# Effects of the first reinforcement depth for different types of geosynthetics

Elif Cicek[1*] Erol Guler[2] Temel Yetimoglu[3]

1*. Department of Civil Engineering, Hacettepe University, Ankara, Turkey

Email: elif.cicek@hacettepe.edu.tr, elifflower25@gmail.com

2. Department of Civil Engineering, Bogazici University, Istanbul, Turkey

Email: eguler@boun.edu.tr

3. Department of Civil Engineering, Ataturk University, Erzurum, Turkey

Email: yetimt@atauni.edu.tr

[*] Corresponding Author: Elif CICEK

Address: Hacettepe University, No.418, Department of Civil Engineering, 06800, Ankara, Turkey.

Telephone: +90 312 297 7333

+90 312 780 7462

# Effects of the first reinforcement depth for different types of geosynthetics


## Abstract

In this study, the performance of the first reinforcement layer depth for sand subbase of a road or construction was investigated with plate load laboratory tests. Unreinforced and reinforced experiments for different reinforcement types were made by changing the first reinforcement layer depth ratio. One type of geotextile and two different geogrid specimens were used in the research. Load-settlement curves and Bearing Ratios were studied by measuring the results for different settlement ratios. Finally, laboratory measurements of unreinforced and reinforced soil using geotextile reinforcement were compared with Finite Element Model (FEM) analyses modeled under similar conditions. The results demonstrated the effects of different types of reinforcements for different first reinforcement layer locations. The number of reinforcement layers was another parameter which affected the bearing ratio along with the first reinforcement layer depths. It was also observed that the Bearing Ratio (BR) and load-settlement behavior changed significantly with the first reinforcement depth and settlements. Effects on failure modes for unreinforced and reinforced sand soils were compared for each test.



## Keywords

First reinforcement depth; Settlement; Reinforcement; Sand soil; Geosynthetic, Plate load test

## 1. Introduction

Subbase soil is a significant element of the design of any structure and improvement of bearing capacity and reduction of settlement can be achieved by making use of materials such as geosynthetic reinforcement. Geosynthetic reinforcement is successfully used in stabilization of soils, and helps increase bearing properties and reduces the settlement of footings, railway and highway subgrades, embankments, etc. As it is known from the literature, reinforcements can extend the service span for pavements [1-6]. Additionally, in recent years the behavior of reinforced subgrades has been investigated by many researchers [7-13]. It is well known that the performance of the reinforced systems is enhanced mainly depending on the reinforcement properties such as position [14, 15], strength [16], and mesh size [17, 18] of the reinforcement. The location of reinforcement material within the base layer is very critical for its effect [19]. However, when a detailed literature survey is conducted, it can be seen that there is no unique value for the optimum first reinforcement depth. To illustrate this fact that the following literature citations can be summarized: Al-Qadi et al. [20] reported that for a thin dense layer, placing geogrid material shows better improvement and that the reinforcement should be located at the upper one-third of the base part for a thicker layer. Nevertheless, Hass et al. [21] also founded that effects were not stayed when a single layer of reinforcement was at the midpoint or higher within the base layer for a thick base course over very soft, flexible subgrades. In order to clarify this issue, in this study different first reinforcement depth values were chosen to investigate.

It is a known fact that the geosynthetic properties play a major role in the behavior. However, in most studies, one type of geosynthetic was used. There is only limited information in the literature about the effect of different reinforcement types. Guido et al. [22] and Chen [23] have investigated the reinforcement types and the general outcome was that geogrids show superior performance compared to geotextiles. Mandal and Manjunath [24] investigated the bearing capacity behavior of Geogrid and bamboo stick reinforcements for strip plates on dense sand. An abounded increase in bearing capacity occurred when the reinforcement materials were placed within a distance of 0.5B. The geogrid materials had more effect than bamboo materials. Dash et al. [25] studied the measurements taken from laboratory experiments for strip plates on reinforced sand. Tensile strength of the reinforcement was not an important argument to compute the effect of the reinforcement. Aperture size and orientation of the ribs for geogrid material were significant contribution for load carrying mechanism. Alamshahi and Hataf [26] made experiments and numerical studies to determine the bearing capacity of a strip plate on reinforced slopes. The effects of the geogrid reinforcements and their locations were investigated. However, all studies show a lack of different reinforcement types' behavior on optimum first reinforcement depth and different settlement ratios. For this reason, in this study different geosynthetic types with different mesh size were used to determine the load-settlement behavior of reinforced sand soil.

Most of the tests reported in the literature are conducted on dense sand, and generally small settlement ratios were observed before failure. However, it is known that the bearing failure mode also depends on the density of the soil. However, in the case of loose to medium dense sand larger settlements are observed and during this process, the soil gradually gets denser as well. As a consequence, the behavior observed for different settlement ratios differ. Accordingly, there is a need to analyze the results for different settlement ratios and for different types of reinforcement. Therefore, one of the aims of this paper is to determine the behavior of medium dense soil reinforced with different types of geosynthetics. The literature has reported that the depth of the first reinforcement is a critical parameter affecting the behavior of reinforced soil foundations. To determine the effective reinforced zone depth, the first reinforcement depth is a very significant factor due to improving behavior. However, there is no one value for this value and different studies shows different optimum depth ratios. Therefore, a special emphasis is given to understand how the depth of the first reinforcement layer affects the behavior in this study. As the literature studied, the most effective depth ratios were selected to define the optimum value. Tests were conducted with a geotextile and two different geogrids. It is very common that multiple layers of reinforcement are used in practice, Therefore the effect of the first layer of reinforcement was investigated for multiple reinforcement layers. Because the behavior changes with increasing settlement values as explained above, results have been analyzed for different settlements. The experimental results were also compared by using Finite Element Model.

## 2. Methodology

### 2.1. Material Properties

One type of sand used in the experiments. 2.65 was the specific gravity of the dry soil. The coefficient of uniformity, the coefficient of curvature and the effective particle size were 2.5, 1 and 0.22 mm, respectively. The maximum dry unit of weight was 16.5 $kN/m^3$ and minimum dry unit weight was 13.9 $kN/m^3$. The unit weight and relative density of the sand were kept constant. Their values were 15 $kN/m^3$ and 46%. Subbase soil was layered with 20 or 25 mm into the test tank. Laboratory tests such as standard triaxial compression tests were made to determine the soil behaviors and the friction angle founded as 38°. Sand used in model tests can be classified as poorly graded for Unified Soil Classification System and A-1-b for American Association of State

Highway and Transportation Official's classification system. In this study, three different geosynthetic materials were employed. One of the is a woven geotextile and two different types of geogrids. The characteristics of each reinforcement material can be observed from Table 1.

## 2.2. Test Set up

The boundary conditions of the test tank were selected such that it would not affect the tests. The properties of the test models were selected based on literature researches. Additionally, some finite element analysis was conducted prior to the laboratory tests to find the true model boundary conditions. Test model can be seen from Figure 1. A steel tank (100 cmx50 cmx100 cm). Undesirable movements of the box were restrained by steel I profiles. The tests were conducted for plane strain conditions. To see the effects of the improved subbase on road or foundation soil, loads were applied on a strip steel plate a width of 10 cm (B) and its thickness was 25 mm. Loading was applied up to settlement of plate equal to about 100% of B was achieved. The settlements of the soil were measured using four laser sensors displacement gauges. 2 gauges were used and they placed to centres of each length. Additionally, in order to control the settlement results four laser sensors were used and they putted on four corners. Then results of the laser sensors and the gauges were same. The loading values were measured by a load cell.

The geometrical parameters describing the location of the reinforcement are as follows: depth of the first reinforcement layer 'u', the vertical spacing of reinforcements 'h', the total number of reinforcement layers 'N' and the width of the geosynthetic reinforcement 'L'. Several researchers have investigated the effect of the lengths of reinforcement [27-29]. They concluded that the optimum reinforcement length was

L=3B, because greater lengths are not efficient. As a result, the reinforcement length in this study was kept constant at L=3B.  A similar process was followed to determine the range of vertical spacing of reinforcement layers (h) that gives the maximum bearing capacity according to the results of a literature survey [30]. Therefore, the vertical spacing of reinforcement layers for multi layered reinforced soil tests was taken as h=0.4B in all tests [10]. For this study, the number of reinforcement layers was chosen as N=0, 1, 2 and 3. To see the effect of the first reinforcement depth (u) the values of 'u' were chosen from literature studies indicating optimum values, which are u=0.175B, 0.35B, 0.55B and 0.75B. The variables chosen for the tests are shown in Table 2.

