

REPUBLIC OF TÜRKİYE
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

**INVESTIGATION OF BEHAVIOR OF GEOSYNTHETIC
REINFORCED GYPSEOUS SOIL BY EXPERIMENTAL AND
NUMERICAL ANALYSIS**

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MASTER OF SCIENCE THESIS

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June, 2023

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This study was supported by the Scientific and Technological Research Council of
Turkey (TUBITAK) Grant No: 2210.

ACKNOWLEDGEMENTS

I am writing to thank everyone who helped me while studying for my master's degree. I am grateful for the guidance, criticism, and advice they received, which helped me learn and improve.

First, I would like to express my deep gratitude and sincere appreciation to my supervisor Assist. Prof. Dr. Murat Ergenekon SELÇUK and Assist. Prof. Dr. Makki Kamel Mohsen for their ongoing assistance and guidance throughout the study.

I also thank the staff of the Geotechnical Laboratory for their assistance in completing all the experiments related to my research.

I thank the Department of Civil Engineering at the University of Technology in Iraq for their assistance in completing the work, also the staff of the geotechnical laboratory of the Civil Engineering department at Babylon University.

And I do not forget to thank those who helped me and motivated me to complete my studies, my wife, as well as my mother, who did not forget me in supplication, and my children Afnan, Abdullah, and Hussein.

I thank all my friends who supported me during the study period.

Adil Abdulameer Waleed Al Zabee

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LIST OF SYMBOLS

ω	Water Content %
γ	Unit weight of soil (kN/m ³)
$\gamma_{dmax.}$	Maximum dry unit weight (kN/m ³)
$\gamma_{dmin.}$	Minimum dry unit weight (kN/m ³)
ϕ	Angle of friction (degree)
ν	Poisson's ratio
B	Width of footing (cm)
C	Cohesion (kPa)
E	Modulus of elasticity (kPa)
e	Void Ratio
D_{10}	Effective Size (particle size that 10% of the particles are smaller than size)
D_{30}	Effective Size (particle size that 30% of the particles are smaller than size)
D_{60}	Effective Size (particle size that 60% of the particles are smaller than size)
C_u	Coefficient of Uniformity
C_c	Coefficient of Curvature
G_s	Specific Gravity
CP	Potential collapsible (%)
$O.M.C$	Optimum moisture content (%)
q_{ult}	Ultimate bearing capacity (kPa)
q	Surcharge load (kN)
N_c, N_q, N_γ	Bearing capacity factors

LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
BRC	Improvement ratio of bearing capacity
USCS	Unified Soil Classification System
RD	Relative Density
FEM	Finite Element Method
3D	Three-Dimension
DOT	Double Oedometer Test
SOT	Single Oedometer Test
SF	Factor of Safety

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ABSTRACT

Investigation Behavior of Geosynthetic Reinforced Gypseous Soil by Experimental and Numerical Analysis

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Gypseous soil is a type of soil that can cause problems for engineering structures, which are distributed in various regions around the world, including Iraq, of which they make up roughly 30% of the country's area. The main issue with this soil is that it can collapse suddenly and lose a lot of its ability to support weight when it gets wet. This happens because the bonds that hold the soil particles together break down as a result of the dissolution when they come into contact with water. This can cause the soil to deform and become unstable.

This study aims to enhance the ability of gypseous soil to support weight by increasing the bearing capacity of the soil using geosynthetic reinforcement in different distribution patterns. The soil used in the study was extracted from a location close to Al-Razzaza Lake in Iraq, with a depth of (1.5) m, and has a high gypsum content of 47%. The Soil Model apparatus was used with dimensions of (60 x 60 x 50) cm and a square footing with dimensions of (10 x 10) cm for the experimental investigation.

To achieve this goal, (68) different model tests were performed. These tests involved subjecting the gypseous soil unreinforced and reinforced with geosynthetic materials to head stress (pressure) in both dry and wet (saturation) states at different relative densities (30%,60%). Also (10) numerical models by PLAXIS 3D software were tested for soil

model at $RD = 30\%$ to compare with experimental work. Using the tangent intersection method, the load-settlement curves were evaluated for determining the ultimate bearing capacity for the dry and wet gypsum soil model.

The results of the study tested the effectiveness of using geosynthetic layers (geotextile and E-glass fiber fabric) to reinforce gypsum soil. The study tested different patterns of layering the (geotextile and E-glass fiber fabric) by using (single, double, and triple layers), also the different shapes at triple patterns (U-shape and straight) at relative densities (30% and 60%) in both dry and wet conditions. The results found that the improvement in bearing capacity ratio (BCR%) was higher at saturation state compared to the dry condition, where was 166% when using triple pattern reinforced ($D=0.25B+0.5B+1B$) geotextiles and 271% using E-glass fiber fabric at wet state, while the percentage (BCR%) increased with the same pattern when used U-shape reinforcement to 13%, 14% for geotextiles and E-glass fiber fabric materials, respectively.

The results of the study showed that the best enhancement in the bearing capacity of the soil was achieved at a depth of $0.25B$ when using a single-layer reinforcement and at a depth ($0.25B+0.5B$) when using a double-layer reinforcement while a depth ($0.25B+0.5B+1B$) at triple-layer reinforcement.

The study also showed that the use of the E-glass fiber fabric reinforcement as a layer gives an increase in the bearing capacity of the gypseous soil more than when the use of geotextile reinforcement. The reason for this may be attributed to the specifications and characteristics of the E-glass fiber material.

The results of the numerical analysis carried out with the PLAXIS 3D program were close to the experimental study results.

Keywords: E-glass fiber fabric, geotextile, bearing capacity, gypseous soil, soil reinforcement, PLAXIS 3D.

ÖZET

Deneyisel ve Sayısal Analiz Yöntemleriyle Geosentetik Güçlendirilmiş alçı toprağının Davranışlarının İncelenmesi

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Jipsli zeminler, Irak dahil dünyanın çeşitli bölgelerine dağılmış olan ve ülke yüzölçümünün yaklaşık %30'unu oluşturan, mühendislik yapıları için problem oluşturabilen bir zemin türüdür. Bu toprakla ilgili asıl sorun, aniden çökebilmesi ve ıslandığında ağırlığı taşıma yeteneğinin çoğunu kaybedebilmesidir. Bunun nedeni, toprak taneciklerini bir arada tutan bağların su ile temas ettiğinde çözünme sonucu parçalanmasıdır. Bu, toprağın deforme olmasına ve kararsız hale gelmesine neden olabilir.

Bu çalışma, farklı dağılım modellerinde geosentetik donatı kullanarak zeminin taşıma kapasitesini artırarak jipsli zeminin ağırlığı taşıma kabiliyetini geliştirmeyi amaçlamaktadır. Çalışmada kullanılan toprak, Irak'ta Al-Razzaza Gölü yakınlarındaki (1.5) m derinliğindeki bir yerden alınmış ve %47 gibi yüksek jips içeriğine sahiptir. Deneyisel inceleme için (60 x 60 x 50) cm ölçülerinde ve (10 x 10) cm ölçülerinde kare ayaklı Toprak Modeli aparatı kullanılmıştır, ve kare tabana dikey bir yük uygulanmıştır.

Bu amaca ulaşmak için 68 farklı model testi yapılmıştır. Bu testler, donatısız ve geosentetik malzemelerle güçlendirilmiş jipsli zeminin farklı bağıl yoğunluklarda (%30, %60) hem kuru hems de ıslak (doygunluk) hallerde düşey gerilime tabi tutulmasını içermektedir. Ayrıca 10 PLAXIS 3D yazılımı ile sayısal model, deneyisel çalışma ile

karşılaştırmak için RD =%30'da toprak modeli için test edilmiştir. Tanjant kesişme yöntemi kullanılarak kuru ve ıslak jipsli zemin modelinin nihai taşıma kapasitesini belirlemek için yük oturma eğrileri analiz edilmiştir.

Çalışmanın sonuçları, jipsli toprağın güçlendirmek için geosentetik katmanların (geotekstil ve E-cam elyaf kumaş) kullanımının etkinliğini test ettiğini belirtmektedir. Çalışma, tek, çift ve üçlü katmanlar kullanarak farklı katman modellerini (geotekstil ve E-cam elyaf kumaş) test etti, ayrıca üçlü desenlerdeki farklı şekilleri (U-şekli ve düz) görelî yoğunluklarda (%30 ve Hem kuru hem de ıslak koşullarda %60. Sonuçlar, taşıma kapasitesindeki iyileşmenin (%BCR) ıslak durumda kuru duruma kıyasla daha yüksek olduğunu gösterdi; İyileştirme, üçlü geotekstil takviyesi kullanıldığında %166, E-cam elyaf kumaş doygun durumda kullanıldığında %271 olmuştur ($D = 0.25B + 0.5B + 1B$). U-şekli takviye kullanıldığında yüzde (BCR%) aynı desenle artarken, jeotekstiller ve E-cam elyaf kumaş malzemeleri için sırasıyla %13, %14'e yükseldi..

Çalışmanın sonuçları, zeminin taşıma kapasitesindeki iyileşmenin tek katmanlı donatı kullanıldığında 0,25B derinlikte, çift katmanlı donatı kullanıldığında ise (0,25B+0,5B) derinlikte elde edildiğini göstermiştir, iyi gelişme ($0.25B + 0.5B + 1B$) derinlikte üç katmanlı güçlendirmede olmuştur.

Çalışma ayrıca, E-cam elyaf kumaş takviyesinin bir tabaka olarak kullanılmasının jipsli zeminin taşıma kapasitesinde jeotekstil takviyesi kullanımına göre daha fazla artış sağladığını göstermiştir. Bunun nedeni, E-glass fiber malzemenin özelliklerine ve özelliklerine atfedilebilir.

yapılan analiz sonuçlarının deneysel çalışmalardan elde edilen sonuçlar ile uyumlu olduğu görülmüştür.

Anahtar Kelimeler: E-cam elyaf kumaş, geotekstil, taşıma kapasitesi, jipsli toprak, toprak takviyesi, PLAXIS 3D.

1.1 Literature Review

1.1.1 General Information

In the last two decades, numerous studies were carried out on Iraqi gypseous soil, and all of them were attempts to understand the behavior of such type of soil under the effect of different environments and loads. Also, check the possibility of applying the standard tests directly or if there is a need for some modification. After those studies on determining the shear strength, collapsibility, and compressibility. Simulating the process of gypsum dissolution under immersion of water or leaching conditions by numerical techniques were adopted by many researchers. The plentiful results from all these previous studies in many cases were contradicting which may be attributed to the complex nature of the gypseous soils, so there is a need for extensive studies on the behavior of gypseous soils and methods to improve its properties and behavior under different conditions.

The construction of buildings on gypseous soil requires attention to many requirements, as this soil has problems such as excessive settlement occurring due to many causes such as continuous change of water table or leakage of water to the building by any reason. So, enhancing the properties of such types of soil attracted geotechnical researchers, where many techniques were used to improve one or more property.

Gypseous soil is a type of soil that appears strong and stable in its natural dry condition. However, when it gets wet, it becomes weak and prone to collapse, leading to significant settlements. The primary reason for this is that gypsum, which is present in the soil, dissolves when it touches the water. As a result, the soil loses the cementing bonds that hold its particles together, causing the soil structure to collapse [2].

1.1.2 Gypseous Soil Classification

According to J. G. Van Alphen and F. de los Ríos Romero, (1971), gypsiferous soils are defined as having more than 2% gypsum in them [3]. While Barzanji, (1973) classified the ratio of gypsum content into several types, starting from non-gypseous if the gypsum

content (0-0.3) % to highly gypseous when the gypsum content was (25-50)%, as shown in Table 1.1[4].

Saaed and Khorshid, (1989) gypseous soil is defined as soil that contains more than 6% gypsum [5]. I. H. Nashat, (1990) suggested the classification of gypseous soil as shown in Table 1.2 [1].

Table1.1 Gypseous soil classification as (Barzanji, (1973))

Classification of Soil	Gypsum content %
Non-Gypseous	(0 – 0.3)
Very Slightly Gypseous	(0.3 – 3)
Slightly Gypseous	(3 – 10)
Moderate Gypseous	(10 – 25)
Highly Gypseous	(25 – 50)

Table 1.2 Gypseous soil classification as (Nashat, (1990))

Classification of Soil	Gypsum content %
Slightly	(0-10)
Moderate	(10-25)
Highly	(25-50)
Gypcrete	>50

1.1.3 Iraq Construction Challenges in Gypsum Soils

Gypsum soils are a unique type of soil that pose several challenges for construction projects. Buildings or dams built on gypsum soil may experience major failure due to

unpredictably occurring deformations. Gypsum soils are known for their ability to withstand heavy loads without sinking or compressing. When they are dry, they are very strong and stable. However, when gypseous soil touches the water, they lose their strength and stability. This is because water dissolves the gypsum particles and causes them to collapse, resulting in a sudden loss of bearing capacity and increased compressibility. Therefore, it is important to consider the moisture content of gypsum soils when designing structures or foundations on them[6].

1.1.4 Collapsibility of Gypseous Soil

Collapsibility refers to the degree to which gypseous soil can compress or settle. The single and double oedometer tests (SOT), (DOT) are two common methods for measuring the collapsibility of gypseous soil.

J. H. Dudley, (1970) study conducted by which found that some soils collapse when they become wet without any additional weight or pressure, while others require additional weight or pressure to collapse. The study also found that the rate and amount of collapse depend on various factors such as the mineral composition of the soil, void ratio, water content, shape, and size of the soil particles [7].

K. Knight, (1963) described a method called the single collapse test. In this method, a soil sample is placed into an odometer ring, and a load is gradually applied to the sample until it reaches 200 kPa. Then, the sample is soaked with water and left for a day. After that, the consolidation test is repeated to its maximum loading. As a standard test, this procedure was presented to ASTM (ASTM-D5333-00). It is used to determine the value of collapse by one-dimensional collapse that occurs when unsaturated soils are inundated with water [8].

P. Pells, et al (1975) improved a technique called the double collapse test (DOT), which is used to assess soil collapsibility. This technique is used to determine the likelihood of soil collapsing under different stress levels. The test involves performing the standard consolidation test on two identical soil samples. The first sample is tested at its natural water content without any additional water, while the second sample is submerged in water for a day before testing. The results of the two tests are plotted on a graph of void ratio (e) against effective stress ($\log p$). From this graph, the collapse potential (CP %) can be calculated at any stress level using equation 1.1[9].

$$CP\% = \frac{\Delta e}{1 + e} \times 100 \quad (1.1)$$

Where:

Δe = Change in the void ratio between the two samples.

e = natural void ratio.

Table 1.3 shows the value of potential collapsibility as classified by P. Pells, et al (1975)

Table 1.3 Classification of potential collapsibility [9]

Type of Problem	CP% (Potential Collapsibility)
No problem	(0-1)
Moderate trouble	(1-5)
Trouble	(5-10)
Severe trouble	(10-20)
Very severe trouble	>20

Q.A.J. Al-Obaidi et al (2013) tested samples of gypseous soil with gypsum content 70% of the west of Iraq (Al-Ramadi city) [10]. The authors noted the standard consolidation curve could be the compressive characteristics of the tested soil samples. The study recommended using the Single Oedometer Test (SOT) which introduced more accurate values of collapse potential (CP) and higher than that given by the Double Oedometer Test (DOT) which has been attributed to dissolving gypsum and losing the cementing agent.

H. H. Karim et al (2020), investigated the collapse behavior of Al-Ramadi gypseous soil. The study found that the collapse deformation of the soil increases significantly when it undergoes multi-step wetting, especially under high applied vertical stress, irrespective

of the collapse zone depth [11]. Additionally, the studies found that the volume changes in soil samples for low, medium, and high initial dry densities exhibited the same trend, where an increase in volume change corresponded to a decrease in suction pressure. Finally, the study concluded that the initial dry density of the gypseous soil is a significant factor in determining the extent of the collapse deformation.

A.S.A. Al-Gharbawi et al (2023) investigated the behavior of gypseous soil, which tends to collapse under pressure. has been used varying percentages of Magnesium Oxide and carbonated Magnesium Oxide to treat the soil and tested at two different densities using a modified Rowe cell with moisture sensors. The results of the study show that the collapse potential of the soil increased with the sample size, but treating the soil with Magnesium Oxide and carbonated Magnesium Oxide reduced this potential. The collapse potential decreased by 93% when using a 10% concentration of Magnesium Oxide and carbonating the sample for 3 hours [12].

1.1.5 Soaking Influence on Shear Strength

The shear strength of soil is significantly impacted by the soaking process. Most of the research indicates that soaking gypseous soil causes a significant decrease in the parameters of shear strength of the soil (C & ϕ), where the soaking process causes the softening and dissolves the soil and the values of (C & ϕ) are significantly lowered.

F. F. Al-Qaissy, (1989) study was conducted in Baiji, where the gypsum content was found to be 44%. The study found that the triaxial cohesion (C) was reduced by approximately 80% when the gypsum content was present. Additionally, the water content increased by 5% when the gypsum content was present, but the increase in water content was more gradual when the gypsum content was not present [13].

T. Schanz and H.H. Karim (2018) studied experimentally samples of soil with high contents of gypsum from three different sites in Iraq. The study revealed a reduction in shear parameters after immersing in water for 6 hours, which was 91.5 to 94.2% and 12.2 to 9.2% in cohesion (C) and friction angle (ϕ) respectively compared with dry status [14].

A. Abood et al.(2023) evaluated the suitability of unsaturated gypseous soil as a subgrade layer for machine foundations. Triaxial tests were performed on the soil at 35% relative density and different degrees of saturation (30%, 60%, and 80%). The results showed that increasing the moisture content of the soil led to a reduction in the friction angle and an increase in the cohesion of the soil, up to a saturation degree of 60%. This increased the

soil's shear strength. However, at saturation degrees of 80% and 100%, there was a gradual decrease in shear strength, which could compromise the soil's ability to support machine foundations. The decrease in shear strength ranged from (9.0-12.5) kPa for effective stresses and (9.5-12.5) kPa for total stresses [15].

1.1.6 Methods of Soil Improvement

There are many challenges facing construction sites when the soil is weak and unstable to support structures such as buildings, bridges, roads, dams, etc. In some cases, it is required to remove the weak layer and replace it with strong soil on which the structural foundation can be built. Several techniques are used to improve one or more of the following:

1. Reducing the settlement of structures.
2. Improving the shear strength of soil which increases the bearing capacity of shallow foundations.
3. Increase the safety factors against potential slop failure of earth dam and embankment.
4. Reducing soil shrinkage and swelling (B. M. Das, 1990) [16].

J. E. Bowles, (1996) summarized soil properties modification in several methods such as[17]:

1. Mechanical method (Compaction): This is the most cost-effective method of improving soil.
2. Recompression method: This method is used to reduce settlement and increase shear strength.
3. Foundation grouting: This method involves injecting grout material into the soil to decrease settlement and increase shear strength.
4. Soil stabilization by an admixture: This method involves adding an admixture to the soil to stabilize it.
5. Dynamic consolidation and soil replacement: This method is used to decrease settlement and increase shear strength.
6. Soil reinforcement.
7. Nailing of soil.

1.1.6.1 Soil Reinforcement

Soil Reinforcement is one of the new engineering techniques used to increase soil strength and improve its ability to bear heavy loads. Soil reinforcement technology is characterized by the ability to improve the tensile, compressive, and bending resistance of soils, and is widely used in civil engineering projects. Soil reinforcing technology is to use metal, glass, polymer, or carbon fiber webs inside the soil and connects them to the foundations of structures, floors, or walls. This technology improves the soil's ability to bear capacity and reduces deformations and erosion. It can be used in many engineering applications, such as the reinforcement of slope stability, retaining walls, foundations, roads, sidewalks, and bridges. This technology can be used in various locations, including industrial, commercial, and residential locations.

- **Geosynthetics Reinforcement**

Several types of geosynthetic material were used to reinforce the soil such as geotextile, geogrid, geocell, and geomembrane...etc, which are materials made in the factory, often from polymers, as shown in plate 1.1.

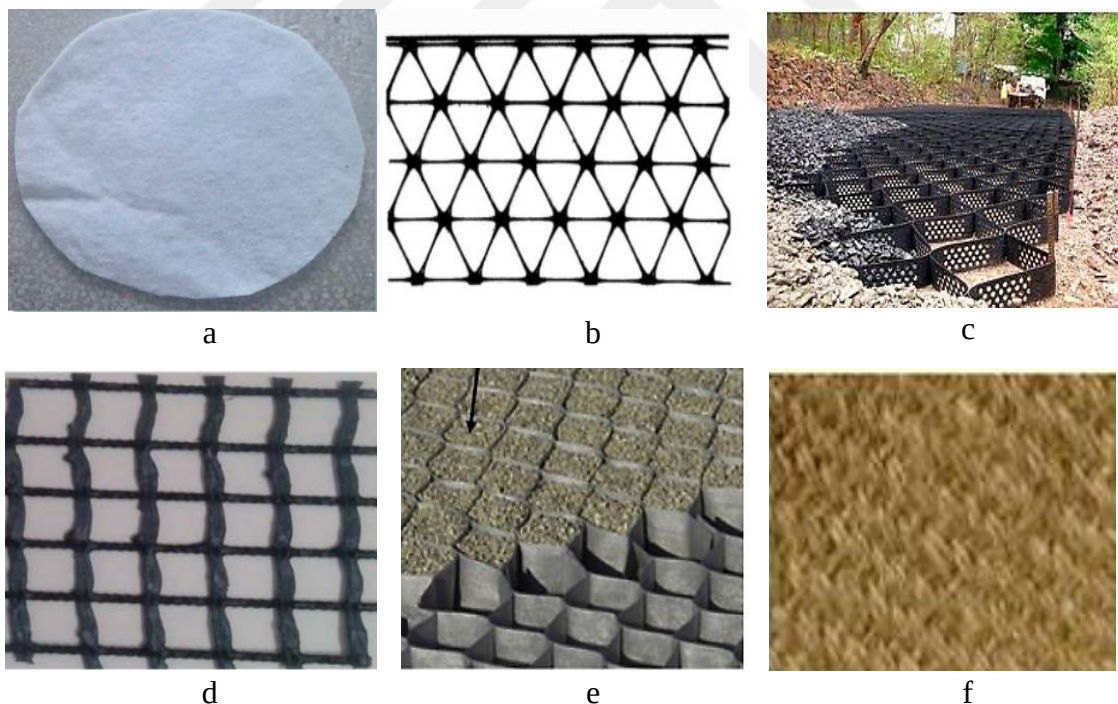


Figure 1.1 Types of geosynthetics. a) Geotextile [16]. b) Triaxial geogrid [17]. c. Geocell with perforated [18]. d) Biaxial polyester geogrid [19]. e) geocell without perforation [20]. f) Geotextiles made of jute [21].

K. Rajagopal et al (1999) experimentally studied the impact of using a geocell (a material used to enhance soil) on the strength and stiffness of granular soils. The researchers

conducted tests using geocells made of different materials to see how their stiffness influenced the results. They found that geocell reinforcement can increase the cohesive strength of cohesionless soils but does not affect the frictional strength of granular soils. The amount of cohesive strength imparted depends on the tensile modulus (a measure of stiffness) of the geocell material [22].

A.H. Boushehrian and N. Hataf (2009) adopted uniaxial polyethylene geogrid for reinforcing and improving soil behavior. The study involved numerical investigation in addition to experimental work. Some parameters were taken into account in the study, such as the number of geogrid layers for reinforcing the sample. It was observed increase in the bearing capacity ratio of the tested soil especially the sandy soil compared with fine-grained soil, which was attributed to a further interlocking process induced between soil particles and reinforcing layers [23].

L.J. Aziz and S. Abdulsatter (2014) adopted two methods for improving the bearing capacity of a specific circular footing resting on gypseous soil. A trench beneath the footing filled with cement dust was the first method of improvement, whereas the second one was reinforcing the tested soil with biaxial geogrids. The study appointed that the second improvement method was effective and able to increase the maximum bearing capacity of such type of granular gypseous soil [24].

