Experimental study of bearing capacity of strip footing on geogrid-reinforced sand slope

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ABSTRACT: In this study the results of a series of reduced-scale laboratory model tests performed on both unreinforced and geogrid-reinforced sand slopes loaded with a strip footing were presented. The aims of this investigation are to determine the effect of the geogrid reinforcement on the bearing capacity and settlement behavior of the strip footing and to suggest an optimum geometry of geogrid placement to obtain maximum reinforcing effect. In the study, the effect of the slope angle, the relative density of sand, the footing dimension, and the geogrid type on the bearing capacity behavior of the strip footing were also investigated. Test results show that the inclusion of geogrid layer at the appropriate location in the fill slope significantly improves the load settlement behavior and ultimate bearing capacity of the strip footing. The maximum improvement was obtained at depth of the 0.5 times the width of the footing. The results also indicate that the bearing capacity of the footing on geogrid reinforced sand slope depends greatly on the slope angle, footing dimension, the geogrid type, and the relative density of sand.

1 INTRODUCTION

In the civil engineering, slope is a term applicable to any soil structure whose surface stands at an inclination with the horizontal. Soil slopes can be natural slopes such as hills or river banks, or man-made slopes such as cut and fill in earth structures. There are many situations where footings are constructed on or adjacent to a slope (e.g., foundations located on sloped embankments used as supports for bridge abutments). The footings constructed on slopes have bearing capacity less than constructed on level ground. The stability of a foundation located on or near a slope is considerably affected by the edge distances and slope angle (Meyerhof, 1957). For this reason, the study about improving the bearing capacity and settlement behavior of footings on slopes is one of the fundamental aspects in the design of these structures as they are more susceptible to failure than other types of structures.

The use of geogrid layers is one of the possible reinforcement techniques to improve the bearing capacity of the foundation on sand slope. Geogrids have an open grid-like appearance and have been used efficiently to improve the stability of embankments and slopes and the bearing capacity of the foundations and bridge abutments. An understanding of bearing capacity and settlement behavior of shallow footings on a reinforced slope is an important problem in geotechnical engineering applications. However, there is no reasonable method for the determination of ultimate bearing capacity of shallow footings on a reinforced slope, therefore, much still remains to be investigated.

2 SCOPE OF THE STUDY

The main purpose of this study is to investigate some explicit aspects that influence of the performance of a strip footing on a cohesionless slope by the inclusion of a single layer of geogrid reinforcement, to understand the reinforcement mechanisms, and to suggest an optimum geometry of geogrid reinforcement. However, the effects of the parameters such as the depth of the reinforcement layer, the angle of the slope inclination, the relative density of sand, the width of the strip footing, and the type of the geogrid reinforcement on the bearing capacity of a strip footing have also been investigated. For this purpose, an extensive series of laboratory model tests have been performed. End of the study recommendations concerning with the optimum geometry of geogrid reinforcement have been made.

3 LITERATURE REVIEW

Although there are a lot of studies both experimental and numerical concerning with improving of the load bearing capacity of foundation using geogrids [Binquet and Lee (1975a, b), Akinmusuru and Akinbolade (1981), Fragazsy and Lawton (1984), Laman and Yildiz (2003) etc.] investigations on the bearing capacity of strip footings on a reinforced slope are limited [Selvadurai and Gnanendran (1989), Huang *et al*. (1994), Lee and Manjunath (2000), Yoo (2001) Bathurst *et al*. (2003), Laman *et al* (2007)].

Selvadurai and Gnanendran (1989) reported the results of an experimental study with respect to a strip footing located at the crest of a geogrid-reinforced sand slope. The results of this study indicated that the load-carrying capacity of a footing on a sloped fill structure can be improved in excess of 50% by using geogrid reinforcement. The study was concentrated on the influence of the depth of a single geogrid layer on the load-settlement behaviour of the footing. End of the study the optimum depth for the geogrid reinforcement layer was found between 0.5 and 0.9 times of the width of the foundation.

Huang *et al.* (1994) performed a series of plane strain model loading tests on the footing placed on both reinforced and unreinforced sand. Phosphor bronze strips were used as reinforcement materials. The results of the study showed that the bearing capacity of the footing can be increased by using stiff reinforcing strips and both the bearing capacity characteristics also failure patterns of reinforced slopes significantly depend on the arrangement of the reinforcement members.

