Experimental and numerical analysis of circular foundations rested on geogrid reinforced clay soils

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Keywords: in-situ tests, bearing capacity, clay, geogrid, shallow foundation, numerical analyses.

ABSTRACT: In the present study, in-situ tests were carried out to determine the improvement of bearing capacity of circular shallow foundations supported by a compacted granular fill with and without geogrid reinforcement over clay soil. This study has been initially directed to evaluate the beneficial effects of the granular fill on clay soil on the shallow foundation performance. Secondly, the effect of granular fill reinforced with geogrid over clay soil has been studied. Rigid and steel circular foundations used in the tests have the diameters of 60cm and 12cm. After in-situ tests, numerical analyses were conducted using geotechnical computer software PLAXIS 2D (Finite Element Code for Soil and Rock Analysis). Test results were compared with numerical results. The results of the experimental and numerical studies indicate that the thickness of the granular fills and the geogrid reinforcement has considerable effects on the bearing capacity of the circular shallow foundations. It is proved that the improvement depends also on the reinforcement geogrid arrangement. The use of geogrid reinforcement in a compacted granular fill over clay soil provides additional improvement of bearing capacity performance.

1 INTRODUCTION

Soil deposits exhibit low strength and high deformability can be found in most of the residential areas around the world. Shallow foundations, when built on these problematic soils, have low load-bearing capacity and undergo large settlements. In many civil engineering applications, the need of soil reinforcement has been enormously raised in recent decades, due to economical and social development of the populations. Depending on these developments, the necessity has been occurred in using soils with problematic geotechnical characteristics as foundation of multiple engineering works. Problematic soils cause difficulties in geotechnical applications. Geogrid reinforcement of these problematic soils together with granular fill is soil improvement technique that has gained great attention in the last decade. Problematic soil behavior can be improved by totally or partially replacing inadequate soils with granular fill compacted in layers. It is also possible to further improve the bearing capacity by reinforcing the base course with geogrid.

Several experimental and numerical studies have been described about the reinforcement of a weak soft soil (Ochiai et al. 1996, Adams & Collin 1997, Yin 1997, Otani et al. 1998, Alawaji 2001, Dash et al. 2003, Thome et al. 2005, Chen 2007, Deb et al. 2007). Ochiai (1996) summarized the theory and practice of geosynthetic reinforcement of fills over extremely soft ground in Japan. Adams & Collin (1997) conducted 34 large model load tests to evaluate the potential benefits of geosynthetic-reinforced spread foundations. It was concluded that the soil–geosynthetic system formed a composite material that inhibited development of the soil-failure wedge beneath shallow spread foundations. Otani et al. (1998) studied the behaviour of strip foundation constructed on reinforced clay. Settlement was found to be reduced with the increase in reinforcement size, stiffness and number of layers. The load carrying capacity of a foundation has been found to increase more on soil in which reinforcements are provided at closer spacing. Alawaji (2001) discussed the effects of reinforcing sand pad over collapsible soil and reported that successive reduction in collapse settlement up to 75% was obtained. Dash et al. (2003) performed model tests in the laboratory to study the response of reinforcing granular fill overlying soft clay beds and showed that substantial improvements in the load carrying capacity and reduction in surface heaving of the foundation bed were obtained. Chen (2007) investigated the potential benefits of using the reinforcement to improve the bearing capacity and reduce the settlement of shallow foundations. The test results showed that the inclusion of reinforcement can significantly improve the soil's bearing capacity and reduce the footing settlement. The geogrids with higher tensile modulus performed better than geogrids with lower tensile modulus. In recent decades, an exponential growth in the area of digital computers and computational mechanics has resulted in the application of the non-linear finite element method to almost all areas of geotechnical engineering, including shallow foundations. The finite element method (FEM) has also become a highly useful tool, and has been widely used for the numerical analysis of reinforced soil structures. It provides the advantage of idealising the material behaviour of soil, which is non-linear with plastic deformations and stress path dependent, in a more rational manner. The FEM can also be particularly useful for identifying the patterns of deformations and stress distribution in and around the reinforcing elements, during deformation and at ultimate state (Laman & Yildiz, 2003).