E. Badakhshan, A. Noorzad (2017) analyzed square and circular footings resting on the geosynthetic reinforced granular bed. In addition to the laboratory achieved models, numerical models were carried out and analyzed. Several parameters that affected the bearing capacity of the tested footings were taken into account, such as the depth of the first and second reinforcing layers and number. The results obtained point that the ultimate bearing capacity at unreinforced conditions was rather equal for both of the two types of tested footings. Whereas for reinforced condition and increasing the number of reinforcing layers, the ultimate bearing capacity increased especially for the circular model compared with the rectangular specimen, so the shape of footings is highly effective [25].

M.K. Fakhraldin and T.S. Ali (2017) investigated the benefits of using geogrid as a material for reinforcement on the California Bearing Ratio (CBR), a measure of treatment effectiveness. To determine the effects of the geogrid initial layer position and soaking on CBR, the study involved laboratory tests on samples of gypseous soil. A CBR value

of 14 kN/m³ was chosen as the standard for comparisons, and soaking times of 4, 15, and 30 days were used. The results demonstrated that the CBR value increased by geogrid reinforcement was used, and the location of the first layer of geogrid had a significant effect on CBR, with an effective depth of 0.15D (where D is the diameter of the CBR mold). When compared to unreinforced soil, the CBR value at the optimal point increased by almost two times. Additionally, the CBR decreased as the soaking period increased for both reinforced and unreinforced soil. The experimental results also showed that the ultimate bearing capacity increased as the CBR increased for both reinforced and unreinforced soil [26].

- **Geotextile Material**

Geotextiles are strong materials that can withstand a lot of pulling force. Soils, on the other hand, are typically not very strong when it comes to being pulled or stretched, but they are good at withstanding pressure or weight. Geotextiles can be used to improve the performance of soil by providing additional strength and stability. This can help prevent soil from collapsing or becoming unstable, which can be important in construction or other applications where the soil needs to be strong and stable [27].

Geotextiles are typically used to improve soil characteristics before building embankments, roads, pipelines, and earth-retaining structures. Geotextiles have several functions, which include filtration, drainage, reinforcement, cushioning, waterproofing and separation [28].



a. Non-woven



b. Woven

Figure 1.2 Geotextile type according to their manufacture

Sa. Aiban et al. (2006) investigated and evaluated the impact of geotextile on sabkha soil performance. The investigation studied several factors such as the effects of soaking,

geotextile class, thickness subbase, and loading situation. This suggests that the tensile strength and thickness of the geotextile are important factors in enhancing the load-carrying capacity of the soil. A geotextile with higher tensile strength and greater thickness can better resist deformation and distribute the load more evenly, resulting in improved load-carrying capacity [29].

B. Albusoda, et al (2013) study was conducted in which gypseous soil was replaced with dune sand from a different depth and reinforced with geotextile. The results showed that the bearing capacity of the soil increased significantly after the replacement and reinforcement [30].

E. Cicek et al (2018) investigated the impact of different types of reinforcement on the bearing ratio of pavements and footings. The researchers used one geotextile and three geogrids and tested various reinforcement depths, vertical spacing, and number of layers. The results showed that Geogrid had the highest bearing ratio values, while geotextile reinforcement had the lowest. The study also found that the effectiveness of reinforcement depended on the type of geosynthetic used and that the depth of the reinforced zone had the strongest influence on the bearing ratio. These findings are important for both pavement and footing design [31].

M.S. Negi and S.K. Singh, (2021) investigated the impact of using geotextile for subgrade reinforcement. Using two different kinds of geotextiles (woven and non-woven), as well as two different types of subgrade soil (sandy and clayey). The effects of the kind of geotextile, position, and number of geotextile layers on the strength of the subgrade were investigated. The geotextile reinforcements were applied to samples in a variety of combinations in one, two, and three layers. Additionally, it was shown that the CBR value increased when woven geotextile reinforcement was added to the subgrade, and woven geotextile outperformed non-woven geotextile in terms of performance [16].

M.G. Shirazi et al (2022) investigate how stiff footings on reinforced soil with various placements and depths of reinforcing layers improved their bearing capacity factor, both numerical analysis and experimental tests were carried out. The findings demonstrated that adding layers of Kenaf geotextile can greatly increase the bearing capacity of reinforced soil, and it was determined that three layers were the ideal number of reinforcement layers, with a depth ratio of roughly $0.25B$ and an optimal spacing of $0.5B$. Accordingly, the study draws the conclusion that Kenaf geotextile can be a useful

reinforcement material for enhancing the bearing capacity of foundations on soft ground [32].

- **E-Glass Fiber Material**

E-glass fiber may be woven or non-woven, and it is widely used for reinforcement, especially in structural elements, due to its high resistance to heat and corrosion, as well as resistance to tensile strength. Many of the previous studies focused on reinforcing different types of soils with glass fibers, but most of them used these fibers in a discrete manner.



Figure 1.3 E-Glass fiber material a. Glass fiber used by A. Ateş, 2016 [33]. b. Glass fiber used by S. Rabab’ah, 2021 [34].

I. Benessalah, et al (2016) studied the impact of discrete glass-fiber content on the shear strength of sandy soil. The study involved conducting direct shear tests on samples with varying percentages of fiber content (0.1%, 0.3%, and 0.5%) and comparing the results with those of unreinforced sand. Before this, the effect of water content on shear strength behavior was also studied. The results showed that the addition of glass fibers improved the mechanical characteristics of the soil, especially for wet specimens, and that 0.3% of fiber content was a critical value for improving mechanical characteristics [35].

T. Yetimoglu et al (2005) investigated the effect of randomly distributed fiber inclusions in sand fill on its load-bearing capacity. The results showed that the peak piston load increased significantly with fiber inclusions, but the initial stiffness was not affected much. The effect of fiber reinforcement was found to be similar to that of geotextile reinforcement [36].

S. M. Hejazi et al (2012) investigated the factors that affect the strength of fiber reinforced soil. The strength of the soil increases when the aspect ratio (length-to-diameter ratio) of the fibers is increased, which allows for better distribution and alignment of the fibers within the soil matrix. Additionally, increasing the fiber content and modulus (stiffness) also contributes to an increase in strength. Finally, increasing the friction between the soil and fiber surface also enhances the strength of the reinforced soil [37].

1.1.7 Effective Depth Layer of Reinforcement

Geosynthetic materials are used to reinforce the soil under the foundation by increasing their bearing capacity.

K. Z. Andrawes et al (1983) investigated the behavior of a strip footing placed on sand that was reinforced with a single layer of geotextile. The results of the study indicated that the best depth of reinforcement was $0.25B$ (B = width of the footing [38].

M. S. Ranadive and N. N. Jadhav, (2004) conducted a study on reinforced soil using geotextile. Their findings showed that the highest bearing capacity was achieved when using 4 layers of reinforcement at a vertical spacing of $0.25 B$ [39].

E. Cicek, et al (2019) investigated the efficiency of the depth of the first reinforcement layer for granular soil. The plate load laboratory tests involved unreinforced samples and reinforced samples with geotextile and two types of geogrid specimens. The results were accomplished and compared with the Finite Element Model. The authors appointed that half of the footing width on granular medium-dense soil is the efficient depth to the first reinforcement layer [40].

B.A. Mir and M. Basit (2019) investigated the bearing capacity of a two-layer soil system and the impact of reinforcement by geogrid on it. The inclusion of reinforcement generally resulted in an increase in bearing capacity ratios (BCRs) at different s/B ratios. The study also found that the bearing capacity increased with an increase in the number of reinforcement layers. Additionally, the BCR reached its maximum value at $u/B=0.25$ at single reinforcement [41].

Y. M. Kadhim, (2022) investigated the ultimate bearing capacity of the gypseous soil when using geotextile reinforcement. The study found that the values were higher bearing capacity at triple layer reinforcement ($0.5B+1B+1.5B$) at dry condition [42].

1.1.8 Determine Bearing Capacity of Shallow Foundation

Different criteria or methods have been developed for determining the failure load of foundations and piles, such as K. Terzaghi (1943) [43], C. Van der Veen (1953) [44], De Beer (1970) [45], Adams (1998) [46], and Fellenius (2009) [47] et al. The following is a description of a few of these requirements:

1. Terzaghi (1943) suggested failure is defined as the load equivalent to a displacement of 10% of the width of the model footing (diameter of the pile).
2. De Beer (1970) suggested determining bearing capacity in a heap settling in a load-settlement relationship (log-log plot). The bearing limit is then determined at the breakpoint of two straight lines with different slopes that intersect on the plot. This is considered a point of failure.
3. Tangent intersection approach, the load-settlement curves are tangent to two specific sections of the graph. The first section is the end section, which serves as the starting point for the curve. The second section is the plastic state, which serves as the elastic state for the curve. This section represents the point at which the foundation has reached its maximum capacity to deform elastically and has begun to undergo plastic deformation. The intersection of these two sections represents the ultimate load as shown in Figure 1.4. In this study, was used this method to determine the ultimate Bearing Capacity of the soil model.

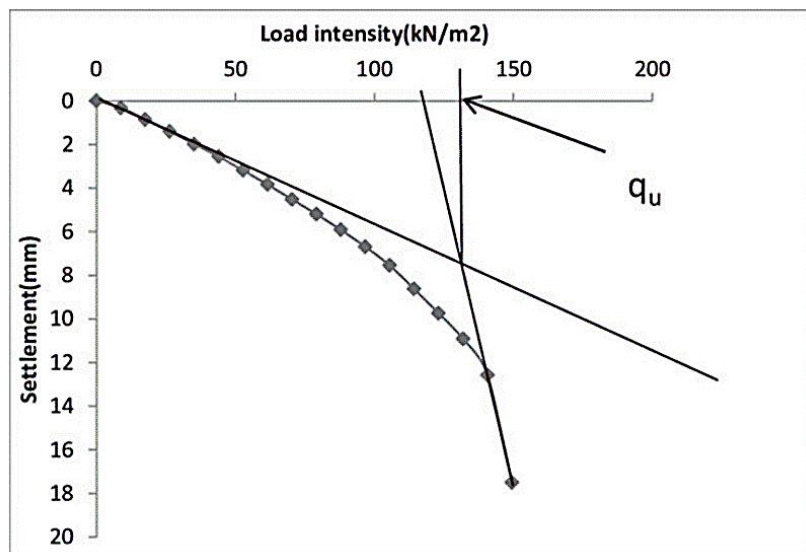


Figure 1.4 Ultimate bearing capacity by TwoTangent Intersection Method

1.1.9 Finite Element Analysis

Finite element analysis (FEA) software is used in soil mechanics to analyze the behavior of soil under various loading conditions. It is a numerical method that divides the soil into small elements and solves the equations of equilibrium and compatibility for each element.

Some commonly used finite element analysis software for soil mechanics are:

1. PLAXIS (2D and 3D): It is widely used in geotechnical engineering for analyzing soil deformation, stability, and settlement.
2. ABAQUS: It is a general-purpose finite element analysis software that can be used for soil mechanics analysis. It is capable of modeling complex soil behavior such as soil-structure interaction, consolidation, and liquefaction.
3. FLAC (2D and 3D): It is finite element analysis software for soil mechanics analysis. It is used for analyzing soil deformation, stability, and seismic response.

This study used the (PLAXIS 3D) software for the analysis of the soil model.

E. Cicek, et al (2019) investigated the impact of the first reinforcement layer depth on the performance of sand subbase in road or construction projects. The study compared laboratory results of reinforced and unreinforced soils using geotextile reinforcement with Finite element Model (FEM) analyses modeled by using PLAXIS 2D in similar conditions. The results showed that the type of reinforcement and the location of the first reinforcement layer had varying effects on the bearing ratio and load-settlement behavior[40].

E. M. Dawson and W. H. Roth (2020) calculated the safety factor of a slope by using FLAC software. This is done by gradually reducing the shear strength of soil until the slope fails, and the resulting factor of safety is the ratio of the soil's actual shear strength to the reduced shear strength at failure. This method is called the "shear strength reduction technique" and has several advantages over the traditional method of slices, including the ability to automatically identify the critical failure surface and analyze failure mechanisms involving deforming wedges of soil [48].

A. Mosadegh and H. Nikraz (2015) numerically calculated the bearing capacity of strip footing by finite element software ABAQUS. this study, soil behavior is represented by

the elastoplastic Drucker-Prager model. The result was of bearing capacity for one layer case has a good agreement with Terzaghi's equation [49].

1.2 Objective of the Thesis

This research aims to enhance the ability of the bearing capacity of gypseous soil by using a geosynthetic material (geotextile and E-glass fiber fabric) in different patterns (single, double, and triple as well as the U-shape reinforcement at triple pattern). The study examines how geosynthetic reinforcement affects the bearing capacity of gypseous soil in both dry and fully saturated states. Evaluate the effect of several parameters, such as the number of reinforcement layers, depth of the reinforcement layer, and the effect of relative density on the percentage of improvement in the bearing capacity of the soil. To achieve these goals, (68) models were tested, and (10) numerical models were by finite element software PLAXIS 3D to compare them.

1.3 Hypothesis and Layout of the Thesis

Gypseous soil is a type of soil that has a high risk of collapsing due to its unstable structure. As a result of its unstable structure, the soil can experience changes in volume and quick settlement. The thesis is structured into five chapters. Chapter One gives a review of previous studies its definition of gypsum soil, and the mechanism of soil collapse upon soaking. It also includes a review of previous research on reinforcement of soil. Chapter two talks about the background of gypseous soil, the distribution of gypseous soil in the world and Iraq, and the type of geosynthetic material. Chapter three provides a detailed account of the experimental work conducted, including the test program, parameters, soil properties, test set-up, and validation of numerical analysis. Chapter four presents and discusses the results obtained from the experimental work and numerical analysis by PLAXIS 3D as they relate to the research. Chapter Five summarizes the conclusions of the study and provides recommendations for further research.

2.1 Introduction

Recently the term gypseous soil is well known and defined previously by numerous researchers, briefly, the soil called gypseous or gypsiferous soil (same synonymous terms) are soils that contain sufficient quantities of gypsum ((hydrated calcium sulphate $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) where the properties of the soil would be changed by the effect of gypsum content [6]

Gypseous soil is a type of problematic soil that is prone to collapse. This type of soil is found all over the world and can collapse due to small changes in water content or weakening of the soil cementation. The collapse can cause significant settlements and loss of bearing capacity, which can be dangerous for any structures or buildings built on top of this soil [50].

2.2 Gypseous Soils Distribution

Gypseous soils cover about (850,000) square kilometers of the world's surface, and are found in several places, including Southern Europe, Spain, South West Asia, Australia, the drier parts of the USA from California to Texas, the middle east, China, Turkey, Libya, Somalia, Tunisia, Algeria, Namibia, Mali [3].

Gypseous soils now cover 1.0-1.5 million km^2 , including major areas in the Middle East and the former Soviet Union's southern regions [51]. Figure 2.1 is provided to illustrate the distribution of gypseous soils around the world.

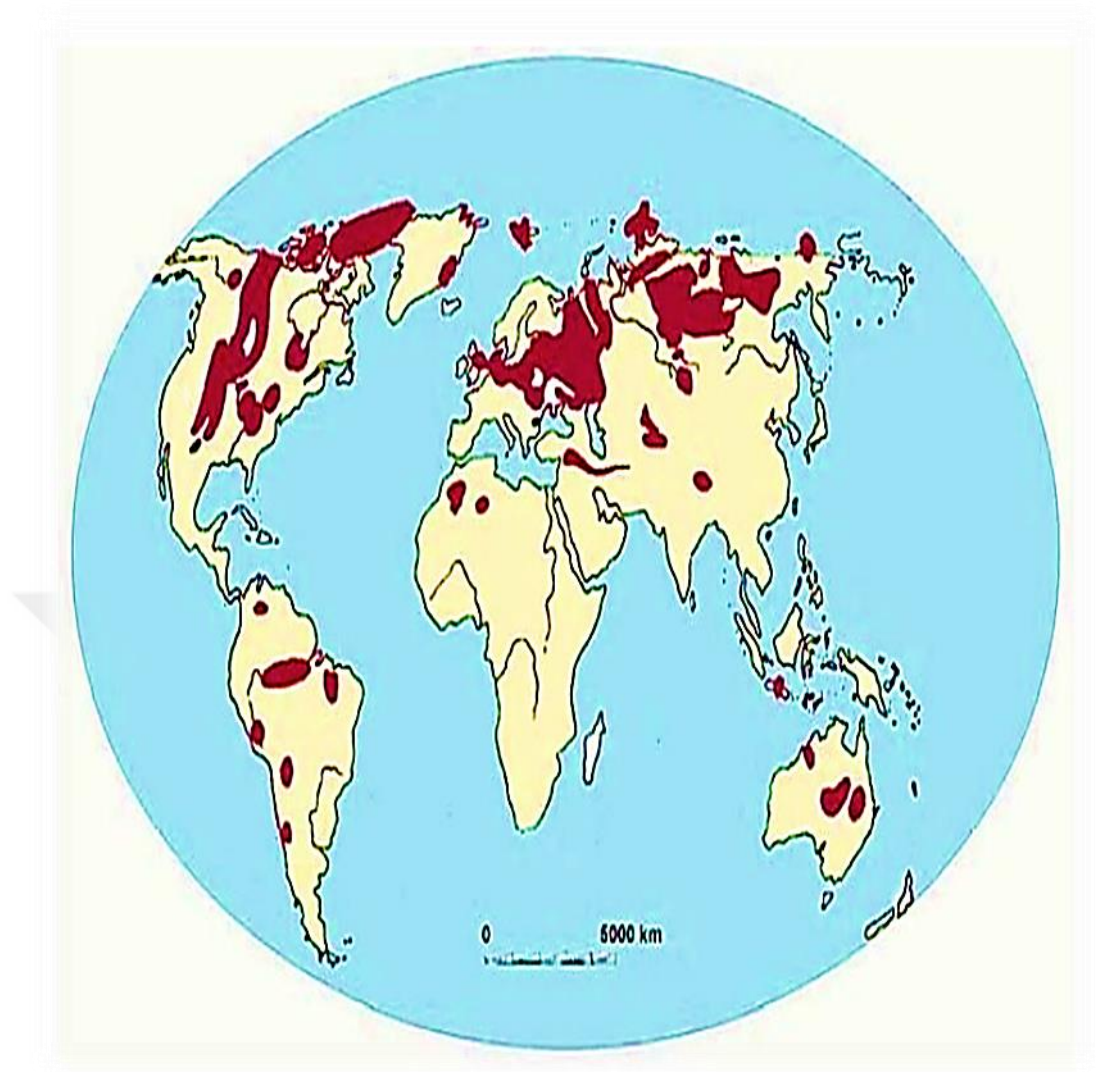


Figure 2.1 Distribution of gypseous soils in the world [51]

Gypseous soil covers approximately 31.7% of the total land area of Iraq. Figure 2.2 illustrate the distribution of gypseous soils in Iraq [54]. These soils are concentrated in various regions including the western, southern, and southwestern [52], [53].

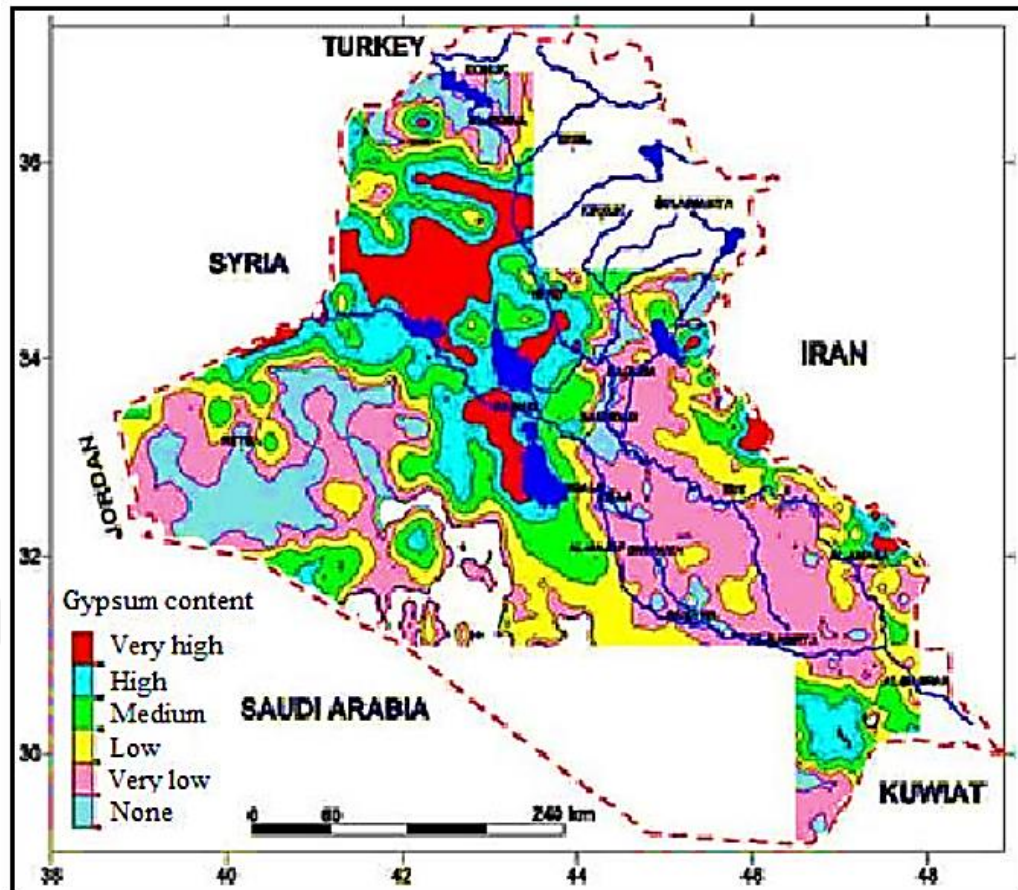


Figure 2.2 Distribution of gypseous soil in Iraq [54]

2.3 Problems of Gypseous Soil in Iraq

Gypseous soils are one of the types of soils with problems related to their chemical properties. The problem is that the solution of gypsum and anhydrite in these soils can lead to the formation of caverns, increased permeability of granular zones, enlarged fissures (resulting in a dramatic increase in flow rate), and excessive settlements [55]. Gypseous soils may be listed as follows.

- Strength decreases when wet.
- Gypseous soils exhibit high primary and secondary consolidation.
- Gypseous soils can dissolve in continuously seeping water [56].

Gypseous soil poses a risk to engineering structures., especially with high contamination of gypsum, because of the problem of collapse of soil under the footings, during the soaking of these soils with water from any source [57].

Many examples of problems have been observed in structures built on gypseous soils in Iraq. These problems include damage and collapse of houses in AL-Thawrra Hai, Mosul

City in 1969 [58], as well as cavities created under the foundation of Mosul Dam due to the continuous dissolution of gypsum under the dam [1].

The dissolution of gypsum can also lead to other issues, such as damages at Al-Anbar University in Al-Ramdi City and cracks in Dijla Hospital in Tikrit City [59].



Plate 2.1 The Mosul Dam in Iraq [1]



Plate 2.2 Collapse of a building in Al-Anbar University in Al-Ramdi City [59]

EXPERIMENTAL WORK & NUMERICAL ANALYSIS

3.1 Introduction

The experimental work of this study consists of two parts, the first is the basic characterization tests of the gypsum soil sample, and the second is the fundamental part, model tests of soil were carried out to investigate the effects of improving collapsible soils using two types of geosynthetics reinforced (geotextile and E-glass fiber fabric) to increasing the bearing capacity of gypsum soils. Additionally, this chapter includes a detailed description of the testing process, testing equipment, and testing methods used in the laboratory.

3.2 Materials

3.2.1 General Description of the Soil

The used soil was brought from the site near Al-Razzaza Lake, Iraq, with a depth of (1.5) m by coordinates (32.564775N, 43.866276E). The soil in this location can be described as medium to dense light brown silty sand with white traces of gypsum particles as shown in Figure 3.1, According to the Unified Soil Classification System (USCS), the soil was classified as (SW-SM), as shown in Figure (3.1). The soil physical and chemical parameters are listed in Table 3.1.



