LABORATORY INVESTIGATION OF STRIP FOOTING ON SANDY SLOPE

M. Salih Keskin[1], Mustafa Laman[2], Erdal Uncuoglu[3] & Levent Yildiz[4]

[1] *Cukurova University. (e-mail: skeskin@cu.edu.tr)*
[2] *Cukurova University. (e-mail: mlaman@cu.edu.tr)*
[3] *Cukurova University. (e-mail: erdalu@cukurova.edu.tr)*
[4] *Cukurova University. (e-mail: leventyildiz@yahoo.com)*

Abstract: Polymeric reinforcement materials called geosynthetics are increasingly being used in various geotechnical engineering applications. In the last decade, there were numerous studies about the improvement of the load bearing capacity of foundations using geosynthetics. These investigations showed that reinforcing the soil could improve the ultimate bearing capacity and the settlement characteristics of the foundations significantly. There are many situations where foundations are constructed on or adjacent to a slope (e.g. foundations located on sloped embankments used as supports for bridge abutments). The bearing capacities of footings constructed on slopes are usually less than the bearing capacities of footings constructed on level ground. Reinforcement can be used to improve the stability of slopes, so it makes it possible to construct slopes steeper and higher. The use of geogrids is one of the possible reinforcement techniques to improve the bearing capacity of the footings on slope. This paper presents the results of laboratory model tests on the bearing capacity behaviour of a strip footing on a geogrid-reinforced slope. The purpose of this study is to perform scaled model tests to provide a database for future studies. Various parameters such as geogrid length, number of geogrid layers, vertical depth to top layer of geogrid layer and distance of the footing to the slope edge were tested. The experimental results were compared with finite element analysis results obtained using a commercially available computer program PLAXIS. The results show that the bearing capacity of strip footings on a slope can be increased by the inclusion of layers of geogrid in the ground, and that the magnitude of bearing capacity increase depends greatly on the geogrid distribution. On the basis of the results of the laboratory model tests and the finite element analyses, optimum values of the geogrid arrangements to obtain the maximum reinforcing effect are suggested.

Keywords: reinforced slope, finite element, geogrid.

INTRODUCTION

Geosynthetics can be classified into categories such as geogrids, geotextiles, geonets and geomembranes based on the methods of manufacturing. 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. Many studies, both experimental and numerical, have been performed concerning with the improvement of the load bearing capacity of foundation using geogrids. Comprehensive information on these studies can be obtained from the literature available from authors, including (Binquet and Lee (1975a, b), Akinmusuru and Akinbolade (1981), Fragazsy and Lawton (1984), Das *et al.* (1994), Laman and Yildiz (2003) and others.

In civil engineering, slope is a term applicable to any soil structure, the surface of which stands at an inclination to 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 capacities lesser than those constructed on level ground. The use of geogrid layers is one of the possible reinforcement techniques to improve the bearing capacity of the foundation rested on a slope.

Reinforced slopes are analysed by design methods based on limit equilibrium (Zhao (1996), Lesniewska (1993), Mandal and Labhane (1992), Schmertmann *et al.* (1987), Michalowsk (1997), Zornberg *et al.* (1998a, b), Sawicki and Lesniewska (1991), and Schneider and Holtz (1986)). In these methods, a circular or wedge-type potential failure surface is determined and then relationships between driving and resisting forces or moments acting on the surface are investigated. The factor of safety is determined according to the relationship between the forces acting on the failure surface. To the authors' knowledge the studies on the bearing capacity of footings on reinforced slopes are limited.

Selvadurai and Gnanendran (1989) reported the results of an experimental study of a strip footing located at the crest of a geogrid-reinforced sloped fill. The results of this study indicated that the load-carrying capacity of a footing on a slope of a fill structure could be improved in excess of 50% by incorporating 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. At the 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 could be increased by using stiff reinforcing strips and both the bearing capacity characteristics and failure patterns of reinforced slopes significantly depended 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 could be considerably improved by the inclusion of a layer of reinforcement at an 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 was independent of the slope angle beyond the distance greater 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 or near the crest of a reinforced slope. The results of the tests indicated that the geogrid layers and the distribution of the geogrids had significant effects 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 a 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.

