Ultimate Bearing Capacity of Eccentrically Loaded Strip Foundation on Geogrid-Reinforced Sand

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Laboratory model test results for the ultimate bearing capacity of eccentrically loaded strip foundation supported by sand reinforced by layers of geogrid have been reported. The model tests were conducted at 70 percent relative density of compaction of sand. The load eccentricity ratio was varied. From the model test results, the critical depth of location of the first layer of geogrid and the extent of the geogrid reinforcement measured from the bottom of the foundation for mobilization of maximum bearing capacity have been presented. Test results have also been presented for determination of the optimum width of the reinforcement layers.

In recent years, the use of reinforced earth in the design and construction of earth-supported and earth-retaining structures has greatly increased. The materials generally used for earth reinforcement are galvanized metal strips, wire mesh, geotextiles, and geogrids. Currently, more emphasis on reinforcement has been placed in studies that relate to the design of retaining walls. However, earth reinforcement can also be used to improve the load-bearing capacity of shallow foundations and reduce the settlement at allowable load as demonstrated by several recent investigations (*1–8*). This paper relates to the study of the ultimate bearing capacity of shallow strip foundation supported by sand reinforced with layers of geogrid and subjected to eccentric loading. The study was conducted by means of small-scale laboratory model tests.

PARAMETERS FOR ULTIMATE BEARING CAPACITY

Figure 1 shows a strip surface foundation supported by a sand layer that is reinforced with N layers of geogrid each having a width equal to b. The strip foundation, which has a width B, is subjected to a loading with an eccentricity equal to e. The first layer of geogrid is located at a distance u measured from the bottom of the foundation. The distance between the consecutive geogrid layers is equal to h; hence the distance between the bottom of the foundation and the last geogrid layer can be given as

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

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For a strip surface foundation supported by a sand layer without geogrid reinforcement, the ultimate load per unit length can be given as (*9*)

$$Q_u = (\tfrac{1}{2}\gamma B' N_\gamma)(B') \tag{2}$$

where

Q_u = ultimate load per unit length,
γ = unit weight of soil,
B = effective width = $B - 2e$,
N = bearing capacity factor (*10*), which is a function of the soil friction angle ϕ.

When geogrids are used as soil reinforcement, the ultimate load per unit length will increase to $Q_{u(R)}$. Also

$$Q_{u(R)} = f(u/B', d/B', b/B', \gamma, \phi) \tag{3}$$

The increase of the ultimate load for similar values of e/B can be expressed in a nondimensional form as (*1*)

$$\text{BCR} = Q_{u(R)}/Q_u \tag{4}$$

where BCR is the bearing capacity ratio.

The purpose of this paper is to determine the variation of the BCR with u/B', d/B', and b/B'.

LABORATORY MODEL TESTS

Laboratory model tests were conducted in a steel box 1.1 m long, 304.8 mm wide, and 914 mm deep. The sides of the box were braced with stiffeners to avoid lateral yielding during soil placement and the loading of the model foundation. The model foundation used for the tests was 304.8 mm long, 101.6 mm wide (B), and 25.4 mm thick; it was made out of hard wood. Its base was made rough by cementing a thin layer of sand using epoxy glue. The sides of the model test box and the foundation were made as smooth as possible to reduce friction during tests. A mild steel plate 6.35 mm thick, having the same plan as the model foundation and grooves along the centerline parallel to its width side, was mounted on the model foundation. The grooves were made to ensure that the applied loads during tests were vertical and had the desired eccentricity ratio e/B.

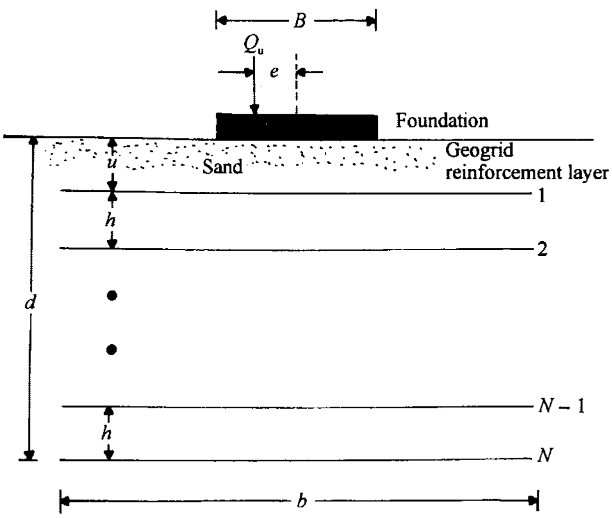

FIGURE 1 Strip surface foundation supported by a sand layer reinforced with geogrid.