In the present study, in-situ tests were carried out to determine the improvement of bearing capacity of circular shallow foundations supported by a compacted granular fill with and without geogrid reinforcement over clay soil. After in-situ tests, numerical analyses were conducted using geotechnical computer software. The results of the experimental and numerical studies indicate that the thickness of the granular fills and the geogrid reinforcement has considerable effects on the bearing capacity of the circular shallow foundations. It is proved that the improvement depends also on the reinforcement geogrid arrangement. The use of geogrid reinforcement in a compacted granular fill over clay soil provides additional improvement of bearing capacity performance.

2 IN-SITU TESTS

Before conducting the tests, a comprehensive soil investigation was performed to determine the soil properties. The site investigation covers an area of about 350m^2 which the sizes of 30m and 11.6m for length and width, respectively and situated in the west part of Adana, Turkey. First layer of 0.80m depth observed as topsoil and the second layer between the depths of 0.80m and 2.60m observed as silty clay from the test pits. Then, boreholes were drilled with depths of 13m. Water table level was determined as 2.40m from borehole drillings. Standard Penetration Test (SPT) was carried out during drilling each borehole the values refer that the soil tested classified as medium stiff clay. Samples were treated that unconfined shear tests are routinely made using a pocket penetrometer for several values with the average recorded (Bowles, 1988). Conventional laboratory tests were performed in Geotechnical Laboratory of Civil Engineering Department at Cukurova University, Adana, Turkey.

2.1 *Model Foundations*

The model foundations with the diameters of 60cm and 12cm used in the tests were made of mild steel. The thickness for the model foundation diameter of 60cm was 3cm and that of 2cm for 12cm foundation diameter. The foundations were loaded with a hydraulic jack against a reaction steel frame. Two different hydraulic jacks were used. Big one which has 60tons of capacity was used for 60cm diameter foundation and small one which has 10tons of capacity was used for 12cm diameter foundation. Calibrations were performed for 60tons and 10tons capacity hydraulic jacks.

2.2 *Test Material*

2.2.1 *Clay Soil*

Laboratory tests were conducted on representative soil samples for gradation, specific gravity, maximum and minimum densities and strength parameters. These properties are summarised in Table 1. As seen that mean water content value of soil is measured at 23% and that of mean unit weight 2.07kN/m^3. Table 1 shows that the soil is normally consolidated (P_0<1).

Table 1. Soil profile in test area

Depth (m)	Soil Type	ω_{mean} (%)	γ_s (kN/m^3)	I_P (%)	c_u (kPa)	P_0 (kPa)
0.8-2.2	CH	20-21	2.57-2.60	30-39	30-45	63-81
2.2-3.5	CL	22-24	2.60-2.69	12-33	15-27	44-67
3.5-5.0	CL	22-24	2.57-2.66	17-19	15-27	40-70

ω_{mean}= mean value of water content (%)
γ_s = soil unit weight (kN/m^3)
I_P= plasticity index (%)
c_u=undrained cohesion (kPa)
P_0= preconsolidation pressure (kPa)

2.2.2 *Granular Fill*

The granular fill material used in the model test was obtained from the Kabasakal region situated northwest of Adana, Turkey. Some conventional tests were conducted on this material. Granular soil was prepared at optimum moisture content of 7% and maximum dry unit weight of 2.17gr/cm^3 obtained from the standard proctor test. The values of internal friction angle and the cohesion of clay soil were obtained as 42° and 1.5kg/cm^2, respectively from direct shear tests. Specific gravity of the granular soil was obtained 2.64gr/cm^3. From the sieve analysis, granular soil was classified as well graded gravel-silty gravel, GW-GM according to the unified soil classification system.

