Shallow Foundations on Geogrid-Reinforced Sand

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Laboratory model test results for the bearing capacity of strip and square foundations supported by sand reinforced with layers of geogrid are presented. On the basis of the present model test results, the bearing capacity ratios with respect to the ultimate bearing capacity (and at levels of limited settlement of the foundation) were determined. For practical design purposes, it appears that for strip foundations the bearing capacity ratio calculated on the basis of the ultimate bearing capacity is 1.7 times the bearing capacity ratio at limited levels of settlement. Similarly, for square foundations, the bearing capacity ratio with respect to the ultimate bearing capacity is about 1.45 times the bearing capacity ratio at limited levels of settlement.

Results are available for several laboratory studies that evaluate the beneficial effects of soil reinforcement for improving the ultimate bearing capacity of shallow strip and square foundations supported by granular soil. Most of the references can be found in the paper of Guido et al. (*1*). The materials for soil reinforcement used in the existing studies were thin metal strips, wire mesh, aluminum foil, rope fibers, geotextiles, and geogrids. The cited studies have evaluated the optimum values of the following parameters for deriving the maximum benefit from the soil reinforcement (Figure 1):

1. Extent of reinforcement, d;
2. Location of first layer of reinforcement with respect to the bottom of the foundation, u; and
3. Width of reinforcement layers, b.

The increase in the ultimate bearing capacity has generally been expressed in a nondimensional form, called bearing capacity ratio (BCR_u), which may be defined as

$$BCR_u = q_{u(R)}/q_u \qquad (1)$$

where $q_{u(R)}$ is the ultimate bearing capacity with the reinforcement in soil and q_u is the ultimate bearing capacity in unreinforced soil.

It has also been observed that with the inclusion of soil reinforcement, the ultimate bearing capacity as well as the settlement of the foundation at ultimate load increases in comparison with that in unreinforced soil. In most cases, shallow foundations are designed for limited settlement(s) levels and, hence, the magnitude of BCR_u becomes meaningless. For that reason it is necessary to determine the BCR at various levels of settlement to aid in the design process of a foundation. The BCR with respect to settlement, BCR_s, may be defined as

$$BCR_s = q_R/q \qquad (2)$$

where q_R and q are the loads per unit area of the foundation at a settlement level s with and without y reinforcement in the supporting soil, respectively.

This paper presents some laboratory model test results on a strip and a square foundation supported by sand reinforced with layers of geogrid. From the model test results, the variations of BCR_u and BCR_s at various levels of s/B (B = width of foundation), and the ratio of BCR_u/BCR_s with d/B, b/B, and u/B were determined.

LABORATORY MODEL TESTS

Laboratory bearing capacity tests were conducted using two model foundations made of aluminum plates. The square model foundation measured 76.2 × 76.2 mm ($B \times B$), and the strip foundation measured 76.2 mm (B) 304.8 mm. The bases of the model foundations were made rough by cementing a thin layer of sand to them with epoxy glue.

A fine silica sand was used for all model tests. The sand had 100 percent passing No. 20 (U.S.) sieve (0.85-mm opening), 26 percent passing No. 40 sieve (0.425-mm opening), and 0 percent passing No. 60 sieve (0.25-mm opening). A biaxial geogrid was used for soil reinforcement. The physical properties of the geogrid are given as follows:

- Structure: punched sheet drawn,
- Polymer: PP/HDPE copolymer,
- Junction method: unitized,
- Aperture size: 25.4 33.02 mm,
- Nominal rib thickness: 0.762 mm, and
- Nominal junction thickness: 2.286 mm.

Laboratory model tests on the strip foundation were conducted in a box 304.8 mm wide, 1.1 m long, and 914 mm high. Model tests on the square foundation were conducted in a box measuring 760 × 760 × 760 mm.

