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BEARING CAPACITY OF AN ECCENTRICALLY LOADED STRIP FOOTING ON REINFORCED SAND SLOPE

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This paper presents the results of experimental tests undertaken to investigate the effect of the slope on the bearing capacity of an eccentrically loaded strip footing on a geogrid reinforced sand slope. Several tests were conducted on a reduced model footing under various eccentric loads. The results obtained are presented in the form of a parametric study in order to examine the effect of the slope on the bearing capacity of the footing under different eccentric loads. This study showed that the location of the load eccentricity relative to the slope crest has a significant effect on the foundation behavior. The bearing capacity is higher in the case of load eccentricity located far away from the slope face compared to that of a load eccentricity located towards the slope face. The results also indicate that the behavior of an eccentrically loaded footing on a reinforced sand slope is different compared to that built on a horizontal base.

1. Introduction

For regions with non-horizontal soil geometry and complex structures, most of the foundations are subjected to eccentric or/and inclined load. The predicting of bearing capacity of shallow foundations placed on sloping ground surface and subjected to eccentric or/and inclined load is a complex problem in geotechnical engineering. It is reported by several researchers that the eccentric loading and sloping ground reduces the soil bearing capacity [1-7]. In this context, Meyerhof [8] proposed a semi-empirical procedure to estimate the ultimate bearing capacity of a shallow foundation subjected to eccentric load, which is generally referred to as an effective width method. In the case of eccentrically loaded strip footing on slope, Saran and Reddy [4] published an analytical solution on determining the bearing capacity using a limit equilibrium approach. Cure et al. [1] conducted a series of model tests to determine the change in the ultimate loads as a function of the eccentricity. The results obtained from those investigations show that the change in ultimate load decreases as the eccentricity increases. This decrease is due to a combination of the eccentricity and slope. One way to improve the bearing capacity would be to reinforce the foundation ground with layers of geogrid. Huang et al. [9], Lee and Manjunath [10], Yoo [11], El Sawwaf [12], and Alamshahi and Hataf [13] reported that when the reinforcements are placed in the optimum depth from the surface of strip footing, the maximum beneficial effect of reinforcement can be achieved. Turker et al. [14] investigated the behavior of footing resting on reinforced sand slope. They found that the use of geotextile reinforcement increased ultimate loads in comparison with unreinforced cases. Failure surfaces were not symmetrical; primary failure surfaces developed on the eccentricity (slope) side, and secondary failure surfaces developed on the other side.

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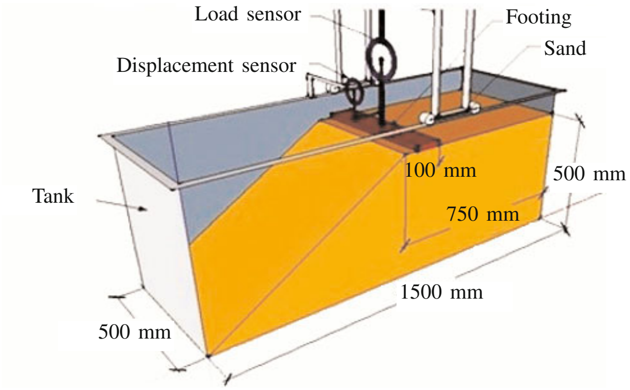

Fig. 1. Schematic view of experimental model.

Lengths of failure surfaces decreased with increasing eccentricity. Patra et al. [15] suggested an empirical formula for determining the bearing capacity of an eccentrically loaded strip footing resting on reinforced sand. Sadoglu et al. [16] stated that the reinforcement increases ultimate loads in comparison with unreinforced cases, and this contribution becomes much smaller with increasing load eccentricity. Lee and Manjunath [10] and Keskin and Laman [17] reported that there are a number of factors that may influence the performance of footings on reinforced slope, including: (1) type of reinforcement; (2) number of reinforcing layers N; (3) depth below the footing to the first layer of reinforcement μ; (4) spacing between reinforcing layers h; (5) dimensions of the reinforcement beyond the dimensions of the footing; (6) type and placement of the fill; (7) footing location relative to the slope crest. It must, however, be noted that most of the studies cited above were basically focused on the behavior of a footing located near slope subjected to centered load. Only few studies have focused on the bearing capacity of eccentrically loaded strip footing on reinforced sloping ground. The main purpose of this investigation was to study the effect of slope and eccentricity on the bearing capacity of strip footing on reinforced sand. In this study, 28 laboratory model tests were carried out to investigate the bearing capacity of a rigid strip footing placed on sand slope with and without layers of geogrid.