Figure 3.1 The site of soil used in a natural state

The conventional tests were conducted in two parts, the basic tests were performed in the laboratory of the civil engineering department of Babylon University in Iraq, and the advanced tests were performed in the geotechnical laboratory of the civil engineering department in Yildiz Technical University, as shown in Figure 3.15.

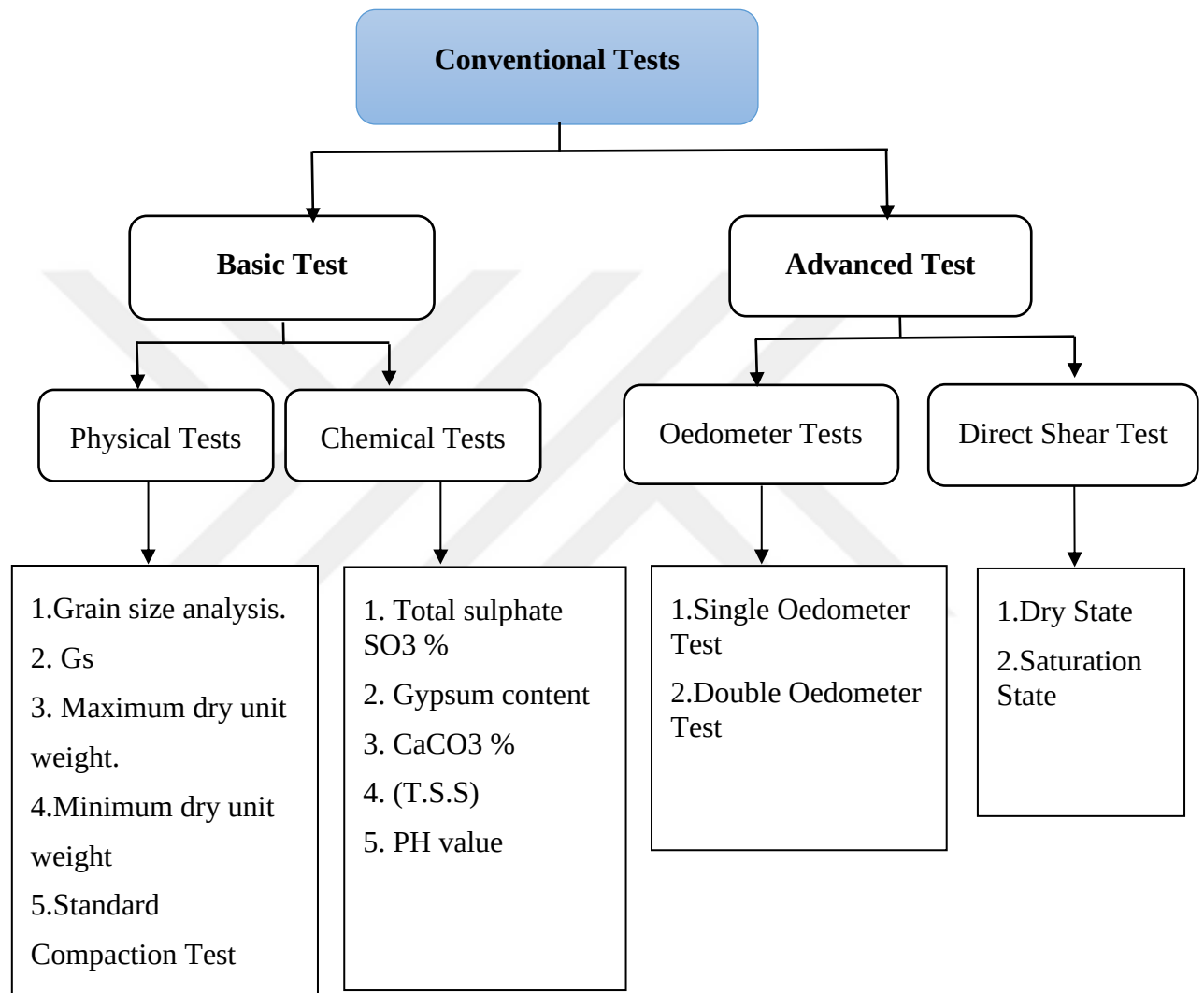


Figure 3.2 Conventional tests procedures

Table 3.1 Physical and Chemical Characteristics of Soil Sample

Physical Properties		
Property	Value	Standard
Water content (ω) %	6 %	ASTM D-2216
D ₁₀	0.12 mm	ASTM D-422
D ₃₀	0.33 mm	
D ₆₀	0.74 mm	
Passing sieve No.200	5.6 %	
Cu	6.17	
Cc	1.23	
Gs	2.32	ASTM D-854
γ_{dmax}	15.9 (kN/m ²)	ASTM D-698
γ_{dmin}	11.45 (kN/m ²)	
O.M.C %	15%	
Cohesion c For dry sample RD= 30% RD= 60% For saturation sample RD= 30% RD= 60%	4 kPa 5.5 kPa 2.2 kPa 3.5 kPa	ASTM D-3080
Friction angle ϕ For dry sample RD=30% RD=60% For saturation sample	30 35	

RD=30%		
RD=60%	27	
	31.27	
Chemical Properties		
Property	Value	Standard
Total sulphate SO ₃ %	21.75	BS 1377
Gypsum content %	47	ASTM D-3155
CaCO ₃ %	13.7	ASTM D-4373-96
(T.S.S) %	44.4	ASA -2510B
PH value	8.1	ASTM D-4972

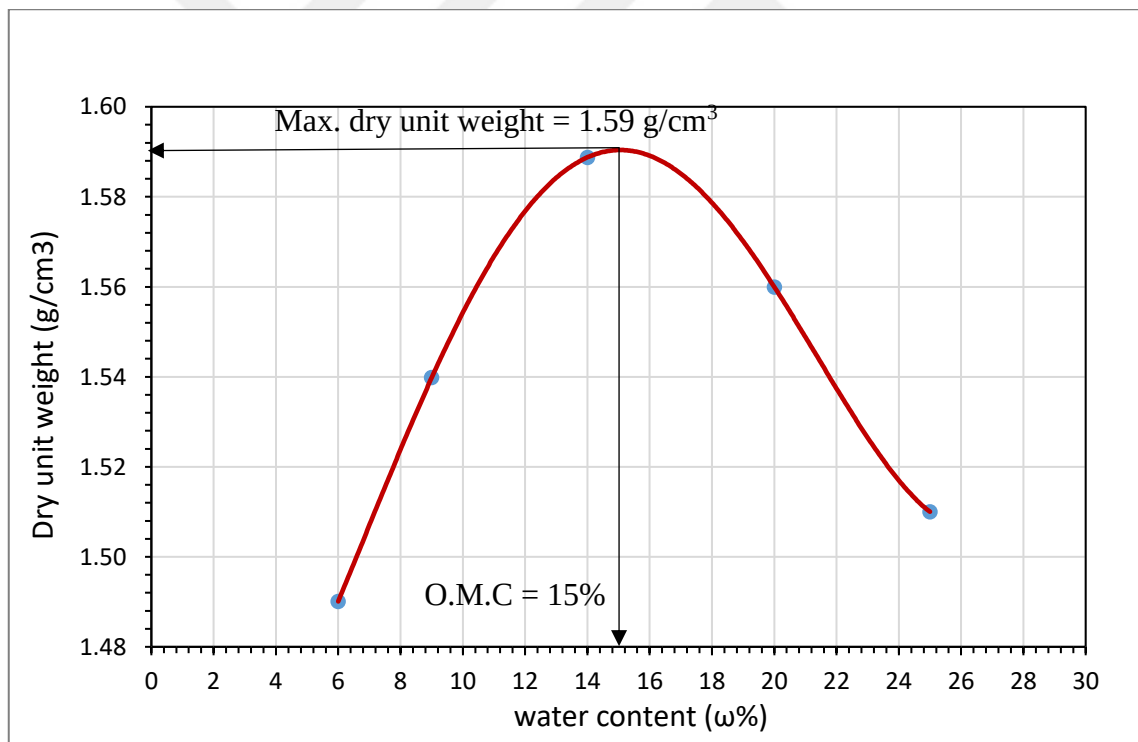


Figure 3.3 Standard proctor test result

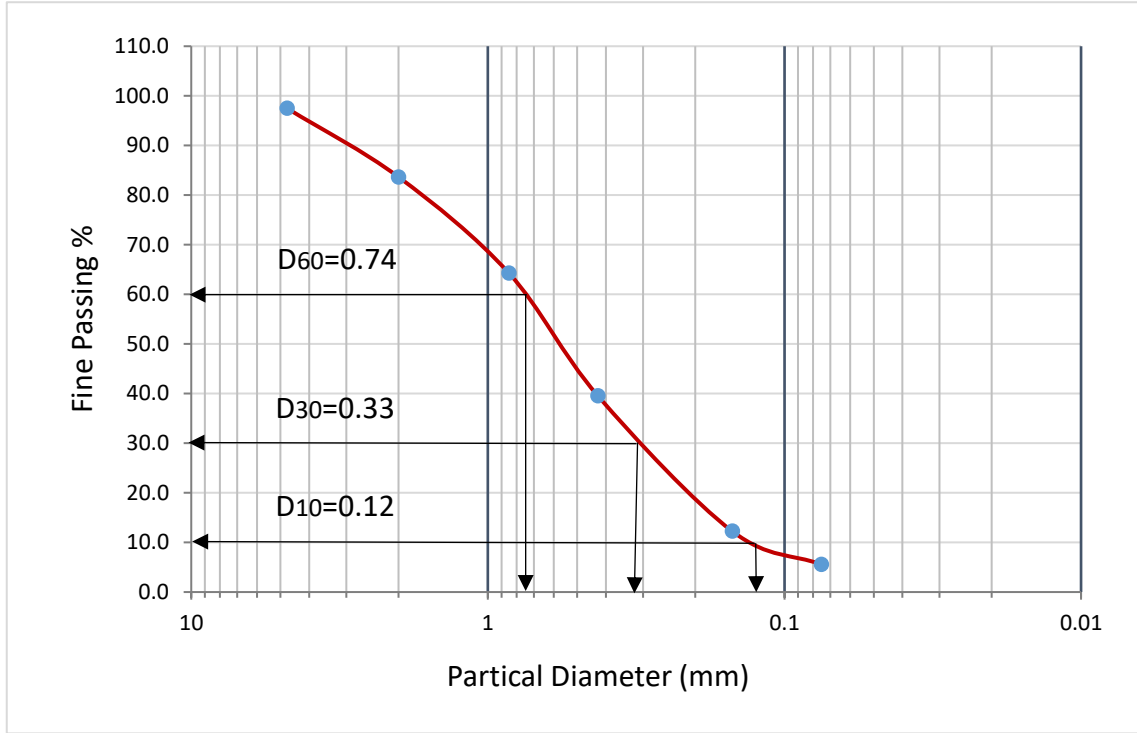


Figure 3.4 Particle size distribution curve result

3.2.2 Gypsum Content Calculation

Al-Mufti and Nashat's [60] method was used to calculate the gypseous content (X)%, which involves placing the soil sample in an oven at a temperature of 45 degrees until the weight is constant, the weight of the soil sample is recorded after it is taken out of the oven. We put the same sample in the oven at a temperature of 110 C⁰ until the weight is constant. To calculate the gypsum content follow the equation (3.1).

$$X = \left[\left(\frac{W_{45^0} - W_{110^0}}{W_{45^0}} \right) \times 4.778 \right] \times 100\% \quad (3.1)$$

Where

X = gypsum content %

W_{45^0} = specimen weight at a temperature of 45 C⁰

W_{110^0} = specimen weight at a temperature of 110 C⁰

The result of the gypsum content of the soil sample was 47%, and therefore the soil is considered to have a high gypsum content according to Barazanji [61], as shown in Table 2.1.

3.3 Direct Box Shear

A direct shear test was performed for the soil sample in the dry condition as well as fully saturation condition, according to ASTM-3080 standard, to determine the (c) cohesion, and (ϕ) friction angle for the relative density of (30%, 60%) and the results were as shown in the Figures 3.5 to 3.8.

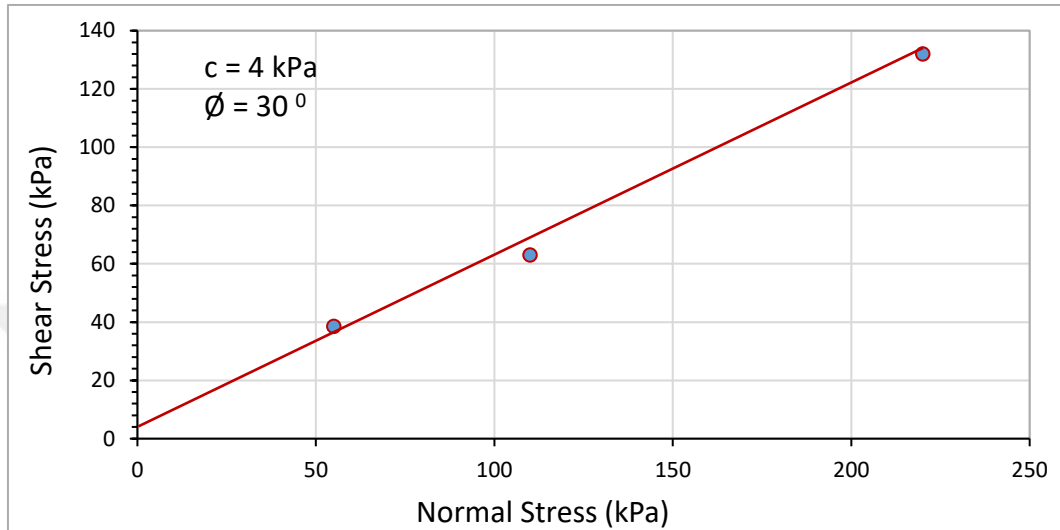


Figure 3.5 Direct shear test result for dry soil sample with unit weight 12.5 kN/m^3 at RD = 30%

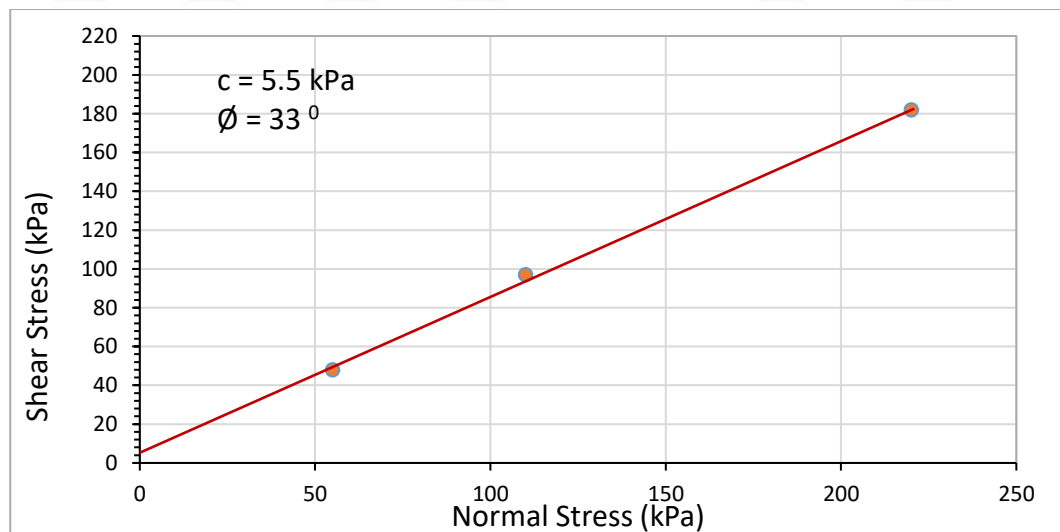


Figure 3.6 Direct shear test result for dry soil sample with unit weight 13.76 kN/m^3 at RD = 60%

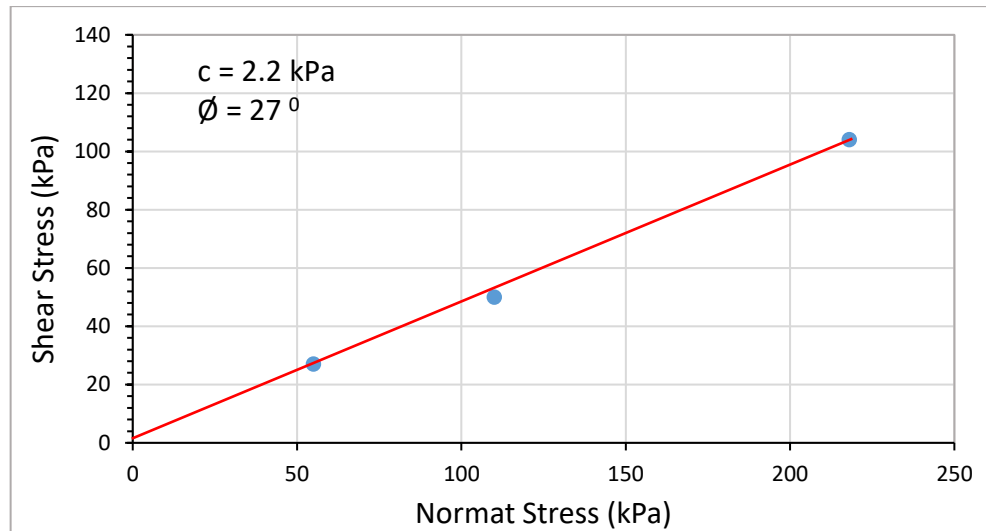


Figure 3.7 Direct shear test result for fully saturation soil sample at RD = 30%

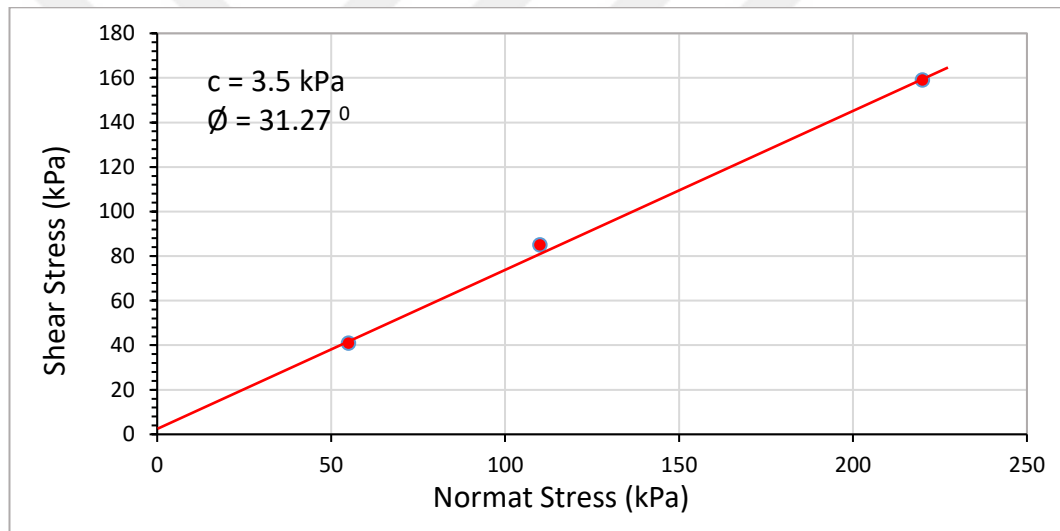


Figure 3.8 Direct shear test result for fully saturation soil sample at RD = 60%

3.4 Collapse Potential by Oedometer Test

3.4.1 Single Oedometer Test (SOT)

In a single oedometer test, the sample soil was gradually loaded until it reached a vertical pressure of 200 kPa, and recording the settlement values, then it has soaked with water for 24 hours, under the same pressure of 200 kPa recording the settlement values that were added. The fast decreases in the void ratio are caused by the sudden crash of the soil structure when water is added at a stress level of 200 kPa. Collapsibility potential (CP%)

was calculated for the gypseous soil sample by equation (2.1), for relative density 30%, and 60% respectively, Figures 3.9 and 3.10 show the result of SOT to determine the CP%.

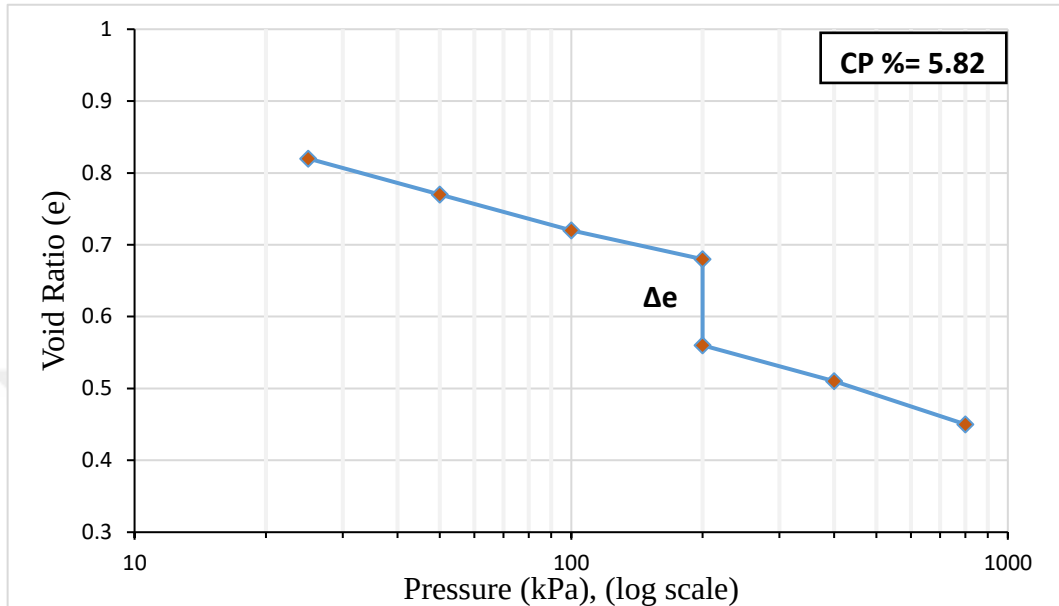


Figure 3.9 Collapse potential CP % by (SOT) at (RD=30%, $e_0=0.86$)

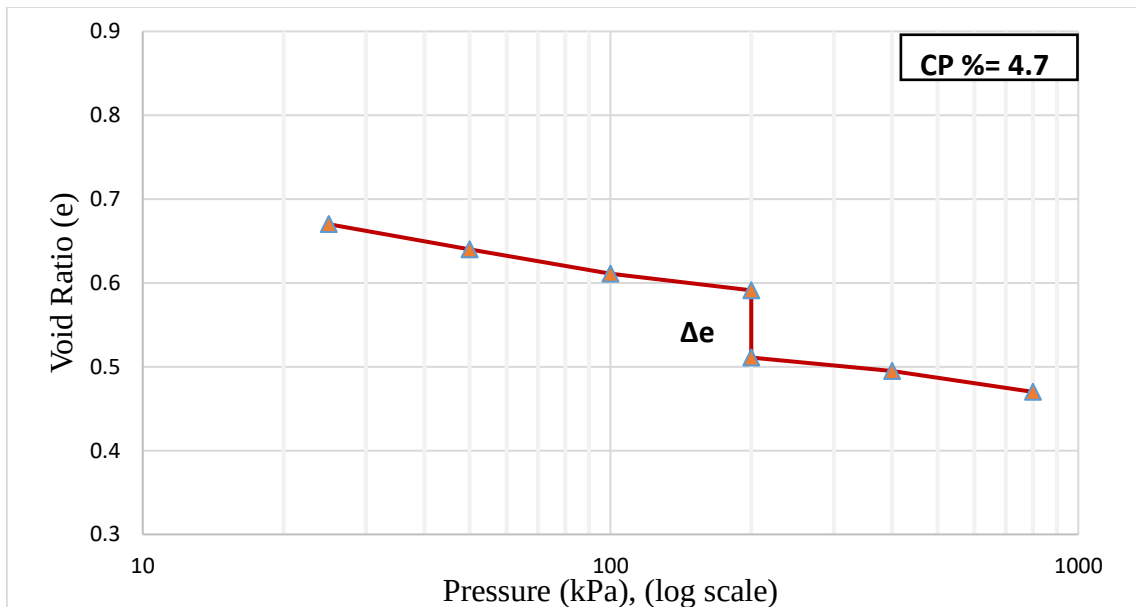


Figure 3.10 Collapse potential CP % by (SOT) at (RD=60%, $e_0=0.69$)

3.4.2 Double Oedometer Test (DOT)

In the double oedometer test, two gypseous soil samples are used for calculating a potential collapsible CP%. The first sample was tested after being soaked in water (fully saturated), and the second sample was tested in a dry state at the same time. Stress has been associated with an increased potential of collapsing. The amount of voids increases as a result of the expansion of water when the connections between soil particles and product dissolved during soil test settling.