Lee and Manjunath (2000) conducted a series of plane strain model tests on reinforced and unreinforced sand slopes loaded with a rigid strip footing. The results showed that the load-settlement behaviour and ultimate bearing capacity of the footing can be considerably improved by the inclusion of a reinforcing layer located at the appropriate depth in the fill slope. The optimum depth of the reinforcement layer was found to be 0.5 times the width of the footing. Furthermore, the bearing capacity of the footing is independent of the slope angle beyond the distance grater than 5 times the width of the footing.

Yoo (2001) demonstrated the influence of geogrid depth and embedment length on the bearing capacity of footing located at the near the crest of a reinforced slope. The results of the tests indicated that the geogrid layers and the distribution of the geogrids have significant affects on the bearing capacity of strip footings.

Bathurst *et al.* (2003) performed an experimental study. Two large-scale geosynthetic reinforced soil embankments and one unreinforced soil embankment were subjected to collapse by loading the strip footing placed close to the crest of the slope. The results of the study showed that the ultimate load capacity of the footing increased with an increase in reinforcement strength and the reinforced soil embankments had a load capacity up to 1.6-2.0 times that of the unreinforced embankment.

Laman *et al*. (2007) investigated the bearing capacity behavior of a strip footing on a geogrid reinforced sloped fill using laboratory model tests. It was concluded that the bearing capacity of a strip footing on sloping ground can, depending on the reinforcement geogrid arrangement, be increased up to 6.0 times that of the unreinforced case.

Most of the reported studies have been carried out on sand with only one relative density and on a strip footing has only one width. Hence, the effects of relative density of sand and the footing width on the bearing capacity behavior cannot to be considered. In the present research, the bearing capacity behavior of a strip footing on a reinforced slope was investigated with various relative densities, footing widths, slope angles and geogrid types.

4 LABORATORY MODEL TESTS

4.1 *Model Box*

The model tests were carried out using the facility in the Geotechnical Laboratory of the Civil Engineering Department of the University of Cukurova. The test setup is shown in Figure 1. Tests were conducted in a test box made of a steel frame, having dimensions of 1.14×0.50m in plan and 0.50m in height. Two side walls of the test box consist of glass plate and the other sides consist of wood plate. The inside walls of the box were smooths enough to minimize side friction. The test box was rigid enough to provide plane strain conditions in the reinforced slope models. Static vertical loads were applied to the model footing by a motor controlled hydraulic jack attached to a loading frame located above the test box. Load measurements were taken using a load cell installed between the jack and the model footing. The settlements were measured using two displacement transducers (LVDT). The load cell and LVDTs were connected to a data acquisition system for recording and data handling.

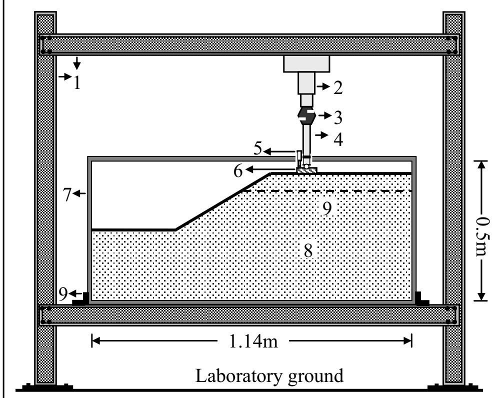

Figure 1. Model test setup

4.2 *Model footings*

Two model strip footings made of steel with a hole at its top centre to accommodate a ball bearing were used. The footings were 403mm in length, 70mm and 50mm in width and 20mm in thickness. The length of the footing was made almost equal to the width of the test box in order to maintain plane strain conditions.

4.3 *Model ground*

Uniform, clean, air-dried fine sand obtained from the Cakit River bed was used as soil bed. Conventional laboratory tests were conducted on representative sand samples for gradation, specific gravity, maximum and minimum densities. These properties are summarized in Table 1.