Although numerical analyses such as finite element or finite difference methods have become popular in design practice, a bearing capacity determination method is an essential part of a routine design of footings on a reinforced slope. However, no rational method for the determination of ultimate bearing capacity of a strip footing on a reinforced slope is available today, and therefore, much still remains to be investigated (Yoo, 2001).

The purpose of this study is to perform scaled-down model tests to provide a database for future studies. Various parameters such as geogrid length, number of geogrid layers, vertical depth to top layer of geogrid layer and distance of the footing to the slope edge were tested. The experimental results were compared with finite element analysis results obtained using a commercially available computer program PLAXIS.

LABORATORY MODEL TESTS

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 experimental set up has been used extensively in the previous studies of the bearing capacity of shallow foundations. The test set up is shown in Figure 1.

Tests were conducted in a test box made of a steel frame with inside dimensions of 1.035×0.405m in plan and 0.68m in height. Two side walls of the box consist of fibreglass plate and the other sides consist of steel plate. Therefore the inside walls of the box were smooth enough to minimise side friction. The test box was rigid enough to provide plane strain conditions in the reinforced slope models.

Tests were performed with a slope angle of 30˚. Static vertical loads were applied to the model footing by a hand-operated mechanical jack attached to a loading frame located above the tank. Load measurements were taken using a dial gauge and a proving ring installed between the jack and the model footing. The settlements were measured using two displacement transducers.

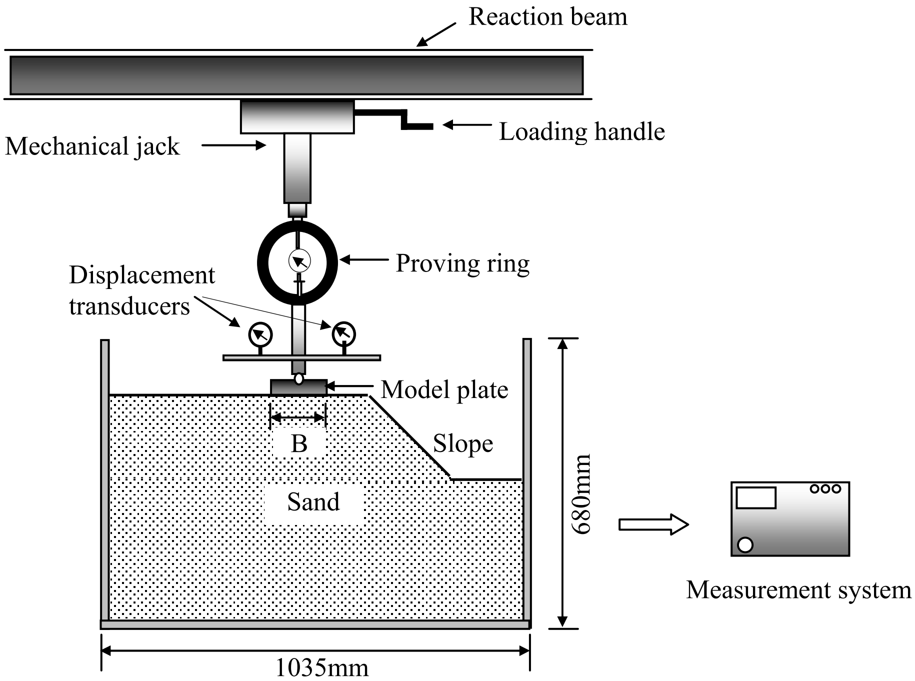

Figure 1. Test set-up

Model Footing

A model strip footing made of steel with a hole in its top centre to accommodate a ball bearing was used. The footing was 403mm in length, 40mm in width and 20mm in thickness. The footing was positioned on the sand bed over the full width of the tank. The length of the footing was made almost equal to the width of the tank in order to maintain plane strain conditions.

Model ground

Uniform, clean, air-dried fine sand obtained from the Seyhan River bed was used as soil bed. Conventional laboratory tests were conducted on representative sand samples for gradation, specific gravity, maximum and minimum densities, and strength parameters. These properties are summarised in Table 1. The particle size distribution was determined using a dry sieving method and the results are shown in Figure 2.