The probability for collapse potential CP% obtained from DOT was larger than the collapse potential obtained from SOT because the soil sample in DOT was exposed to previous amounts of water, the soil sample with the double test was soaked and the quantity of water available since the test starting and the pressure is more dense in compare to a SOT. Figures 3.11 and 3.12 show the results of CP% for DOT.

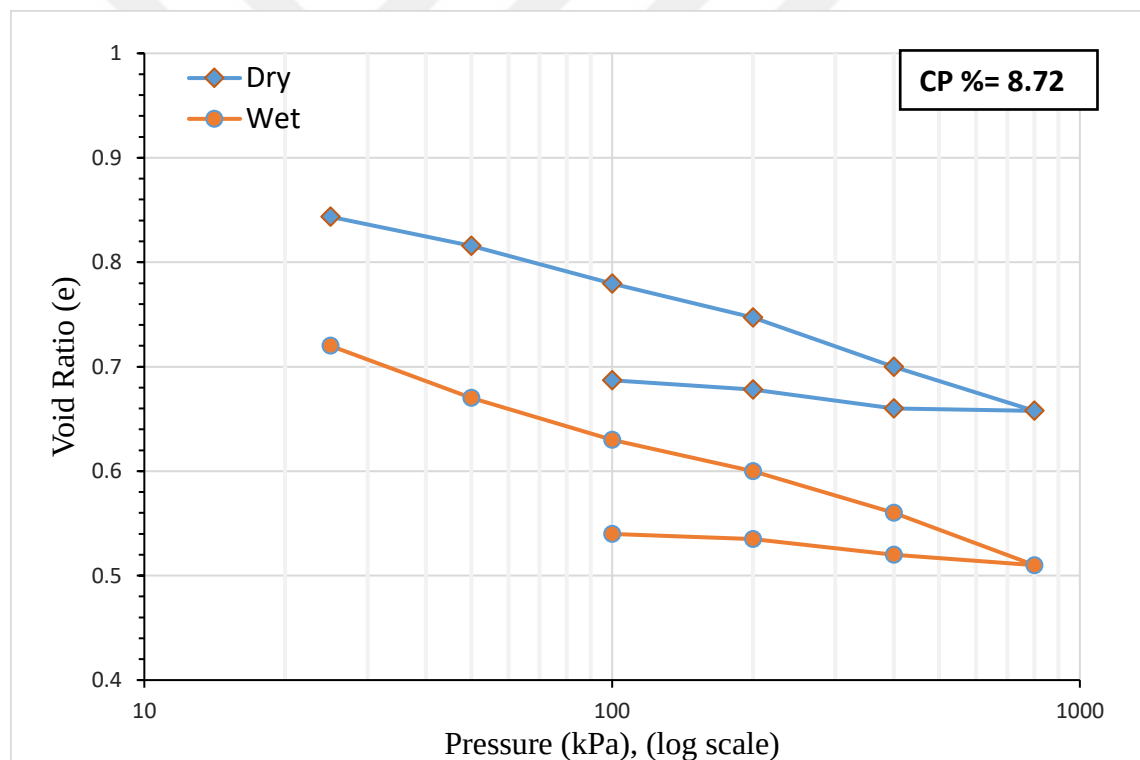


Figure 3.11 Double oedometer test (DOT) result of soil sample at RD=30%

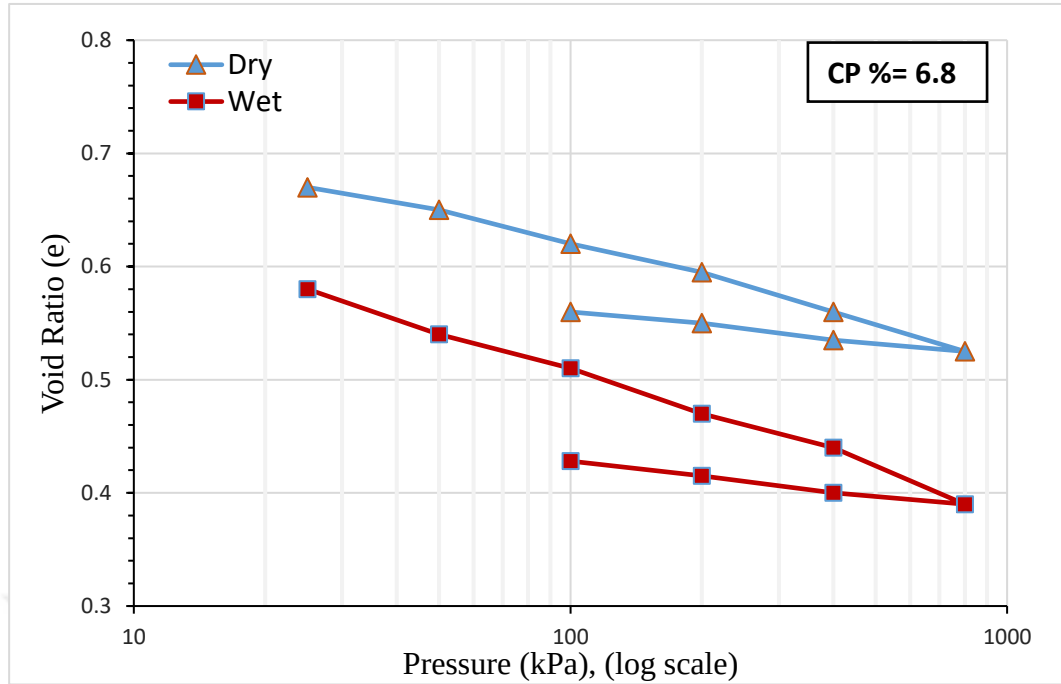


Figure 3.12 Double oedometer test (DOT) result of soil sample at RD=60%

3.5 Geosynthetic material

3.5.1 Geotextile Material

Geotextile is one new geosynthetic material. It is a material comprised of polyester or polypropylene that is permeable to water. Geotextiles are used for various purposes in civil engineering projects, including stabilizing soil on roads and railways, protection against corrosion in waterways and on beaches, and more. It is used for many applications, including as drainage, filtration, reinforcement, and stabilization [27].

Plate 3.1 and Table 3.2 show the specifications and characteristics of the geotextile reinforcement used in this study.

Table 3.2 Geotextile properties

Properties (standard)	Value
Geotextile type	Nonwoven
Fiber type	Polypropylene
Trade name	S72
Weight (g/m ²)	125
Thickness (mm)	1.4
Tensile strength (kN/m)	25
Elongation at max. load (%)	80
CBR puncture resistance (kN)	1.4
water permeability (m/s)	0.1



Plate 3.1 Geotextile material used in this study

3.5.2 E-Glass Fiber Fabric Material

The use of E-glass fiber fabric is very limited in soil works, Where the discrete fibers were used in some research to affect tensile strength as well as enhance soil strength for pavement application. in this study used the E-glass fiber fabric to investigate the effect on the bearing capacity of gypsum soil, Plate 3.2 and Table 3.3 illustrate the E-glass fiber fabric reinforcement utilized in this investigation.

Table 3.3 E-glass fiber fabric properties

Properties (standard)	Value
Glass fiber type	E-Glass fiber fabric
Weave pattern	Plain woven
Weight (g/m ²)	300
Thickness (mm)	0.3
Tensile strength (kN/m)	110
Elongation at max. load (%)	80
CBR puncture resistance (kN)	1.4
water permeability (m/s)	0.1



Plate 3.2 E-glass fiber fabric material used in this study

3.6 Soil Model Apparatu

All models were tested using the following elements in the configuration as the diagram shown in Figure 3.13.

1. Steel load frame with axial load system.
2. Steel Soil Model Box
3. Load cell with data logger system
4. Square steel plate and dial gage

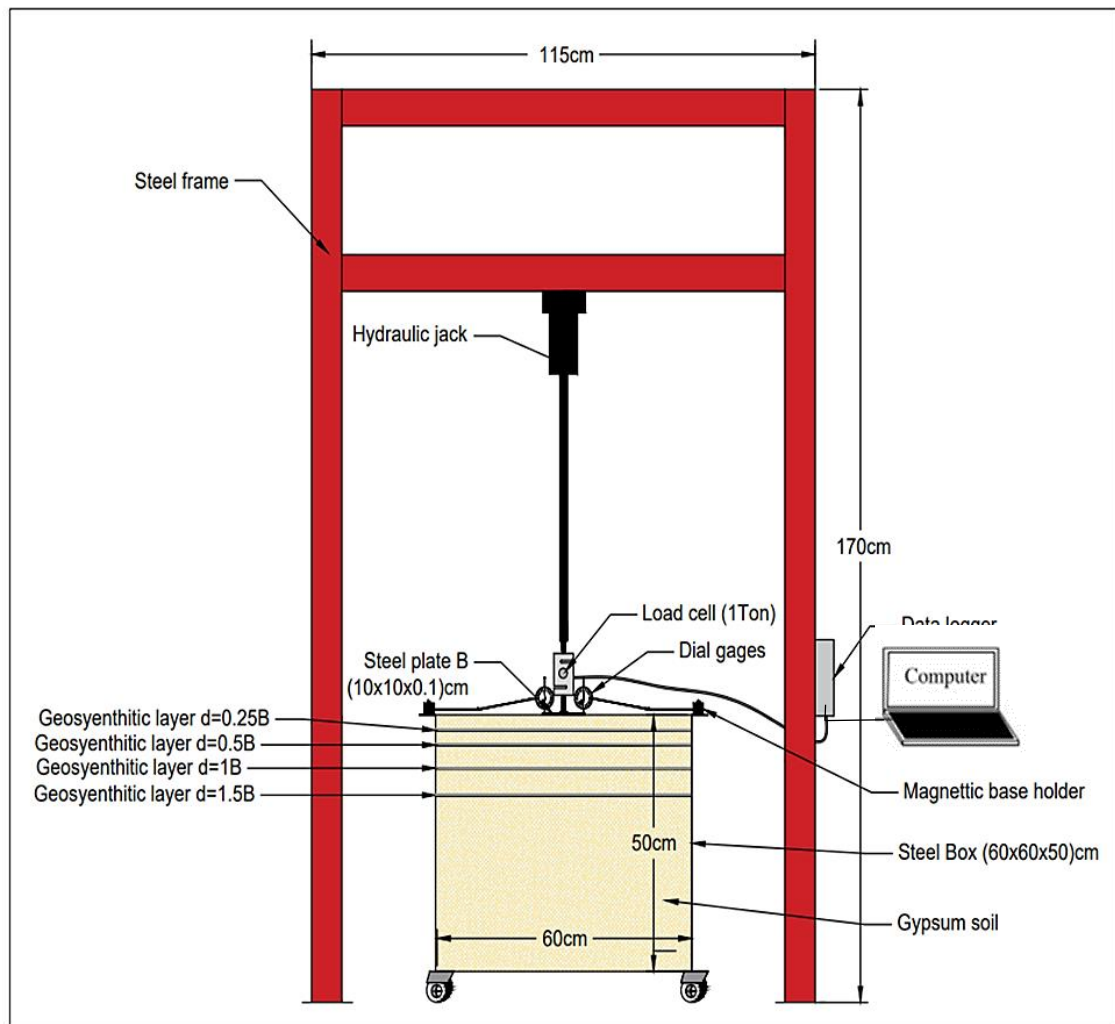


Figure 3.13 Diagram of load system model

3.6.1 Steel load frame with axial load system

The steel loading frame consists of four steel columns with four beams, all of which consist of square steel sections measuring $(80 \times 80 \times 4)$ mm and dimensions $(117 \times 170 \times 55)$ cm, with a main load system consisting of a hydraulic jack in the middle of the frame and at a height of 1.2 meters from the base of the frame. As shown in Plate 3.3.



Plate 3.3 Steel load frame with axial load system.

3.6.2 Steel Soil Model Box

The soil model box is made of steel with inside dimensions are $(600 \times 600 \times 500)$ mm (length, width, and height), and a thickness of 5mm, as shown in plate 3.4

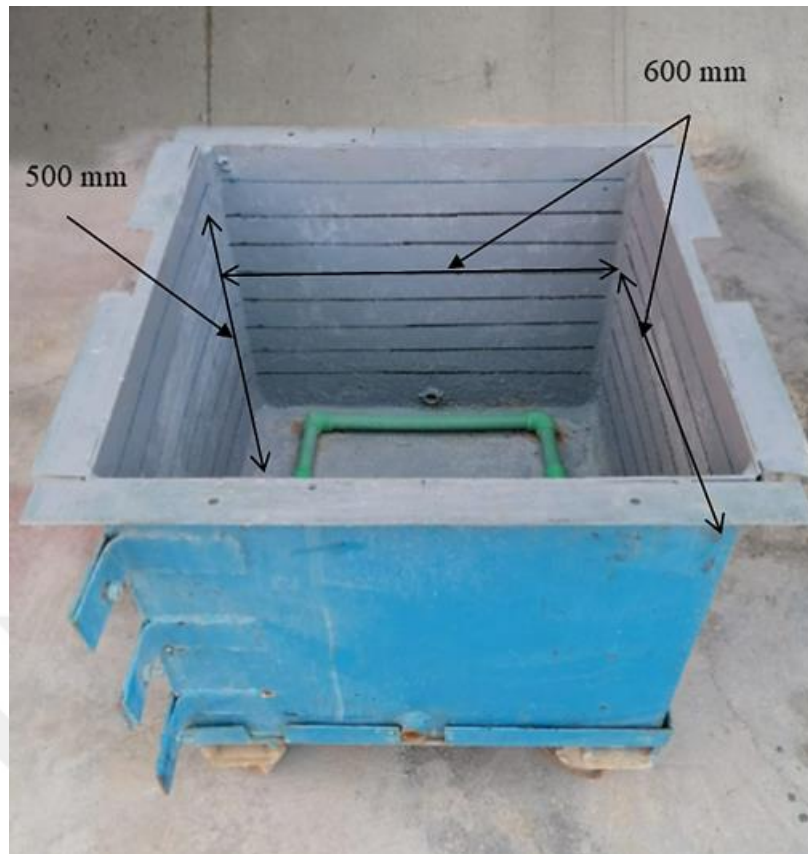


Plate 3.4 Steel soil model box

3.6.3 Load cell with data logger system

An S-type load cell with a capacity of 1 Ton was used for measuring the applied static load with a data logger system which consists of the following components for recording the reading of loading as shown the plate 3.5.

1. Amplifier (HX711).
2. Data logger (Arduino).
3. Data cable.
4. Programs (software).

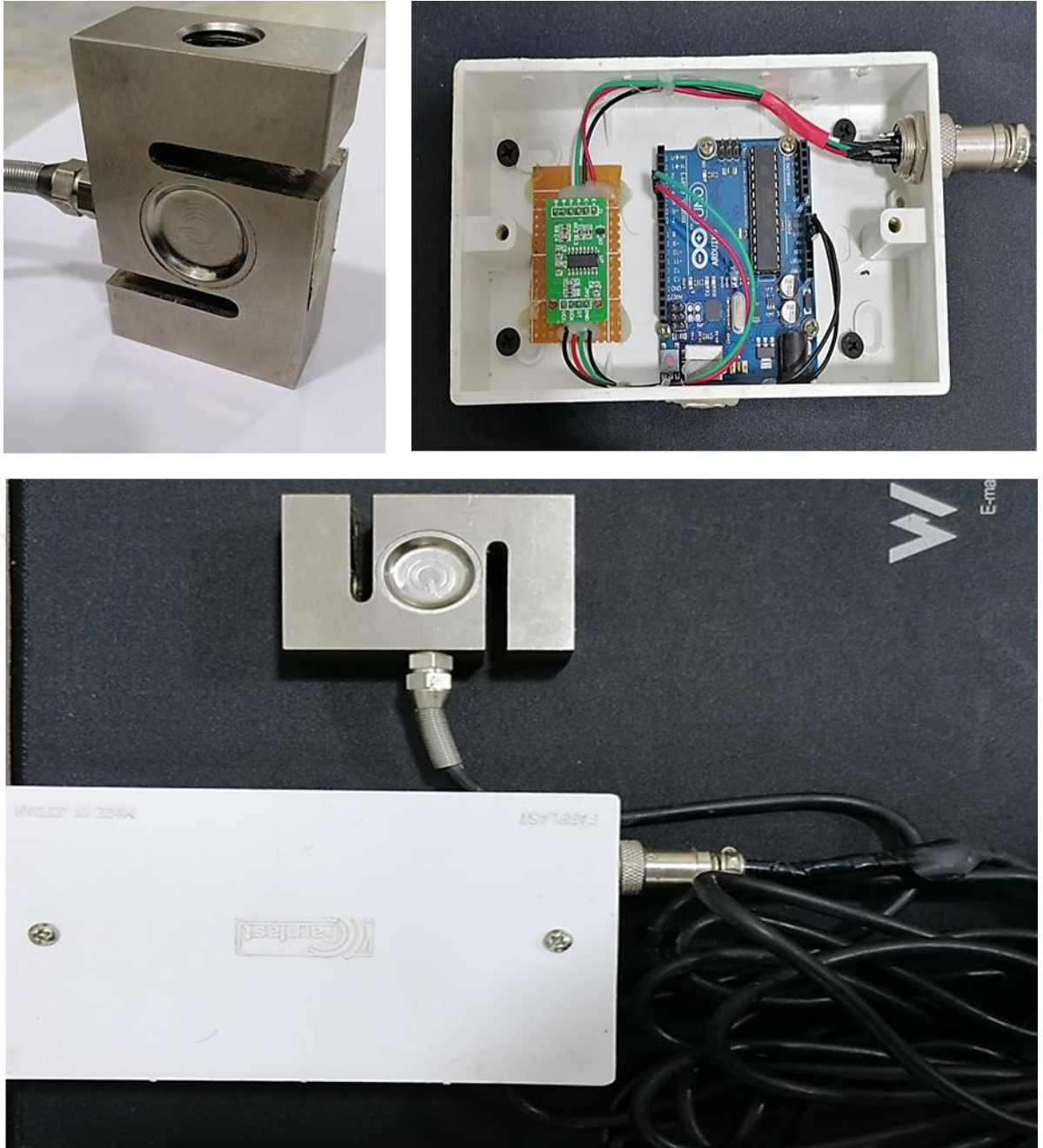


Plate 3.5 Load cell with data logger system components

3.6.4 Square steel plate (Footing)

The footing was represented in the model by using a square steel plate (100 x 100 x 10) mm, as shown in plate 3.6.



Plate 3.6 Square steel plate and dial gage

3.7 Test Method

3.7.1 Soil Sample Preparation

In this study, two natural soil model was prepared in the test box. The first one, dry unit weight is 12.5 kN/m^3 , corresponding to $RD = 30\%$. And second, the dry unit weight is 13.76 kN/m^3 , corresponding to $RD =$ of 60% . To calculate the required unit weight according to the relative density, Equation 3.3 was used. To prepare the soil sample in the box, it was divided into layers, the thickness of each layer was 5 cm , and the layer is of $(60 \times 60) \text{ cm}$. The weight of the samples was calculated according to the unit weight which corresponds to the relative density of 30% , 60% , for each layer, so that the weight of each layer was 22.5 kg for the sample with a density of 30% and 24.77 kg for the density of 60% . Each layer was leveled using a manual compactor tool to obtain the required density for all layers. To simulate the wet condition the model sample was submerged in water for roughly a day. The sample was soaked by raising water from the base to the surface of the soil sample box, as shown in plates 3.7 and 3.9.

$$RD = \left[\frac{\gamma_d - \gamma_{d(\min)}}{\gamma_{d(\max)} - \gamma_{d(\min)}} \right] \frac{\gamma_{d(\min)}}{\gamma_d} \quad (3.3)$$

Where:

RD = Relative density 30% , 60% .

$\gamma_{d(\max)}$ =Maximum dry unit weight kN/m^3 .

$\gamma_{d(\min)}$ = Minimum dry unit weight kN/m^3 .

γ_d = Required dry unit weight according to relative density kN/m³.

3.7.2 Calculating the Theoretical Ultimate Bearing Capacity of the Footing

Terzaghi's theory was used to estimate the theoretical ultimate bearing capacity to the square footing through equation 3.4, to obtain the value of load applied in the footing.

$$q_{ult} = 1.3cN_c + qN_q + 0.4\gamma BN_\gamma \quad (3.4)$$

Where:

q_{ult} = Ultimate bearing capacity (kPa).

c = Cohesion of soil, (kPa).

γ = Unit weight of soil, (kN/m³).

$q = \gamma D_f$, surcharge load.

B = width of the footing, (m).

N_c, N_q , and N_γ = bearing capacity factors.

3.7.3 Procedures for Testing

The ASTM D1194-94 test method was used for estimating the soil-bearing capacity by applying static plate load. The gypsum soil sample was prepared according to the required relative density and placed in layers with a thickness of 5 cm to ensure a similar density for each layer. Apply the last layer, then used a straight edge to carefully level the surface. The bearing capacity of the different layers reinforced was tested using two types of geosynthetic material (geotextile and E-glass fiber fabric). The square steel footing was placed in the center of the test steel box in the x and y direction, then installed two dial gages by the magnetic base holder on the edge of the steel box to measure the vertical displacement for the footing after the applied continuous load by hydraulic jack on the load cell that provided the force applied, which is measured by the data logger system. To monitor the water level in the soil bed as a piezometer and to signal when the soil reaches the saturated stage, a valve was installed and connected by a 900 mm long rubber tube. Apply load according to ASTM D1194-94 consistently and calculated the ultimate bearing capacity vs vertical settlement up until a model failure. Failure occurs when the increase in the settlement is at constant load magnitude. For wet models and as a way to

model site conditions when groundwater flow is upwards directed through soil layers, the water was allowed to move in the soil from the bottom to the top (in an upward direction).

3.8 Program Testing Models

The testing program comprises a total of (68) experimental model tests. Were performed using three systems of geosynthetic reinforced layers, the first of which was a single layer test at a depth (D) of (0.25 B, 0.5 B, 1 B,), where B indicates a width of steel footing, the second model was a double layer uses at depth of (0.25B+0.5B, 0.5B+1B), and finally was a triple layer uses at depth (0.25B+0.5B+1B, 0.5B+1B+1.5B). at triple layer was used the U-shape reinforced in some models and compared with the straight layer, as follows:

1. Fifty-eight (60) models of gypsum soil with relative densities of 30% and 60% were tested under both dry and saturated conditions. The models were reinforced with two types of geosynthetic (geotextile and E-glass Fiber) in different layer patterns (single, double, and triple) by using the load cell to subject vertical load.
2. Eight (8) models were tested at the triple layer pattern by geosynthetic reinforcement (0.25B+0.5B+1B) using the U-shape geosynthetic reinforced.