2. Experimental Study

2.1. Model test

A series of model tests was performed using a scaled footing model to study the effect of load eccentricity and slope on the bearing capacity. The test tank used in laboratory tests was made of rigid steel with inside dimensions of 1.5×0.5 m in the plane and 0.6 m in high. To visualize each layer level of sand during the construction of the desired slope, one of the two sidewalls of the tank is made of thick and transparent glasses. Plane strain conditions during all tests are ensured by constructing the test tank walls rigid with melted steel. All tests were carried out with an artificially made slope $\beta = 33.69°$. The loading system is a moving lever mechanism consisting of a rigid metal beam. The load is applied to the footing by masses placed sequentially on the lever and measured by a load sensor (15 kN). The displacements were measured by a sensor placed on the load point application as shown in Fig. 1.

2.2. Test materials

The model strip footing is made of steel plates of 20 mm thickness to provide the rigid footing condition. The location of the footing edge with respect to the slope crest is fixed at 50 mm. The footing is 499 mm in length and 100 mm in width, with the length of footing taken to be almost equal to the width of the tank to ensure the condition of plane strain. The tow ends of footing have been polished to minimize all forces resulting from the friction with the tank walls. The footing is 498×100 mm in the plane and 20 mm in thickness. Several imprints are created on the upper side of the footing, con-

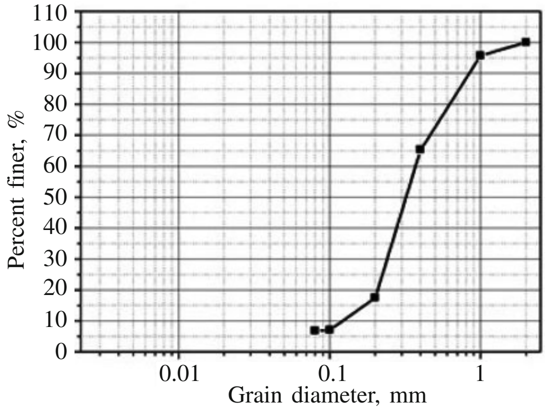

Fig. 2. Particle size distribution curve for the sand.

TABLE 1

Parameter	Value
Maximum dry density (kN/m^3)	19.30
Minimum dry density (kN/m^3)	13.92
D10 (mm)	0.12
D30 (mm)	0.24
D60 (mm)	0.37

sidered as loading points during the application of different eccentric loads. A rough base condition was provided by using rough sandpaper on the base of the model footing.

The sand used in the present investigation is "Pit Sand," extracted from the region of Tebessa in the southeast of Algeria with coefficient of uniformity (C_u) of 3.08 and coefficient of curvature (C_c) of 1.29. The maximum and minimum dry unit weights of the sand are found to be 19.3 and 14.1 kN/m^3. The particle size distribution was characterized using the dry sieving method, and the results are shown in Fig. 2. The sand was dried until the moisture content was almost zero throughout all tests. The tank is filled by sand using the pouring-compacting technique in layers of 5 cm thickness to guarantee uniform compaction. The procedure of reinforced soil models construction was carefully controlled during model preparation to ensure uniform soil densities. The model footing tests were performed at relative densities of approximately 60% with a total (dry) unit weight of 16.2 kN/m^3. The internal friction angle of compacted sand at relative density of 60% measured from a series of direct shear tests is approximately 38°, which correspond to dense sand. Other parameters of the tested sand are shown in Table 1.

The geogrid R6 80/20 was tested in this study. It is made of high-density polyethylene with mesh aperture size of 30×73 mm and a maximum tensile strength of 56 KN/m. Elongation is from 20% to 80%, resistance to traction is from 20 to 80 kN/m (for 1% of elongation is 16 kN/m).

2.3. Slope preparation and the test program

The procedure adopted for the reinforced model slope construction was the same as those used by Selvadurai and Gnanendran [18], Lee and Manjunath [10], and El Sawwaf [19]. The sand slope model is made by pouring and compacting in 50 mm thick sand layers to cover the entire plane surface of the test tank. For the construction of the slope model, the sand was poured in 50 mm thick layers up to a height of 500 mm from the bottom of the test tank and covering its entire area. Each layer is compacted and a geogrid layer is placed on it. A fill thickness (μ) was leaved over the reinforcement layer before the next is poured over it. All the reinforcement layers have a uniform length of 0.6 m and were arranged such that their ends are located back from the slope face. The geometry of the slope was drawn on both sides of the test tank and the sand was excavated, accordingly. The desired slope angle was achieved by using a rigid metal blade.