Table 1. Properties of sand bed

Property	Value
Coarse sand (%)	0.0
Medium sand (%)	34
Fine sand (%)	66
D10 (mm)	0.28
D30 (mm)	0.36
D60 (mm)	0.42
Uniformity coefficient, C_u	1.5
Coefficient of curvature, C_c	1.1
Specific gravity	2.68
Maximum dry unit weight (kN/m^3)	17.8
Minimum dry unit weight (kN/m^3)	16.0
Classification (USCS)	SP

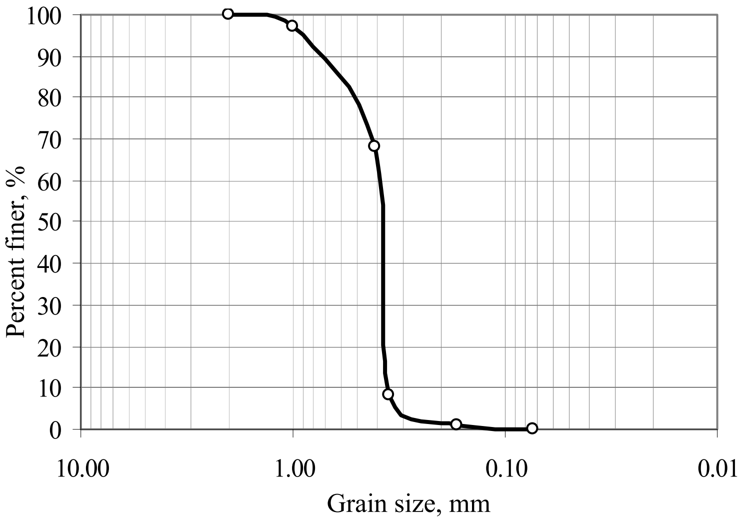

Figure 2. Grain size distribution of the sand

Geogrid reinforcement

Typical physical and technical properties of the geogrids obtained from manufacturer data sheet are given in Table 2.

Table 2. Properties of the geogrid reinforcement

Length	min.50m – max.70m
Width	1.0m
Thickness	0.95mm
Colour	Black
Weight	0.5 kg/m² (± 0.1 gr)
Strength	%11.6 strain at 28.60 kN/m

FINITE ELEMENT ANALYSIS

A series of two-dimensional finite element analyses (FEA) on a model footing-slope system with the same model geometries as those in the tests were carried out using PLAXIS (Version 7.2). PLAXIS is a finite element package specially developed for the analysis of deformation and stability in geotechnical engineering problems (Brinkgreve and Vermeer, 1998). Stresses, strains and failure states of a geotechnical problem can be determined by PLAXIS.

The soil bed was modelled by using 15-node triangular elements. The constitutive relations for the behaviour of the soil were defined by elastoplastic hyperbolic model named as Hardening Soil Model (HSM). The parameters of the model were obtained from the results of drained triaxial tests (Table 3). Limiting states of the soil were defined by the friction angle (ϕ),cohesion (c) and dilatancy angle (ψ). Soil stiffness was described using three different input stiffness values including triaxial loading stiffness, E_{50}, unloading-reloading stiffness, E_{ur}, and oedometer loading stiffness, E_{oed}. The initial state of stress in the soil was generated using Jaky's formula stated in the below.

$K_0=1-\sin\phi$

where K_0 is the coefficient of lateral earth pressure at rest and ϕ is the friction angle of model soil.

The footing was modelled as a rigid plate and considered to be very stiff and rough. The footing was modelled as a linear-elastic material. The values of Young's modulus and poisson's ratio values of the model footing were chosen as $207\text{x}10^6$ kN/m² and 0.20 respectively.

Table 3. Parameters of finite element model

Parameters	**Symbol**	**Unit**	**Value**
Reference stress	p^{ref}	kN/m^2	100
Triaxial loading stiffness	E_{50}	kN/m^2	28000
Unloading-reloading stiffnes	E_{ur}	kN/m^2	72500
Oedometer loading stiffness	E_{oed}	kN/m^2	28000
Cohesion	c	kN/m^2	0
Friction angle	ϕ	(˚)	41
Dilatancy angle	ψ	(˚)	11
Lateral earth pressure at rest	K_0	-	0.34

PLAXIS includes a fully automatic mesh generation procedure, in which the geometry is divided into elements named as finite elements. The plane strain analyses were carried out for the problem. The boundaries of the mesh were based on the soil bin dimensions used in the physical modelling. Slope geometry, generated mesh, and boundary conditions are shown in Figure 3.