In conducting the tests, sand was poured into the test boxes in a layer 25.4 mm thick using a raining technique. During placement of sand, the geogrid layers were positioned at desired values of u/B and h/B. At the end of sand placement, the model foundation was placed on the surface of the sand layer. Load to the model foundation was applied with a hy-

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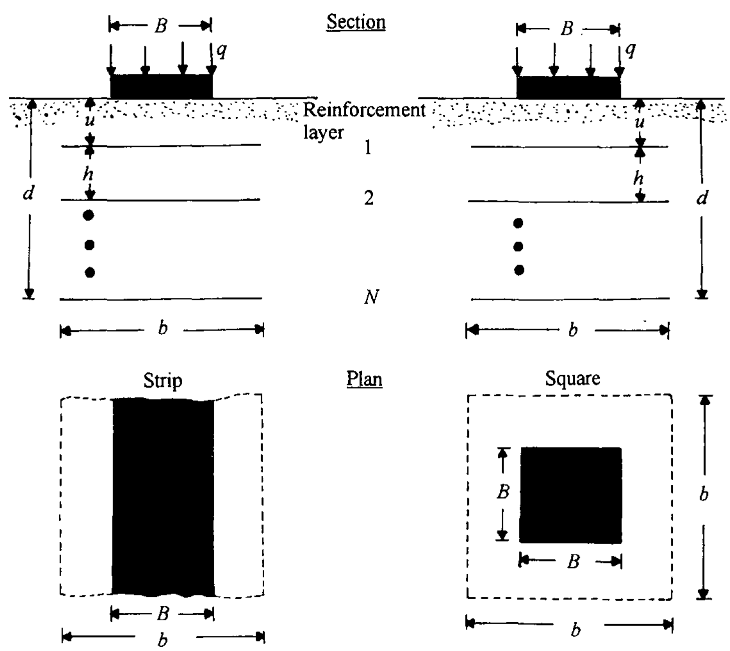

FIGURE 1 Strip and square foundations supported by reinforced sand.

draulic jack. The loads on the foundation and the corresponding settlement were measured by a proving ring and two dial gauges, respectively. The average value of the dry unit weight of sand, its relative density of compaction, and friction angle (as measured by direct shear tests) were 17.14 kN/m³, 70 percent, and 40.3 degrees, respectively. The testing parameters of the laboratory model tests are given in Table 1.

MODEL TEST RESULTS

Series A-1 and A-2

Tests in these series were conducted to obtain the variation of the load per unit area q with the foundation settlement s on unreinforced sand. Plots of q versus s for the strip and

TABLE 1 Laboratory Test Parameters

Test series	Model foundation	Constant parameter	Variable parameter	Purpose
A-1	Strip	D_r = 70%		To determine q_u
A-2	Square	D_r = 70%		
B-1	Strip	D_r = 70%; $u/B = h/B$ = 1/3; b/B = 10	N = 1, 2, 3, 4, 5, 6, 7	To determine $(d/B)_{cr}$
B-2	Square	D_r = 70%; $u/B = h/B$ = 1/3; b/B = 6	N = 1, 2, 3, 4, 5, 6	
C-1	Strip	D_r = 70%; $u/B = h/B$ = 1/3; N = 6	b/B = 2, 4, 6, 8, 10	To determine $(b/B)_{cr}$
C-2	Square	D_r = 70%; $u/B = h/B$ = 1/3; N = 4	b/B = 1, 2, 3, 4, 5, 6	
D-1	Strip	D_r = 70%; h/B = 1/3; b/B = 8; N = 6	u/B = 0.333, 0.5, 0.667, 1, 1.2, 1.5, 1.8	To determine $(b/B)_{cr}$
D-2	Square	D_r = 70%; h/B = 1/3; b/B = 4; N = 4	u/B = 0.333, 0.5, 0.667, 1, 1.2, 1.5, 1.8	

D_r = relative density of compaction of sand; N = number of geogrid layers square foundations are shown in Figure 2. For the present tests, the ultimate bearing capacities were obtained at s_u/B values of 6.6 percent for the strip foundation and 2.8 percent for the square foundation (s_u = settlement at ultimate load).