A medium, round silica sand was used for the 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 reinforcement. The physical properties of this geogrid are as follows:

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

In conducting a model test, sand was poured into the test box in 25.4-mm-thick layers using a raining technique. The accuracy of sand placement and consistency of placement density were checked by placing small cans with known volumes at different locations in the box. Geogrid layers were placed in the sand at desired values of u/B' and h/B'. The model foundation was placed on the surface of the sand bed. Load to the model foundation was applied by a hydraulic jack. The load and the corresponding foundation settlement s along the centerline were measured by a proving ring and two dial gauges. For all tests the average unit weight and the relative density of compaction of the sand were 17.14 kN/m^3 and 70 percent, respectively. The average friction angle at this relative density of compaction as determined from direct shear tests was 40.3 degrees.

Details of all tests conducted under this program are given in Table 1. The ultimate load for each model test was determined using the criteria described by Vesic (*10*).

MODEL TEST RESULTS AND ANALYSIS

Ultimate Load in Unreinforced Sand

Figure 2 shows the variation of Q/B (Q = load per unit length of foundation) against s/B (s = settlement along the centerline of the foundation) for all tests conducted in Series A in which the model foundation was supported by unreinforced sand. As the ratio of e/B increased, the magnitudes of Q_u and s/B at ultimate load decreased as expected. The experimental variation of Q_u for all cases was about 4 to 7 percent higher than that calculated using Equation 2 and Vesic's theoretical bearing capacity factor N_γ (*10*).

Optimum Location of First Layer of Geogrid: $u/B'' = (u/B')_{cr}$

Test Series B, C, and D were conducted primarily to determine the critical nondimensional depth $u/B' = (u/B')_{cr}$ for placement of the first layer of geogrid reinforcement. Binquet and Lee (*2*) showed that at u/B' $(u/B')_{cr}$, the first layer of reinforcement acts somewhat like a semirigid rough base, and the entire failure surface in sand is located above it. For deriving the maximum benefit from reinforcement, u/B' should be less than $(u/B')_{cr}$.

Figures 3 and 4 show the plots of Q_R/B against s/B [Q_R = load per unit length (m) of reinforced foundation] for various u/B' ratios as obtained from tests conducted in Series B and D. These tests were for e/B = 0 and 0.125. As can be seen from these plots, for a given value of e/B the magnitude of $Q_{u(R)}/B$ decreases with the increase of u/B'. For a given eccentricity ratio e/B, the BCR can be determined as

$$\mathrm{BCR}_{e/B,u/B',H/B',b/B,d/B'} = \frac{\left[\dfrac{Q_{u(R)}}{B}\right]_{e/B,u/B',h/B',b/B,d/B'}}{\left(\dfrac{Q_u}{B}\right)_{e/B}} \tag{5}$$

On the basis of the experimental values of Q_u/B determined from Test Series A and the values of $Q_{u(R)}/B$ obtained from Test Series B, C, and D, the variations of the BCR with u/B' were calculated; they are shown in Figure 5. From this figure, it appears that $(u/B')_{cr}$ for significant values of e/B is approximately equal to 1. This is slightly higher than 2/3, as predicted by Binquet and Lee (*2*). However, the limited test results preclude a general statement for all values of e/B. In any case, the reduced benefits of reinforcement of u/B equal to and greater than 1 is clearly demonstrated in Figure 3. If the BCR-versus-u/B' curves are extrapolated, they give a BCR of about 1 at $u/B' \approx 2.5$. This is in general agreement with the experimental study conducted by Das (*11*) for the ultimate bearing capacity of eccentrically loaded strip foundations supported by a sand layer with a rigid rough base at a limited depth.

