Bearing capacity of shallow foundations on reinforced clay soil

Guler, E.[1], Yetimoglu, T[2], Cicek, E.[2].
[1]*Department of Civil Engineering, Bogazici University, Istanbul, Turkey*
[2] *Department of Civil Engineering, Ataturk University, Erzurum, Turkey*

Keywords: reinforced soil, clay , shallow foundation, safety factor

ABSTRACT: In this study, safety factors of shallow strip foundations on reinforced clay foundation soils were investigated. The problem was analyzed using the finite element code, Plaxis. The foundation soil was modeled as a Mohr-Coulomb material and the reinforcement was modeled as a linear elastic material. Safety factors were calculated by using the Phi-c reduction method in the analyses. First the effects of foundation width, surcharge load and soil cohesion on an unreinforced clay soil was analyzed. The ultimate bearing capacities obtained using this technique was compared to the values obtained using limit analysis techniques proposed by Terzaghi. A good agreement was observed between Terzaghi and finite element solutions. In order to investigate the influence of the reinforcement configuration on the factor of safety, a parametric study was conducted. The parameters investigated were number of reinforcement layers and vertical spacing of reinforcement layers. The parametric study indicated that bearing capacity increased with increasing reinforcement layer numbers and vertical spacing of reinforcement layers.

1 INTRODUCTION

Many researchers investigated the behavior of surface foundations constructed on reinforced sand (Omar et al. 1993; Khing et al. 1993; Yetimoglu et al. 1994; Das & Omar 1994; Adams & Collin 1997). However most of the problematic foundation soils are of cohesive nature. Therefore in this study the effect of reinforcing cohesive foundation soils was investigated. Normally the cohesive soil excavated would be replaced by a granular fill. This means that improvement will be obtained due to the geosynthetic reinforcement but also because of the soil exchange. In order to see the effect of geosynthetic reinforcement alone, in this study the backfill was considered to have the same properties as the natural cohesive soil.

The foundation behavior is assessed using limit equilibrium and finite element method (FEM). In this study as the finite element code, Plaxis was used. A parametric study was conducted using different foundation widths, soil cohesions, surcharge loads and reinforcement configurations.

2 FINITE ELEMENT ANALYSIS

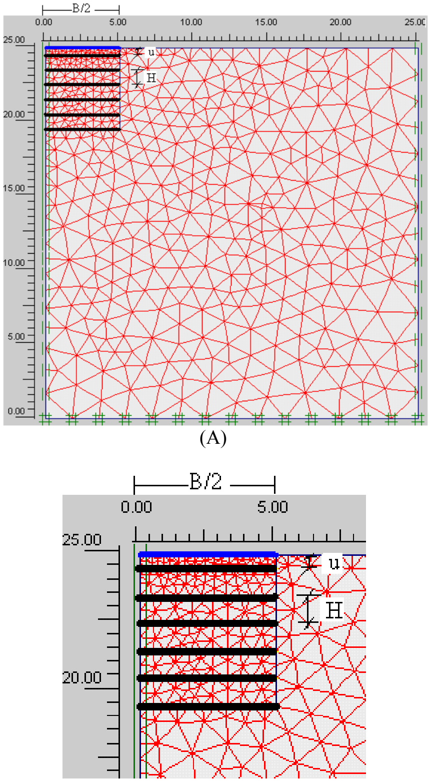
The finite element program Plaxis Ver.8 was used to carry out the numerical simulations in the current analyses. Safety factors were calculated by using the “Phi-c reduction” method in the finite element analyses. In the “Phi-c reduction” approach the shear strength parameters $\tan\phi$ and c of the soil are successively reduced until failure occurs. The safety factors are computed as:

$$\text{FS}=\frac{\text{available shear strength}}{\text{shear strength at failure}} \tag{1}$$

The mechanical behavior of soils was modeled using the Mohr-Coulomb model (MC). The elastic-plastic Mohr-Coulomb model involves six input parameters, i.e. γ (unit weight), E (Young modulus), ν (Poisson’s ratio), c (cohesion), ϕ (internal friction angle) and ψ (dilatancy angle) of the soil. The reinforcement was modelled as a linear elastic material. In the analyses, no specific interaction model between soil and reinforcement was used.