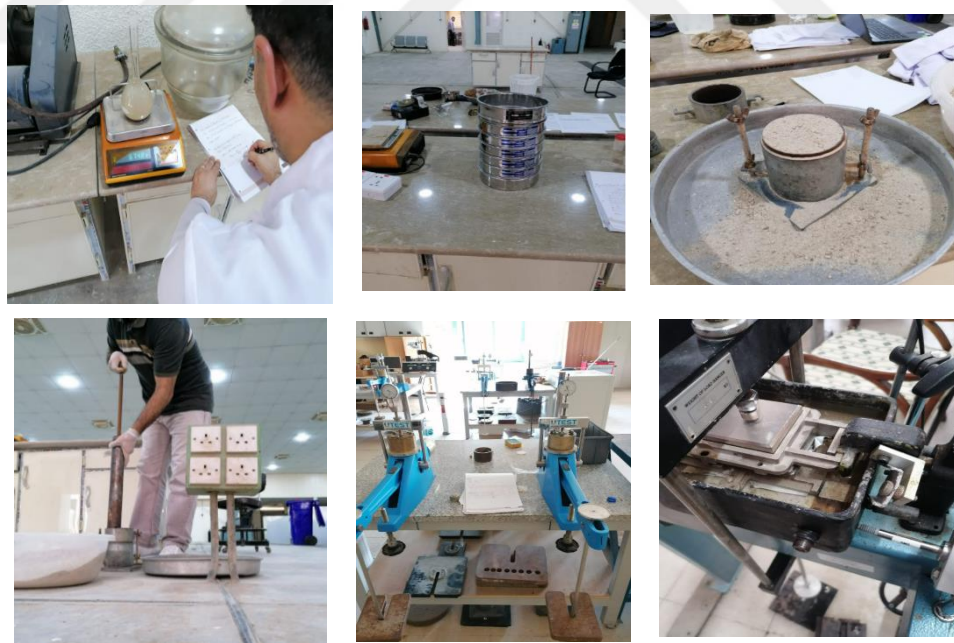


Plate 3.7 Conventional tests of soil sample



Plate 3.8 Preparing to place the soil and test at a dry state

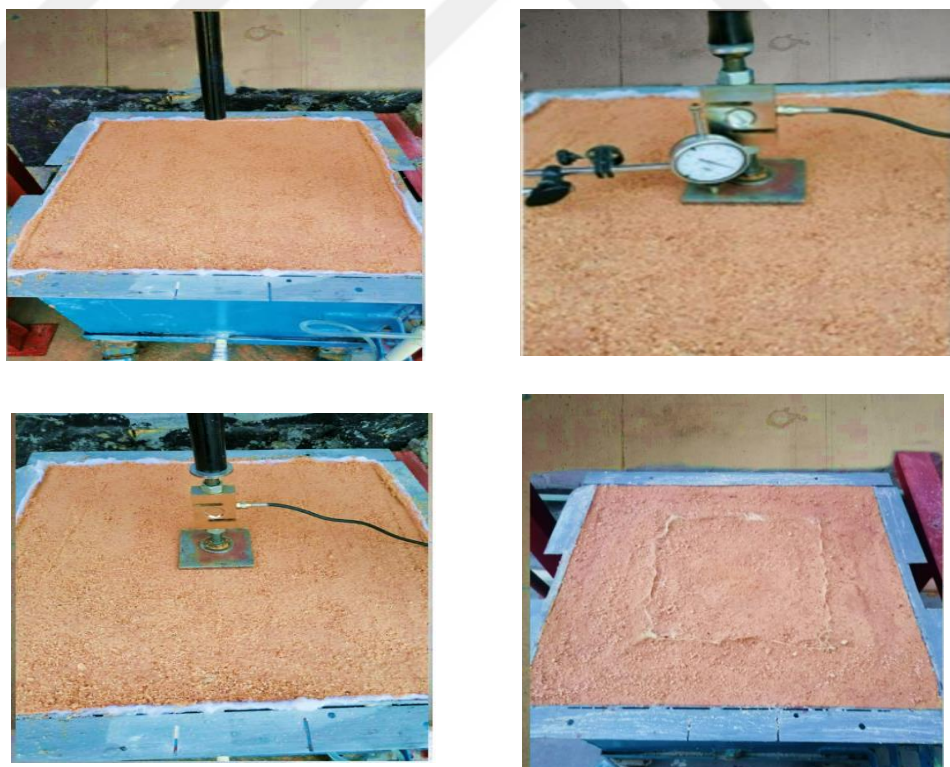


Plate 3.9 Preparing to place the soil and test at saturation state (saturation)

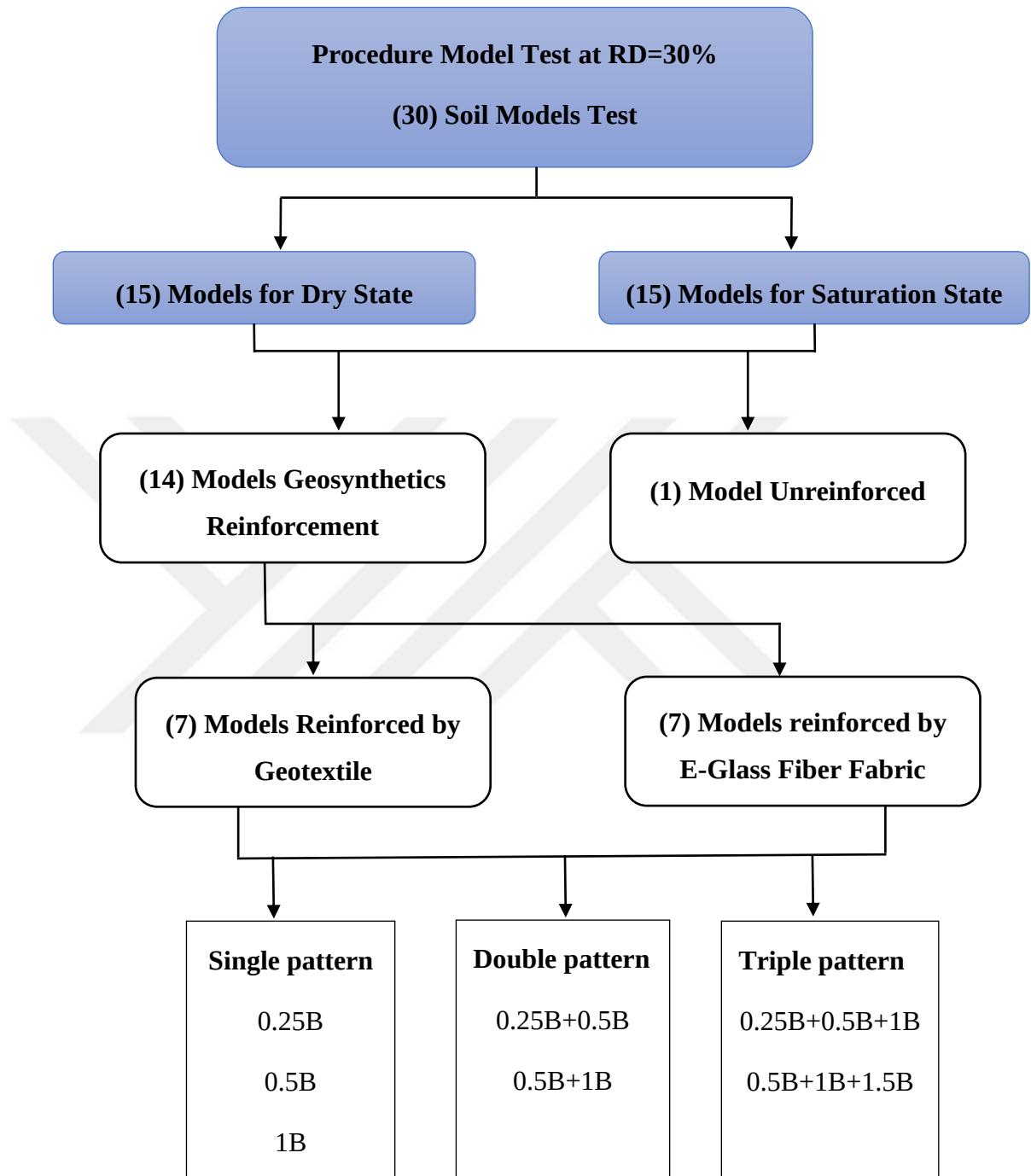


Figure 3.14 Flowchart procedure modeling test of soil at RD=30%

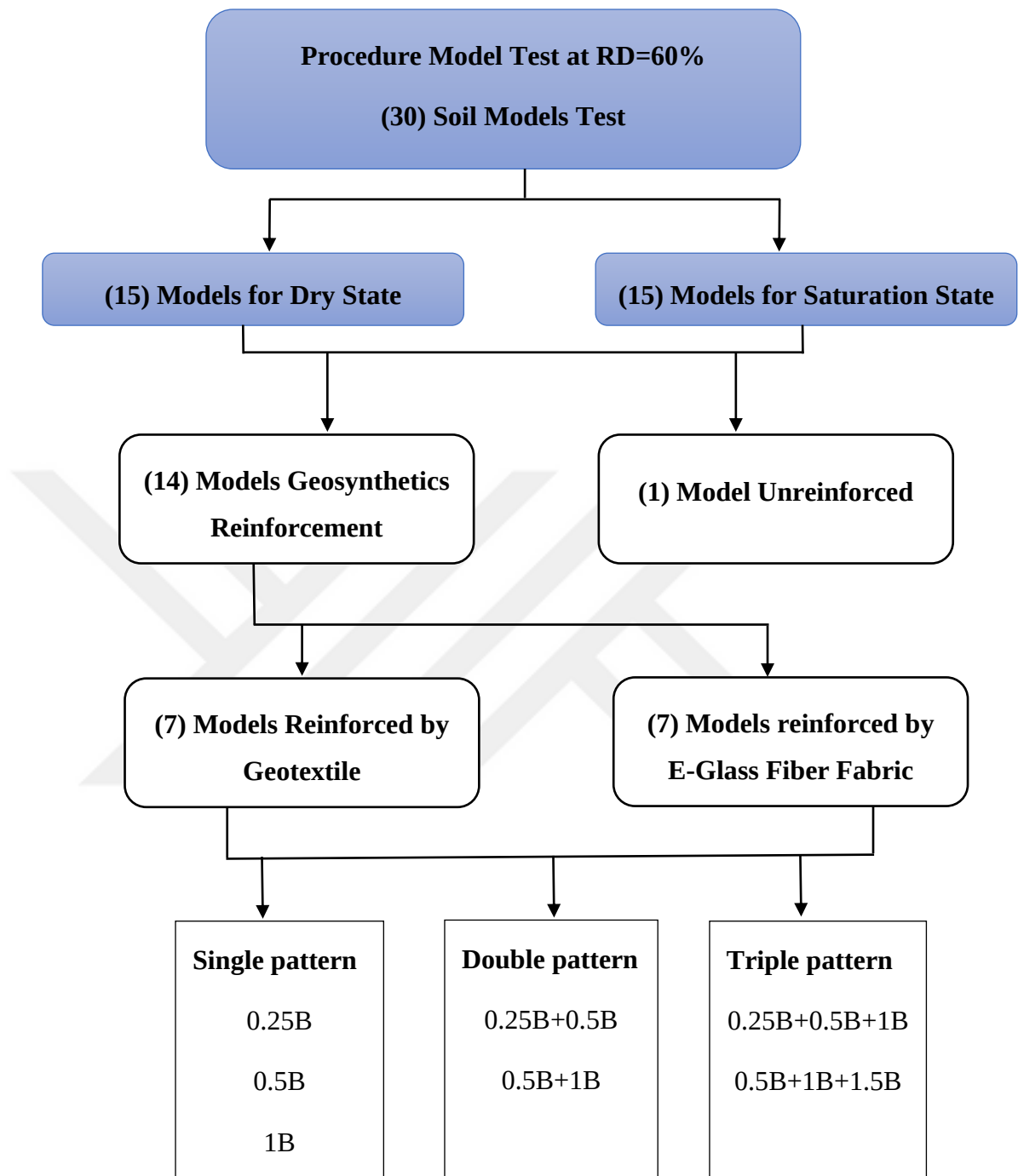


Figure 3.15 Flowchart procedure modeling test of soil at RD=60%

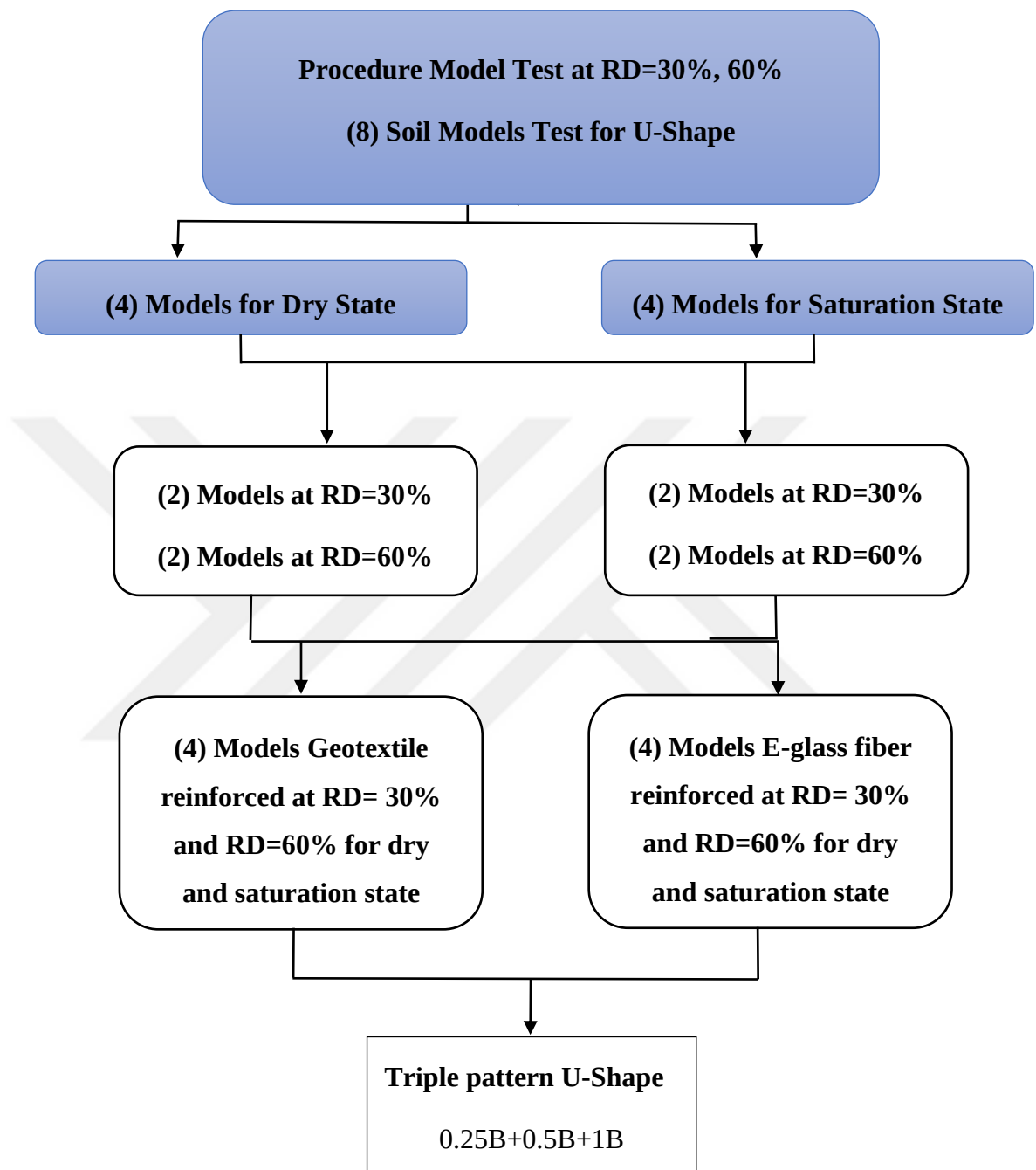


Figure 3.16 Flowchart procedure modeling test for U-shape reinforcement at RD=30% and 60%

3.9 Numerical Modelling by PLAXIS Software

The finite elements method (FEM) was used by the PLAXIS 3D to represent the model and analyze the results and compare them with the experimental work results. The model was made using the program and is as follows.

3.9.1 Geometry and Boundary Condition

The first step to represent the soil model in the PLAXIS 3D program was to define the geometry of the model, which includes the dimensions in the direction of the X-axis and the Y-axis, where the dimension of the model has represented by the same dimensions of the experimental work model (60 x 60 x 50) cm.

3.9.2 Modelling of Soil

The behavior of soil under stress was described by the widely used Mohr-Coulomb model of soil. The user can simulate how the soil will behave under various states by selecting this model in the PLAXIS application.

Five parameters were required in total to represent the Mohr-Coulomb in the Plaxis 3D program: two for stiffness (Young's modulus (E) and Poisson's ratio (ν)), and three for strength (cohesion c , friction angle ϕ , and dilatancy angle ψ). The unit weight of soil was also required for dry and saturated conditions.

3.9.3 Modelling of Footing

To represent the footing, the plates were chosen from the set type toolbox from the material sets window. Young's modulus of steel (E) and Poisson's ratio (ν) are the stiffness parameters of the steel structures.

3.9.4 Modelling of Geosynthetic

To represent the reinforcing layer using (geotextiles and E-glass fiber) using the type of geogrid and introducing the characteristics of the material, after that, we make an interface between the soil layer and the material.

3.9.5 Mesh Generation

After defining the model (soil, footing, and surface load), it was divided into finite elements to perform the analysis and calculating results, where selecting a mesh that gives accurate results in calculations.

3.9.6 Construction Stage and Result of Analysis

At this stage, the outputs were created, and the results are analyzed by building stages for the calculation, starting with the initial phase through which the (k0 procedure) is analyzed, and then adding another phase in which the parameters that include the footing and surface displacement are activated, where the type of calculation was plastic. After completing all the phases, the calculations are made and then the required results are displayed.

3.9.7 Testing Model

In this study, 10 numerical models were tested using the PLAXIS 3D program to model gypsum soil in both dry and saturation conditions, with a relative density of 30%.

The models were implemented using reinforcing layers using two types of geosynthetics (Geotextile and E-glass fiber fabric) according to the flow chart below.

Table 3.4 Properties of soil and footing for modeling in this study

Parameter	Soil at RD=30%	Footing (Steel)
Material modal	Mohr-Coulomb	Linear
Drainage type	Drained	Non-porous
γ (kN/m ³)	12.5	78.5
E (kPa)	6500	2E10 ⁶
ν	0.25	0.2
c (kPa)	4	-
ϕ (°)	30	-

Table 3.5 Properties of geosynthetics used for modeling.

Geotextile		E-glass fiber fabric	
Material type	Elastic	Material type	Elastic
EA ₁	25 kN/m	EA ₁	110 kN/m
GA	80%	GA	80%

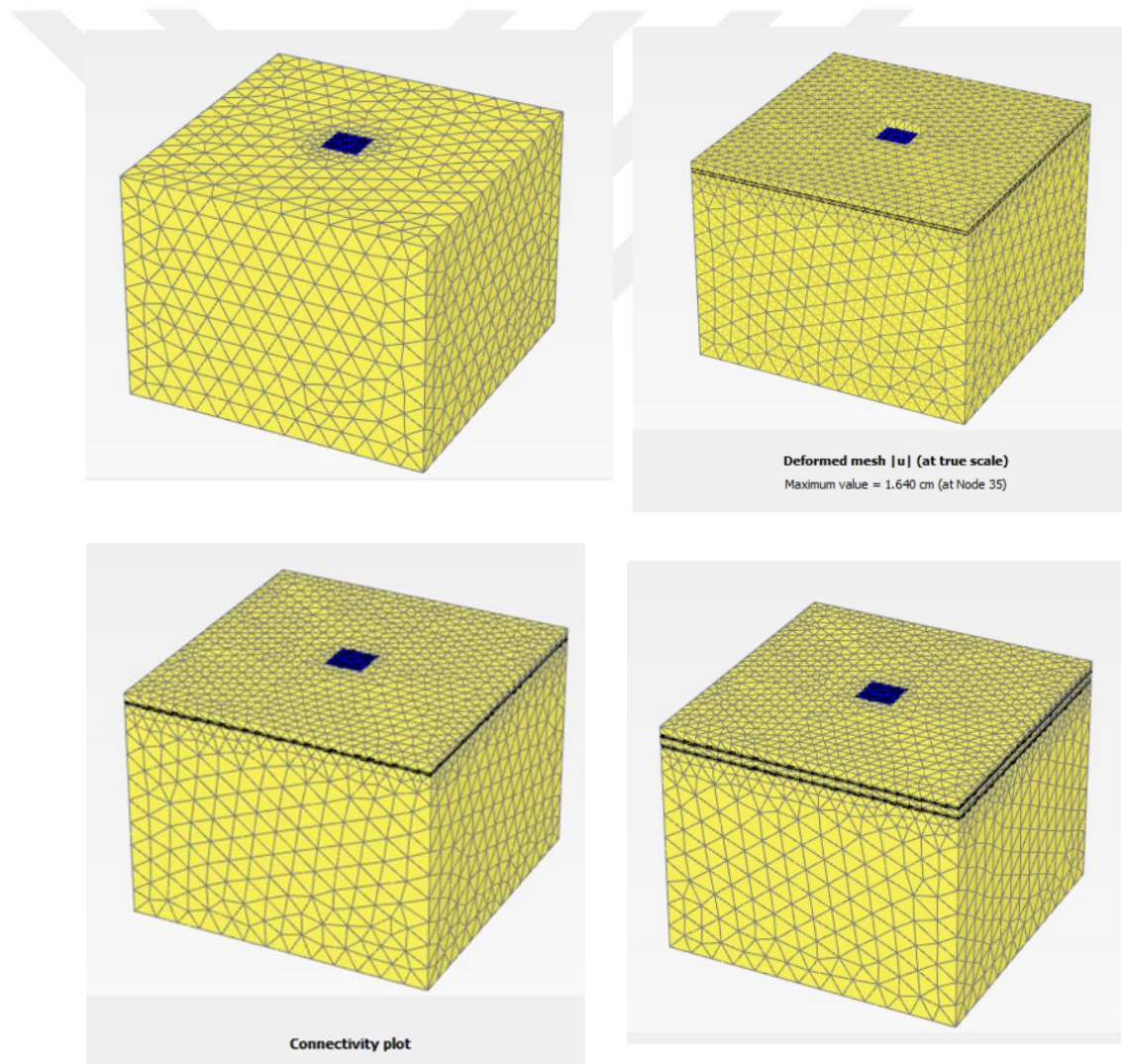


Figure 3.17 PLAXIS 3D finite element mesh

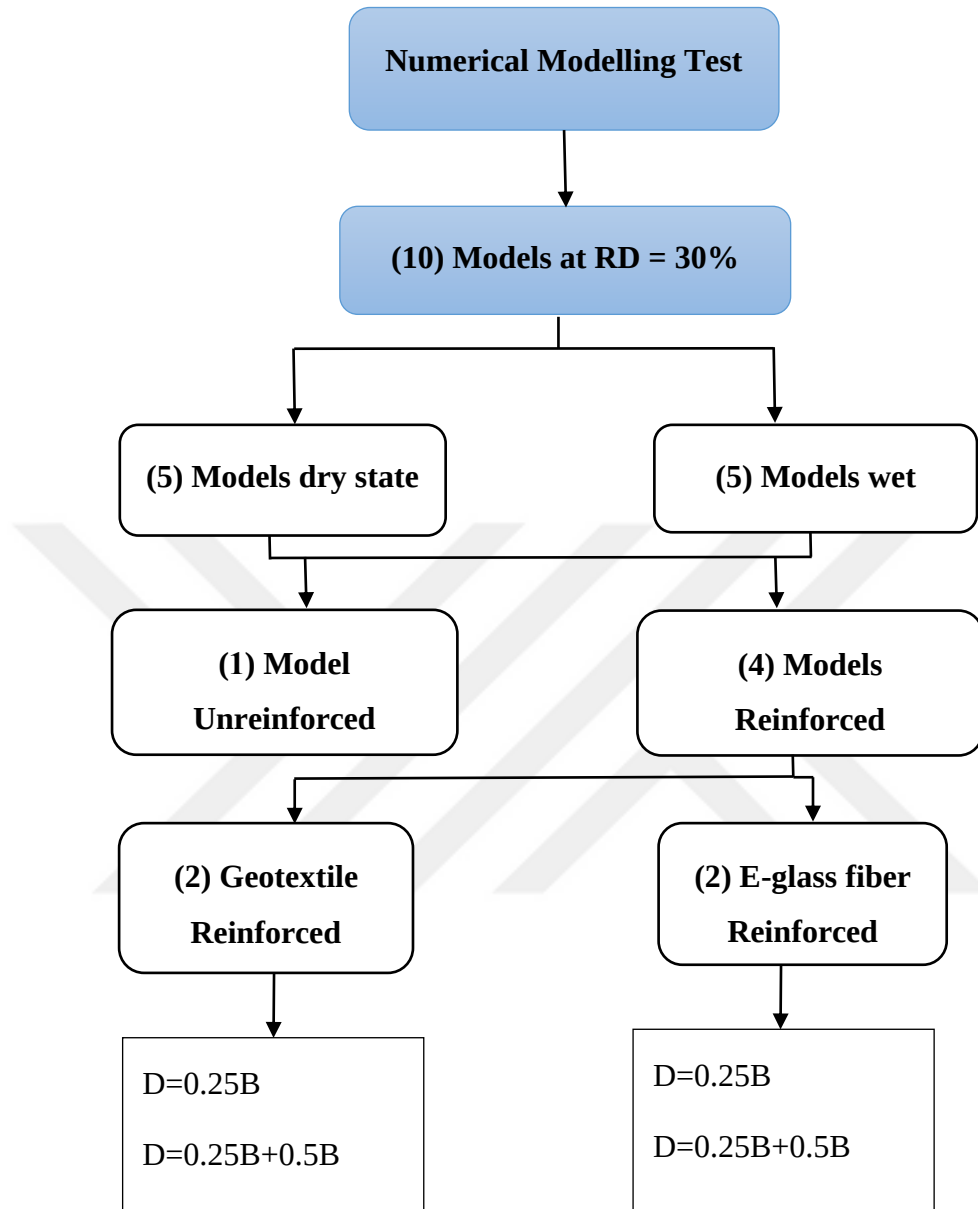


Figure 3.18 Flow chart for numerical modeling in PLAXIS 3D

3.10 Validation PLAXIS Model

It is necessary to verify the numerical model before starting to investigate the problem. In this study, the numerical model of the PLAXIS 3D was verified in two ways, the first with the results of the experimental result of the soil model unreinforced at RD=30% and the second with the research by S. Gupta and A. Mital, (2022) [61].