Initially, unreinforced models were made and then reinforced soil model tests were conducted. To compare the differences reported from the tests load-settlement curves and Bearing Ratio (BR) values were used. (BR=q/qu, where, qu is the contact pressure on plate for unreinforced condition at a settlement 's' and q is the pressure for reinforced soil at the same settlement value 's')

**2.3. Finite Element Model Properties**

Finite Element Analyses were made to compare the laboratory test results and to determine reason of the different behaviors for different reinforced conditions. The plane strain conditions were used and laboratory test conditions were simulated. To reduce the boundary effects a detailed survey was made before the laboratory tests and some numerical analyses were made to determine the model of the study. Therefore, a negligible level was chosen and the width of the test tank was used as bigger than 10 times according to loading plate width (B). For more sensitive computation, the mesh size was further refined in the near vicinity of the plate and 15 node triangular elements were used. 5 node beam elements were used to model the plate and its properties were

EI (flexural rigidity) =260 kNm$^2$ /m, EA (axial stiffness) =5x106 kN/m. The vertical boundaries were chosen to have only horizontal fixity and the lower boundary to have both horizontal and vertical fixities. The system was symmetric with the center of plate, so only half of the system was modeled as literature studies [31]. The subbase soil was modelled by using Hardening Soil Model and the soil properties can be observed from Table 3.

The cohesion was taken as c=1 kN/m$^2$ due to the Plaxis finite element program recommendation for sand soils. Dilatancy angle was founded from φ-30 as recommended by the Plaxis manual. The elasticity module is secant elasticity modules for hardening soil model. However, for reinforcement only geotextile was modeled since the apertures of a geogrid is not possible to be correctly represented in a 2D analysis. Because only interface as a friction rate between soil and reinforcement material and elastic rigidity (EA) can be determined for reinforcement materials in the program. Elastic rigidity (EA) uses to determine the geosynthetic mechanical behaviour. E is the material tension stiffness and 'A' is the cross sectional areas for each reinforcement. It is similar thing with axial stiffness as in the literature studies. In this study, for reinforcement was taken as EA=550 kN/m and interfaces between soil and geotextiles were as 0.7. This information was chosen by laboratory tests and taking form the manufactured firm of the geotextiles.

## 3. Results

### 3.1. Test Results

The load-settlement curve of the unreinforced soil is given in Figure 2. As can be seen from the figure, the failure surfaces started to develop in the soil when the load value reached at qu=61 kPa and the settlement ratio (s/B) was approximately 10-15%. After failure, the curve becomes steeper. Hence, it was interpreted that the soil behaves in an elastic way before failure, and the plastic deformations prevail after the yield point. The soil is medium dense, and the deformations measured are the results not only of elastic but also of plastic behaviors. The tests were repeated and similar results were obtained. The number of reinforcement layers was chosen as N=1, 2 and 3 for Geotextile reinforced models. The first reinforcement depth was chosen as u=0.175, 0.35, 0.55 and 0.75 based on literature studies. The load (q)-settlement (s) results for smaller and larger settlement ratios measured are given in Figure 3. For a single reinforcement layer, the load –settlement curves indicate a failure point (Figure 3.a). However, as the reinforcement layers add (N≥2), a clear failure point can no longer be observed even for large settlement values (Figure 3.b and Figure 3.c). As the first reinforcement depth ratios increase, the Bearing Ratio values of the reinforced soils becomes greater. For multilayered soil at small settlement ratios the bearing ratio increases up to the first reinforcement depth of u/B=0.75. At greater settlement ratios (approximately s/B>0.2) suddenly the load-settlement behavior of multi layered soils curve changes. The load value of the plate has suddenly decreases, but after this decrease the plate start to take up loads again. Generally, the maximum bearing ratio is observed for the first reinforcement depth of u/B=0.55. Small and big settlement ratios for one and three reinforcement layers show different behavior. As the settlement ratio increases, BR values also increase. This behavior was interpreted as the reinforcement taking more load. Additionally, as the settlements increase, the bearing ratio increases consequently.

The same tests were repeated with geogrid reinforcements to see the difference. Two types of geogrids were used. In this series of the experiments the first reinforcement depth was taken as u/B=0.35, 0.55 and 0.75. The value of u/B=0.175 was not used in this series, because at such shallow depth the failing soil pushes the reinforcement beyond the loading plate to the surface. Additionally, the desired anchorage cannot be achieved. It should be noted that this is because the model scale, and it is not expected in real structures. Furthermore, there is a sudden change and decrease in the load carrying capacity in the experiments where the first reinforcement depth is greater than 0.75. Hence, the larger reinforcement depths were not used. Figures 4 and 5 show the load (q)-settlement (s) results at different settlement ratios for soils reinforced with Geogrids. It can be seen from Figures 4 and 5 that the maximum BR values were generally measured for u/B=0.55 for both Geogrid types. However, the first reinforcement depths give approximately the same BR values at small settlement ratios for u/B=0.35 and 0.55. As the settlement ratios increase, Bearing Ratio values also increase. The load decreases suddenly as in the Geotextile reinforced model. The load-settlement curves of u/B=0.35 and 0.55 show a linear increase in BR values, as the settlement ratio increases.

To determine the effect of the different reinforcement types with various first reinforcement depths, the Bearing Ratio values were compared. In Figure 6 the results for N=3 are given at different settlement ratios. The different reinforcement types showed different behaviors, as expected. For both geogrid reinforcements similar behavior was observed. However, the behavior was different than obtained for geotextile reinforcement. Generally, Geogrid 1 reinforcement increases the Bearing Ratio values more than the other reinforcement types at s/B≥0.2. However, the Geotextile reinforced model has bigger BR values than others for u/B=0.75 at s/B≥0.1. Additionally, the BR-u/B curve of the Geotextile reinforced system behaves differently from the geogrids. Its curve has similar behavior at greater settlement ratios (s/B≥0.3). Generally, the first reinforcement depth ratio which is u/B=0.55 has greater Bearing Ratio values than the others.

Most studies for u/B=1 in the literature reported that reinforcement cannot increase the bearing capacity. Hence, u/B=1 was not used in this study. As can be seen from Figure 7, the load-settlement behaviors of reinforced medium dense sand for u/B=0.75, different geosynthetic types show a similar effect for the same settlement ratio. The load values suddenly decrease at approximately s/B=0.25. As loading continues, the load values start to increase. However, the load-settlement curve for u/B=0.75 has a sudden decrease. A possible reason for this behavior is that triangular failure surface is on the reinforcement line for greater first reinforcement depths such as u/B=1. Yet, this failure surface touches the reinforcement for lower first reinforcement depth values such as u/B=0.75. But, the depth is not enough to carry the load and the loading curve suddenly decreases. However, as can be known the sol used in the study is not dense. Therefore, when the model was loaded, the soil became denser and reinforcement started to behave more effective thereby increasing the loading values for load-settlement curve. It can be seen in Figure 7 that the curve line of load-settlement for Geotextile reinforcement is steeper. Table 1 shows that Geotextile and Geogrid 2 have more or less similar tensile strength values, and their tensile strengths are greater than Geogrid 1. However, the Geotextile has greater bearing ratios than the other reinforcements for u/B=0.75 as can be seen in Figure 7. As an interpretation for this behavior is the fact that the soil-reinforcement contact surface is much larger for the geotextile. Since the soil is a medium sand, the interlocking of the geogrid cannot be as sufficient as for coarser particles. For different u/B ratios, the number of reinforcement layers affects the Bearing Ratio values (Figure 8). Tests with Geogrid reinforcements for small settlement ratios such as s/B=0.1 had similar Bearing Ratios (BR) at different first reinforcement depths. Geotextile and Geogrid reinforcements shows different maximum Bearing Ratios at different first reinforcement depths. When settlement ratios increases, maximum BR values increases as the number of reinforcement layer increases. Settlement ratios become an important parameter on the bearing ratio values for multiple layered reinforcements and for the first reinforcement depth. For greater settlement ratios, this behavior changes. As settlement ratios increase, the differences between the bearing ratio values for each number of reinforcement layers decrese via different u/B ratios. The bearing ratio and number of reinforcement layer relationship changes for different u/B values. The type of the load-settlement curve line begins to be more linear.

