Bearing capacity of eccentrically loaded strip foundation on geogrid-reinforced sand

Capacité portante d′une semelle filante, sous charge excentrée, reposant sur un sable renforcé par géo grilles

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ABSTRACT
Results of laboratory model tests conducted to determine the ultimate bearing capacity of an eccentrically loaded strip foundation supported by sand reinforced with layers of geogrid are presented. Only one type of geogrid and a sand at one relative density were considered. Based on the present laboratory test results, an empirical relationship for the reduction factor has been developed. This relationship can be used to estimate the ultimate bearing capacity under eccentric load if the corresponding value under centric loading is known.

RÉSUMÉ
On présente les résultats d′essais menés sur un modèle en laboratoire en vue de determiner la capacité portante d′une semelle filante, sous charge excentrée, reposant sur un sable renforcé par couches de géo grilles. Un seul type de géo grille et un sable à densité relative fixée ont été testés. A partir des résultats expéreimentaux enregistrés on propose une corrélation permettant d′estimer le facteur de réduction de la capacité portante ultime, sous charge excentrée, à partir de la capacité portante correspondante sous charge centrée supposeé connue.

Keywords : Bearing capacity, eccentric load, geogrid, reduction factor, sand

1 INTRODUCTION

During the last twenty-five years or so, results of several studies that relate to the evaluation of the bearing capacity of shallow foundations supported by sand reinforced with multiple layers of geogrid have been published (Omar et al. 1993, Das & Omar, 1994, Yetimogul et al. 1994, Khing et al. 1993, Adams & Collin 1997). All of these studies were conducted for surface foundation conditions. The effect of the depth of embedment of the foundation, which is the normal situation in all practical cases of construction, has not received enough attention. To the best of the knowledge of the authors, the only published results presently available in the literature that addresses the effect of the depth of embedment of foundation (d_f) are those of Shin & Das (2000) and Shin et al. (2002). Furthermore, none of these studies addresses the effect of vertical eccentric load on the bearing capacity of the foundation. This paper will report some recent laboratory model tests results related to the bearing capacity of an eccentrically loaded strip foundation supported by sand with multiple layers of geogrid reinforcement. The depth of embedment of the foundation was also varied.

2 BEARING CAPACITY OF UNREINFORCED SAND UNDER ECCENTRIC LOADING

Meyerhof (1953) proposed a semi-empirical procedure to estimate the bearing capacity of a shallow foundation subjected to eccentric loading. Prakash & Saran (1971) provided a comprehensive mathematical formulation to estimate the bearing capacity for rough strip foundations under eccentric loading

Purkayastha & Char (1977) carried out the stability analysis of an eccentrically loaded strip foundation on sand using the method of slices. Based on this study, they proposed that

$$\frac{q_{u(e)}}{q_u} = 1 - R_K \qquad (1)$$

where R_K = reduction factor, q_u = bearing capacity for centrally loaded foundation, $q_{u(e)}$ = bearing capacity of foundation with a load eccentricity e, and B = width of foundation.

The reduction factor is given by the relationship

$$R_K = a\left(\frac{e}{B}\right)^K \qquad (2)$$

The variations of a and K with embedment ratio d_f/B are given in Table 1. Note that a and K are not functions of the soil friction angle ϕ.

Table 1. Variations of a and K

D_f/B	a	K
0	1.862	0.730
0.25	1.811	0.785
0.50	1.754	0.800
1.00	1.820	0.888

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3 BEARING CAPAPCITY OF GEOGRID-REINFORCED SAND UNDER ECCENTRIC LOADING

Figure 1 shows a strip foundation of width B on geogrid-reinforced sand subjected to an eccentric loading (load eccentricity = e). The ultimate load per unit length of the foundation is $Q_{uR(e)}$. There are N layers of geogrid reinforcement, each with a width b. The first layer of geogrid is placed a depth of u below the foundation. The distance between consecutive layers of geogrid is h. Thus the depth of reinforcement (d) from the bottom of the foundation is

$$d = u + (N-1)h \tag{3}$$

Assuming that the failure mechanism under eccentric loading is as shown in Fig. 1 is correct, it will be shown that [similar to Equation (1)]

$$\frac{q_{uR(e)}}{q_{uR}} = 1 - R_{KR} \tag{4}$$

where $q_{uR(e)}$ = bearing capacity due to eccentric loading, q_{uR} = bearing capacity due to centric loading, R_{KR} = reduction factor for geogrid-reinforced sand.