It is reasonable to speculate that the increase in the load bearing capacity of the foundation with the decrease of u/B' is primarily due to the relative stiffness of the top layer of the geogrid. For that reason, a limited number of laboratory tests were conducted to observe the failure mode in soil at ultimate load. For these tests, one side of the test box was made of Plexiglas. For all tests it was observed that at ultimate load, failure in soil occurred by pullout of geogrid layers. It should also be pointed out that Akinmusuru and Akinbolande conducted several laboratory model tests with very flexible, naturally occurring rope fibers as reinforcement in sand (*1*). These

TABLE 1 Details of Model Tests

Test series	Type of test	Test details	Remarks
A	WO*	e/B = 0, 0.0625, 0.125, 0.1875, 0.25	
B	WR**	$e/B = 0$; $h/B' = 0.375$; $N = 6$; b/B = 10.75; u/B' = 0.375, 0.75, 1.0, 1.25, 1.5, 2	For determination of $(u/B')_{cr}$
C	WR**	$e/B = 0.0625$; $h/B' = 0.429$; $N = 6$; b/B = 10.75; u/B' = 0.429, 0.858, 1.286, 1.71, 2	
D	WR**	$e/B = 0.125$; $h/B' = 0.5$; $N = 6$, b/B = 10.75; u/B' = 0.5, 0.67, 1.0, 1.33	
E	WR**	$e/B = 0$, $u/B' = h/B' = 0.375$; b/B = 10.75; N = 1, 2, 3, 4, 5, 6	For determination of $(d/B')_{cr}$
F	WR**	$e/B = 0.125$, $u/B' = h/B' = 0.5$; b/B = 10.75; N = 1, 2, 3, 4, 5, 6	
G	WR**	$e/B = 0.25$, $u/B' = h/B' = 0.75$; b/B = 10.75; N = 1, 2, 3, 4, 5, 6	
H	WR**	$e/B = 0$, $u/B' = h/B' = 0.375$; $N = 6$, b/B = 2, 4, 6, 8, 10.75	For determination of $(b/B)_{cr}$
I	WR**	$e/B = 0.125$, $u/B' = h/B' = 0.5$; $N = 6$, b/B = 2, 4, 6, 8, 10.75	
J	WR**	$e/B = 0.1875$, $u/B' = h/B' = 0.6$; $N = 6$, b/B = 2, 4, 6, 8, 10.75	
K	WR**	$e/B = 0.25$, $u/B' = h/B' = 0.75$; $N = 6$, b/B = 2, 4, 6, 8, 10.75	

*WO--without reinforcement; **WR--with geogrid reinforcement
Relative density of sand for all tests, D_r = 70%

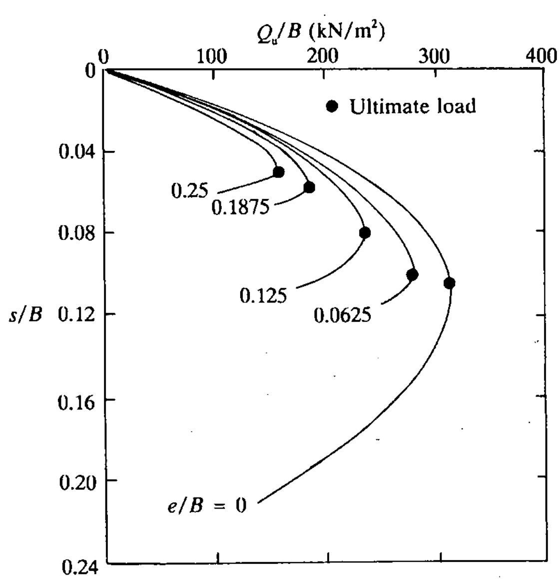

FIGURE 2 Variation of Q/B with s/B (Test Series A).