Series B-1 and B-2

For all tests in these series, the ratios of u/B and h/B were kept at 0.333. In Series B-1 the b/B ratio was 10, and, similarly, in Series B-2 it was 6. Figures 3 and 4 show the plots of q_R versus s/B for various numbers of reinforcement layers, N. The depth of the reinforcement, measured from the bottom of the foundation, can be calculated as

$$d = u + (N - 1)h \qquad (3)$$

From the plots given in Figures 3 and 4, it can be see that as the number of reinforcement layers N and thus the ratio of d/B increased, the magnitude of $q_{u(R)}$ increased. However, this increase of $q_{u(R)}$ was also accompanied by an increase of $s_{u(R)}$. On the basis of the values of q_u and $q_{u(R)}$ obtained from Figures 2, 3, and 4, the variations of BCR_u with d/B and N are shown in Figure 5. For each foundation under consideration, the magnitude of BCR_u increased with d/B up to an approximate maximum value [at $d/B = (d/B)_{cr}$] and remained constant thereafter. From the plots for BCR_u shown in Figure 5, it appears that $(d/B)_{cr\text{-strip}} \approx 2.25$ and $(d/B)_{cr\text{-square}} \approx 1.33$ to 1.5. Guido et al. (*1*) determined $(d/B)_{cr\text{-square}}$ to be about 1.25. Using the experimental plots of load per unit area versus settlement given in Figures 2, 3, and 4 and Equation 2, the variations of BCR_s at settlement levels of s/s_u = 25, 50, and 75 percent for both foundations were calculated and are plotted in Figure 5. Although there is some scatter, a single curve for each foundation for the variation of BCR_s with d/B can be plotted (as shown in Figure 5). On the basis of the average curves of BCR_u and BCR_s shown, the experimental variations of $\text{BCR}_u/\text{BCR}_s$ versus d/B are plotted in Figure 6. From the plots shown in Figure 6, it appears that for $d/B \geq 0.667$, $\text{BCR}_u/\text{BCR}_s$ is about 1.8 for the strip foundation about 1.4 for the square foundation.

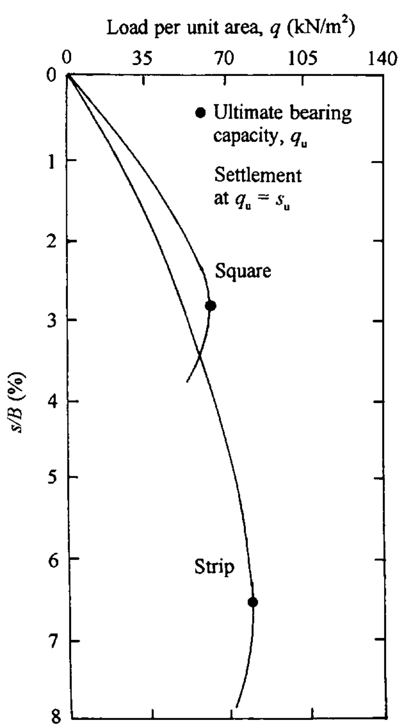

FIGURE 2 Plot of q versus s/B (Series A-1 and A-2).

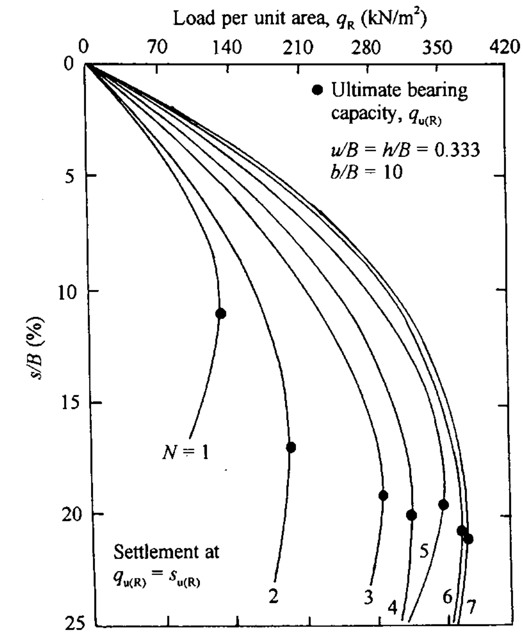

FIGURE 3 Variation of q_R with s/B for strip foundation (Series B-1).