The first reinforcement depth can affect the behavior of footings on the reinforced soil in a significant manner. An optimum depth should be used to have a significant improvement by reinforcements. In the literature generally one type of reinforcement was used to see the effects of reinforcement [32], but in this study the tests were conducted by using different type of reinforcement materials. For geotextile, and both geogrids behave perfectly when the first reinforcement layer is almost u=B/2. Although for the geotextile the number for reinforcement layer changes the optimum depth value is same. Additionally, for same number of reinforcement layers, the models reinforced with geogrids behave similar when the first reinforcement layers changes. However, the samples reinforced with the geotextile behave differently from the other geogrids. Although the geotextile reinforcement has the maximum tensile strength (Table 1) than the geogrids, the geogrids have more improvement effect than the geotextile regarding as bearing ratio values. Because of the aperture sizes of the geogrids improve the friction behavior between the soil and the reinforcements. Additionally, the soil particles can fill the aperture gaps, and so they can behave more efficiently than the geotextile. However, for u=0.75B, the model reinforced with geotextile has more impact on the bearing ratios. It can be assumed for this different behavior that the geotextile layer behaves a rigid plate for higher depths and it can try to restrain settlements. Furthermore, there can be no enough compaction effect by footing loading to fill the soil particles into apertures of the geogrids. It can be said for real projects that the geotextile can give more improvement effect for higher first reinforcement depths such as u=0.75B.

Another interesting point is that, generally, Geogrid 1 has more improving effect than Geogrid 2 though Geogrid 1 has bigger tensile strength than Geogrid 2. However, Geogrid 1 has two times smaller aperture size than Geogrid 2. This means that when the soil particles can fill the smaller aperture sizes of the reinforcement, they can more connect and increase the taking loads. So, this behavior is important for real projects. Because the behavior can be changed by different projects. For illustrate, a building or road projects different reinforcements can be needed because the particle size of the subbase materials. Therefore, the particles and aperture sizes of the geogrids or scale effects of the materials used in the field should be considered.

The test results show that for small and bigger settlement ratios are important for improvement effects of different reinforcement types. If the small settlement rates are important a project, material types of the reinforcements have more significant importance than bigger settlement ratios. Because the settlement rate increases the different type of reinforcements such as geotextile and geogrids start to behave similarly.

As can be seen from this study that after the footing settles about s=2.5B, the all models show a sudden decreasing for taking loading. However, after almost the settlement ratio is s=3B, the geotextile and both geogrid reinforced models can be loaded more and the models have more linear load-settlement behaviors. Therefore, it may be assumed by this study that before the real project, for example before constructing a building or road, a preloading department can be prepared. After the reinforced field loaded and the desired uniform settlements become, the intended structure can be constructed on the preloaded reinforced field. Thus, more bearing ratios can be obtained.

**3.2. Finite Element Model Results**

To compare the results of the laboratory tests and understand the behaviour of the models, Finite Element analyses were conducted. In order to verify the Finite element model, firstly, the unreinforced case was modelled. The load – settlement curves can be observed in Figure 9. It can be seen that for small settlement values the curves behave almost similar (until about s/B=0,15). That is to say, the measured values from the experimental test and the load-settlement curves obtained from FEM agree well [10]. However, for bigger loading values the differences start to be seen for two different methods. Thus, it can be estimated that for medium dense conditions small settlement ratios can be simulated by FEM easily, but after the settlements and bigger loadings the soil start to be compacted by footing loading and upper soil parts become denser, and then its mechanical behaviour changes. In that respect, this case is one of the limitation of the FEM analysis, so for small settlements can be modelled in this study.

Another limitation of the 2D modelling is the determining the reinforcement materials which have different aperture size properties. For 2D analysis, the aperture properties and their interaction between the soil particles cannot be modelled in same conditions with the real laboratory tests. Therefore, in this study, only geotextile reinforced model was analyzed.

For reinforced models, different number of reinforcement layers were analyzed and their effects on the improvement of mechanical behavior were studied. Figure 10 illustrates the load-settlement curves for different number of reinforcement layers founded by finite element models. The number of reinforcement layers increase the loading and bearing capacity of the model rises. The maximum improvement influence can be obtained by multi layered reinforcement conditions and for three reinforcement layered model (N=3). Therefore, Number of reinforcements were N=3 and analyses were conducted until a settlement ratio of s/B=0.1 due to fact that the small settlement conditions can be compared with test results. The load settlement curves were analyzed for different first reinforcement depths as can be observed in Figure 11 and the bearing ratio values (BR) were compared in Figure 12. As the loading and settlement increase the behaviors of different models start to be changed by the effect of the first reinforcement depth. It was seen that a good agreement between FEM and Geotextile reinforced results was also obtained for small settlement ratio values.

In order to understand the reason of the sudden decreasing for u=0.75B in the laboratory tests, FEM analyses were conducted. In these analyses, as the small loading and settlement ratios can be compared with the test results, the loading value of q=50 kPa was used. The results of unreinforced and reinforced models were compared in terms of the failure wedge for stress behaviors in the reinforced models (Figure 13). The real figures were cut and zoomed to show the difference of the stress distributions under the footing. The scale is same but only changes in the stress were shown. The dark color parts show that there is no settlement and stress distribution. By this way, it can be also said that the boundary conditions are suitable. The stresses occur under the footing plate. The fluctuation on the reinforcements can determine that each reinforcement taking loads and divide them into parts. In unreinforced soil the triangular failure wedge can be seen in Figure 13.a and it can be observed as a normal behavior. However, for u/B=0.175 or smaller first reinforcement depth the failure plane has to pass through many reinforcement layers, but for u/B=0.75 or greater first reinforcement depth the failure plane intersects less reinforcement layers (Figure 13.b and Figure 13.c). Therefore, it can be interpreted that the reason for the sudden change observed in the load-settlement curve for u/B=0.75 is due to the fact that when the reinforcement lies below this depth, the failure wedge of the soil does not intersect as many reinforcement layers and therefore the contribution of the reinforcement is reduced. After some further settlement, the stresses are transferred to lower layers and therefore the reinforcements start to function again. So consequently, suddenly the inclination of the load-settlement curve changed. Thus it was seen that the figure can explain the reason of the sudden decrease.

## 4. Conclusion

The laboratory model experiments and Finite Element model analyses were made to determine the effect of the first reinforcement depth. The reinforcements were a geotextile and two different geogrids. The results indicated that the behavior changes depending on the whether the settlement ratio is small or large. Laboratory test results for geotextile reinforced models were also compared to Finite Element Model analysis. Based on results obtained from the present study many new and useful conclusions were drawn. These conclusions on the effects of the first reinforcement depth for reinforced medium dense sand are summarized below.

- This study shows that the first reinforcement depth has an important role for bearing ratio of footings on reinforced soils. It can be said that effective depth for first reinforcement layer is approximately half of the footing width (u=B/2).
- As it is expected, the geotextile reinforced system behaves differently from the geogrids.
- Different settlement ratios have important roles for reinforced soil performances.

• As settlement ratios increases, the bearing ratio values increases, but the difference for all combinations of u/B ratios and number of reinforcement layer decreases.

• For larger settlement ratios the Bearing Ratio-Number of reinforcement layer relation changes for different u/B values.

• Aperture size of reinforcement materials is important for interlocking effect to improve the bearing ratio values. Although the reinforcement with smaller the tensile strength, it can increase the mechanical behavior by interlocking effect. Hence, the tensile strength cannot be only determinant to determine the efficient reinforcement.

• The settlement rate increases the different type of reinforcements such as geotextile and geogrids start to behave similarly. This behavior can be significant for choosing the economical reinforcement type.

• The simple finite element model used in this study showed that it can be used to model unreinforced and reinforced soil models very well at small settlement ratios. Since in a civil engineering structure design the settlements have to be limited, it can be stated that the Finite Element model may be used successfully to model the reinforced subbase.