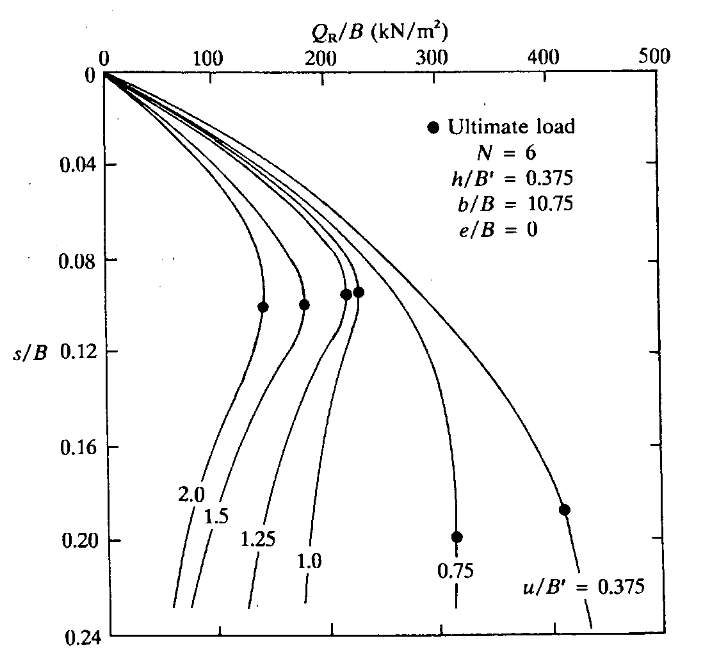

FIGURE 3 Variation of Q_R/B with s/B for various values of u/B' (Test Series B; e/B = 0).

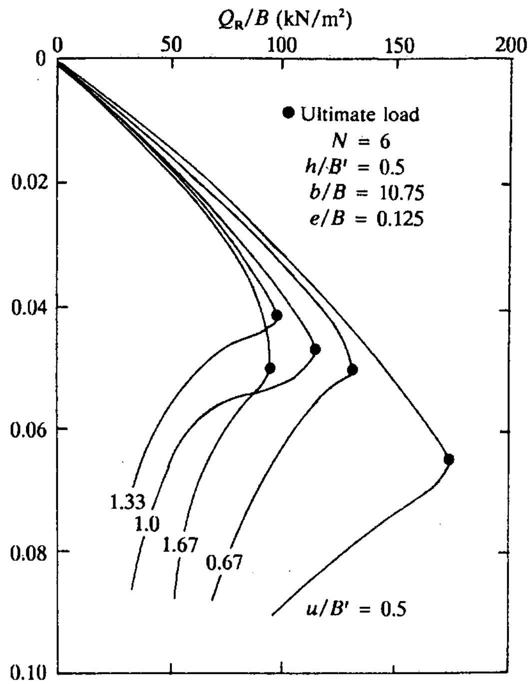

FIGURE 4 Variation of Q_R/B with s/B' for various values of u/B' (Test Series B; e/B = 0).

tests were conducted with a square model foundation and concentric load. The results of their tests show that, other factors remaining constant, the magnitude of the BCR increased with a decrease of u/B'. However, for u/B' less than about 0.25, the BCR decreased. Thus it appears that reinforcement layers that are not very stiff can also increase the load-bearing capacity of a foundation when the first layer is very close to the bottom of the foundation.

Critical Nondimensional Depth of Geogrid Reinforcement: $(d/B')_{cr}$

In all practical cases, the effect of reinforcement will be insignificant below a critical depth measured from the bottom of the foundation. To determine the magnitude of $(d/B')_{cr}$, tests in Series E, F, and G were conducted. For each test series, the magnitudes of e/B, u/B', h/B', and b/B were kept constant. However the magnitude of d/B' was varied by increasing the number of reinforcement layers. Using the experimental results and Equation 5, the variations of BCR with N were calculated and are shown in Figure 6. It can be seen from Figure 6 that for a given value of e/B, the magnitude of BCR increases with N up to a maximum value (at $d = d_{cr}$) and remains constant thereafter. From these plots, the $(d/B')_{cr}$ values are 2.25, 2.5, and 2.25 at e/B = 0, 0.125, and