2.2.3 *Geogrid*

A white coloured, Secugrid Q type geogrid with maximum tensile strength of 60kN/m was used as reinforcing material in the model tests. The physical and mechanical properties of the geogrids as listed by the manufacturer are given in Table 2.

Table 2. Engineering properties of geogrid

Parameter	Value
Structure	biaxial
Aperture shape	squared
Aperture size	30mm x 30mm
Mass per unit area	360g/m^2
Unit weight	2.60 gr/cm^3
Raw material	polypropylene
Elongation at nominal strength	8 %
Tensile strength at 2% elongation	22 / 22 (md/cmd)
Tensile strength at 5% elongation	48 / 48 (md/cmd)

2.3 *Experimental Procedure*

The experimental set-up has been used extensively for the bearing capacity of shallow foundations on reinforced clay soils. The schematic view of the test is shown in Figure 1, where, D is the foundation diameter and N is the number of geogrids.

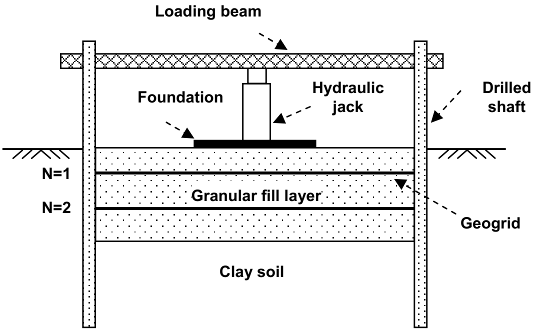

Figure 1. Schematic view of the test (unscaled)

In the tests, steel loading beam (I240) with a length of 3.5m was assembled on drilled shafts. The loads were applied against this reaction steel frame. Then model foundation, transducer, hydraulic jack and two LVDTs were placed. Hydraulic jack and LVDTs were connected to a data logger unit and data logger unit was connected to a computer. Load-settlement curve was drawn with loading simultaneously during tests. Loading was performed until the vertical deformation, i.e. settlement recorded until 10% of foundation diameter. In the tests, granular fill layer with different thicknesses was located under the foundation. Geogrids were laid inside granular fill in predetermined depths. A total of 12 tests were performed in the experimental studies and the details of the tests are given in Table 3.

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Table 3. Details of the tests

Test No	D (cm)	H	N	Description
1	60	-	-	unreinforced
2	12	-	-	
3	60	0.33D	-	granular fill effect
4	60	0.67D	-	
5	60	1.00D	-	
6	12	0.33D	-	
7	12	0.67D	-	
8	12	1.00D	-	
9	60	0.67D	1	geogrid effect
10	60	0.67D	2	
11	12	0.67D	1	
12	12	0.67D	2	

D=foundation diameter
H=thickness of granular fill layer
N=number of geogrids

2.3.1 *Tests without Reinforcement*

These tests were conducted using two different foundation diameters of 60cm and 12cm. The aims of carrying out these tests are to investigate the bearing capacity of clay soils with different foundation sizes and to create a reference for the oncoming tests with granular fills and geogrids.

2.3.2 *Tests with Granular Fill*

In this group, six model tests were conducted using two different foundation diameters (60cm and 12cm). The aim of carrying out these tests is to analyse the contribution of granular fill on the bearing capacity of clay soils. In the tests granular fill thickness was changed depending on the foundation diameters (0.33D; 0.67D and 1.00D). Typical plots for bearing capacity-settlement behaviour obtained from the experimental test for diameters of 12cm and 60 cm foundations are shown in Figure 2 and Figure 3, respectively.

