators (Guido et al., 1987; Akinmusuru and Akinbolande, 1981; Yetimoglu, 1994; Shin and Das, 1999) that, for given values of h/B, d/B, and b/B, the magnitude of BCR (= BCR_γ) increases with u/B and attains a maximum value of $(u/B)_{cr}$. For $u/B > (u/B)_{cr}$, the magnitude of BCR decreases. By compiling several test results Shin and Das (1999) determined that $(u/B)_{cr}$ for strip foundations can vary between 0.25 to 0.5. In a similar manner, for given h/B, u/B, and d/B values, the optimum value of b/B for surface foundation condition for deriving the maximum benefit from reinforcement can vary from 6 to 8 for strip foundations (Huang and Tatsuoka, 1988; Mandal and Manjunath, 1990; Fragaszy et al., 1983; Khing et al., 1993; and Omar et al., 1993). Keeping the above findings in mind, it was decided to adopt the following parameters for the present tests: u/B = 0.4, h/B = 0.4, b/B = 6. The sequence of the present model tests is given in Table 1

Table 1. Sequence of bearing capacity tests

Test series	Relative density of sand, D_r (%)	D_f/B	Reinforcement parameters
A	59	0, 0.37, 0.75	N = 0,1,2,3,4,5,6; u/b = 0.4; h/B = 0.4; b/B = 6
B	74	0, 0.3, 0.6	N = 0,1,2,3,4,5,6; u/b = 0.4; h/B = 0.4; b/B = 6
Note: N = 0 are for tests without reinforcement Average unit weights of sand at D_r = 59% and 74% were 15.7 kN/m^3 and 16.05 kN/m^3, respectively.			

Figures 2 and 3 show the variations of the ultimate bearing capacities [$q_{u(D_f/B)}$ and $q_{u(R)(D_f/B)}$] with d/B and D_f/B for test series A and B, respectively. Using Eqs. 8, 9, and 10, the experimental variations of BCR_q, BCR_γ, and BCR, with d/B and D_f/B were calculated and are shown in Figures 4, 5, and 6. Based on these plots, the following general observations can be made.

1. BCR, BCR_q, and BCR_γ for both relative densities of sand increase with d/B to a maximum value at $\frac{d}{B} \approx 2 = (d/B)_{cr}$. This value of $(d/B)_{cr} \approx 2$ is consistent with that reported by Omar et al. (1993) for the condition of D_f/B = 0 (Figures 4, 5, and 6).
2. For a given relative density of sand and, at any given d/B, the magnitude of BCR_q is larger than BCR_γ (Figures 4 and 5).
3. With the range of the tests ($0.3 \le D_f/B \le 0.75$) for a given D_r and d/B, the magnitude of BCR_q decreased with the increase in D_f/B (Figures 4 and 5).
4. For a given value of D_r, the plots of BCR vs. d/B were approximately the same and were not a function of D_f/B (Figure 6).

For the present tests, the variation of the ratios of BCR/BCR_γ with d/B were calculated and are shown in Figure 7, from which it can be seen that all the data points fall in a rather narrow range. Also it is obvious that, for a given foundation, geogrid, and its configuration, the magnitudes of BCR and BCR_γ determined for surface foundations ($D_f/B = 0$) will give a conservative estimation of $q_{u(R)(Df/B)}$ for $D_f/B > 0$.

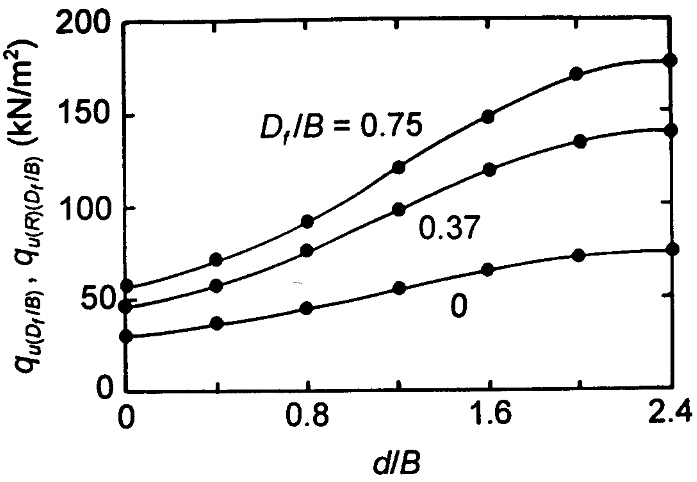

Figure 2. Plot of $q_{u(Df/B)}$ and $q_{u(R)(Df/B)}$ with D_f/B and d/B–Series A (D_r = 59%, b/B = 6, $u/B = h/B$ = 0.4)

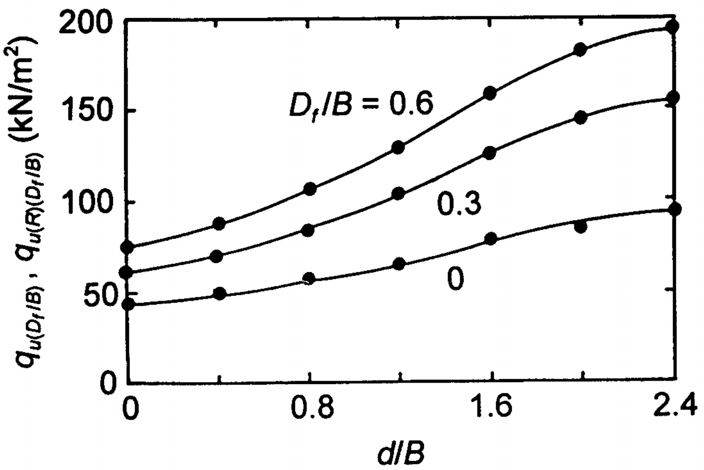

Figure 3. Plot of $q_{u(Df/B)}$ and $q_{u(R)(Df/B)}$ with D_f/B and d/B–Series B (D_r = 74%, b/B = 6, $u/B = h/B$ = 0.4)