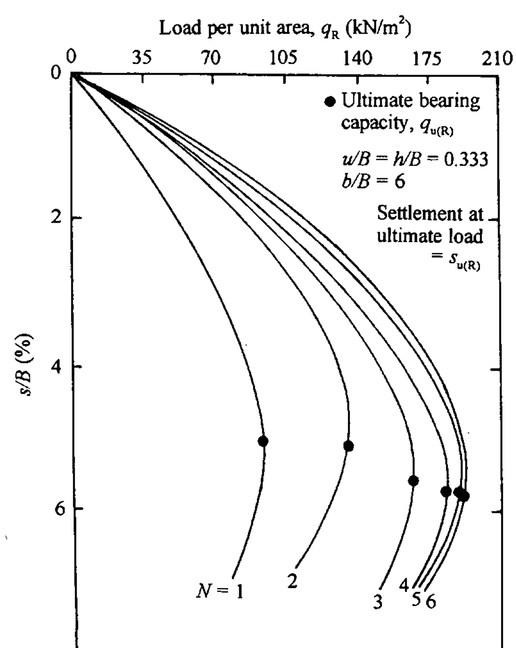

FIGURE 4 Variation of q_R with s/B for square foundation (Series B-2).

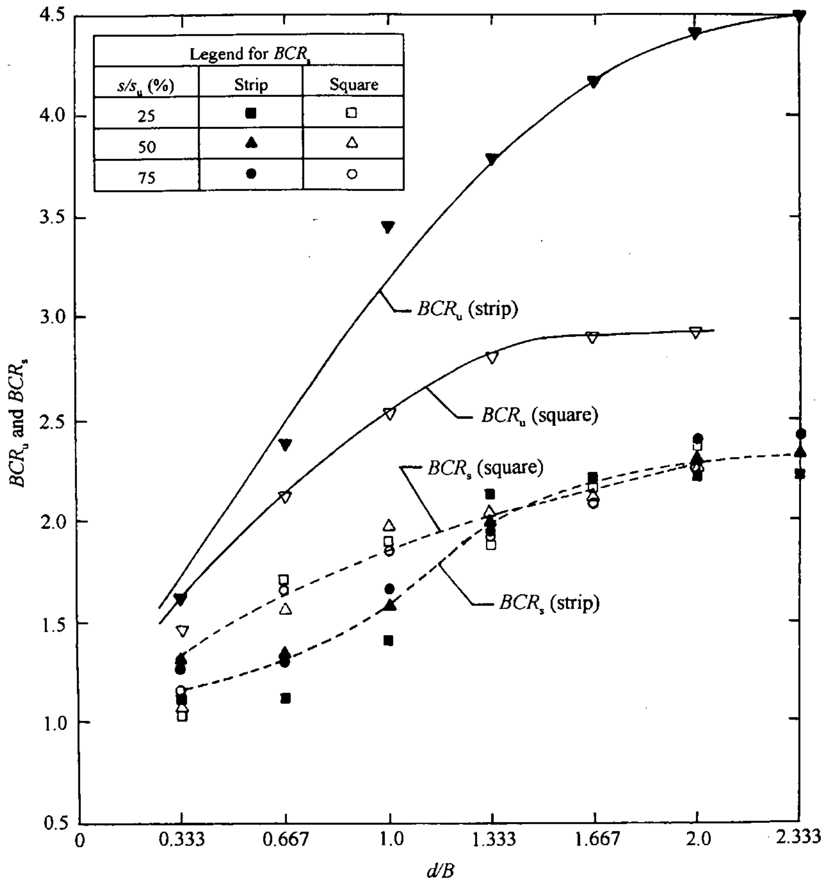

FIGURE 5 **Variation of BCR$_u$ and BCR$_s$ with d/B (Series B-1 and B-2).**

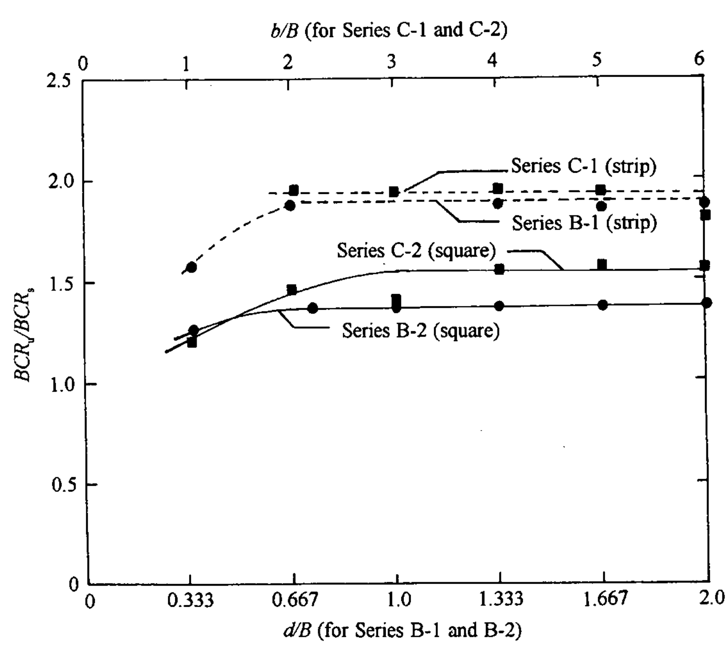

FIGURE 6 **Plot of BCR$_u$/BCR$_s$ versus d/B and b/B (Series B-1 and B-2 and Series C-1 and C-2).**

Series C-1 and C-2

In these series the magnitudes of u/B, h/B, and N for each foundation were kept constant; however, the ratio b/B was varied. The variations of BCR_u and BCR_s with b/B were obtained from the plots of load per unit area versus settlement in a similar manner as that discussed under Test Series B-1 and B-2; they are shown in Figure 7. The nature of the variations of BCR_u and BCR_s with b/B for any foundation is similar, in that the variations increase with b/B and reach a maximum value at $(b/B)_{cr}$. For the present model tests, $(b/B)_{cr\text{-strip}} \approx 8$ and $(b/B)_{cr\text{-square}} \approx 4$. In the study of Guido et al. (*1*), the magnitude of $(b/B)_{cr\text{-square}}$ was found to be between 2.5 to 3. On the basis of the average curves plotted in Figure 7, the ratio of BCR_u/BCR_s for various values of b/B for each foundation was calculated; these ratios are shown in Figure 6. It can be seen that for $b/B \geq 2$, BCR_u/BCR_s is about 1.8 for the strip foundation and about 1.5 for the square foundation.

Series D-1 and D-2

It has been observed in the past that to obtain maximum benefit from the reinforcement, it is desirable that u/B be less than about 0.67. For larger u/B ratios, the failure surface in soil at ultimate load will be fully located above the top layer of reinforcement and, in that case, the top layer of reinforcement will act as a semirigid surface. In bearing capacity tests with a square foundation supported by sand with geogrid reinforcement, Guido et al. (*1*) determined $u/B = (u/B)_{cr}$ to be about 0.75. To verify these results, the tests in this series were conducted with u/B as the variable parameter. For these tests, h/B, b/B, and N were kept constant. The experimental variations of BCR_u with u/B obtained from these tests are shown in Figure 8.