Table 1. Properties of sand bed

Property	Value
Coarse sand (%)	0.0
Medium sand (%)	46.4
Fine sand (%)	53.6
D_{10} (mm)	0.18
D_{30} (mm)	0.30
D_{60} (mm)	0.50
Uniformity coefficient, C_u	2.78
Coefficient of curvature, C_c	1.00
Specific gravity	2.68
Maximum dry unit weight (kN/m^3)	17.9
Minimum dry unit weight (kN/m^3)	15.5
Classification (USCS)	SP

Sand bed was constructed in 50mm thick layers by compaction method. Using the compaction method seemed to be reliable to practice. The model tests were performed on sand with relative densities of 45%, 65% and 85% with unit weights of 16.5, 17.0 and 17.5 kN/m^3, respectively.

A series of direct shear tests was carried out on sand specimens to obtain the shear strength parameters. The estimated internal friction angles at the relative densities of 45%, 65% and 85% were 40.6°, 42.4° and 43.5°, respectively.

4.4 *Reinforcements*

The properties of geogrids used as reinforcing material in the model tests are shown in Table 2.

Table 2. Properties of geogrids

	Secugrid (GG1)	Combigrid (GG2)	Tenax (GG3)	Cevregrid (GG4)
Structure	biaxial	biaxial composite	biaxial	mono-oriented
Aperture (mm)	31×31	31×31	28×38	14×80
Length (m)	4.75×100	4.75×100	4×75	1×60
Strength (kN/m)	60/60	60/60	17.5/31.5	10/45

GG2 is a flat composite geogrid from GG1 series. The basic difference between other geogrids and GG2 is having firmly welded junctions and centrally integrated nonwoven component for reinforcing, separating and filter applications.

4.5 *Preparation of sand slope and test program*

Model sand slopes 200mm high and 500mm wide with slope angles, β, of 20°, 25° and 30° were prepared by using compaction method in layers 50mm thick. The geometry of the slope was first marked on the glass walls for reference. The sand was compacted in layers up to slope toe and then a special apparatus was placed to constitute the sloping surface (detailed in Keskin, 2009). The developed apparatus is useful to form a sloping surface with a desired angle and allows to compact the sand uniformly. After the reinforcement was placed the process continued until the height of the slope was reached. The model strip footing was then placed on the surface of the compacted sand and the load was applied until reaching failure (Figure 2).

In this study the following series of tests were carried out:

(i) tests with different reinforcement embedment depths (u) below the footing resting on a slope with a gradient of β=30°, distance of the footing to the slope crest (b) was kept constant b=1.0B (B is the footing width), and the reinforcement material used were GG1; this series of tests is very similar to that

conducted by Selvedurai and Gnanedran (1989) and Lee and Manjunath (2000).
(ii) tests with different slope angels (β=20°, 25° and 30°)
(iii) Tests with different relative densities of sand (D_r=45%, 65% and 85%)
(iv) tests with different footing width (B=50mm and 70mm).
(v) tests with different reinforcements (GG2, GG3 and GG4).

In test series (ii), (iii), (iv) and (v), the depth of reinforcement was kept constant and equal to the optimum value obtained from series (i). In all series, the length of the reinforcement (L_R) was extended from the boundary of the test box to the face of the slope.

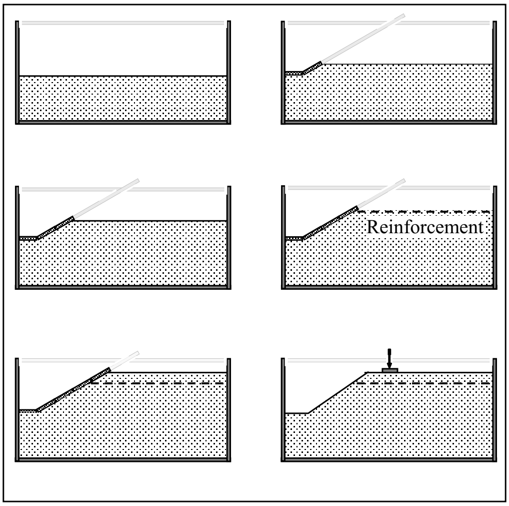

Fig 2. Procedures for the preparation of slope model

5 TEST RESULTS AND DISCUSSION

5.1 *Effect of reinforcement embedment depth*

A series of tests were performed to determine the optimum depth of the reinforcement to the footing for various u/B ratios (u/B=0.25, 0.50, 0.75, 1.00, 1.25 and 1.50). Obtained load-settlement curves for five different u/B ratios are presented in Figure 3. The variation of BCR (bearing capacity ratio) with u/B is shown in Figure 4. The BCR factor is defined as the ratio of the footing ultimate pressure on reinforced slope ($q_{u\ reinforced}$) to the footing ultimate pressure on unreinforced slope (q_u).