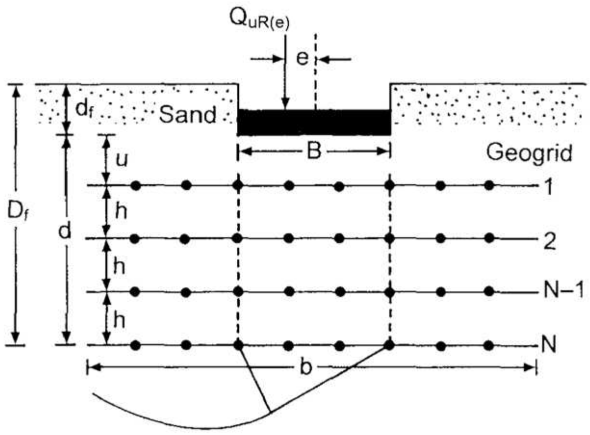

Figure 1. Assumed failure mode under an eccentrically loaded strip foundation on geogrid-reinforced sand.

4 LABORATORY MODEL TESTS

The model foundation used for this study was 80mm wide and 360mm long. It was made from a mild steel plate with a thickness of 25mm. The bottom of the model foundation was made rough by coating it with glue and then rolling it in sand. Bearing capacity tests were conducted in a box measuring 0.8m × 0.365m × 0.7 m (length × width ×depth). The inside walls of the box and the edges of the model were polished to reduce friction as much as possible. The sides of the box were heavily braced to avoid lateral yielding. The sand used for the tests had 100% passing 1.18mm size sieve and 0% passing 0.075mm size sieve. The average unit weight and the relative density of compaction were kept at 14.81 kN/m^3 and 71% respectively for all tests. The average peak friction angle of the sand (ϕ') at the test conditions was 41° (as determined from direct shear tests). A uniaxial geogrid was used for the present tests, and the physical properties are given in Table 2.

In conducting a model test, sand was placed in lifts of 25mm in the test box. For each lift, the amount of soil required to produce the desired unit weight was weighed and compacted with a flat-bottomed wooden block. Geogrid layers were placed in the sand at desired values of u/B and h/B. The model foundation was placed on the surface as well as at desired depths below the surface of the sand bed. Centric or eccentric load was applied to the model foundation by a hydraulic jack. The settlement of the foundation was recorded by two dial gauges (having 0.01mm accuracy) placed on either side of the model foundation. Load was applied in small increments and the resulting settlements recorded so that the entire load-settlement curve could be obtained. Since the length of the model foundation was approximately the same as the width of the test box, it can be assumed that an appropriate plane strain condition did exist during the tests.

Table 2. Physical properties of the geogrid

Peak tensile strength	60 kN/m
Tensile strength at 2.0% strain	14 kN/m
Tensile strength at 5.0% strain	30 kN/m
Strain at break	8%
Aperture size	94mm × 42 mm

For the present test program, the following parameters were adopted for the geogrid reinforcement layers: u/B = 0.35, h/B = 0.25, and b/B = 5. The sequence of the model tests is given in Table 3.

Table 3. Sequence of model tests.