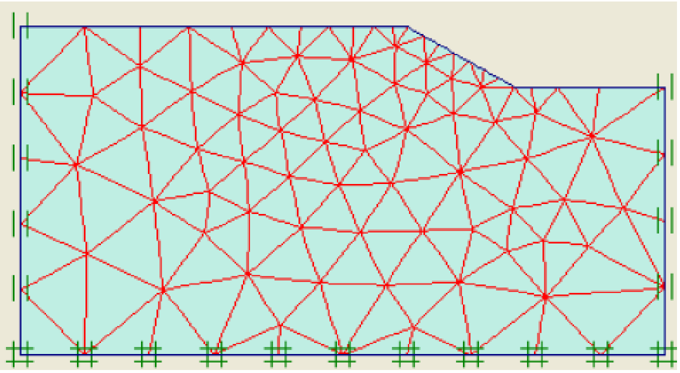

Figure. 3. Slope geometry, generated mesh and boundary conditions

RESULTS AND DISCUSSIONS

In this paper, the effects of the depth of the first reinforcement layer (u), number of the reinforcement (N) and distance of the footing to the slope crest (b) on the bearing capacity have been investigated by experimental and numerical studies. The bearing capacities against different parameters predicted by the HSM are in very good agreement with the experimental results.

The failure type, ultimate bearing capacity (q_u) and settlement at the failure of the reinforced sand have been determined from the load-settlement curves obtained from the results.

In the studies, the geometric parameters concerning with the reinforcement (u and b) were presented in dimensionless forms (u/B and b/B) by dividing the values with the width of the footing (B).

The effect of the depth of the first reinforcement layer (u)

A series of experimental study were performed to investigate the effect of the depth of the first reinforcement layer on the bearing capacity for different values of u. The constant values of the other parameters were adopted as follows: The number of the reinforcement layer, N=1, the relative density of the model soil, Dr=%65 (±3), the length of the reinforcement layer, L=10B, the distance of the footing to the slope crest, b=2B and the angle of the slope, $\beta=30^o$. The relationship between u and q_u are shown in the Figure 4.

As seen in Figure 4, the bearing capacity of the reinforced sand increases between u=0.25B and u=0.50B. The peak value of the bearing capacity is reached when u=0.5B and in this case the ratio of the bearing capacity of the reinforced sand to the unreinforced sand is 1.75. However, the bearing capacity decreases between u=0.50B and u=1.0B.

The effect of the number of the reinforcement layer (*N*)

The effect of the number of the reinforcement layer on bearing capacity of the footing has been investigated by increasing the number of the reinforcement layer one by one from N=1 to 5. The constant values of the other parameters were adopted as follows: u/B=0.5, h/B=0.375, b/B=2, L/B=10, where h is the distance between two reinforcement layer. The relationship between N and q_u is presented in Figure 5.

Figure 5 shows that the bearing capacity of the reinforced sand increases with the number of the reinforcement layer increasing. The rate of the increment decreases where N is equal to or greater than 4. The experiments suggest that the optimum number of the reinforcement layer is 4. The ratio of the bearing capacity of the case of N=4 over that of the case of N=1 is 3.5 and this ratio for the cases of N=4 and unreinforced state is 6.2.