• As the settlement ratio of the footing increase, different reinforcement types can achieve almost similar Bearing Ratios. So, it may be considered that if a medium dense sand foundation soil is reinforced with a geosynthetic reinforcement, and if the structure is placed upon it, the medium dense soil gets compacted under the load and the reinforcement will function even better. In other words, by preparing the preloading effect before the construction of the structure, more loading values can be obtained.

**Acknowledgement**

The authors thank the Scientific and Technical Research Council of Turkey (TUBITAK) and the Bogazici University Research fund.

**References:**

[1] Al-Qadi, I.L., Brandon, T.L., and Bhutta, S.A. ‘‘Geosynthetic stabilized flexible pavements’’, Proceedings of the conference geosynthetics ’97, Long Beach, CA, USA, pp. 647–661 (1997).

[2] Cancelli, A. and Montanelli, F. ‘‘In-ground test for geosynthetic reinforced flexible paved sand soils’’, Proceedings of the conference geosynthetics ’99, Boston, MA, USA, pp. 863–878 (1999).

[3] Perkins, S.W. ‘‘Evaluation of geosynthetic reinforced flexible pavement systems using two pavements test facilities’’, Federal Highway Administration Report FHWA/MT-02-008/20040, Montana Department of Transportation, Helena, MT, USA, pp. 120 (2002).

[4] Hufenus, R., Rueegger, R., Banjac, R., Mayor, O., Springman, S. M., and Bronnimann, R. ‘‘Full-scale field tests on geosynthetic reinforced sand soils on soft subgrade’’, Geotextiles and Geomembranes, 24 (1), pp. 21 – 37 (2006).

[5] Abu-Farsakh, M.Y., Chen, Q. ‘‘Evaluation of geogrid base reinforcement in flexible pavement using cyclic plate load testing’’, International Journal of Pavement Engineering, 12 (3), pp. 275–288 (2011).

[6] Abu-Farsakh, M.Y., Akond, I., Chen, Q. ‘‘Evaluating the performance of geosynthetic-reinforced sand soils using plate load tests’’, International Journal of Pavement Engineering, 17 (10), pp. 901-912 (2016).

[7] Badakhshan, E., Noorzad, A. ‘‘Effect of footing shape and load eccentricity on behavior of geosynthetic reinforced sand bed’’, Geotextiles and Geomembranes, 4 (5), pp. 58-67 (2017).

[8] Moffat, R. Jadue, C., Beltran, J.F., Herrera, R. ‘‘Experimental evaluation of geosynthetics as reinforcement for shotcrete’’, Geotextiles and Geomembranes, pp. 1-8 (2017).

[9] Kargar, M., Hosseini, S.M. Mir Mohammad. ‘‘Effect of reinforcement geometry on the performance of a reduced-scale strip footing model supported on geocell-reinforced sand’’, Scientia Iranica A, 24 (1), pp. 96-109 (2017).

[10] Cicek, E. ‘‘Analysis of strip plates on geosynthetic reinforced sand’’, Ph.D. dissertation, Institute of Science in Ataturk University, Erzurum, Turkey (2011).

[11] Pasquini, E., Bocci, M., Ferrotti, G. and Canestrari, F. ‘‘Laboratory characterization and field validation of geogrid-reinforced asphalt pavements’’, Road Materials and Pavement Design, 14 (1), pp. 17–35 (2013).

[12] Nair, A.M., Latha, G.M. ‘‘Repeated load tests on geosynthetic reinforced sand soil sections’’, Geomechanics and Geoengineering: An International Journal, 11 (2), pp. 95-103 (2016).

[13] Tang, X., Palomino, A.M., Stoffels, S.M. ‘‘Permanent deformation behavior of reinforced flexible pavements built on soft soil subgrade’’, Road Materials and Pavement Design. 17 (2) 311-327 (2016).

[14] Tuna, S.C. and Altun, S. ‘‘Mechanical behaviour of sand-geotextile interface’’, Scientia Iranica A, 19 (4), pp. 1044–1051 (2012).

[15] Sobhan, K., Tandon, V. ‘‘Mitigating reflection cracking in asphalt overlay using geosynthetic reinforcements’’, Road Materials and Pavement Design, 9(3), pp. 367–387 (2008).

[16] Fallah, S., Khodaii, A. ‘‘Developing a fatigue fracture model for asphalt overlay reinforced with geogrid’’, Materials and Structures, 49, pp. 1705–1720 (2016).

[17] Canestrari, F., Grilli, A., Santagata, F.A. and Virgili, A. ‘‘Interlayer shear effect of geosynthetic reinforcements’’, Proceedings of the 10th International Conference on Asphalt Pavements, Quebec City, pp. 811–820 (2006).

[18] Komatsu, T., Kikuta, H., Tuji, Y. and Muramatsu, E. ‘‘Durability assessment of geogrid-reinforced asphalt concrete’’, Geotextiles and Geomembranes, 16 (5), 257–271 (1998).

[19] Webster, S.L. ‘‘Geogrid reinforced base courses for flexible pavements for light aircraft: test section construction, behavior under traffic, laboratory tests, and design criteria’’, Technical Report GL-93-6, USAE Waterways Experiment Station, Vicksburg, MS, USA, pp. 86 (1993).

[20] Al-Qadi, I.L., Dessouky, S., Kwon, J. and Tutumluer, E. ‘‘Geogrid in flexible pavements: validated mechanism’’, Transportation Research Record: Journal of the Transportation Research Board, No. 2045, National Research Council, pp. 102–109 (2008).

[21] Hass, R., Walls, J. and Carroll, R.G. ‘‘Geogrid reinforcement of granular bases in flexible pavements’’, Transportation Research Record: Journal of the Transportation Research Board, No. 1188, pp. 19–27 (1988).

[22] Guido, V.A., Chang D.K. and Sweeney M.A. ‘‘Comparison of geogrid and geotextile reinforced earth slabs’’, Canadian Geotechnical journal, 23 (4), pp. 440-435 (1986).

[23] Chen, Q. ‘‘An experimental study on characteristics and behavior of reinforced soil foundation’’, PhD dissertation, Louisiana State University, US (2007).

[24] Mandal, J.N. and Manjunath, V.R. ‘‘Bearing capacity of strip plate resting on reinforced sand subgrades’’, Construction and Building Materials, 9 (1), pp. 35-38 (1995).

[25] Dash, S.K., Krishnaswamy, N.R. and Rajagopal, K. ‘‘Bearing capacity of strip plates supported on geocell-reinforced sand’’, Geotextiles and Geomembranes 19, pp. 235–256 (2001).

[26] Alamshahi, S. and Hataf, N. ‘‘Bearing capacity of strip plates on sand slopes reinforced with Geogrid and grid-anchor’’, Geotextiles and Geomembranes, 27, pp. 217–226 (2009).

[27] Chakraborty, M. and Kumar, J. ‘‘Bearing capacity of circular foundations reinforced with geogrid sheets‘‘, Soils and Foundations, 54 (4), 820–832 (2016).

[28] Dawson, A.R., Moghaddas Tafreshi, S.N. ‘‘Comparison of bearing capacity of a strip plate on sand with geocell and with planar forms of geotextile reinforcement’’, Geotextiles and Geomembranes, 28, pp. 72-84 (2010).

[29] El Sawwaf, M. and Nazir, A.K. ‘‘Behavior of repeatedly loaded rectangular plates resting on reinforced sand’’, Alexandria Engineering Journal, 49 (4), pp. 349-356 (2010).

[30] Shin, E.C., Das, B.M., Lee, E.S., Atalar, C. ‘‘Bearing capacity of strip foundation on geogrid-reinforced sand’’, Geotechnical and Geological Engineering, 20 (2), pp. 169–180 (2002).

[31] Cicek, E., Guler, E. and Yetimoglu, T. ‘‘Comparison of Measured and Theoretical Pressure Distribution below Strip Footings on Sand Soil’’, International Journal of Geomechanics, 14 (5), (2014).

[32] Harikumar, M., Sankar, N. and Chandrakaran, S. ‘‘Behaviour of model footing resting on sand bed reinforced with multidirectional reinforcing elements’’, Geotextiles and Geomembranes, 44, pp. 568-578 (2016).

**Figures Captions:**

**Figure 1.** Test set-up.

**Figure 2.** Load-settlement behavior of unreinforced sand.

**Figure 3.** Load (q)-settlement (s) behavior of strip plate on Geotextile reinforced sand for different first reinforcement depths; a. N=1, b. N=2, c. N=3.