Test No.	d_f/B	N	D_f/B	e/B
1	0	4	1.1	0
2	0	4	1.1	0.05
3	0	4	1.1	0.075
4	0	4	1.1	0.10
5	0	4	1.1	0.15
6	0.5	4	1.6	0
7	0.5	4	1.6	0.05
8	0.5	4	1.6	0.075
9	0.5	4	1.6	0.10
10	0.5	4	1.6	0.15
11	0.25	4	1.35	0
12	0.25	4	1.35	0.1
13	0.75	4	1.85	0
14	0.75	4	1.85	0.1
15	1.0	4	2.1	0
16	1.0	4	2.1	0.1
17	0	2	0.6	0
18	0	2	0.6	0.1
19	0	3	0.85	0
20	0	3	0.85	0.1

5 MODEL TEST RESULTS

The ultimate bearing capacities [i.e. q_{iR} and $q_{uR(e)}$] obtained for Test Nos. 1 through 10 are plotted in Fig. 2. From Equation (3) the reduction factor can be expressed as

$$R_{KR} = 1 - \frac{q_{uR(e)}}{q_{uR}} \tag{6}$$

The reduction factor for the present study will be a function of $D_f/B = (d_f + d)/B$ and e/B. Thus

$$R_{KR} = \beta_1 \left(\frac{D_f}{B}\right)^{\beta_2} \left(\frac{e}{B}\right)^{\beta_3} \tag{6}$$

The reduction factors (R_{KR}) obtained from the experimental values given in Fig. 2 for D_f/B = 1.1 and 1.6 (Test Nos. 1 to 5 and 6 to 10) are shown in Fig. 3. It is obvious that, for a given value of D_f/B, β_3 is approximately equal to 1.21, or

$$R_{KR} \propto \left(\frac{e}{B}\right)^{1.21} \tag{7}$$

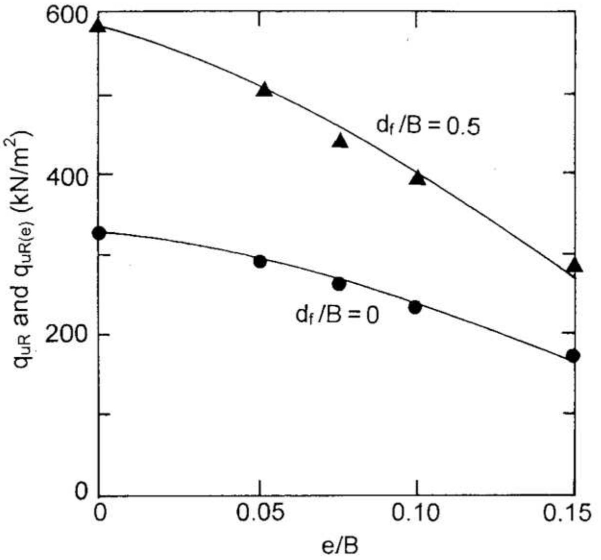

Figure 2. Plot of q_{uR} and $q_{uR(e)}$ versus e/B (Test Nos. 1 through 10).

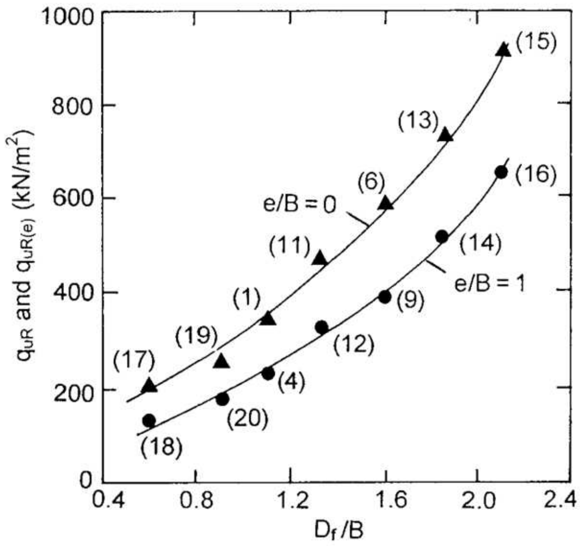

Figure 4. Plot of q_{uR} and $q_{uR(e)}$ versus D_f /B. (Note: The number in parenthesis is the number of the tests shown in Table 3.)