TABLE 2

Test reference	*N*	*e*/*B*
00 T01 T02 T03 F01 F02 F03	0	0 0.1 0.2 0.3 -0.1 -0.2 -0.3
1025, 2050, 3075	1 - 2 - 3	0
T1125, T2150, T3175	1 - 2 - 3	0.1
T1225, T2250, T3275	1 - 2 - 3	0.2
T1325, T2350, T3375	1 - 2 - 3	0.3
F1125, F2150, F3175	1 - 2 - 3	-0.1
F1225, F2250, F3275	1 - 2 - 3	-0.2
F1325, F2350, F3375	1 - 2 - 3	-0.3

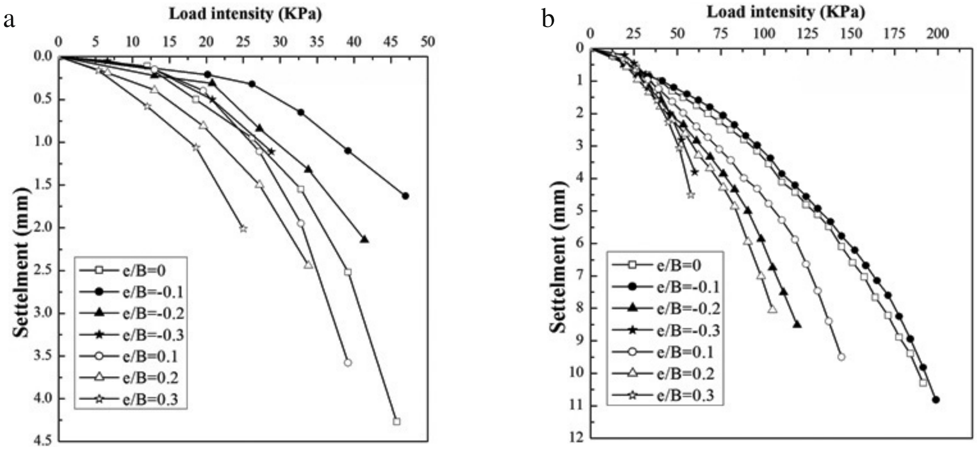

Fig. 3. Load-settlement curves at different *e*/*B* ratios: a) unreinforced sand, b) reinforced sand.

Then three series of tests were conducted to study the effect of the slope on the eccentrically loaded footing behavior, including: (1) centric load; (2) positive eccentric load when the load eccentricity is toward the slope face; (3) negative eccentric load when the load eccentricity is far away from the slope face. Each series of tests was conducted to study the response of one parameter while the other ones remained constant (μ/B = 0.25, d/B = 0.5, and $\tan\beta$ = 2/3). The varied conditions include the eccentricity value (e/B) and the number of geogrid layers (N). Table 2 shows the test program conducted for geogrid reinforced slope for this study. The testing program for load eccentricity towards the slope face was also similar to that for eccentricity load far away from the slope face.

3. Results and Discussion

The results obtained in the 28 experimental tests described above are used to plot the load versus settlement curves in both unreinforced and reinforced conditions as illustrated in Fig. 3. The tangent intersection method, suggested by Trautmann and Kulhawy [20], was used to estimate the ultimate bearing capacity for each model test. The obtained results of the investigation reveal that the ultimate bearing capacity is highly affected by the load eccentricity and its relative location to the slope face. The bearing capacity of strip footings on unreinforced sand slopes increases as the absolute value of eccentricity decreases (regardless of sign). A similar conclusion was reported by Saran and Reddy [4] and Cure et al. [1]. Furthermore, the ultimate bearing capacity increases as the eccentric load is located far

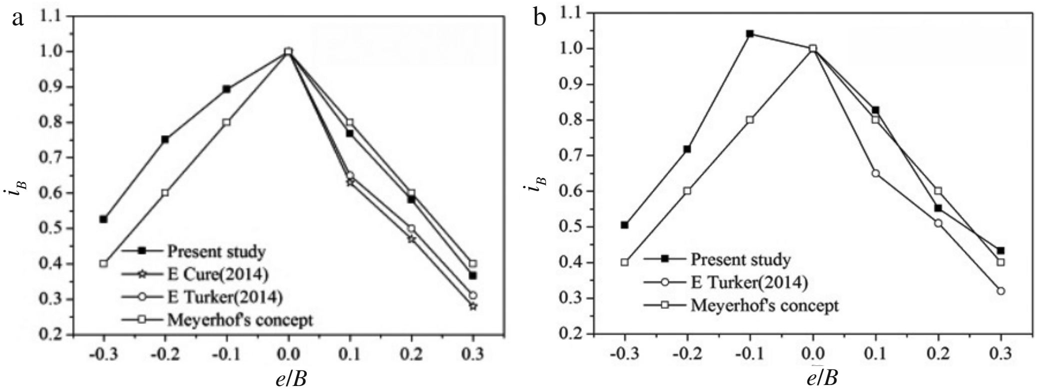

Fig. 4. Reduction ratio i_B versus eccentricity ratio e/B:
a) unreinforced sand, b) reinforced sand.