**Figure 4.** Load-settlement behavior of first reinforcement depths for Geogrid 1 reinforced soil

**Figure 5.** Load-settlement behavior of first reinforcement depths for Geogrid 2 reinforced soil

**Figure 6.** Comparison of different reinforcement types to investigate behavior of BR-u/B; a. s/B=0.05, b. s/B=0.1, c. s/B=0.2, d. s/B=0.3, e. s/B=0.5, f. s/B=0.6.

**Figure 7.** Load-settlement behavior of different reinforcement types for u/B=0.75.

**Figure 8.** Bearing Ratio-Number of Reinforcement layers behavior for different u/B ratios; a. s/B=0.1, b. 0.4, c. 0.6

**Figure 9.** Comparison of FEM analysis and Test measurements for unreinforced sand soil

**Figure 10.** Behaviors of the different number of reinforcement layers for finite element models

**Figure 11.** Load-settlement behavior of different reinforcement layers for FEM

**Figure 12.** Comparison between FEM and test results for Bearing ratio-first reinforcement depth

**Figure 13.** Behaviors of models for different first reinforcement ratios; a. unreinforced, b. u/B=0.175, c. u/B=0.75

**Table Captions:**

**Table 1.** Properties of geosynthetic reinforcements

**Table 2.** Variables chosen for the laboratory model tests of reinforced foundation soils

**Table 3.** FEM soil properties

**Figures:**

**Figure 1.** Test set-up [10].

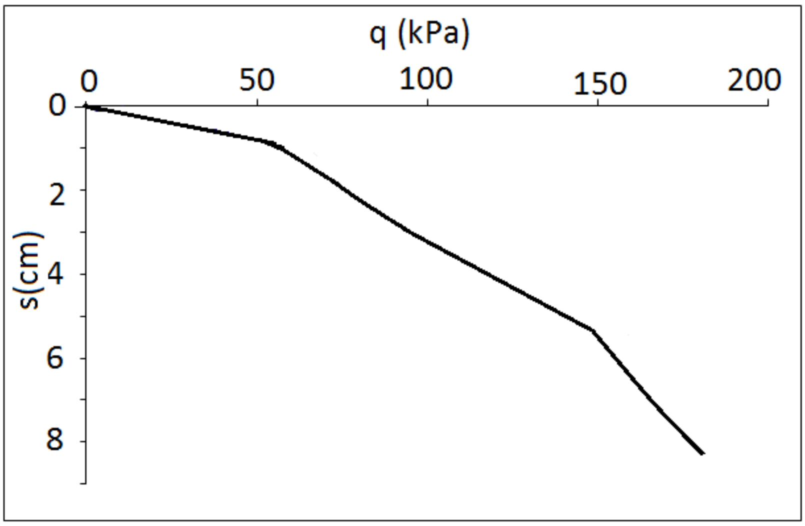


**Figure 2.** Load-settlement behavior of unreinforced sand.

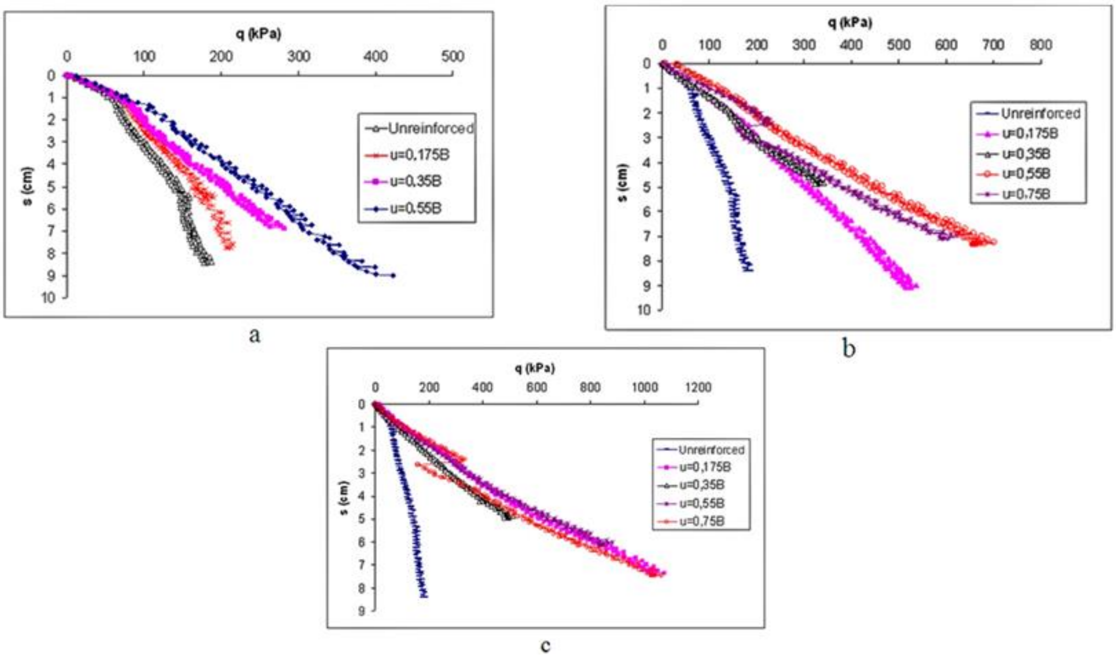


**Figure 3.** Load (q)-settlement (s) behavior of strip plate on Geotextile reinforced sand for different first reinforcement depths; a. N=1, b. N=2, c. N=3.