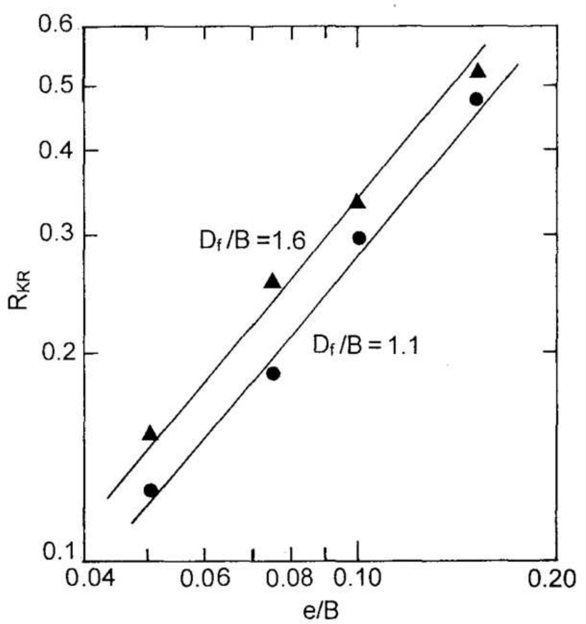

Figure 3. Plot of R_{KR} versus e/B for D_f/B = 1.1 (Test Nos. 1, 2, 3, 4 and 5) and D_f/B = 1.6 (for Test Nos. 6, 7, 8, 9 and 10).

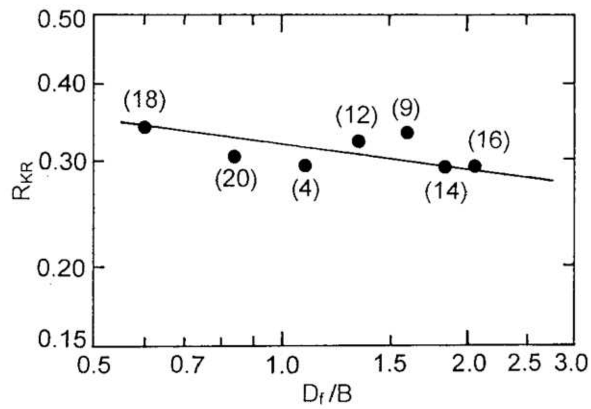

Figure 5. Plot of R_{KR} versus D_f/B for e/B = 0.1.(Note: The number in parenthesis is the number of the tests shown in Table 3.)

In order to obtain the magnitudes of β_1 and β_2, the experimental values of the bearing capacity from Test Nos. 1 and 4, 6 and 9, 11 and 12, 13 and 14, 15 and 16, 17 and 18, and 19 and 20 can be compiled, and the variation of R_{KR} (for e/B = 0.1) with D_f/B can be evaluated. Figure 4 shows the plots of q_{uR} and $q_{uR(e)}$ for e/B = 0.1 against D_f /B. The reduction factors thus obtained from these values are plotted in Fig. 5. From this figure

$$R_{KR} \approx 0.315\left(\frac{D_f}{B}\right)^{-0.14} \tag{8}$$

Thus, comparing Equations (6), (7), and (8)

$$\beta_2 = -0.14$$

and

$$\beta_1\left(\frac{e}{B}\right)^{\beta_3} = \beta_1(0.1)^{1.21} = 0.315$$

Hence, $\beta_1 \approx 5.11$. Substituting the values of β_1, β_2, and β_3 into Equation (6)

$$R_{KR} = 5.11\left(\frac{D_f}{B}\right)^{-0.14}\left(\frac{e}{B}\right)^{1.21} \tag{9}$$

The predicted values obtained by the preceding empirical relationship for the reduction factor is within ±8% of the present experimental results. The relation can be further improved when additional field and laboratory experimental results are available.

6 CONCLUSIONS

A limited number of laboratory model test results on the bearing capacity of an eccentrically loaded strip foundation supported by sand with multiple layers of geogrid reinforcement has been presented. The e/B ratio was varied from zero to 0.15. Tests were conducted with surface and embedded foundations. Based on the present test results, the following conclusions can be drawn.

1. Load eccentricity reduced the bearing capacity of the foundation.

2. The bearing capacity of an eccentrically loaded foundation can be estimated by the load reduction factor.

3. The load reduction factor is a function of e/B and D_f/B.

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