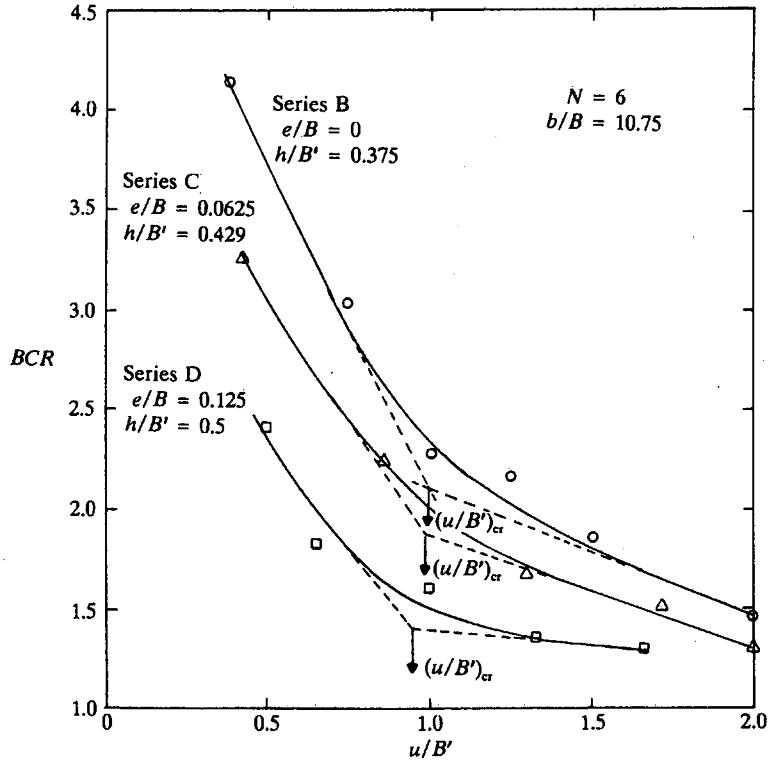

FIGURE 5 Variation of BCR with u/B' (Test Series B, C, and D).

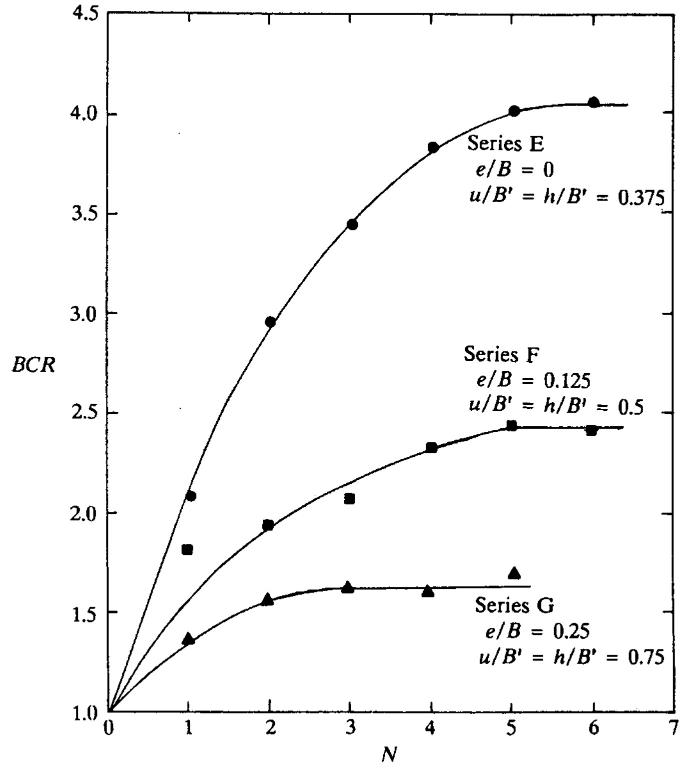

FIGURE 6 Variation of BCR with *N* (Test Series E, F, and G).

0.25, respectively. It is interesting to note that for a square foundation subjected to concentric loading ($e/B = 0$), Guido et al. have determined that $(d/B')_{cr}$ 1 to 1.25 (*6*).

Optimum Width of Reinforcement Layers: (b/B)

Tests in Series H, I, J, and K were conducted to determine, other parameters remaining constant, the critical value of $(b/B)_{cr}$ at which the maximum value of BCR is obtained. These tests were conducted for $e/B = 0$, 0.125, 0.1875, and 0.25. Using Equation 5 and the present laboratory test results, the variations of BCR with b/B were calculated and are shown in Figure 7. Contrary to the original expectations, for all values of e/B, b/B increased and reached a maximum value $BCR = BCR_{max}$ at $(b/B)_{cr} \approx 8$. This is true irrespective of the eccentricity ratio e/B. However, for $b/B < (b/B)_{cr}$, the magnitude of $\Delta(BCR)/(b/B)$ decreases as the eccentricity ratio increases.