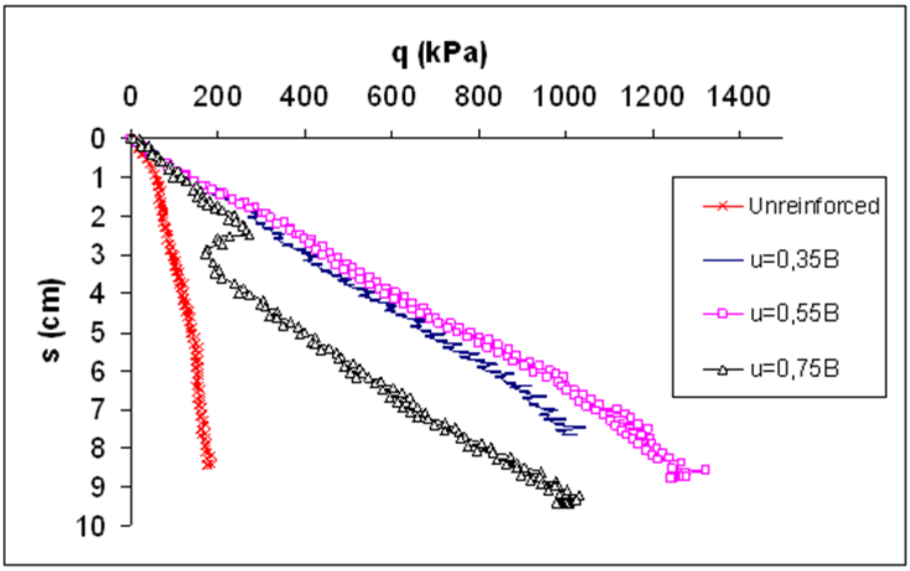


**Figure 4.** Load-settlement behavior of first reinforcement depths for Geogrid 1 reinforced soil

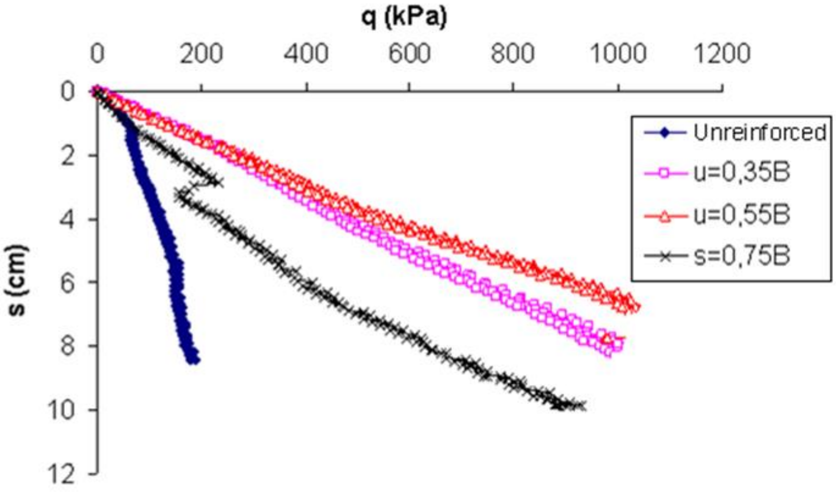


**Figure 5**. Load-settlement behavior of first reinforcement depths for Geogrid 2 reinforced soil

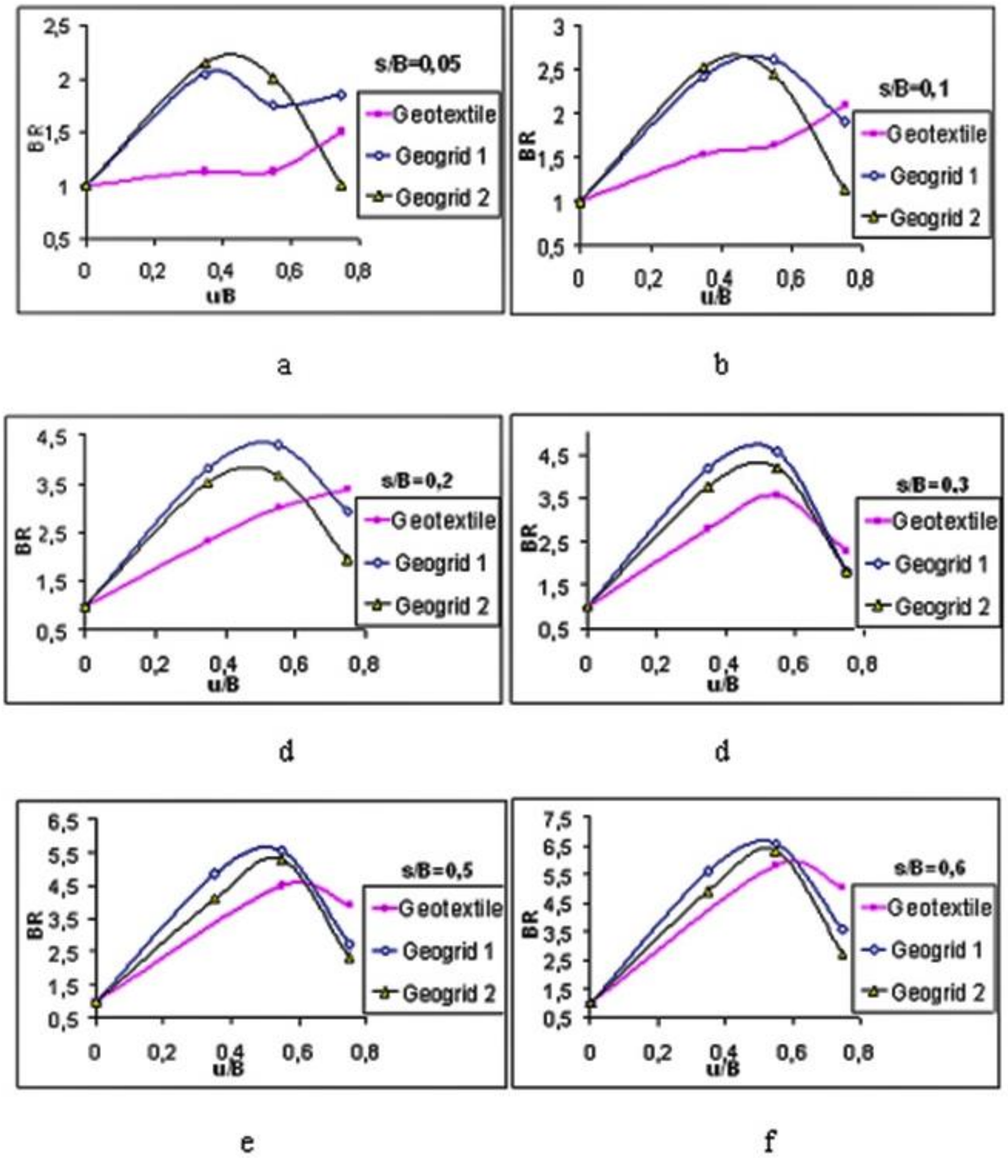


**Figure 6.** Comparison of different reinforcement types to investigate behavior of BR-u/B; a. s/B=0.05, b. s/B=0.1, c. s/B=0.2, d. s/B=0.3, e. s/B=0.5, f. s/B=0.6.