2.1 Boundary Conditions and Material Properties

The analyses presented in this study involve strip foundations on clay soil. The problem was analyzed under plane strain condition. The material properties were chosen in accordance with those in the literature to represent an average stiff clay soil. The soil parameters adopted were: $\gamma = 15\ \text{kN/m}^3$; $E = 25{,}000$ kPa ($500 * c_u$); $\nu = 0.30$; $c = 50\text{-}100$ kPa; $\phi = 0^{o}$; $\psi = 0^{o}$. Footing thickness was chosen as 0.143 m and was placed directly on the surface without any embedment. Geosynthetic axial stiffness per unit width was selected as J=2,000kN/m (Deb et al. 2007). The boundary conditions and finite element mesh are presented in Figure 1. For the finite element analyses, vertical boundary was chosen to have only horizontal fixity and bottom boundary has both horizontal and vertical fixity. The size of the finite element mesh used was the same for all the analyses. It was chosen to be large enough to reduce the boundary effects to a negligible level. Therefore the distance from both the base and edge of the footing was placed at a minimum distance of 1.5B.



(A)

(B)

Figure 1. (A) The Boundary Conditions and Finite Element Mesh for Strip Foundation; (B) Detail of reinforced section

2.2 Safety Factors of Clay Foundation Soil

Factor of Safety (FS) for bearing capacities were calculated first by FEM and then by Limit Equilibrium analysis. The footing width (B=2.5, 5, 10 and 20 m), cohesion of the foundation soil (c=50 and 100 kPa), and surcharge load on footing (w_s=100 and 200 kPa) were varied to assess their influence on the safety factor of the shallow foundation.

The ultimate bearing capacity of the foundation based on the finite element analyses is calculated as:

$$q_{u,FE} = FS * w_s \tag{2}$$

where, FS is obtained from Equation (1) using the FEM analysis, w_s = applied surcharge load on foundation used as an input in the finite element analysis.

The ultimate bearing capacity values from the limit equilibrium analysis proposed by Terzaghi (1943) for cohesive soils is be calculated as:

$$q_{u,T} = c * N_c = 5.7 * c \tag{3}$$

where, $q_{u,T}$ = ultimate bearing capacity calculated by Terzaghi approach, c = cohesion of soil, N_c= bearing capacity factor.

Table 1 gives the results of the bearing capacity calculations. A good agreement was achieved between bearing capacity calculated using the Terzaghi approach ($q_{u,T}$) and finite element solutions ($q_{u,FE}$). Table 1 also indicates that the bearing capacity calculated with the FEM is almost independent of footing width and that the bearing capacity of the footing increases proportionally with increasing cohesion. These results are also consistent with the Terzaghi bearing capacity theory.

Table 1. Safety Factors and Ultimate Bearing Capacities

B	c (kPa)	w_s (kPa)	FS	$q_{u,FE}$ (kPa)	$q_{u,T}$ (kPa)
2.5	50	100	2.75	275	285
2.5	50	200	1.37	274	285
2.5	100	100	5.46	546	570
2.5	100	200	2.75	550	570
5	50	100	2.64	264	285
5	50	200	1.33	266	285
5	100	100	5.30	530	570
5	100	200	2.64	528	570
10	50	100	2.60	260	285
10	50	200	1.30	260	285
10	100	100	5.19	519	570
10	100	200	2.60	520	570
20	50	100	2.60	260	285
20	50	200	1.30	260	285
20	100	100	5.20	520	570
20	100	200	2.60	520	570

In Figure 2 the displacement vectors of the deformed shape are given. It can be seen that the outer boundary of the zone that participates in the displacement, matches very well with the failure mechanism given by Terzaghi (1943). These failure lines are marked on the same figures with bold lines. It can be seen that plastic or active zone, the radial shear zone and passive zone described by Terzaghi (1943) are almost exactly reproduced by the displacement vectors obtained from the finite element analyses and given in Figure 2.

2.3 Safety Factors for Reinforced Soil

In order to investigate the influence of the reinforcement on the factor of safety, a parametric study was conducted using different reinforcement configurations. Number of reinforcement layers and vertical spacing of reinforcement layers were chosen as parameter in the analyses.