From Figure 8, it appears that for a given foundation, the variation of BCR_u with u/B can be approximated by two straight lines. The magnitude of u/B at the point of intersection of these two straight lines may be approximately defined as $(u/B)_{cr}$. For the present test results, $(u/B)_{cr}$ is about 1 for the strip foundation and about 0.8 for the square foundation. For $u/B > (u/B)_{cr}$, the straight lines of the BCR_u-versus-u/B plots, when extended, give $BCR_u \approx 1$ at $u/B \approx 2.5$. Laboratory model tests on foundations supported by sand with a rigid rough base at a limited depth have shown similar results (*2*). As in Test Series B-1 and B-2 and C-1 and C-2, the variations of BCR_s at s/s_u = 25, 50, and 75 percent, obtained from the load-settlement curves, are also shown in Figure 8.

Figure 9 shows the plots of BCR_u/BCR_s with u/B that were obtained using the average curves shown in Figure 8. For the strip foundation, the magnitude of BCR_u/BCR_s decreases from about 1.75 at $u/B = 0.333$ to about 1 at $u/B = 1$. Similarly, for the square foundation, the magnitude of BCR_u/BCR_s decreases from about 1.5 at $u/B = 0.333$ to about 1.1 at $u/B = 1$. For most reinforced earth foundation works, u/B is kept between 0.25 and 0.4. Hence, for practical purposes

$BCR_u \approx 1.7BCR_s$ for strip foundations

and

$BCR_u \approx 1.45BCR_s$ for square foundations

CONCLUSIONS

The results of a number of laboratory model tests for determining the bearing capacity of shallow strip and square foundations supported by sand reinforced by layers of geogrid have been presented. The following conclusions may be drawn from the model test results:

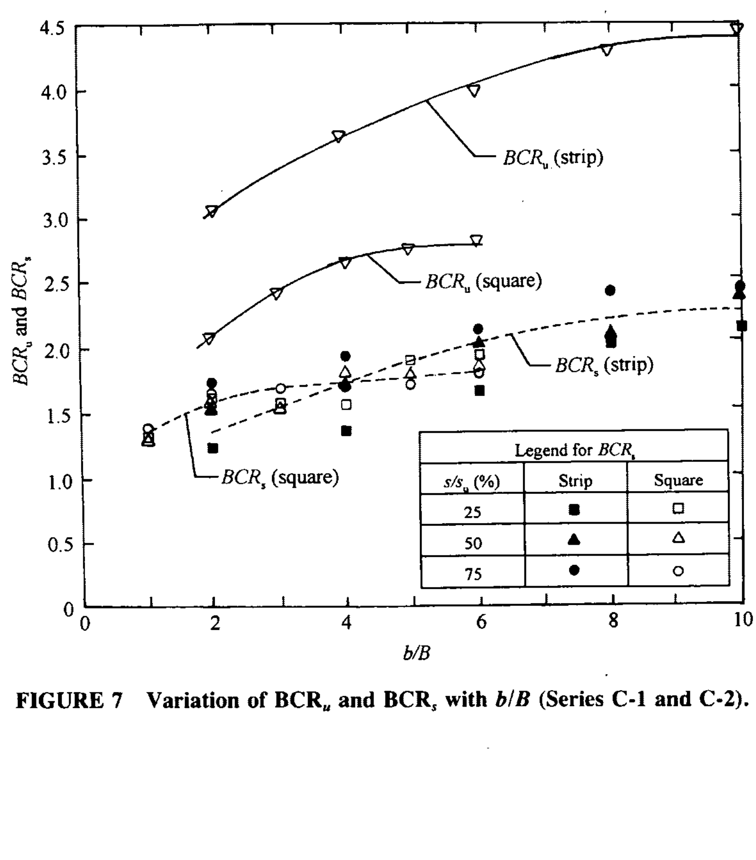

FIGURE 7 Variation of BCR_u and BCR_s with b/B (Series C-1 and C-2).