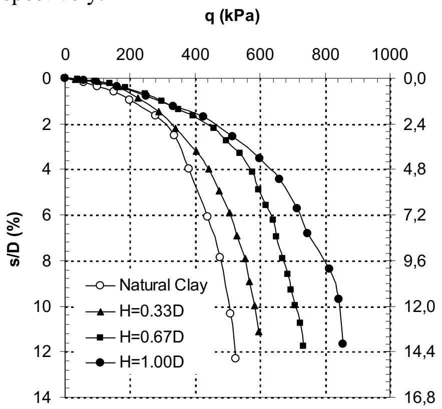

Figure 2. The effect of H/D (D=12cm)

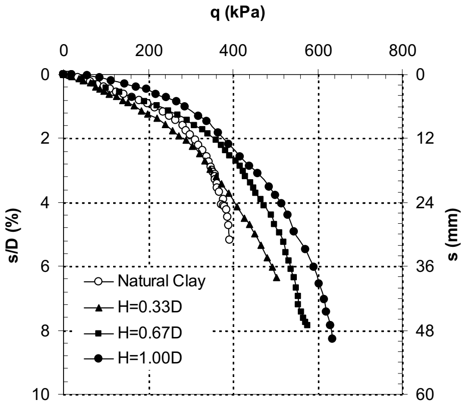

Figure 3. The effect of H/D (D=60cm)

2.3.3 *Tests with Geogrid*

In this group, four model tests were conducted using two different foundation diameters (60cm and 12cm). The aim of carrying out these tests is to determine the contribution of geogrid on the bearing capacity of clay soils and granular fill reinforced soil. In the tests, while the thickness of the granular fill was kept constant as 0.67D and the location of geogrid was changed in granular fill. Typical plots for bearing capacity-settlement behaviour obtained from the experimental test for two different model foundations are shown in Figure 4 and Figure 5, respectively. The test results showed that the inclusion of reinforcement can redistribute the applied load to a wider area, thus minimizing stress concentration and achieving a more uniform stress distribution. The redistribution of stresses below the reinforced zone can result in reducing the consolidation settlement of the underlying weak clayey soil (Chen, 2007).

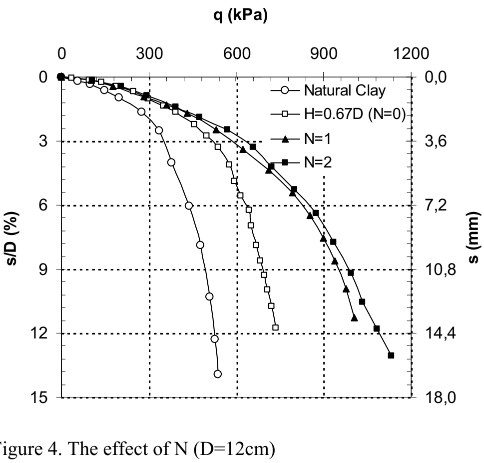

Figure 4. The effect of N (D=12cm)

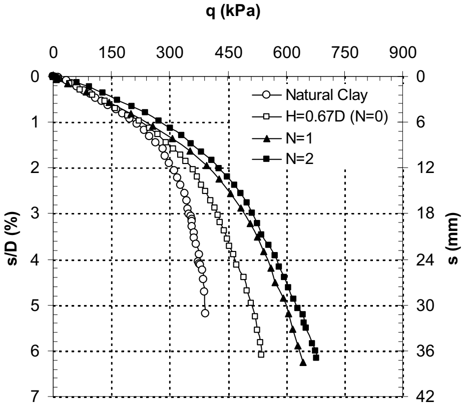

Figure 5. The effect of N (D=60cm)

3 FINITE ELEMENT ANALYSES

The finite element studies of the bearing capacity of shallow foundations resting on stabilized fill bed with and without geogrid and clay soil were carried out. The finite element package used in this study was specially developed for the analysis of deformation and stability in geotechnical engineering problems (Brinkgreve et al., 2004). Stresses, strains and failure states of a given problem can be calculated. Mohr Coulomb (MC) Model was used to define clay soil and granular fill behavior in this study. In the analysis MC model parameters for clay soil and granular fill are given in Table 4 and Table 5, respectively. Analyses were performed in axisymmetric and undrained soil conditions. In the analyses model foundation (EA=5e+06 kN/m; EI=8500 kNm^2/m) and geogrid (EA=1000 kN/m; EI=0.05 kNm^2/m) were assumed rigid and elastic plate, respectively.