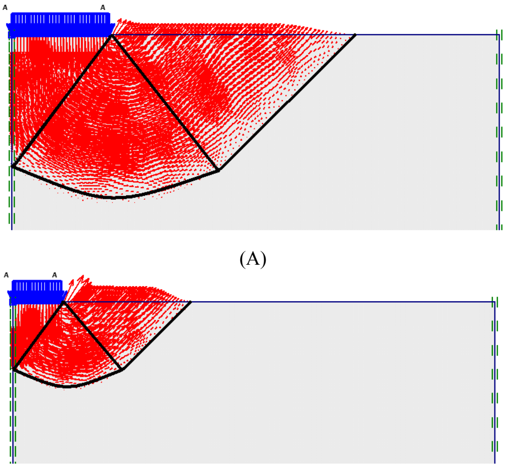


Figure 2. Failure Zones for Shallow Foundations; (A) B =10m strip foundation, (B) B=5m strip foundation.

Reinforcement width (L) was chosen to be the same as the foundation width (B). The cohesion of the foundation soil was taken as c=50 and 100kPa. Only one type of geosynthetic reinforcement (i.e., reinforcement stiffness) was used. The number of reinforcement layer was varied from one to six. The depth ratio (u/B) was kept constant as 0.05 in the analyses. The depth ratio is defined herein as the ratio between the depth of the first reinforcement layer from the footing base (u) and the footing width (B) as can be seen in Figure 1. The vertical spacing between horizontally placed reinforcement layers (H) were taken as 0.025B, 0.05B and 0.1B. A series of analyses were performed for different footing widths namely B=5 m, 10 m and 20 m under a surcharge load of 100 kPa by using the “Phi-c reduction” method.

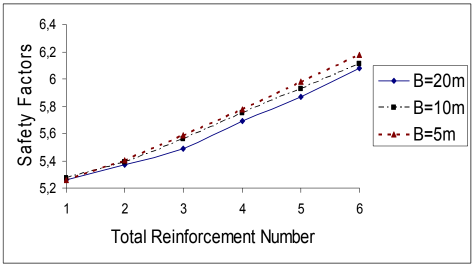


Figure 3. Safety Factors of Strip Foundations on Reinforced Clay Soils (c = 100kPa; H/B = 0.1; w_S = 100kPa)

Safety factors of foundations on reinforced soft soil with different footing widths and different number of reinforcements is given in Figure 3 and Table 2. Safety factors with different (H/B) ratio for a foundation with a width of B = 10 m is given in Table 3 and Figure 4.

Table 2. Safety Factors of Reinforced Clay (H/B = 0.1; w_S = 100 kPa; N = No. of Reinforcement Layers)

	B = 20 m		B = 10 m		B = 5 m	
N	c=100 (kPa)	c = 50 (kPa)	c = 100 (kPa)	c = 50 (kPa)	c = 100 (kPa)	c = 50 (kPa)
1	5.26	2.63	5.27	2.63	5.26	2.63
2	5.37	2.68	5.39	2.7	5.4	2.71
3	5.49	2.74	5.56	2.78	5.59	2.79
4	5.69	2.83	5.75	2.88	5.78	2.89
5	5.87	2.94	5.93	2.97	5.98	2.99
6	6.08	3.04	6.11	3.06	6.18	3.09

Table 3. Safety Factors for Reinforced Clay (B = 10m; w_S = 100 kPa; N= No. of Reinforcement Layers)

H/B	0.025		0.05		0.1	
N	c = 100 (kPa)	c= 50 (kPa)	c = 100 (kPa)	c = 50 (kPa)	c = 100 (kPa)	c = 50 (kPa)
1	5.26	2.63	5.27	2.63	5.27	2.63
2	5.31	2.67	5.34	2.69	5.39	2.70
3	5.35	2.69	5.45	2.73	5.56	2.78
4	5.42	2.71	5.57	2.79	5.75	2.88
5	5.49	2.75	5.69	2.84	5.93	2.97
6	5.58	2.79	5.81	2.91	6.11	3.06