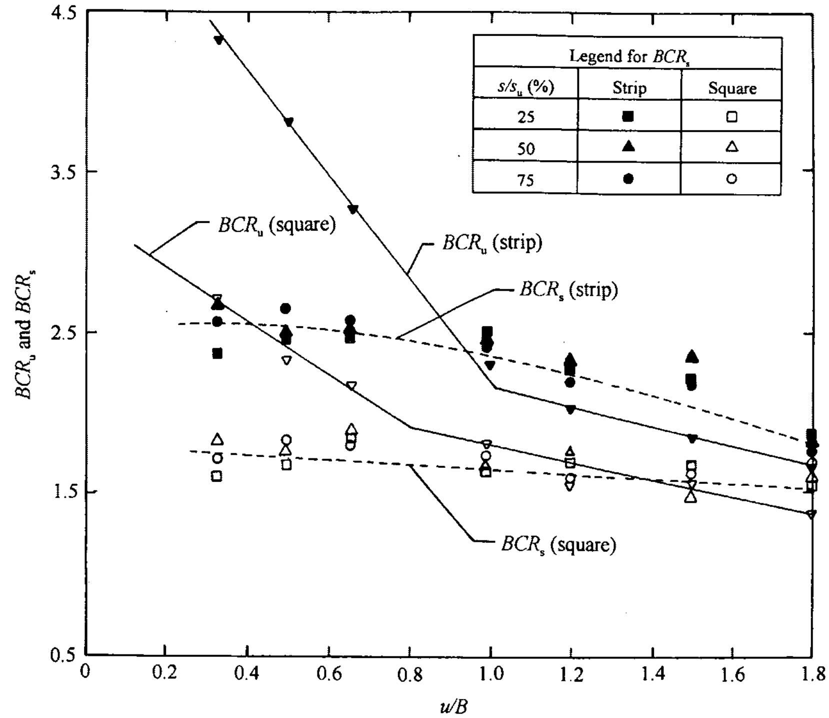

FIGURE 8 Variation of BCR_u and BCR_s with u/B (Series D-1 and D-2).

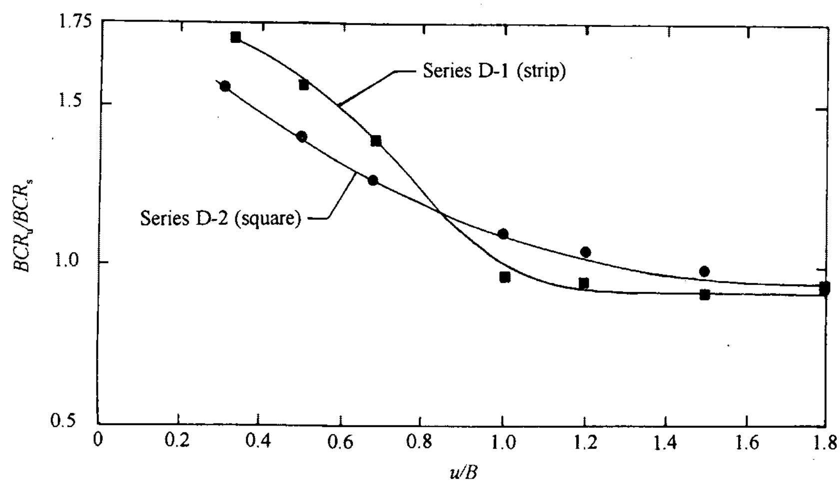

FIGURE 9 Plot of BCR_u/BCR_s versus u/B (Series D-1 and D-2).

1. For deriving the maximum benefit of soil reinforcement toward improving the allowable and the ultimate bearing capacities, the values for the geogrid are

–For strip foundations, $(d/B)_{cr} \approx 2.25$, $(b/B)_{cr} \approx 8$, $(u/B)_{cr} \approx 1$; and

–For square foundations, $(d/B)_{cr} \approx 1.33$ to 1.5, $(b/B)_{cr} \approx .4$, $(u/B)_{cr} \approx 0.8$.

The effect of the soil friction angle as well as the type, thickness, and aperture size of the geogrid may have some influence on these critical parameters. Hence, further study in that regard is required.

2. The BCR calculated on the basis of ultimate bearing capacity is somewhat misleading for actual foundation design, since most foundations are constructed on the basis of limited settlement. The magnitude of BCR_u is about $1.7BCR_s$ for strip foundations and about $1.45BCR_s$ for square foundations.

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