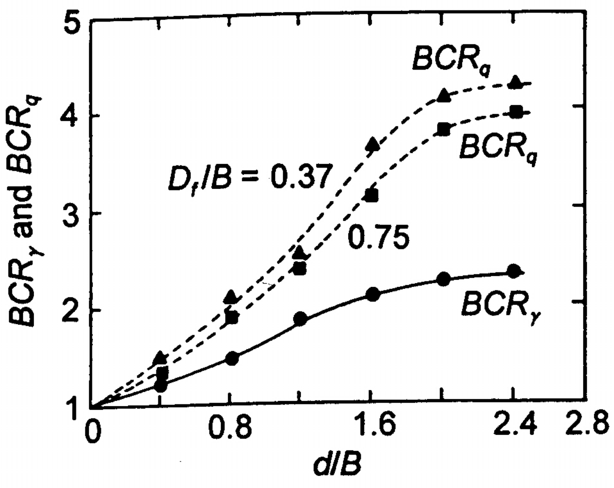

Figure 4. Plot of BCR_γ and BCR_q vs. *d/B*–Series A(D_r = 59%)

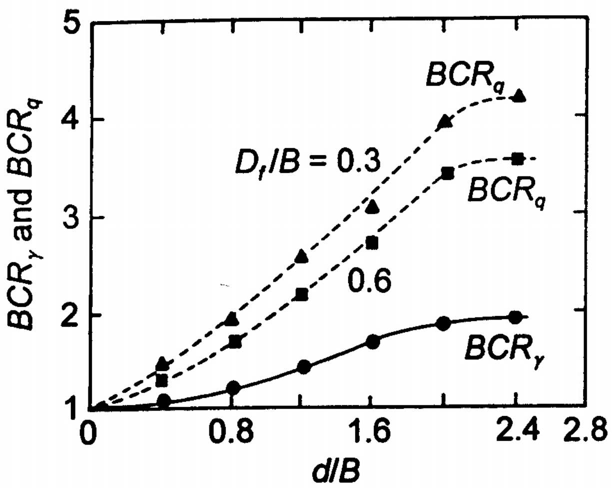

Figure 5. Plot of BCR_γ and BCR_q vs. *d/B*–Series B (D_r = 74%)

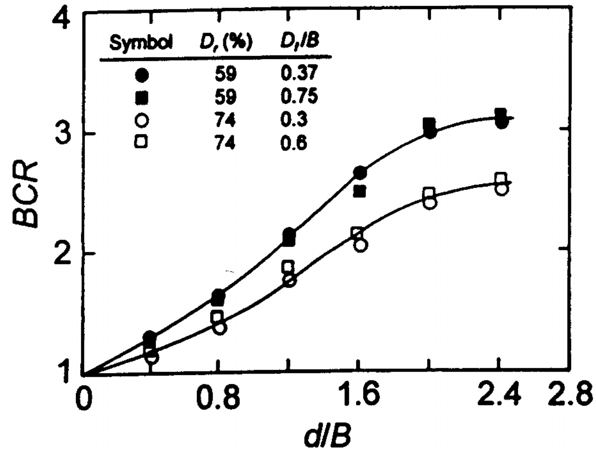

Figure 6. Plot of *BCR* with *d/B*–Series A and B

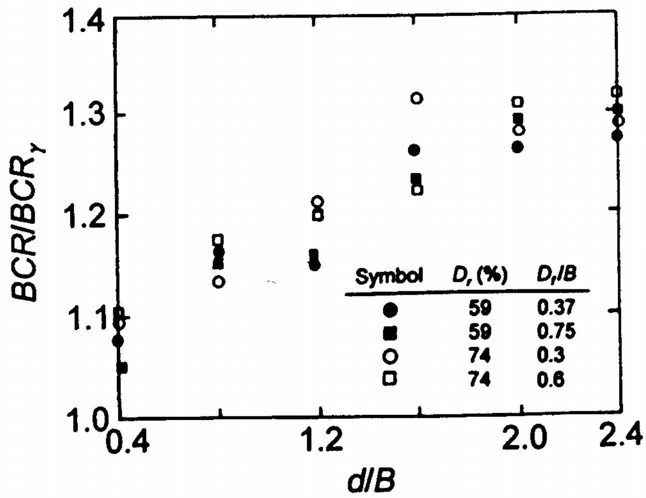

Figure 7. Plot of *BCR/BCR*$_{\gamma}$ vs. d/B

5 CONCLUSIONS

Small-scale laboratory model test results to determine the ultimate bearing capacity of a strip foundation supported by sand reinforced with multiple layers of geogrid are presented. The tests were conducted with one type of sand compacted at two relative densities and only one type of geogrid. The depth of embedment of the foundation was varied from zero to 0.75B. Based on the model test results, the following conclusions can be drawn.

1. The critical reinforcement-depth ratio (*d/B*)cr for *BCR*, BCR_q , and BCR_{γ} is about 2 for multiple layers of rein-forcement.
2. With the range of the present tests ($0 \le D_f/B < 0.75$), BCR_q was larger than BCR_{γ} .
3. The magnitude of *BCR* for $0 < d/B \le 2$ is greater than BCR_{γ}. It implies that the BCR determined from surface footing tests will provide conservative estimates of ultimate bearing capacities for foundations having depths of embedment greater than zero.

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