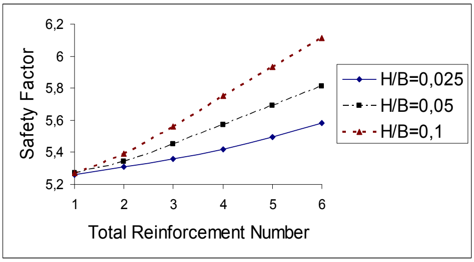
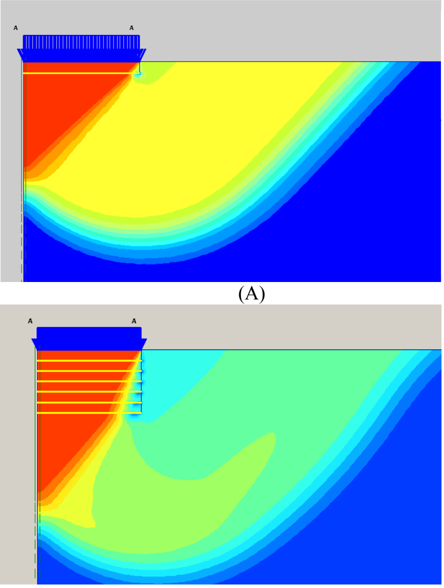


Figure 4. Safety Factors for Different H/B Ratios
(B = 10; c = 100 kPa; w_S = 100 kPa)

Failure zones in the soil indicated that the reinforced zone behaves different than the rest of the clay and the inclination of the failure plane directly below the foundation increases when a geosynthetic reinforcement is used. An example is seen for H/B=0.05 (Figure 5).



(A)

(B)

Figure 5. Shear stress shading for reinforced soils (Light-colored zones represent large shear stresses) A) N=1, B) N=6

3 CONCLUSION

For unreinforced cohesive soils, ultimate bearing capacities determined by finite element analysis and Terzaghi limit analysis technique show a very good agreement.

The finite element analysis gave factor of safety values directly proportional to cohesion of the clay soil as expected.

The safety factor increases as the number of reinforcement layers increases.

Regardless of total number of reinforcement layers the foundation width did not have a significant effect on the bearing capacity.

One layer of reinforcement increased the factor of safety about 1.5%. When six reinforcement layers were used the increase in the factor of safety values were calculated as: 7.5%, 12% and 17% for H/B values of 0.025, 0.05 and 0.1 respectively.

For the same number of reinforcement layers the safety factor increases as the H/B value increases. This fact indicates that the bearing capacity increases as the total depth of the reinforced zone increases.

The shapes of failure planes indicated by the finite element analyses agree very well with the failure surfaces suggested by Terzaghi’s limit equilibrium theorem for the unreinforced cohesive soil. For the reinforced case, the inclination of the failure surface directly below the foundation has an inclination that is steeper than the inclination of the failure zone in pure clay within the reinforced zone. Outside the reinforced zone the inclination of the failure zone reduces to its average inclination in clay soil.

ACKNOWLEDGMENT

The last author thanks the Scientific and Technical Research Council of Turkey (TUBITAK) for doctorate scholarship.

REFERENCES

Adams, M.T. & Collin, J.G. 1997. Large model spread footing load tests on geosynthetic reinforced soil foundations. *Jour. of Geotech.and Geoenvironmental Eng., ASCE* 123(1), pp. 66–72.

Das, B. M. & Omar, M. T. 1994. The effects of foundation width on model tests for the bearing capacity of sand with geogrid reinforcement. *Geotech. and Geological Eng.*12 (2), pp. 133–141.

Khing, K. H., Das, B. M., Puri, V. K., Cook, E. E. & Yen, S. C. 1993. The bearing capacity of a strip foundation on geogrid-reinforced sand. *Geotextiles and Geomembranes* 12 (4), pp. 351–361.

Omar, M.T., Das, B.M., Puri, V.K., & Yen, S.C. 1993. Ultimate bearing capacity of shallow foundations on sand with geogrid reinforcement. *Canadian Geotechnical Journal* 30 (3), pp. 545–549.

Terzaghi, K. 1943. Theoretical Soil Mechanics. John Wiley and Sons, New York.

Yetimoglu, T., Wu, J.T.H. and Saglamer, A. 1994. Bearing capacity of rectangular footings on geogrid-reinforced sand. *Journal of Geotechnical Engineering, ASCE*, 120(12), pp. 2083-2099.

Deb, K., Sivakugan, N., Chandra, S. and Basudhar, P.K. 2007. Numerical Analysis of Multi Layer Geosynthetic-Reinforced Granular Bed over Soft Fill. *Geotechnical and Geological engineering,* 25 (6), pp. 639-646.