GENERAL COMMENTS ON EXPERIMENTAL RESULTS

The present model tests were conducted with the sand being placed at a relative density of about 70 percent with an average friction angle of about 40 degrees. In actual practice, the soil at such a high relative density may not need reinforcement. Hence, questions may arise as to whether similar relationships will be realized with soil that is weaker, as might be the case in real life. Model test results of Guido et al. on a square foundation supported by geogrid-reinforced sand are particularly instructive for this consideration (*6*). These tests were conducted with sand at a relative density of compaction of about 55 percent. The average friction angle of sand was about 37 degrees. The maximum BCR observed in those tests was about 3, which is of the same order as obtained in this test program. Hence, it can be speculated that similar relationships can be obtained with weaker soil reinforced with geogrid.

The results of this model test program have been expressed in terms of B and B'. It should be noted that B' is a fictitious term that allows a computation as if the load were concentric. For Test Series B, C, and D, the model test results indicated that there was a simple relationship between BCR and u/B' (rather than u/B). In a similar manner, on the basis of the results of Test Series E, F, and G, it was obvious that the critical value of the depth of reinforcement (d) had approximately a constant relationship with B' (not with B). For that reason, the test results have been described in terms of nondimensional parameters u/B', h/B', and d/B', and not as u/B, h/B, and d/B.

CONCLUSIONS

A limited number of laboratory model test results for the ultimate bearing capacity of eccentrically loaded strip foundation on geogrid-reinforced sand has been presented. All tests were conducted at an average relative density of 70 percent for sand. The eccentricity ratio e/B was varied from 0 to

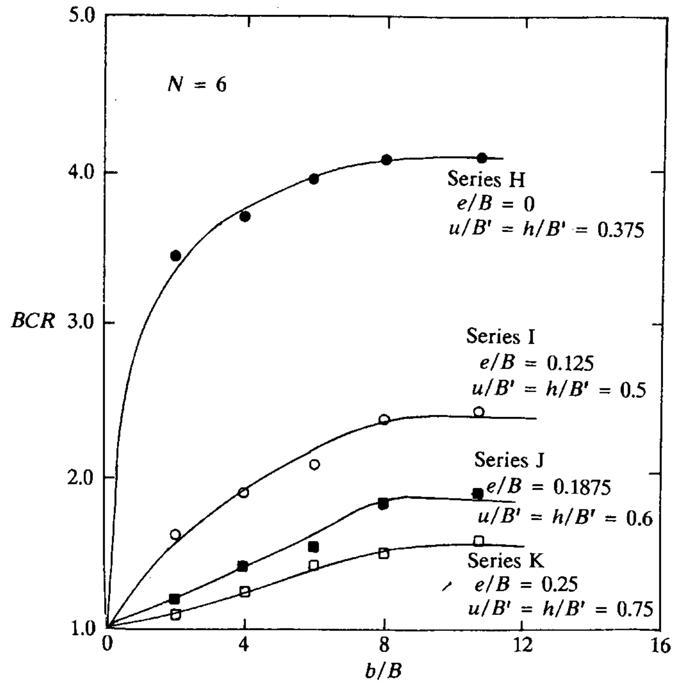

FIGURE 7 Variation of BCR with *b/B* (Test Series H, I, J, and K).

0.25. On the basis of the model test results, the following conclusions can be drawn:

1. To derive the most beneficial effects from the reinforcement, the first layer of the geogrid must be placed at a depth of $u < B'$ ($= B - 2e$) measured from the bottom of the foundation.
2. Reinforcements placed beyond the depth $d \approx 2.25(B - 2e)$ to $2.5(B - 2e)$ do not contribute to the increase of the ultimate bearing capacity.
3. Other parameters remaining the same, the width of geogrid layers for maximum ultimate bearing capacity mobilization is about $8B$, irrespective of the load eccentricity ratio. This may be treated as a specific conclusion since the interface friction parameters between the soil and the geogrid and the overall stiffness of the tested reinforced mass may dictate the results. More experimental and theoretical studies are needed.

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