From the results of Figures 3 and 4, it is clear that the inclusion of geogrid would improve the performance of the footing by increasing the bearing capacity and reducing the settlement of the system.

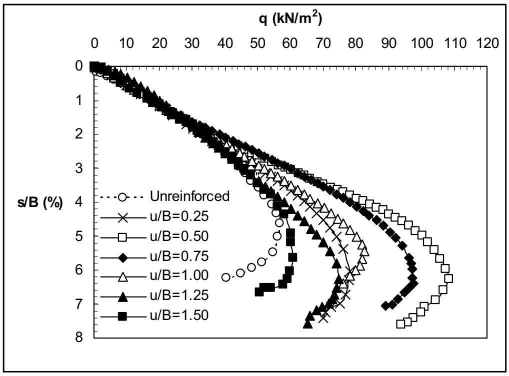

Fig 3. Load-settlement curves at different u/B ratios

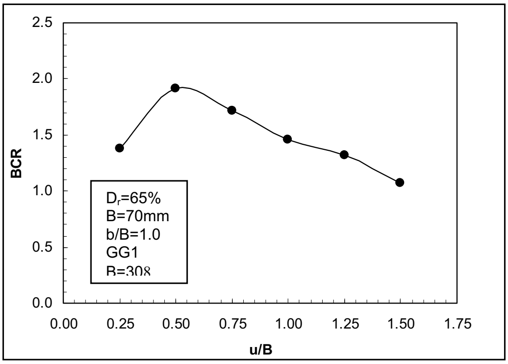

Fig 4. Variation of BCR with u/B

As seen from Figure 4, there is an optimum reinforcement depth about u=0.50B where the maximum improvement was obtained. It can be concluded that, maximum benefits could be obtained when reinforcement are placed at shallow depths under the footing. At these depths soil displacements are greater and lateral resistances for soil lateral displacements are maximum.

5.2 *Effect of slope angle*

A series of tests were performed for a strip footing on a reinforced slope with three different angles (β) of 20°, 25° and 30°. For each slope angle, distance of the footing to the slope crest was kept constant b=1.0B. The relative density of sand was D_r=65%, the reinforcement used was GG1 and the depth of the reinforcement was constant at the optimum value (u/B=0.50). The variation of BCR with slope angle, β is shown in Figure 5. Although, the ultimate bearing capacity is decreases with an increase in slope angles, the results clearly indicate that, the BCR increases with an increase in slope angles. That is to say, the reinforcement is more effective in steeper slopes.

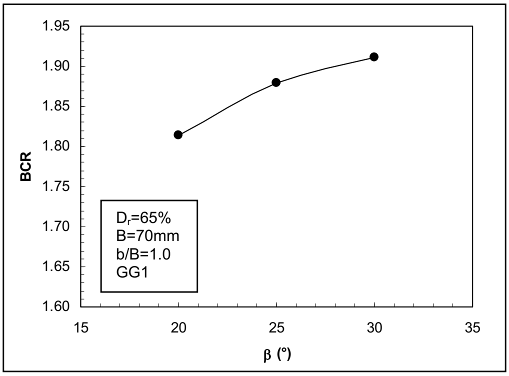

Fig 5. Variation of BCR with slope angle, β

5.3 *Effect of relative density of sand*

To investigate the effect of relative density of sand tests were performed with three different relative densities (D_r) of 45%, 65% and 85%. The variation of BCR with relative density, D_r is shown in Figure 6.