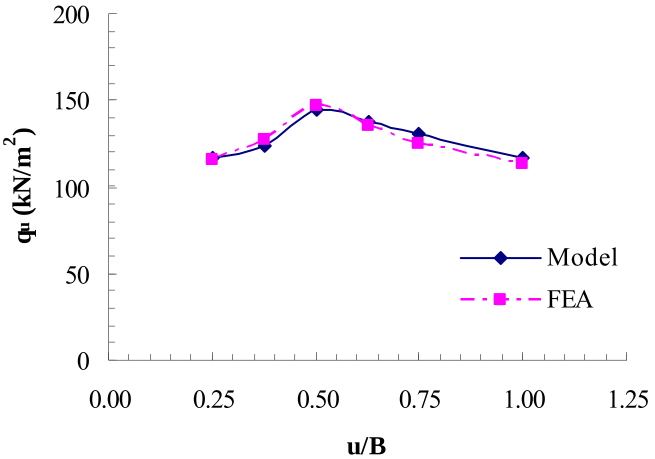

Figure 4. The relationship between u and q_u

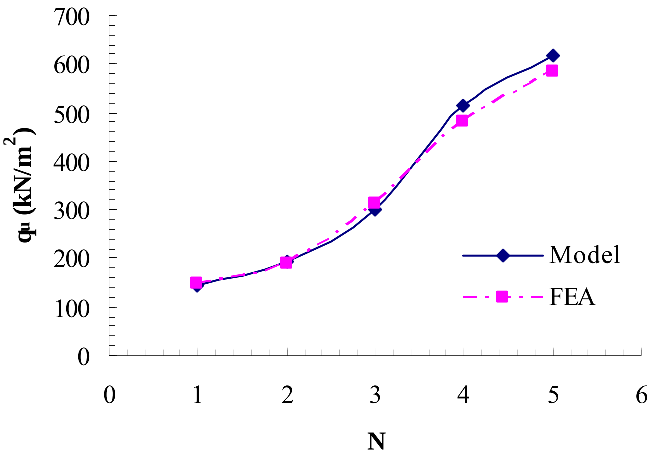

Figure 5. The relationship between N and q_u

The effect of the distance of the footing to the slope crest (b)

Experimental studies were performed to investigate the distance of the footing to the slope crest on the bearing capacity for the different values of the b. The constant values of the other parameters were adopted as follows: N=3, u=0.5B, h=0.375B, and L=20. The relationship between b/B and q_u is shown in Figure 6. In the experimental studies, the distance of the footing to the slope crest has been increased from b=B to b=5B with an increment 1B. The bearing capacity of the footing obtained for b=5B is equal to the bearing capacity of the footing in the level ground state. According to the results, the maximum bearing capacity value of the footing is obtained when b=5B.

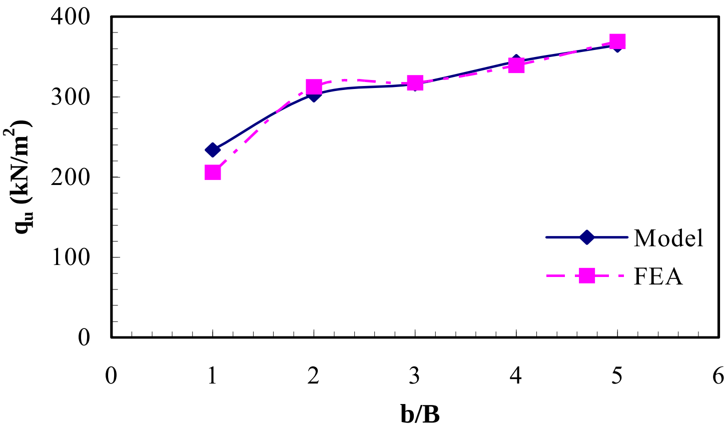

Figure 6. The relationship between b/B and q_u.

Limitations

The physical model adopted in this study is reduced to a certain scale and therefore, does not correspond to prototype footing-soil systems encountered in the field. This might have some influence on the interpretation and application of the experimental results.

CONCLUSIONS

The ultimate bearing capacities of strip footing on sandy slope supported by a sand bed with and without geogrid reinforcement were investigated using PLAXIS and physical modelling. Based on this investigation, the following main conclusions can be drawn.

- The bearing capacities against different parameters predicted by the HSM are in very good agreement with the experimental results.
- The use of the reinforcement layer increased the bearing capacity of the strip footing rested on the slope significantly.
- Reinforcement depth, number of the reinforcement layer and the distance of the footing to the slope crest are the important parameters affecting the failure mechanism of the slope.
- The optimum depth for the first reinforcement layer was obtained when u=0.50B. In this case, the bearing capacity ratio between reinforced and unreinforced is 1.75.
- The optimum number of the reinforcement layer was found to be 4. In this case, the bearing capacity of the footing is 3.5 times that of the case of N=1, and the bearing capacity ratio between N=4 and unreinforced is 6.2.
- The optimum distance to the slope crest was obtained when b=5B. In this case, the angle of the slope has no effect on the bearing capacity.

Corresponding author: Mr M. Salih Keskin, Cukurova University, Balcali, Adana, Turkey. Tel: +903223386084. Email: skeskin@cu.edu.tr.

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