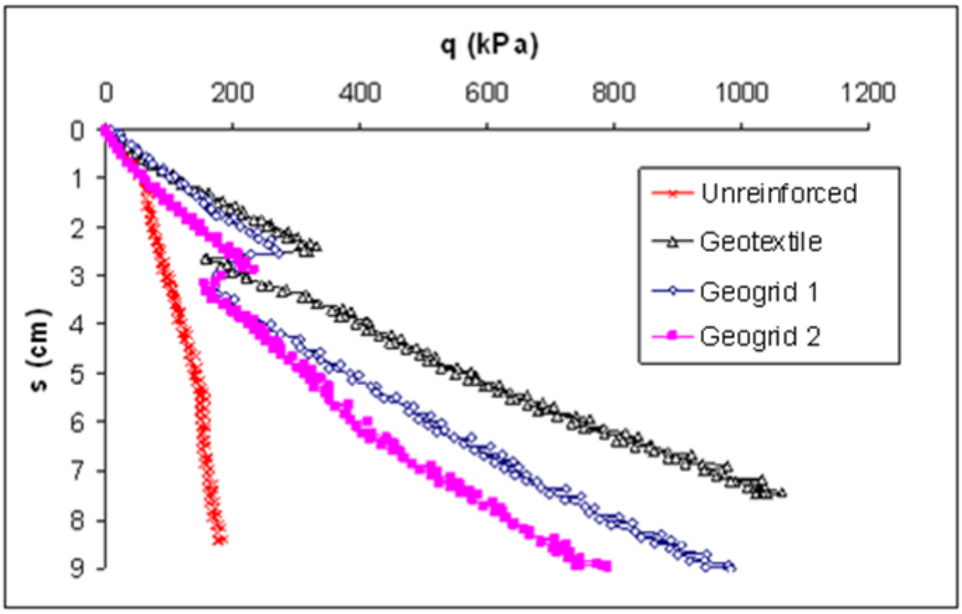


**Figure 7.** Load-settlement behavior of different reinforcement types for u/B=0.75.

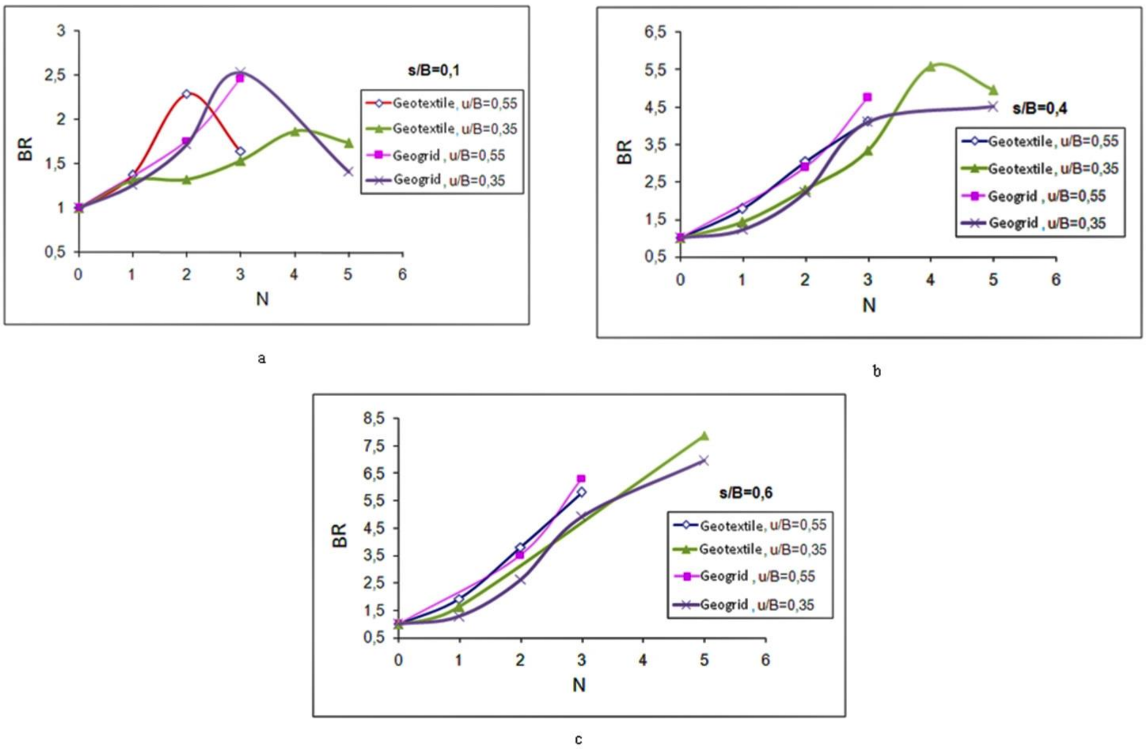


**Figure 8.** Bearing Ratio-Number of Reinforcement layers behavior for different u/B ratios; a. s/B=0.1, b. 0.4, c. 0.6

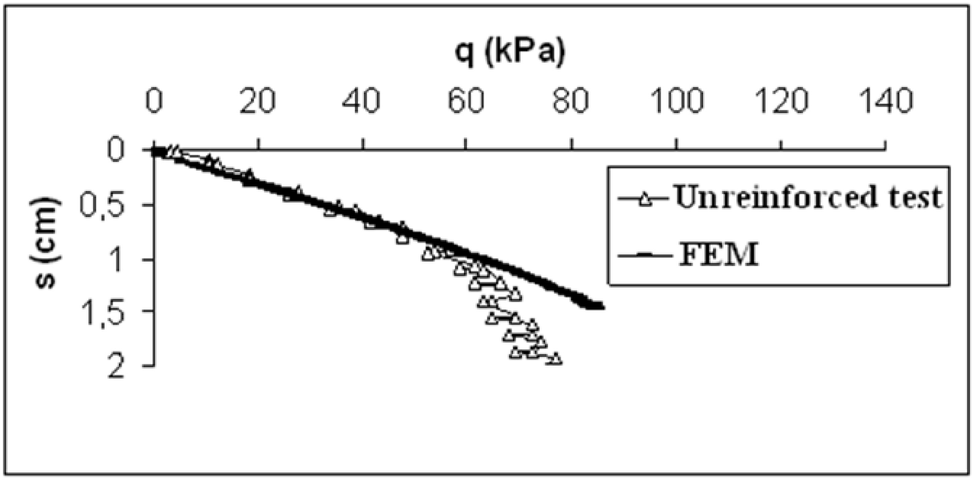


**Figure 9.** Comparison of FEM analysis and Test measurements for unreinforced sand soil [31]

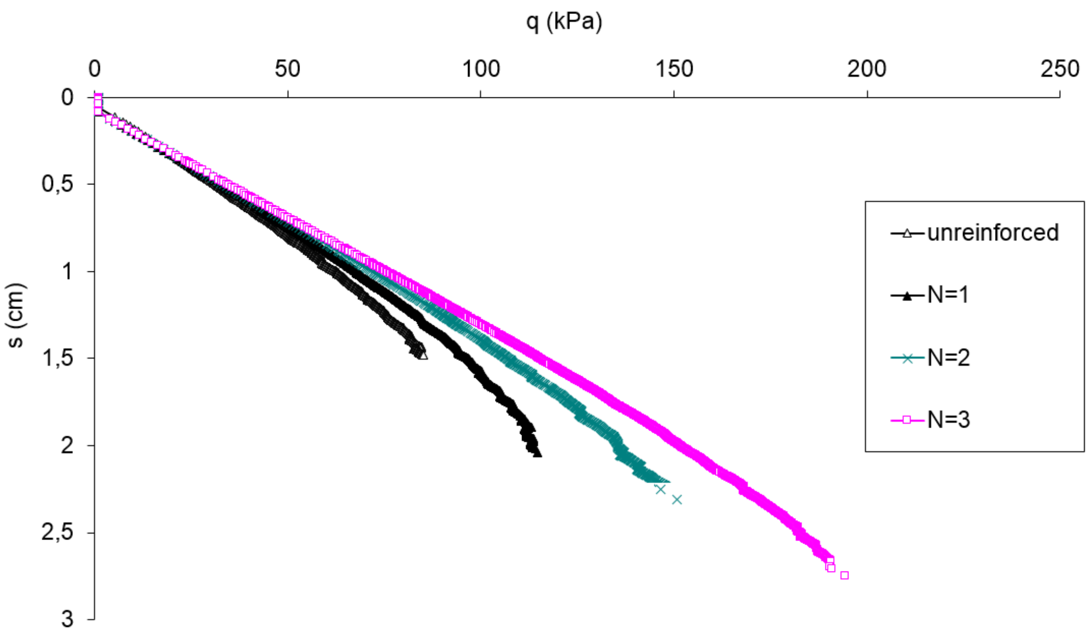


**Figure 10.** Behaviors of the different number of reinforcement layers for finite element models

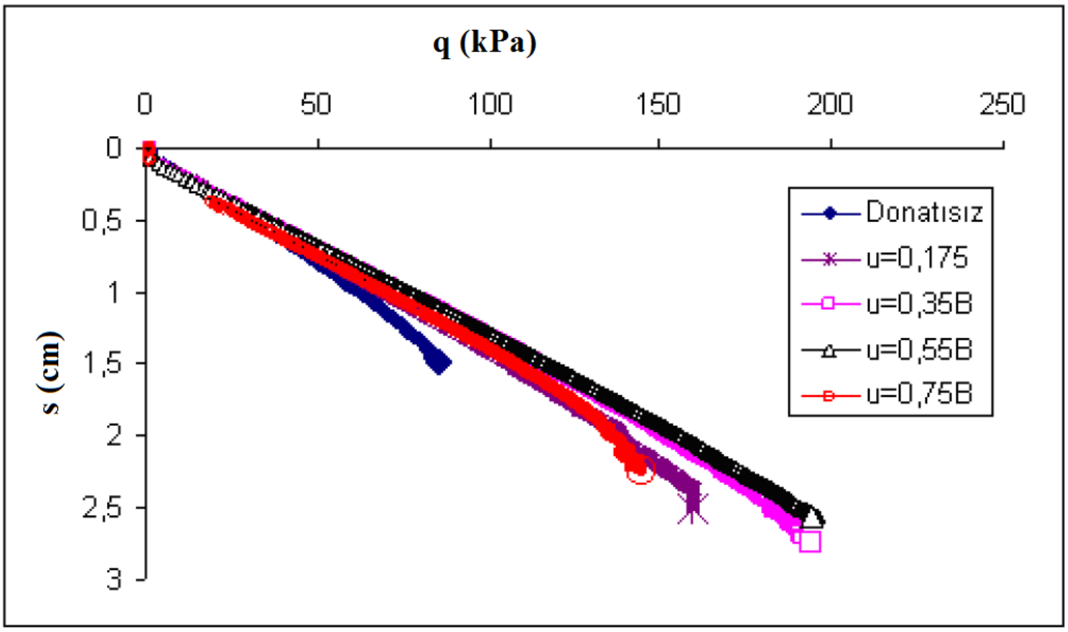


**Figure 11.** Load-settlement behavior of different reinforcement layers for FEM

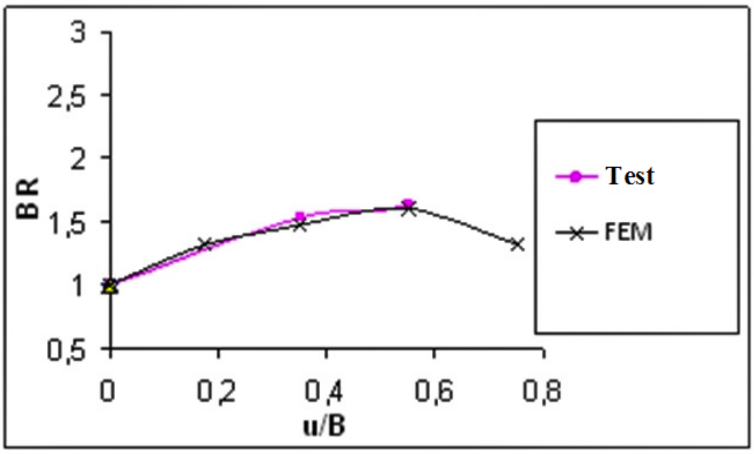


**Figure 12.** Comparison between FEM and test results for Bearing ratio-first reinforcement depth

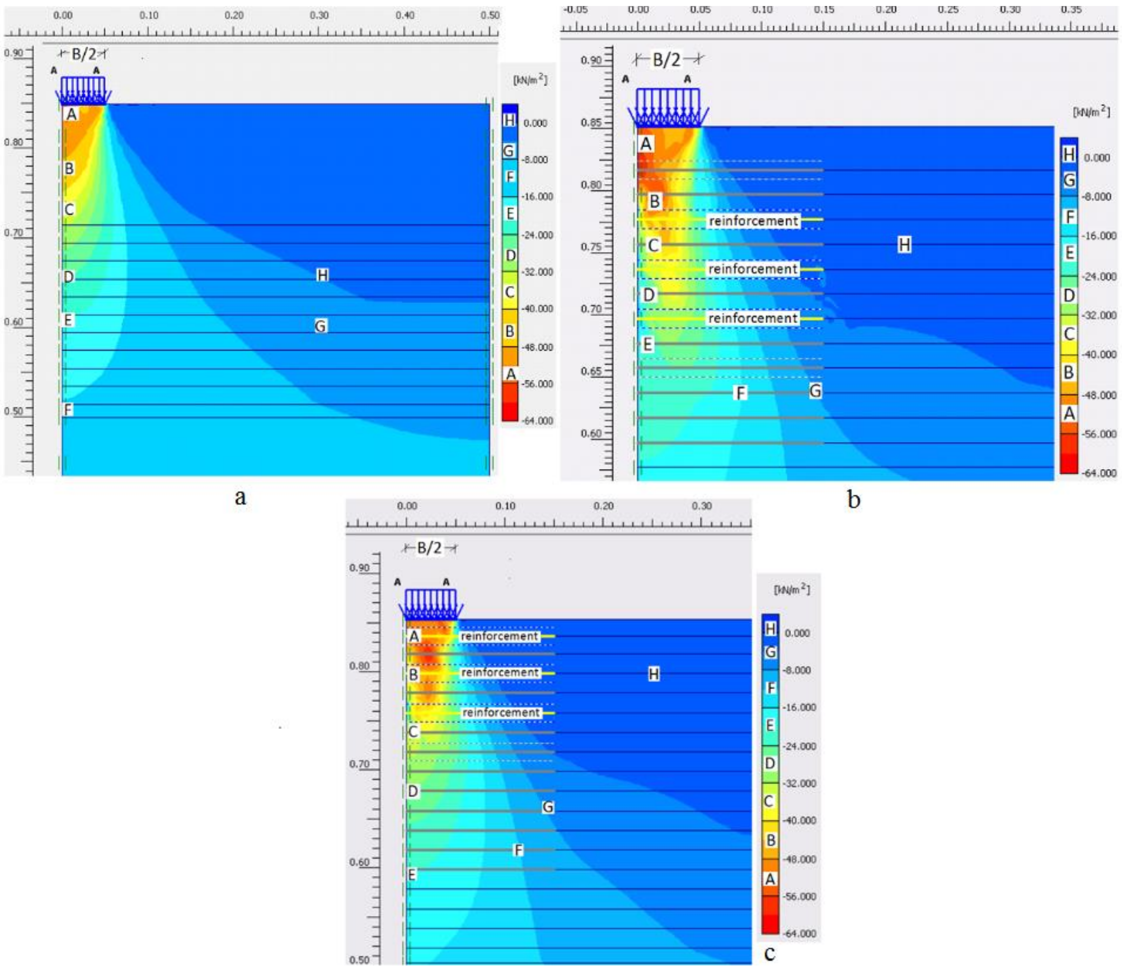


**Figure 13.** Behaviors of models for different first reinforcement ratios; a. unreinforced, b. u/B=0.175, c. u/B=0.75

**Tables:**

**Table 1.** Properties of geosynthetic reinforcements

| Property | Type of geosynthetic material | | |
|---|---|---|---|
| | **Geotextile** | **Geogrid 1** | **Geogrid 2** |
| Material property | polypropilen | polyester | polyester |
| Type | woven | - | - |
| Ultimate tensile strength (kN/m) | 60 | 35 | 55 |
| Failure strain (%) | 16 | 8.5 | 12 |
| Mass per unit area (g/m$^2$) | 310 | 220 | 300 |
| Aperture size (mm) | - | 20x20 | 40x40 |

**Table 2.** Variables chosen for the laboratory model tests of reinforced foundation soils

| N | h/B | L/B | u/B | Reinforcement type |
|---|---|---|---|---|
| 0 | - | - | - | Unreinforced |
| 1 | - | 3 | 0.175, 0.35, 0.55 | Geotextile Reinforced |
| 2 | 0.4 | 3 | 0.175, 0.35, 0.55, 0.75 | Geotextile Reinforced |
| 3 | 0.4 | 3 | 0.35, 0.55, 0.75 | Geotextile Reinforced |
| 3 | 0.4 | 3 | 0.35, 0.55, 0.75 | Geogrid 1 Reinforced |
| 2 | 0.4 | 3 | 0.35, 0.55 | Geogrid 2 Reinforced |
| 3 | 0.4 | 3 | 0.35, 0.55, 0.75 | Geogrid 2 Reinforced |

**Table 3.** FEM soil properties

| **Parameter** | **Sign** | **Unit** | **Value** |
|---|---|---|---|
| Unit weight | $\gamma$ | kN/m$^3$ | 15 |
| Elasticity modulus | $E_{ur}$ | 25000 | kN/m$^2$ |
| Poisson ratio | $\upsilon$ | - | 0.25 |
| Cohesion | c | kN/m$^2$ | 1 |
| Friction angle | $\varphi$ | $^o$ | 38 |