TABLE 3

N	Centrically loaded footing q_u (kPa)	Eccentrically loaded footing q_u (kPa)					
		far away from the slope face			towards the slope face		
	$e/B = 0$	$e/B = -0.1$	$e/B = -0.2$	$e/B = -0.3$	$e/B = 0.1$	$e/B = 0.2$	$e/B = 0.3$
0	30.1	26.9	22.6	15.8	23.1	17.5	11.03
1	39.31	40.9	28.2	19.8	32.5	21.7	17
2	54.6	58.3	48.9	25.3	52.3	43.79	18.3
3	65.4	66.8	55.6	26.1	59.3	46.98	18.5

away from the slope face side (i.e. the negative eccentricities). As reported by many authors, the improvement observed in ultimate bearing capacity of the tested strip footing is due to the increase in soil passive resistance from the slope side to the active wedge beneath the footing. When the passive resistance becomes wide and deep, a much greater pressure is therefore needed for the failure surface to reach the slope. The experimental results in the case of reinforced sand have shown that for strip footing loaded by small negative load eccentricity ($e/B = -0.1$), the bearing capacity becomes greater than that of the same footing subjected to a centric load ($e/B = 0$). This result demonstrates that small and negative load eccentricities have a small effect on the ultimate bearing capacity because the passive area from the slope side becomes deeper and larger and therefore has a greater impact than the eccentricity one. The results of this study were compared with the results of Turker et al. [14], Cure et al. [1], and Meyerhof's concept as shown in Fig. 4. Here the i_B factor is defined as the ratio of bearing capacity of footing subjected to eccentric vertical load to that of footing subjected to a centric vertical load. The experimental results are in good agreement with Meyerhof's concept when the load eccentricity is located towards the slope face (Table 3).

4. Effect of the Slope on the Bearing Capacity

In the present research, a dimensionless parameter, called eccentric bearing capacity ratio (EBCR) is used to measure the effect of the slope and eccentricity on the bearing capacity. It is given in the form of the ratio of the ultimate load in eccentric and reinforced condition to that in centric and unreinforced condition.

The effect of the slope upon the bearing capacity of eccentrically loaded footing resting on unreinforced and reinforced sand by varying the eccentricity location is investigated. Figure 5 represents the variation of EBCR versus the eccentricity. For centrically and eccentrically loaded footings, three different numbers of geogrids layer including 1, 2, and 3 are considered with the same depth ratio ($\mu/B = 0.5$). It can be observed that the ultimate bearing capacity decreases with increasing load eccentricity for

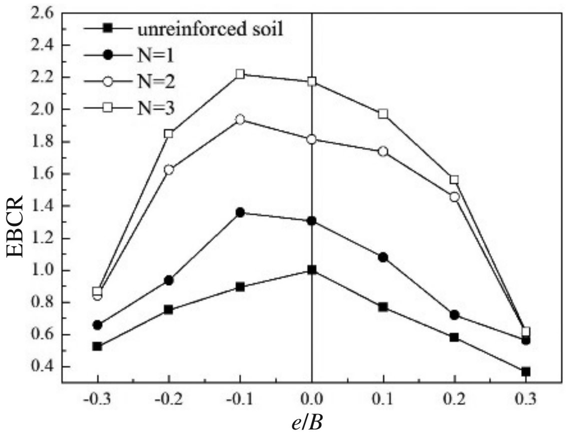

Fig. 5. EBCR versus eccentricity ratio *e*/*B*.

unreinforced sand. A similar conclusion was drawn by Badakhshan and Noorzad [21], Patra et al. [15], and Sadoglu et al. [16]. The obtained results show also that, unlike the footings resting on horizontal ground, the bearing capacity of the strip footings located in the vicinity of a reinforced slope can increase with increase in eccentricity for small and negative load eccentricities (e/B>-0.1). The bearing capacity for an eccentrically loaded strip footing ($e/B = -0.1$) resting on sand reinforced with three layers of reinforcement is 2.21 times greater than the bearing capacity of the strip footing if it is subjected to a centric load ($e/B = 0$) and resting on unreinforced sand. This result demonstrates the significant effect of the load eccentricity location on the load-bearing capacity of strip footings resting on reinforced sand slope and particularly for small negative load eccentricities ($-0.1 < e/B < 0$).

Conclusion

The experimental study of an eccentrically loaded strip footing resting on a reinforced sand slope showed that the effect of slope on the bearing capacity is higher when the load eccentricity is far away from the slope face. In addition, the bearing capacity of an eccentrically loaded footing when $e = -0.1B$ is higher than that of a centric footing under the same conditions of reinforcement. The rate of increase of the bearing capacity of the reinforced soil is of greater significance in the case of small eccentricities than in the case of large eccentricities.

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