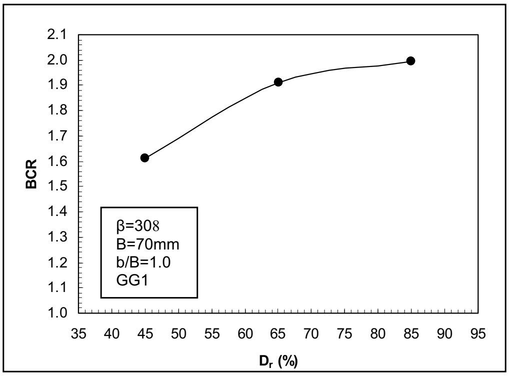

Fig 6. Variation of BCR with relative density, D_r

Figure 6 clearly shows that soil reinforcement is very effective in improving the bearing capacity of the footing on slope made of with D_r=45% to 65% sands. When the relative density increases from D_r=65% to 85% geogrid reinforcement cause relatively minor improvement on the bearing capacity of strip footing. This increase in bearing capacity of footing with relative density can be attributed to soil-geogrid interaction. As the relative density increases, the angle of friction of the sand increases, and therefore, the adhesion, the friction, and interlocking between geogrid and soil increases leading to greater bearing capacity.

5.4 *Effect of footing width*

In order to study the effect of footing width, tests were performed using two different model footing of B=50mm and 70mm. Figure 7 shows the variation of BCR with footing width, B.

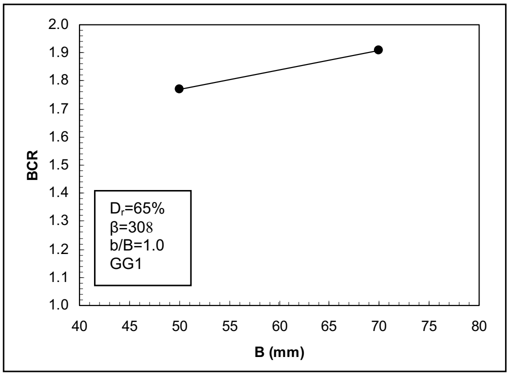

Fig 7. Variation of BCR with footing width, B

As can be seen from Figure 7, the BCR increases with an increase in footing width. When the footing width increases the stress zone between footing, soil and geogrid increases and this gives greater BCR.

5.5 *Effect of reinforcement type*

A series of tests were performed using various reinforcements. Figure 8 shows the variation between BCR with reinforcement types.

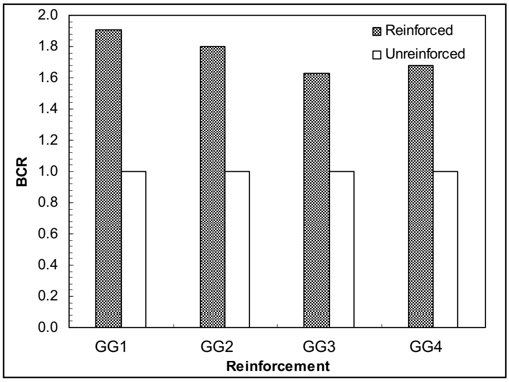

Fig 8. Variation of BCR with reinforcement types.

Results clearly indicate that performance of GG3 which has lower tensile strength was less than that of other geogrids. It should be noted that, although the maximum tensile strength of the GG1 and GG2 are same, GG1 have better performance than GG2 which has a continuous sheet of reinforcement and does not allow penetration of soil particles into the fabric.

6 CONCLUSIONS

A series of model tests was performed to investigate the bearing capacity behavior of a strip footing resting on reinforced sand slopes. The following conclusions are drawn from the present study:

- Test results show that the inclusion of geogrid layer at the appropriate location in the fill slope significantly improves the load settlement behavior and ultimate bearing capacity of the strip footing.
- The optimum embedment depth of the reinforcement was about 0.5 times the width of the footing. In this case, the ultimate bearing capacity of strip footing can be increased up to 1.91 times that of the unreinforced case.
- The BCR increases with increase in slope angle, relative density of sand, and width of the footing. That is to say, the soil reinforcement is more effective in steep and dense slopes.
- The effectiveness of geogrids in improving the bearing capacity of strip footing on slopes is attributed to its tensile strength.

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