3.10.1 Validation with Experimental Result

The numerical model has been verified by comparison with the experimental test results of the gypsum soil model with a relative density of 30% in the dry state. Table 3.4 represents the soil properties used in the PLAXIS 3D model. The model was used with dimensions that simulate the experimental model (60 x 60 x 50) cm with the use of the square plate with dimensions (10 x 10) cm to simulate the representation of the shallow foundation, as shown in Figure 3.19.

Figure 3.18 shows the comparison between the results of the experimental work and the numerical model in the PLAXIS 3D software, where there is a great convergence between the results, which gives the impression that the model is validated.

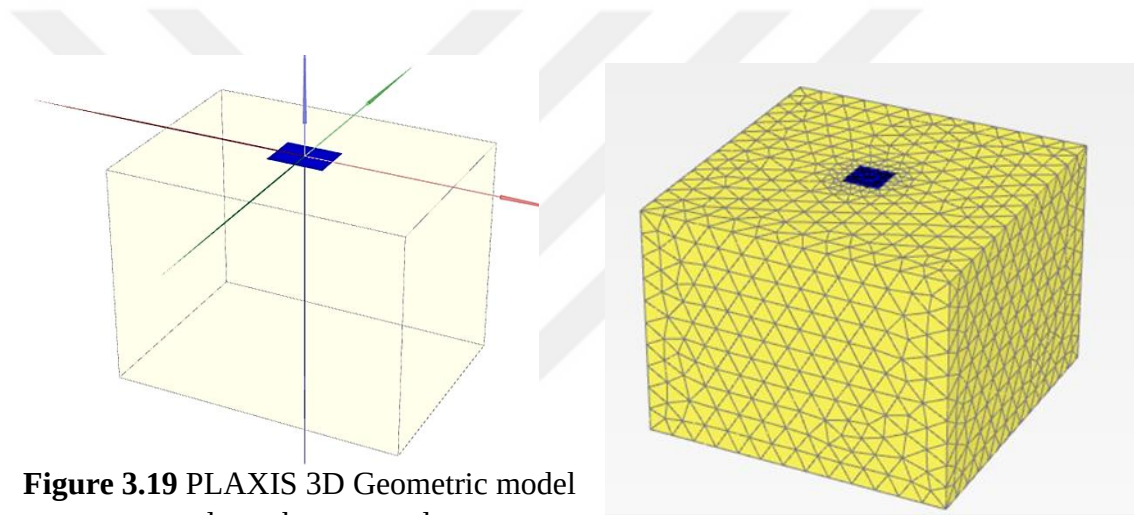


Figure 3.19 PLAXIS 3D Geometric model and mesh generated

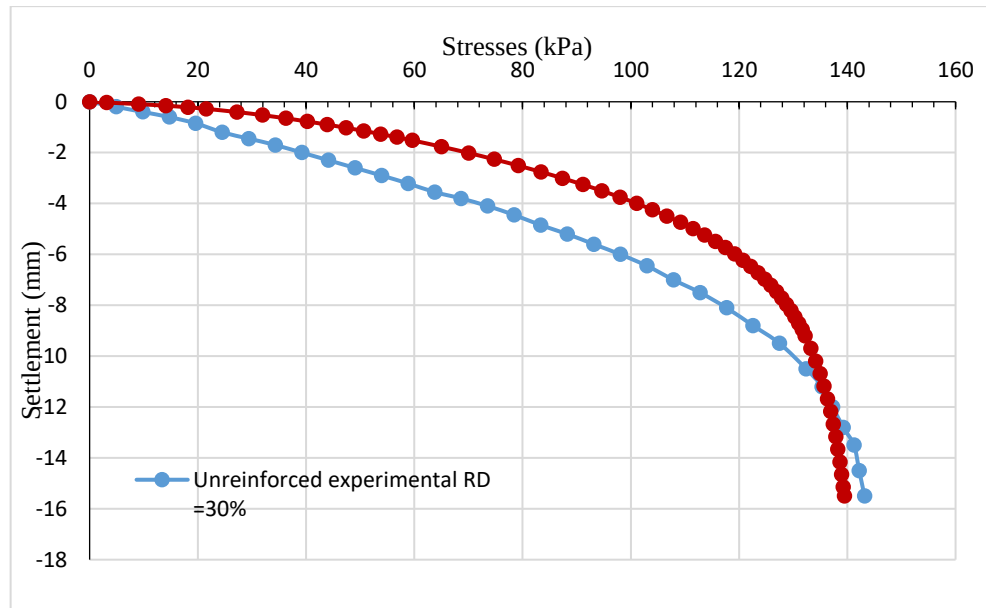


Figure 3.20 Validation PLAXIS 3D model with experimental work of soil at RD=30%

3.10.2 Validation with S. Gupta, (2022)

The numerical analysis model was verified by previous research, where S. Gupta and A. Mital, (2022) [61] conducted a comparative study of the bearing capacity of shallow feet under different loading conditions using the PLAXIS 3D software. The model dimensions were (1.24 x 0.9 x 0.93) m with a dimension of the plate (0.25 x 0.18) m to represent a footing, as shown in Figure 3.21. Materials properties used were as shown in Table 3.5.

Table 3.5 Materials properties used by S. Gupta and A. Mital, (2022)[61]

Parameter	Value
Unit weight of sand (kN/m ³)	15.71
Unit weight of steel (kN/m ³)	78.5
Cohesion, C (kPa)	1
Angle of friction (ϕ^0)	36
ν	0.33
E (kPa), for sand	65×10^3
E (kPa), for steel	20×10^7
ψ^0	6

Figure 3.22 shows the results of the model implemented in the PLAXIS 3D program compared with the results obtained by S.Gupta and A.Mital (2022) for the soil model unreinforced, it can be seen that the results were very similar, and this shows the validation of the model.

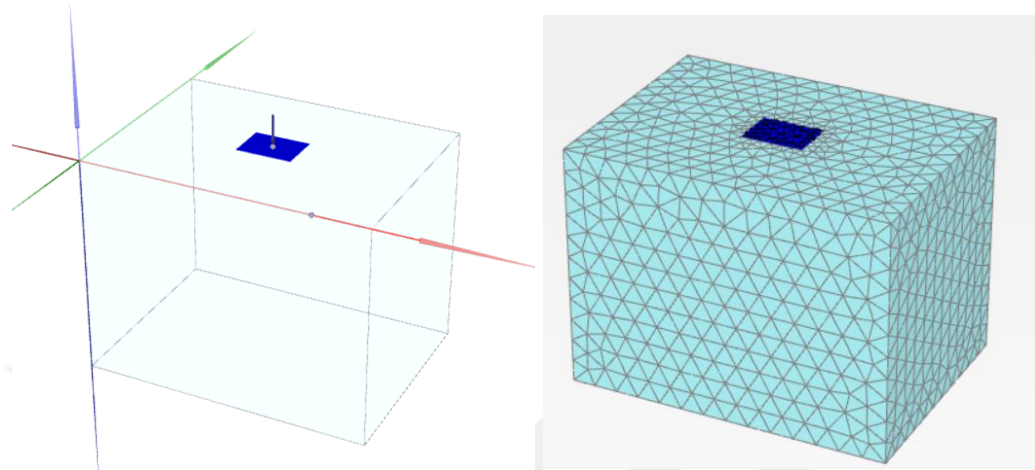


Figure 3.21 PLAXIS 3D Geometric model and mesh generated

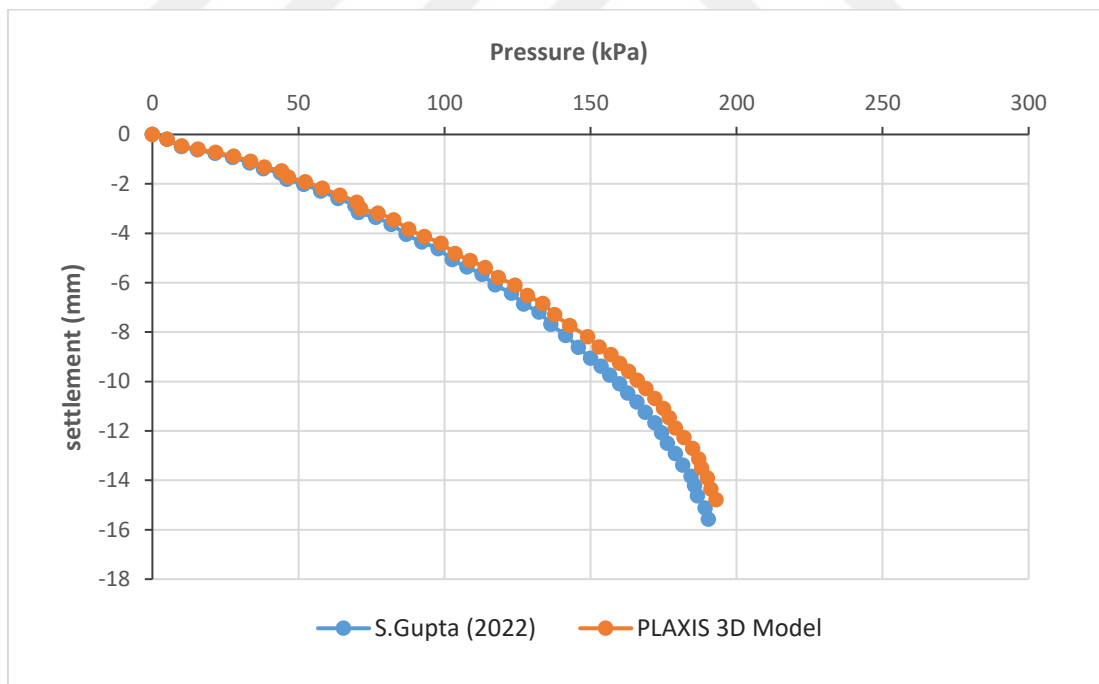


Figure 3.22 Validation PLAXIS 3D model with S.Gupta,(2022) [61]

RESULTS AND DISCUSSION

4.1 Introduction

In this study, (68) models of gypsum soil were tested to find collapse and shear stress under constant vertical pressure in both dry and wet (saturated) conditions. The models were put to the test and reinforced with single, double, and triple layers of two types from the geosynthetic Introduction material (geotextiles and E-glass fiber fabric) at different (depths, and shapes), as shown in Figure (3.5), and 10 models were analyzed of gypseous soil model at $RD = 30\%$ by finite element program (PLAXIS 3D).

According to ASTM D1194-94, soil sample failure can be estimated when the load leads to a 10% settlement of the width of the foundation. The following are the major subjects discussed in this chapter:

1. The ultimate bearing capacity was determined using the two tangent intersection approach for gypsum soil models in the dry and saturation conditions according to the load vs settlement correlations curves.
2. The results discussed how the number of geosynthetic reinforcing layers affected the bearing capacity improvement ratio (BCR%) of gypsum soil at various patterns and compare the types of reinforced (geotextile and E-glass fiber fabric) and the shape of the geosynthetic reinforced layer.
3. Discussion of the effect of the number of geosynthetic reinforcement layers on the Improvement ratio in bearing capacity of gypseous soil at different patterns.
4. Numerical analysis, finite element software (PLAXIS 3D) was used to represent the behavior of gypsum soil under the foundation of relative density 30%.

4.2 Results of Load-Settlement Relationship of Models at $RD = 30\%$, 60% (dry and fully saturation state)

From the results of the stress-settlement curves, the ultimate bearing capacity value of the reinforced gypseous soil model was calculated by two types of geosynthetic material (geotextile and E-glass fiber fabric) using the two tangent intersection method, three different thicknesses of geosynthetic reinforcement layers were used: a single layer at a depth of (0.25B, 0.5B, and 1B), a double layer at a depth of (0.25B+0.5B, and 0.5B+1B)

and a triple layer at a depth of $(0.25B+0.5B+1B)$, and $0.5B+1B+1.5B$), also were used the U-shape reinforced for a triple layer at depth of $(0.25B+0.5B+1B)$.

The behavior of reinforcing soil under incremental loads can be shown to increase nonlinearly until the stress-settlement curve makes a sharp bend, at which point the load applied begins to stabilize concurrently with the increase in settlement. The soil begins to weaken at this point. A general shear failure occurred there.

4.2.1 Determine Ultimate Bearing Capacity of Gypseous Soil Models at RD= 30% for Dry State

Figures 4.1 to 4.3 show the stress-settlement experimental results for gypseous soil models in a dry state with a relative density (30%) after treating the soil with geosynthetic reinforcement (geotextile and E- glass fiber) at different layers (single, double and triple) with different depths.

Figures (4.4) to (4.18) illustrate the ultimate bearing capacity for unreinforced and reinforced models based on the results of experimental work using the method of two tangents intersection, these results demonstrated that the values of the settlement increase as the load increases to the point where the settlement increases while the load magnitude approximately constant. This can be taken as an indication that the soil is starting to fail. Where the final values of bearing capacity of the soil model increased from 130 kN/m² for the unreinforced model to (195,188,164)kN/m² and (245,225,190) kN/m² for single-layer reinforcement soil models at a depth $(0.25B, 0.5B, 1B)$, to geotextile reinforcement, and for E-glass fiber fabric respectively, while when using the double layers reinforcement at a depth $(0.25B+0.5B, 0.5B+1B)$ the value of ultimate bearing capacity increased to (245,200) kN/m² for geotextile reinforcement and (366,315) kN/m² for E-glass fiber fabric, and reinforcement by triple layers at a depth $(0.25B+0.5B+1B, 0.5B+1B+1.5B)$ the value of ultimate bearing capacity was (300,257) kN/m² for geotextile and (431,390) kN/m² for E-glass fiber fabric. The results indicate that the maximum value of ultimate bearing capacity when using the single layer reinforcement was (195,245) kPa for geotextile and Eglass fiber fabric reinforcement at $D = 0.25 B$, and the minimum value was (164, 190) kPa at $D = 1B$, while the maximum value when using the double layer reinforcement was (245, 366) kPa at $D = (0.25B+0.5B)$ for geotextile and E-glass fiber reinforced respectively, and when using triple layers reinforced the maximum value of ultimate bearing capacity was (300, 431) kPa at $D=0.25B+0.5B+1B$

for geotextile and E-glass fiber reinforced respectively. According to these results, the value of bearing capacity increased from 130 kPa for the unreinforced model to (300, 431) kPa when using geotextile and E-glass fiber reinforcement respectively, at $D = (0.25B+0.5B+1B)$.

The use of geosynthetic material (geotextile and E-glass fiber fabric) in gypsum soil with 47% gypsum content increased the bearing capacity, and soil structure stability is achieved by maintaining the cementation connection between soil particles and reducing deformation. Geotextile and E-glass fiber reinforcement provides a higher total resistance and vertical confinement, both of which increase friction between soil particles and the geosynthetic material. Furthermore, accordingly, with geosynthetic function, soil can become stiffer and more resistant to shear caused by transmitted stress from the foundation.

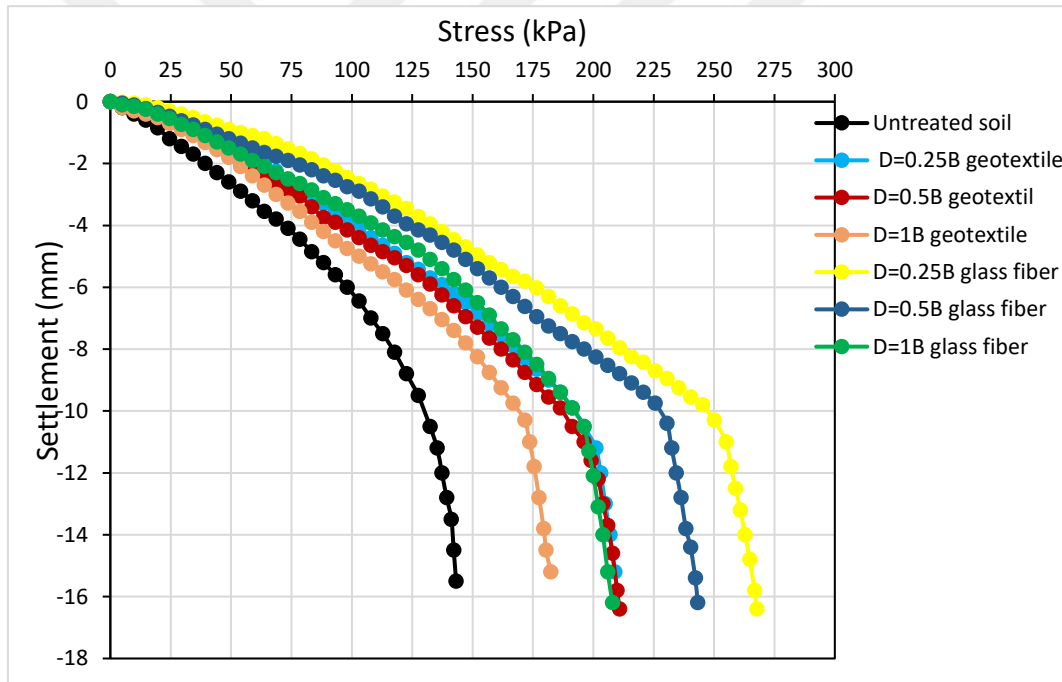


Figure 4.1 Stress - settlement curve for soil model reinforced by single layers for RD=30% (dry state)

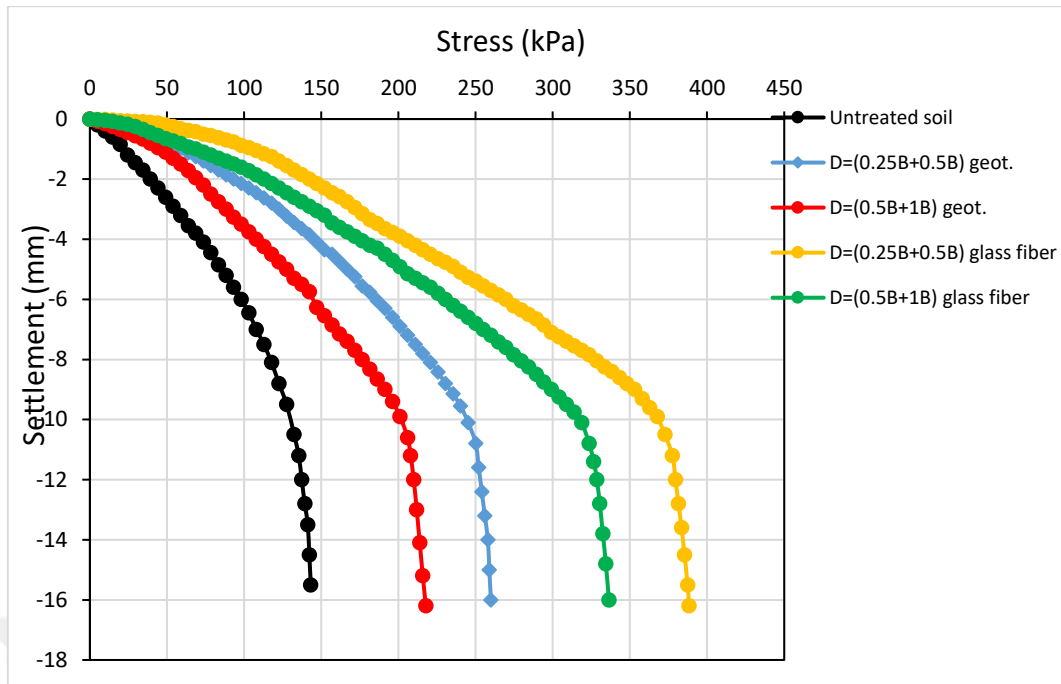


Figure 4.2 Stress - settlement curves for soil model reinforced by double layers for RD=30% (dry state)

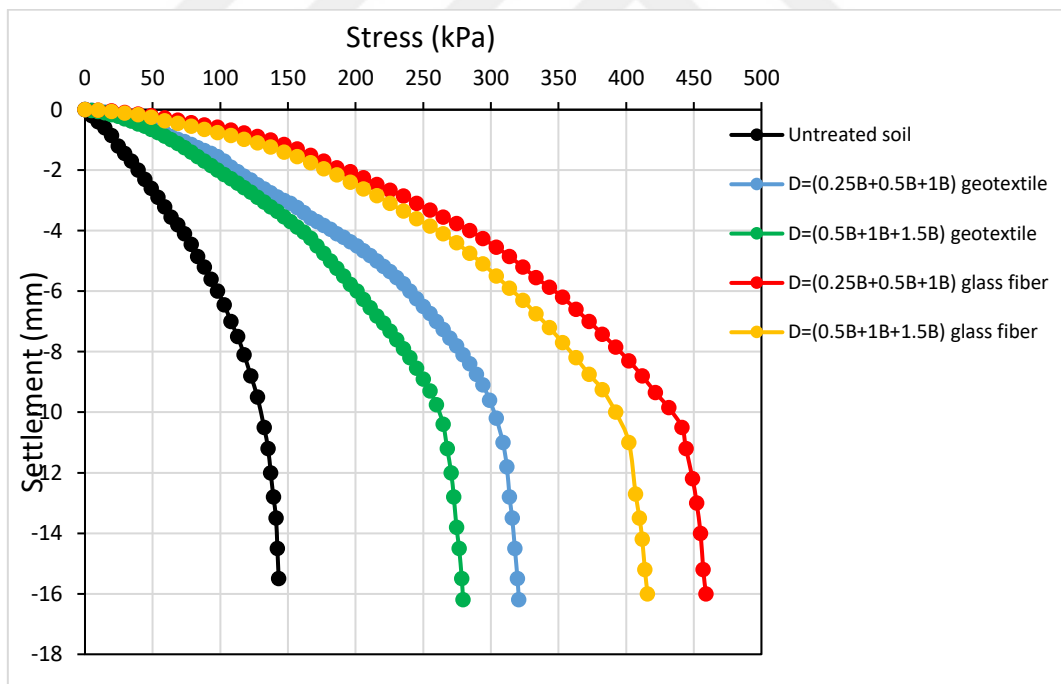


Figure 4.3 Stress-settlement curves for soil model reinforced by triple layers for RD=30% (dry state)