| Dilatancy angle | $\psi$ | $^o$ | 8 |
| Reference stress for stifnesses | $p^{ref}$ | kN/m$^2$ | 100 |
| Power for stress-level dependency of stiffness | m | - | 0.50 |

**Biographies:**

**Elif CICEK** received her PhD degree in June 2011 in Civil Engineering at Ataturk University, Turkey. She took many courses from Istanbul Technical University and Marmara University, Turkey. Her thesis' numerical and experimental studies were conducted at Bogazici University, Turkey was supported with doctorate scholarship by Scientific and Technical Research Council of Turkey (TUBITAK). She is working as Asst. Prof. Dr. in Civil Engineering Department of Hacettepe University since 2015. Her research interests include effects of geosynthetic reinforcements, pressure distribution of soils, slope stability, earthquake, limit equilibrium approaches, numerical methods, transportation geotechnic, traffic engineering, highway design, material properties, concrete roads, numerical calculations, limit equilibrium methods, etc.

**Erol GULER** is Professor of Civil Engineering at Bogazici University, Istanbul, Turkey. He is IGS Council member. He founded the IGS Turkish Chapter in 2001 and served as its president until 2005, and was re-elected as President again in 2011. He represents Turkish Standards Institute (TSE) at the International Standards Organization (ISO) and the European Committee for Standardisation (CEN). He is Convener of the WG2 of the ISO TC221 (Technical Committee on geosynthetics) and is also the Convener of the WG2 of the CEN TC189 (Technical Committee on geosynthetics). He is currently an international member of the USA TRB Committee on Geosynthetics. His research subjects are mainly geosynthetics and specifically geosynthetic reinforcement and liner systems. Has vast experience in design of foundations, deep excavations, landslide mitigation and site investigations.

**Temel YETIMOGLU** is emeritus Professor of Civil Engineering in Ataturk University, Erzurum, Turkey. He obtained his PhD degree in Istanbul Technical University. He has a lot of academic studies in the geotechnical engineering field. Some of his research areas are reinforced soils, piles, numerical analyses, plate load tests, geosynthetics, laboratory experiments and environmental geotechnic.