Table 4 MC Model parameters for clay soil

Parameter	Symbol	Value
Unit weight	γ	18 kN/m^3
Loading stiffness	E_{ref}	8500 kN/m^2
Poisson's ratio	ν	0.35
Cohesion,	c	75 kN/m^2
Friction angle	ϕ	0°
Dilatancy angle	ψ	0°

Table 5 MC Model parameters for granular fill

Parameter	Symbol	Value
Unit weight	γ	20 kN/m^3
Loading stiffness	E_{ref}	42500 kN/m^2
Poisson's ratio	ν	0.20
Cohesion	c	1 kN/m^2
Friction angle	ϕ	43°
Dilatancy angle	ψ	0°

4 COMPARISON BETWEEN TEST AND NUMERICAL RESULTS

In this study, in-situ tests and numerical analyses were carried out on granular fill beds with and without geogrid overlying clay soil. After the tests and analyses were completed, bearing capacity – displacement curves for various arrangements were obtained and discussed. The bearing capacity was defined as a pressure across a specific settlement which is s/D=%10 and %5 for foundation diameters 12cm and 60cm respectively. The term "bearing capacity ratio" (BCR) is commonly used to express and compare the test data of the reinforced and unreinforced soils. The following well-established definition (Binquet and Lee 1975) is used for BCR:

$$BCR = q_R / q_0 \quad (1)$$

Where q_R and q_0 are the bearing capacity for the reinforced and unreinforced soils, respectively. The parameters investigated, including the settlement of foundation plate, s, are normalised by the diameter of the foundation plate, D (Laman and Yildiz 2003).

4.1 *Tests without granular fill*

Typical plots for the load–settlement behavior obtained from the test and numerical analysis of the unreinforced natural clay soil case are shown in Figure 6 and Figure 7. As seen from the figures that there is a similar tendency between test and numerical results.

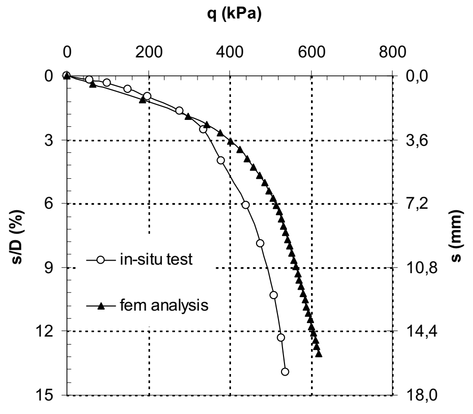

Figure 6. Curves of loading against settlement (D=12cm)

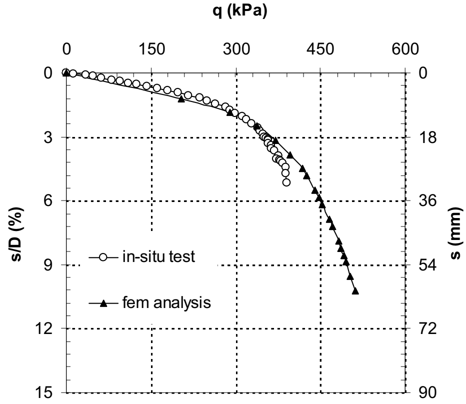

Figure 7. Curves of loading against settlement (D=60cm)

4.2 *Effect of granular fill*

The test results were defined using bearing capacity ratios (BCR).