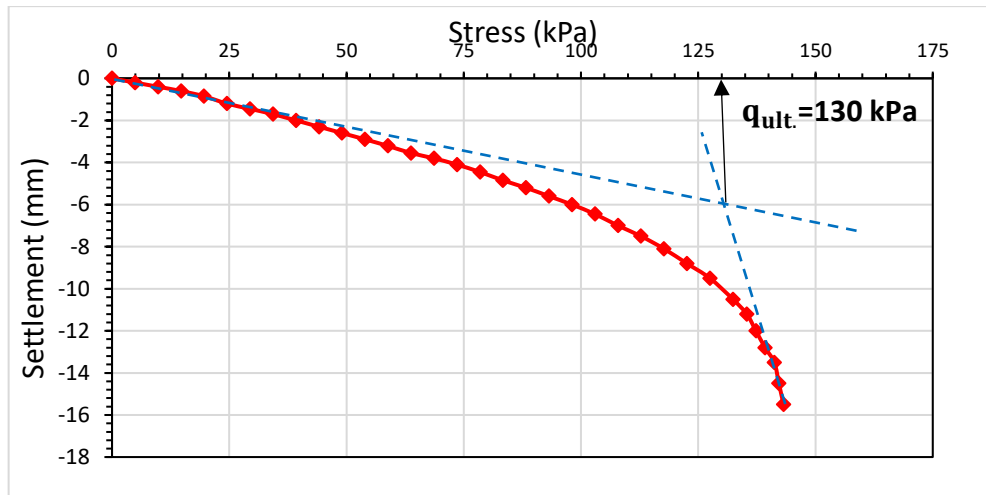


Figure 4.4 Stress - settlement curve for unreinforced soil model at RD=30% (dry state)

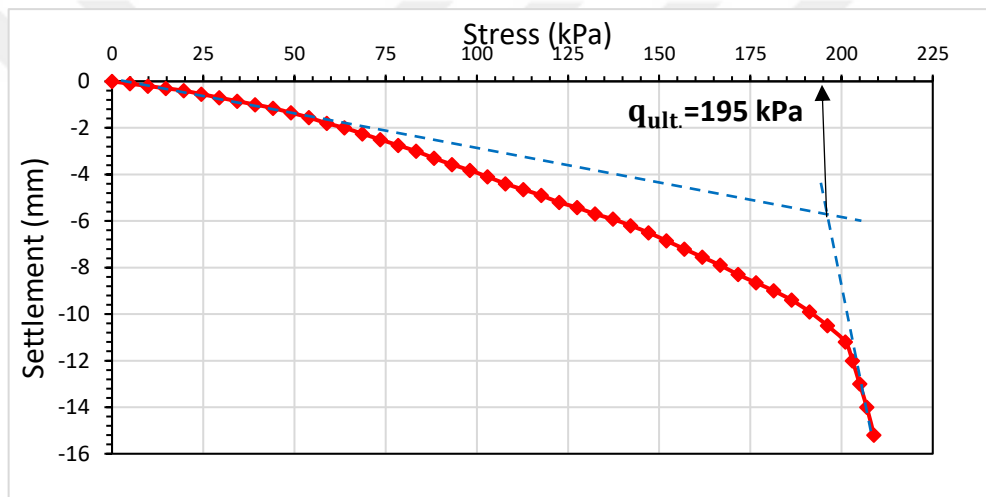


Figure 4.5 Stress - settlement curve for geotextile reinforced soil model at D=0.25B for RD=30% (dry state)

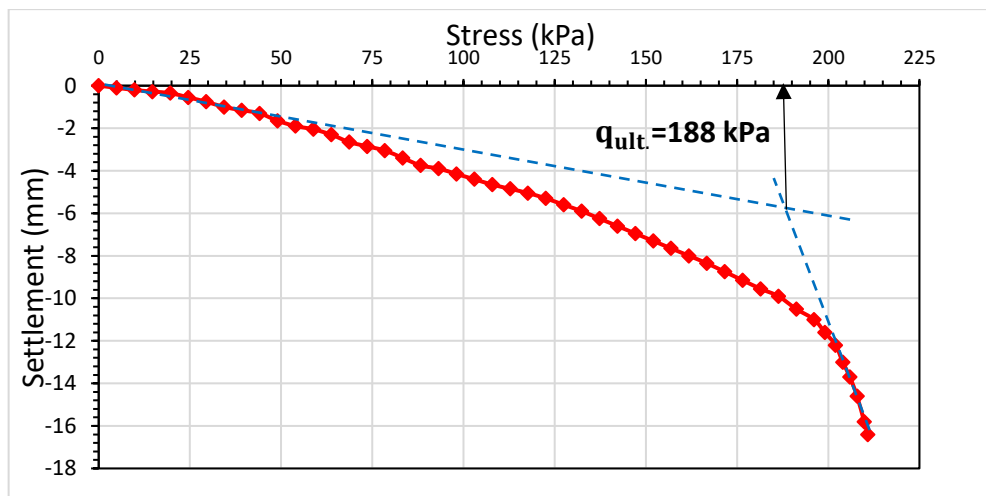


Figure 4.6 Stress - settlement curve for geotextile reinforced soil model at D=0.5B for RD=30% (dry state)

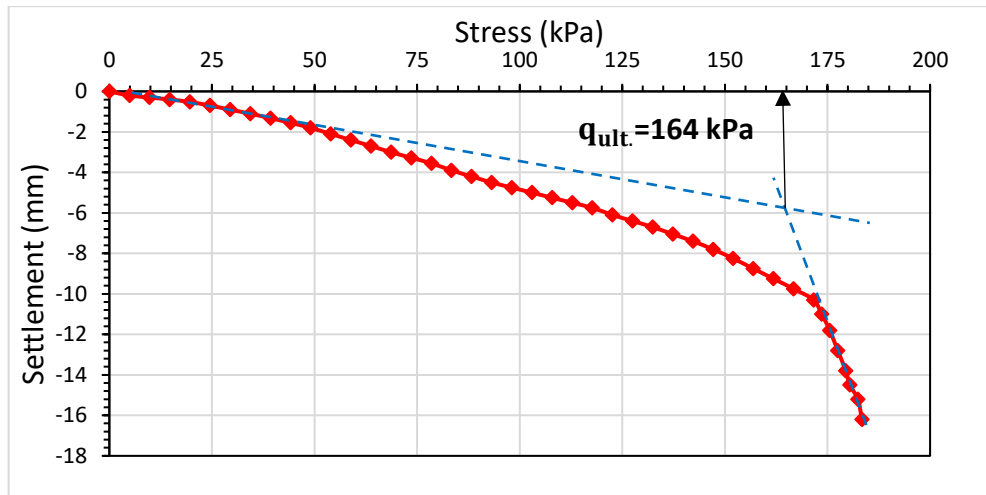


Figure 4.7 Stress - settlement curve for geotextile reinforced soil model at $D=1B$ for $RD=30\%$ (dry state)

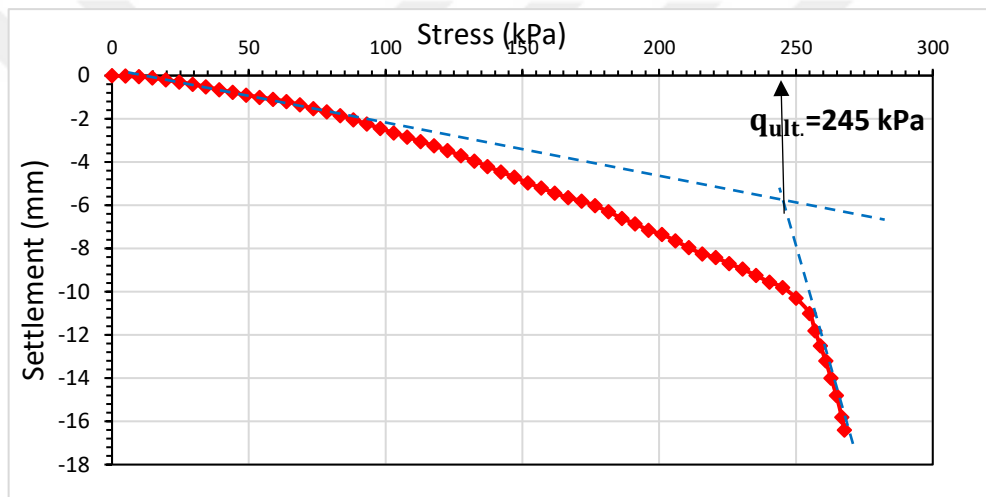


Figure 4.8 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.25B$ for $RD=30\%$ (dry state)

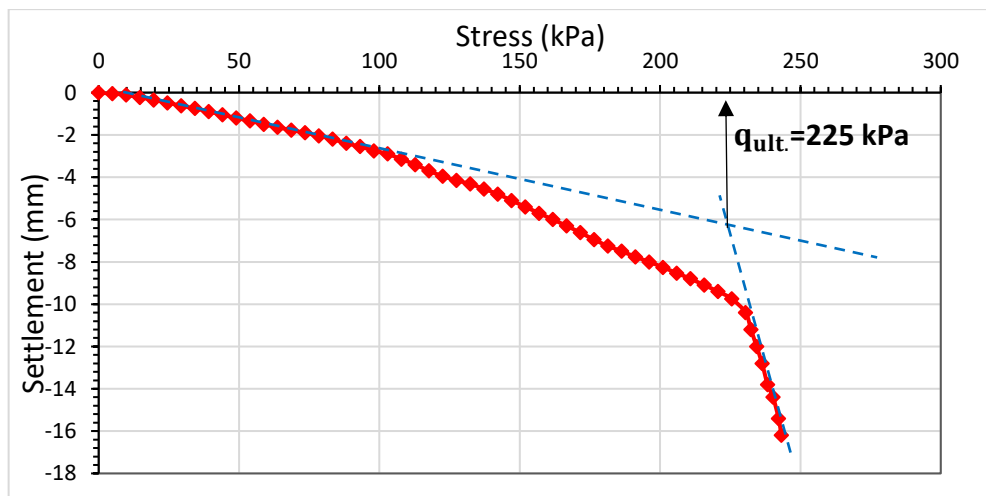


Figure 4.9 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.5B$ for $RD=30\%$ (dry state)

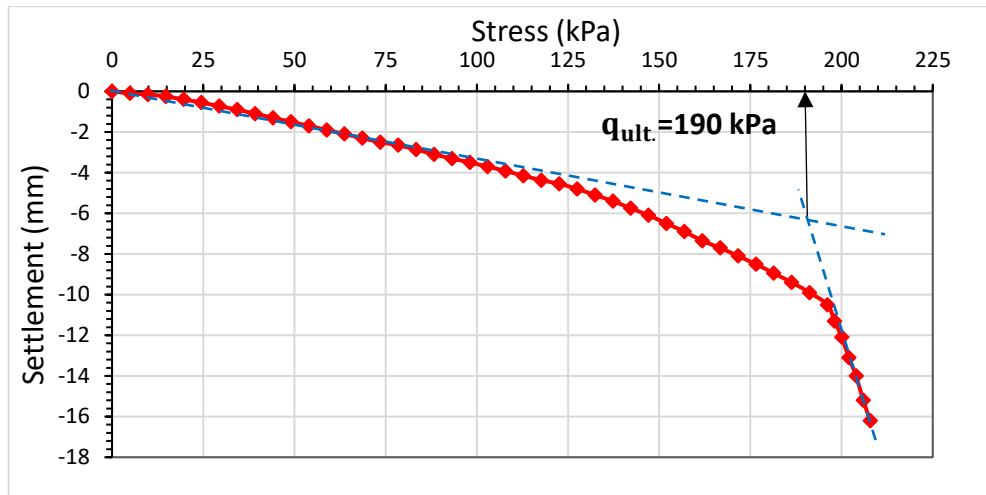


Figure 4.10 Stress - settlement curve for E-glass fiber reinforced soil model at $D=1B$ for $RD=30\%$ (dry state)

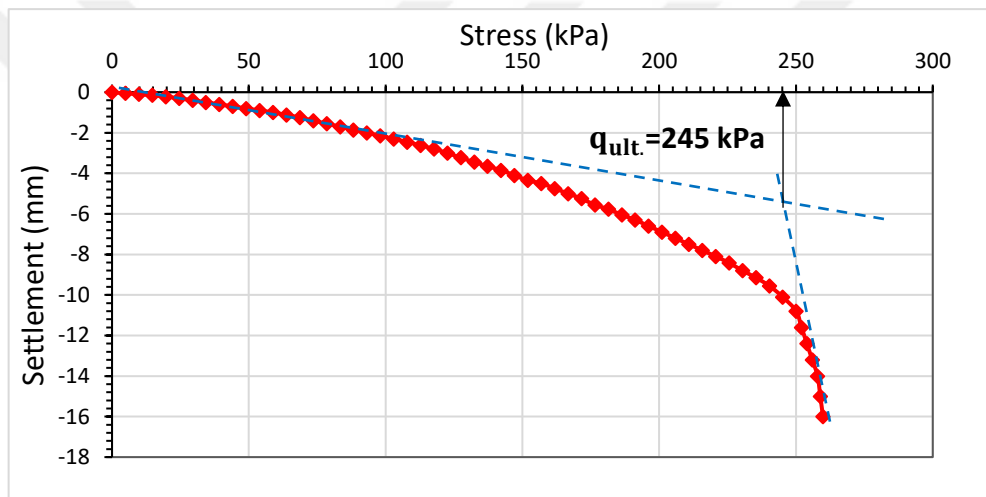


Figure 4.11 Stress - settlement curve for geotextile reinforced soil model at $D=0.25B+0.5B$ for $RD=30\%$ (dry state)

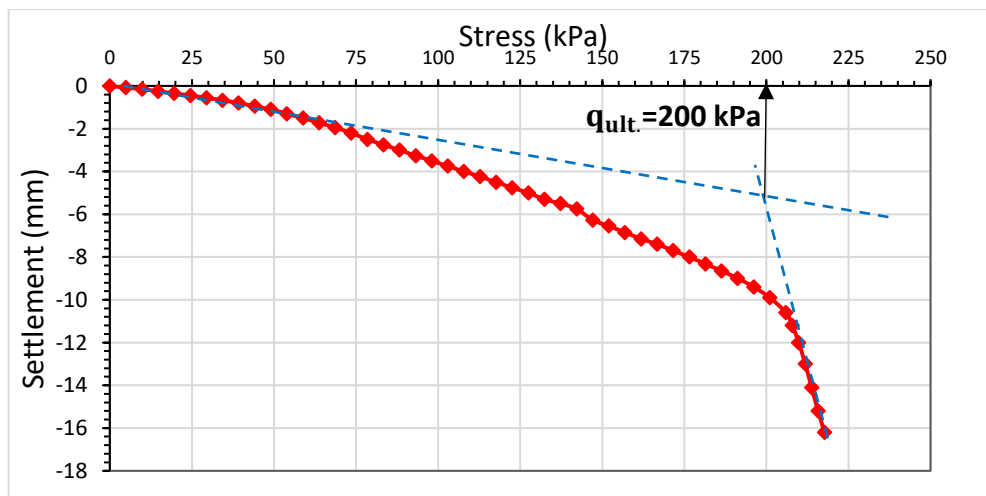


Figure 4.12 Stress - settlement curve for geotextile reinforced soil model at $D=0.5B+1B$ for $RD=30\%$ (dry state)

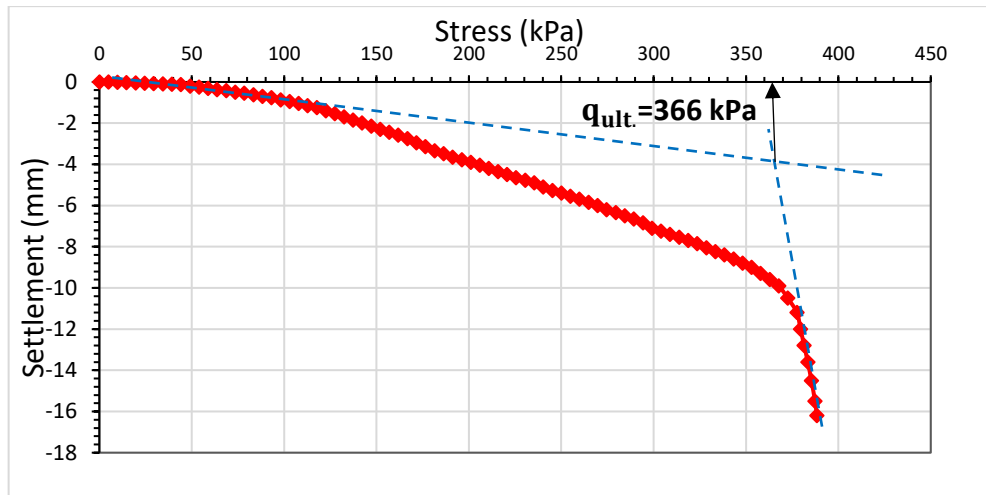


Figure 4.13 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.25B+0.5B$ for $RD=30\%$ (dry state)

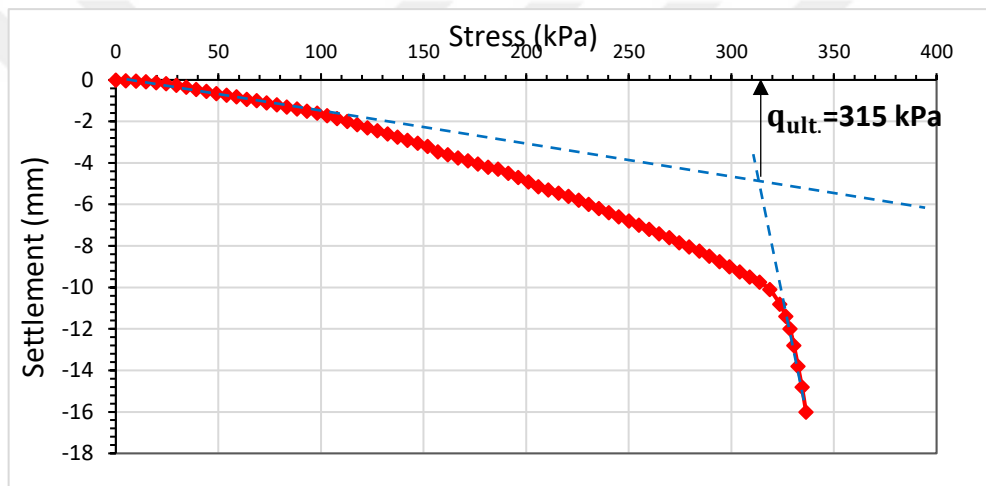


Figure 4.14 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.5B+1B$ for $RD=30\%$ (dry state)

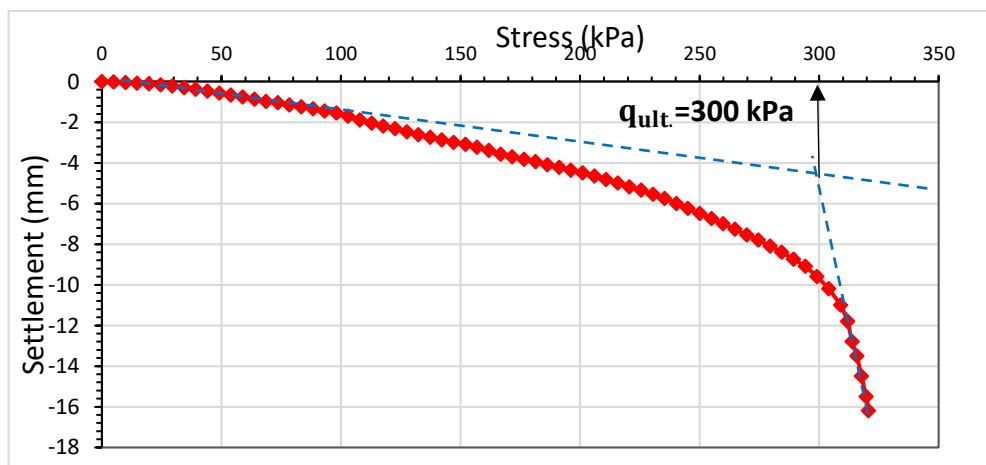


Figure 4.15 Stress - settlement curve for geotextile reinforced soil model at $D=0.25B+0.5B+1B$ for $RD=30\%$ (dry state)

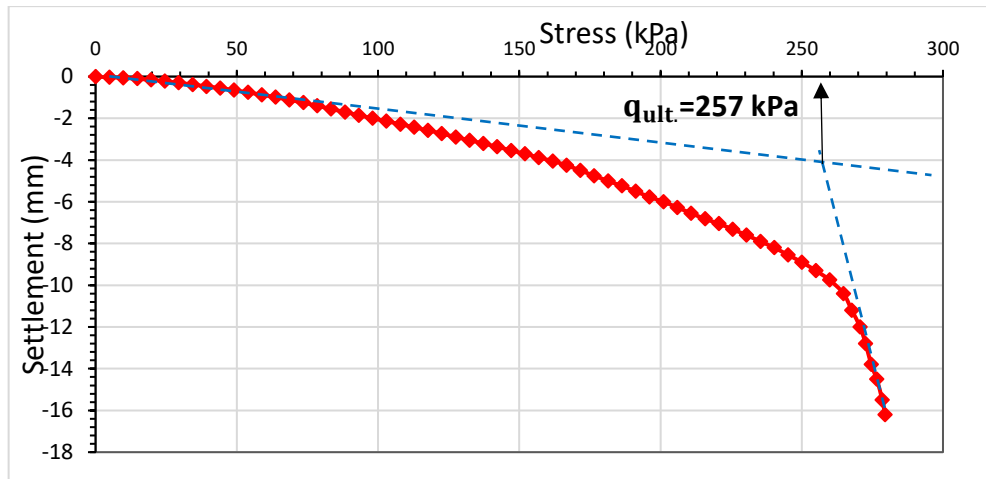


Figure 4.16 Stress - settlement curve for geotextile reinforced soil model at $D=0.5B+1B+1.5B$ for $RD=30\%$ (dry state)

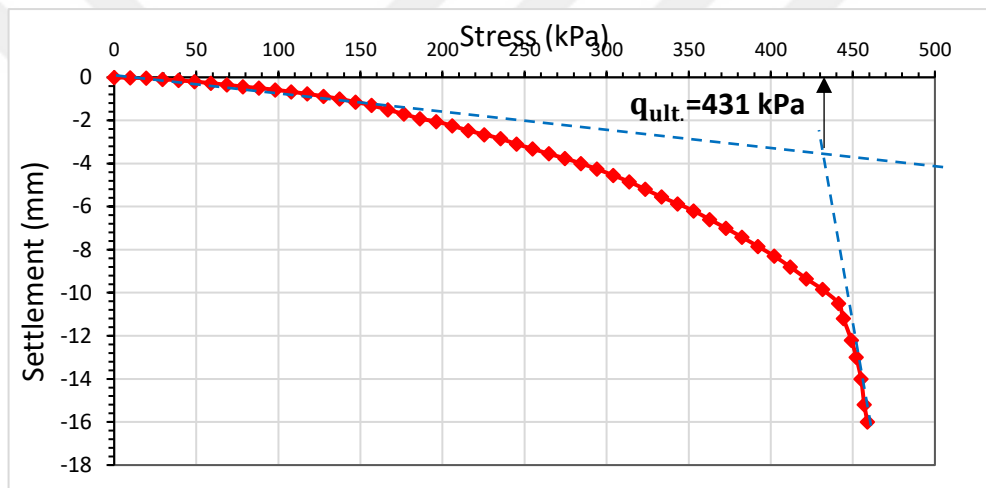


Figure 4.17 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.25B+0.5B+1B$ for $RD=30\%$ (dry state)

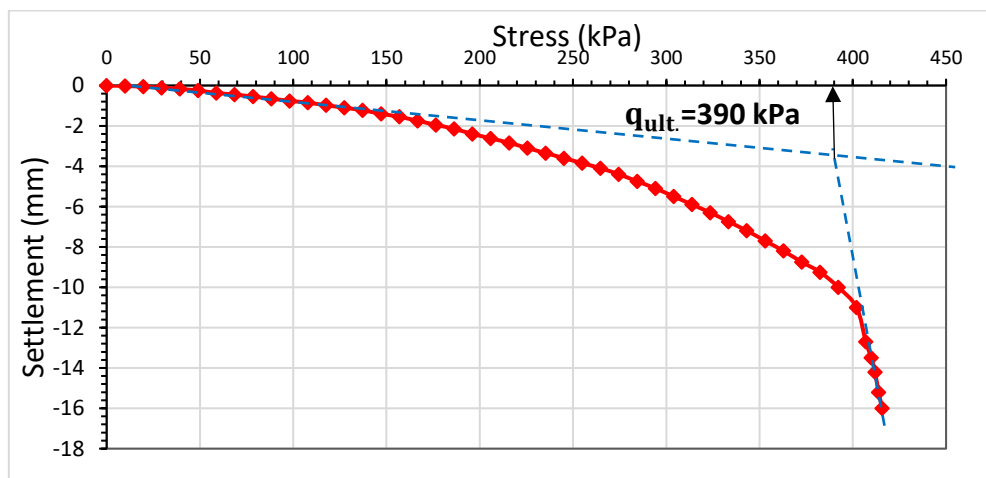


Figure 4.18 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.5B+1B+1.5B$ for $RD=30\%$ (dry state)

Figures (4.19) to (4.21) illustrate the amount of ultimate bearing capacity for using the U-shape reinforcement models and a striate layer of triple layers ($0.25B+0.5B+1B$) at an $RD = 30\%$.