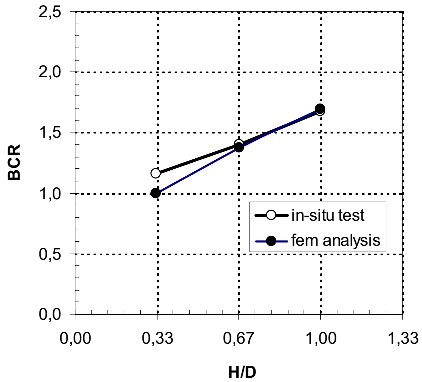

Figure 8. BCR versus H/D (D=12cm)

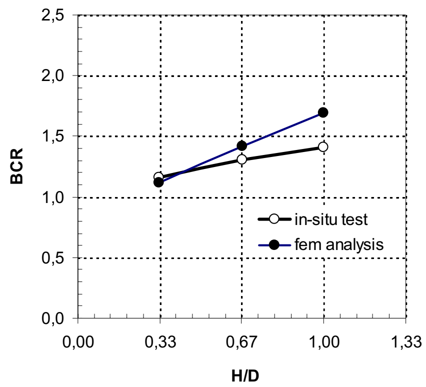

Figure 9. BCR versus H/D (D=60cm)

It is shown from the Figure 8 and Figure 9 that BCR increases with an increase in the granular fill thickness for diameters of D=12cm and D=60cm circular model foundations, respectively. In other words, bearing capacity increases with granular fill thickness. There is a good agreement between the results obtained from the model tests and numerical analyses.

4.3 *Effect of geogrid reinforcement*

The relation between BCR and the number of reinforcement layers, N, obtained from numerical analysis and in-situ tests are shown in Figure 10 and Figure 11 for two different foundations, respectively. As seen from the figure the behavior predicted in the analysis is agreed well with the test results especially for diameter of 60cm.

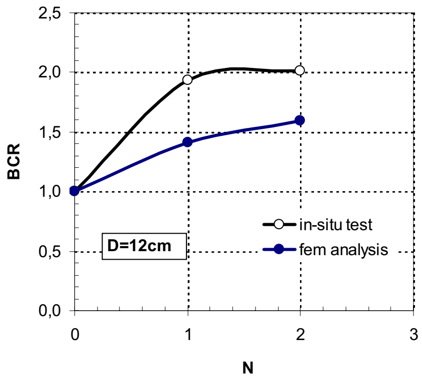

Figure 10. Relation between BCR and N (D=12cm)

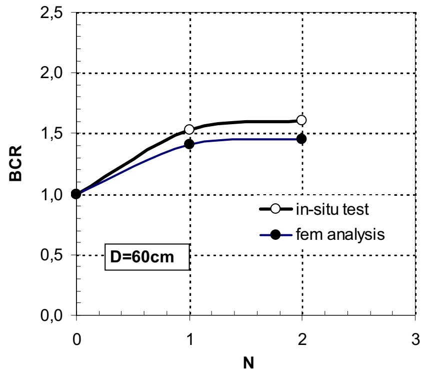

Figure 11. Relation between BCR and N (D=60cm)

5 CONCLUSIONS

In this study, in-situ tests and numerical analyses were carried out to determine the improvement of bearing capacity and settlement behaviour of circular shallow foundations supported by a compacted granular fill with and without geogrid over natural clay soil. Based on the results from this investigation, the following main conclusions can be drawn:

- Finite element solutions gave results that closely match those from physical model tests.
- Clay soil deposit replaced partially by a granular fill increases the bearing capacity. Bearing capacity increase is about %30 at H=0.67D for 60cm foundation diameter. The first reinforcement layer in granular fill increases bearing capacity but the second reinforcement layer does not increase the bearing capacity significantly. BCR value was obtained as 1.53 for N=1 and D=60cm.
- This investigation is considered to have provided a useful basis for further research leading to an increased understanding of the application of soil reinforcement to bearing capacity problems.

Acknowledgements: The work presented in this paper was carried out with funding from TUBITAK (The Scientific and Technological Research Council of Turkey) grant number 106M496.

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