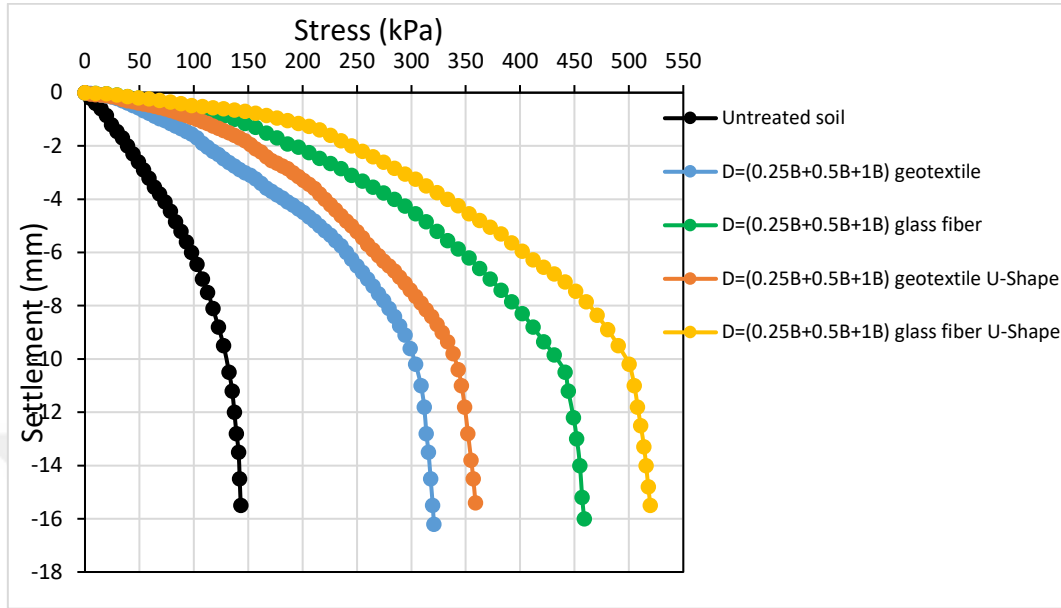


Figure 4.19 Stress-settlement curves for soil model reinforced U-shape and straight by triple layers for $RD=30\%$ (dry state)

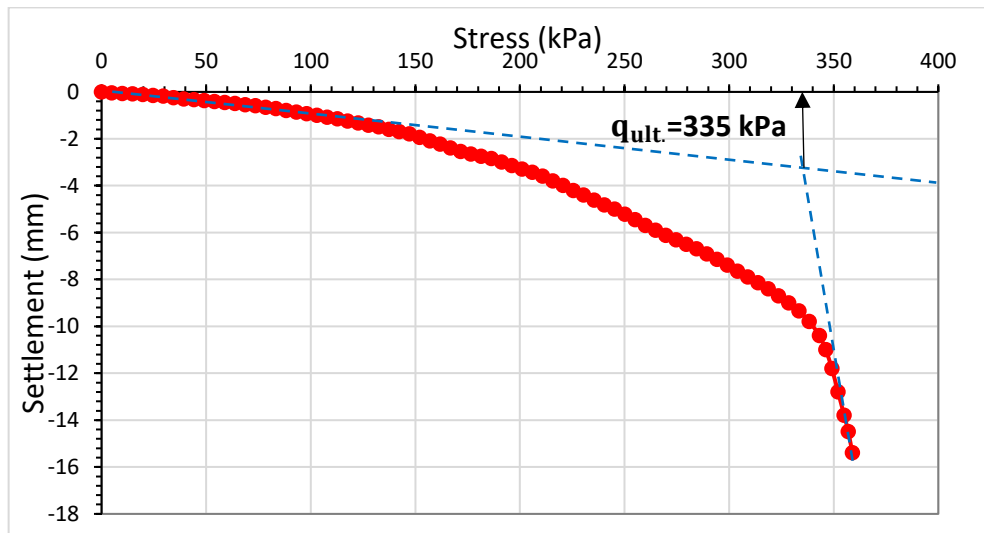


Figure 4.20 Stress - settlement curve for U-shape geotextile reinforced soil model at $D=0.25B+0.5B+1B$ for $RD=30\%$ (dry state)

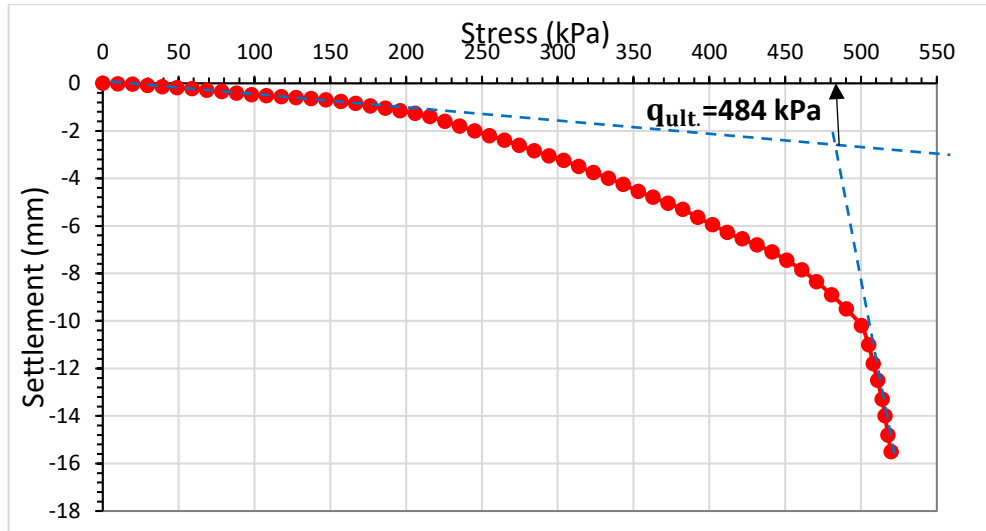


Figure 4.21 Stress - settlement curve for U-shape E-glass fiber reinforced soil model at $D=0.25B+0.5B+1B$ for $RD=30\%$ (dry state)

4.2.2 Determine Ultimate Bearing Capacity of Gypsum Soil Models at $RD= 60\%$ for Dry State

Figures 4.22 to 4.24 show the stress-settlement experimental results for soil models in a dry state with a relative density (60%) after reinforcing by geotextile and E-glass fiber fabric with different patterns (single, double, and triple) at different depths.

Figures (4.25) to (4.39) show the ultimate bearing capacity values for the unreinforced and reinforced models based on the results of the experimental work using the method of two tangents intersection. Where the final values of the bearing capacity of the soil model increased from 230 kN/m^2 for the unreinforced model to $(330, 310, 290) \text{ kN/m}^2$ for geotextiles, and $(400, 385, 348) \text{ kN/m}^2$ for E-glass fiber fabric using a single-layer reinforcement soil models at a depth of $(0.25b, 0.5b, 1b)$ respectively, when using double layer reinforcement at the depth $(0.25B + 0.5B, 0.5B + 1B)$ the ultimate bearing capacity increased to $(392, 360) \text{ kN/m}^2$ for geotextile and $(482, 425) \text{ kN/m}^2$ for E-glass fiber fabric respectively, and when using triple layers reinforcement at a depth $(0.25B+0.5B+1B, 0.5B+1B+1.5B)$ the value increased to $(518, 488) \text{ kN/m}^2$ for geotextile and $(600, 542) \text{ kN/m}^2$ for E-glass fiber fabric. The results indicate that the maximum value of ultimate bearing capacity when using the single layer reinforced was $(330, 400) \text{ kPa}$ for geotextile and E-glass fiber fabric at depth $D=0.25B$, and the minimum value was $(290, 348) \text{ kPa}$ at $D = 1B$, while the maximum value when using the double layer reinforced was $(392, 482) \text{ kPa}$ at $D = (0.25B+0.5B)$ for geotextile and E-glass fiber reinforced respectively, and

when using triple layers reinforced the maximum value of ultimate bearing capacity was (518, 600) kPa at $D=0.25B+0.5B+1B$ for geotextile and E-glass fiber reinforced respectively.

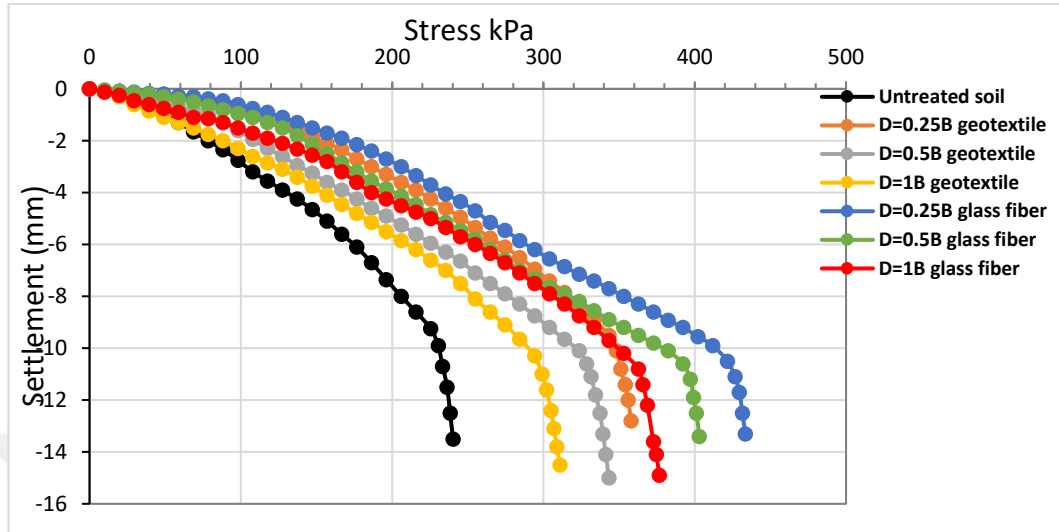


Figure 4.22 Stress-settlement curves for soil model reinforced by single layers for RD=60% (dry state)

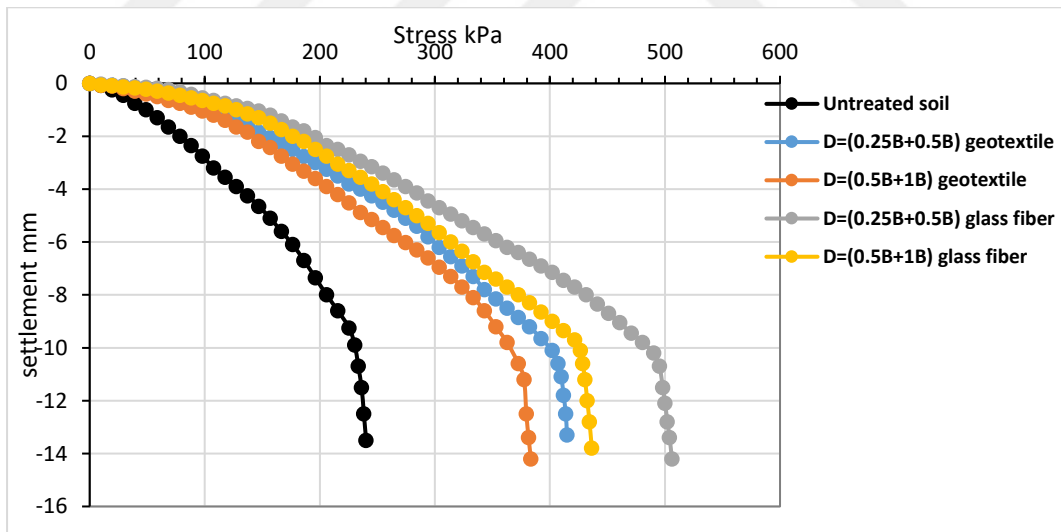


Figure 4.23 Stress-settlement curves for soil model reinforced by double layers for RD=60% (dry state)

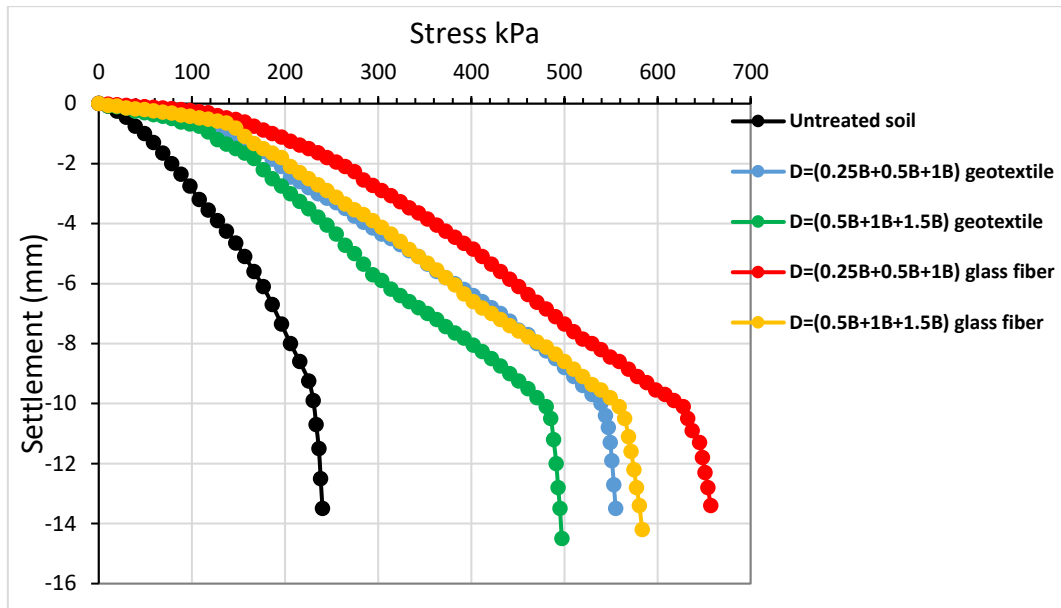


Figure 4.24 Stress - settlement curves for soil model reinforced by (triple layers) for RD=60% (dry state)

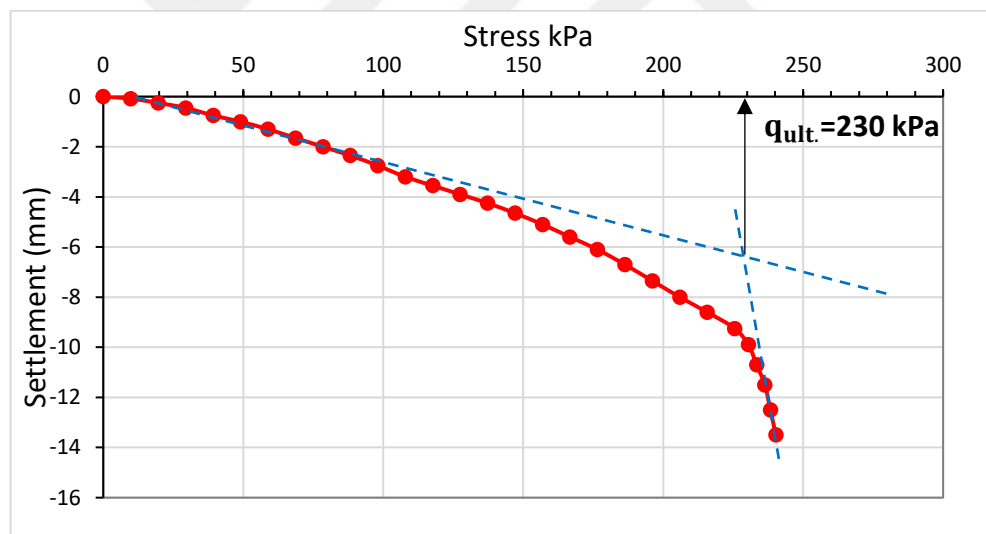


Figure 4.25 Stress - settlement curve for unreinforced soil model for RD=60% (dry state)

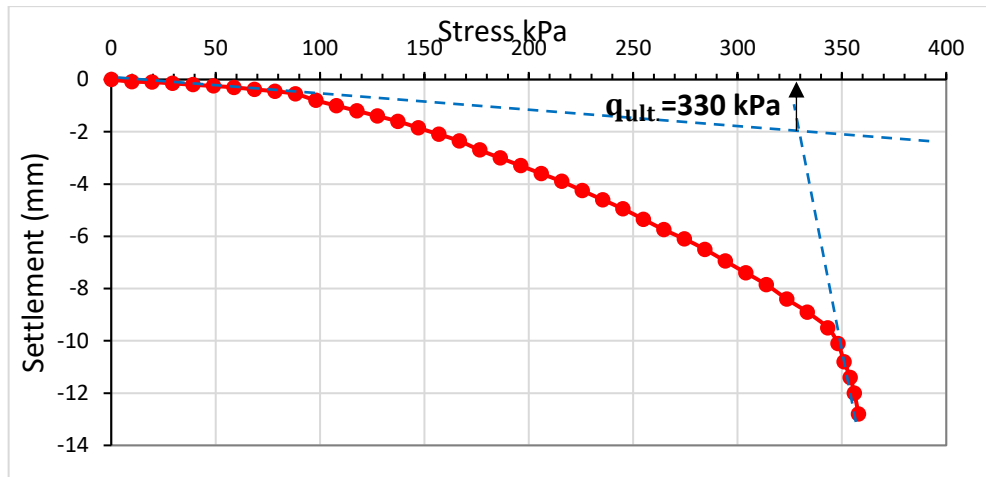


Figure 4.26 Stress - settlement curve for geotextile reinforced soil model at $D=0.25B$ for $RD=60\%$ (dry state)

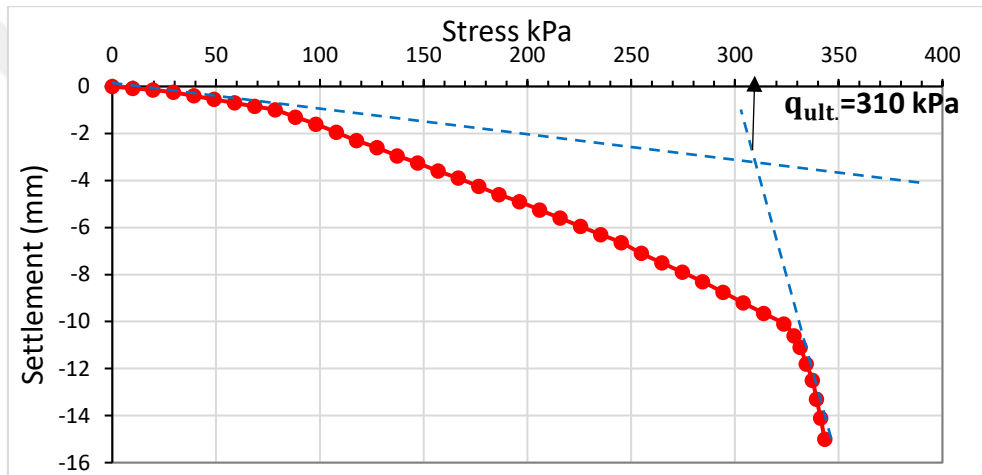


Figure 4.27 Stress - settlement curve for geotextile reinforced soil model at $D=0.5B$ for $RD=60\%$ (dry state)

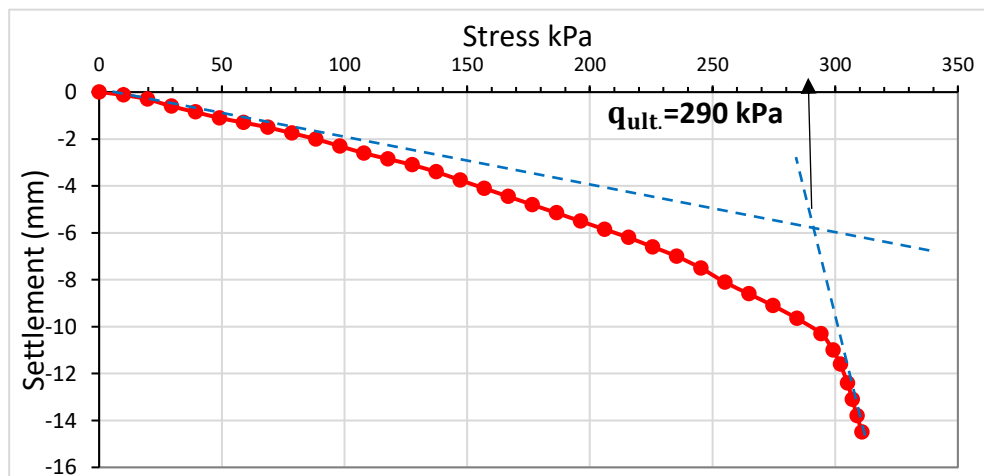


Figure 4.28 Stress - settlement curve for geotextile reinforced soil model at $D=1B$ for $RD=60\%$ (dry state)

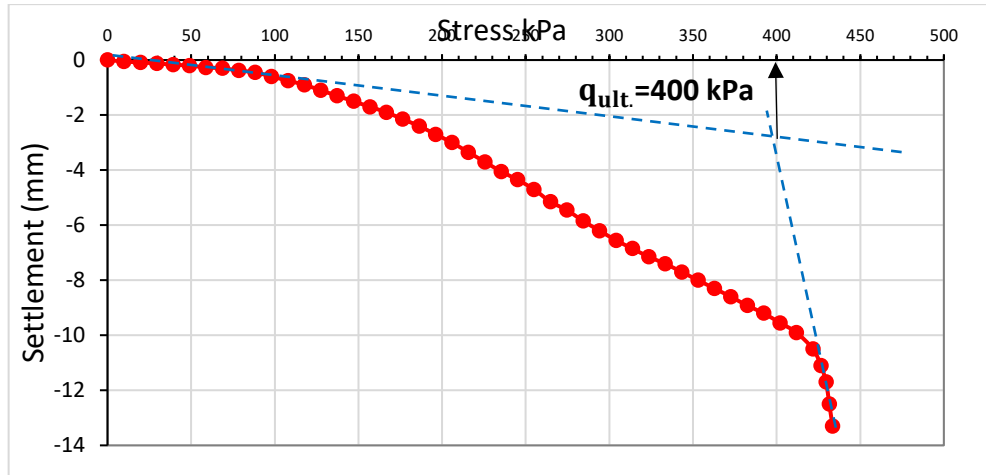


Figure 4.29 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.25B$ for $RD=60\%$ (dry state)

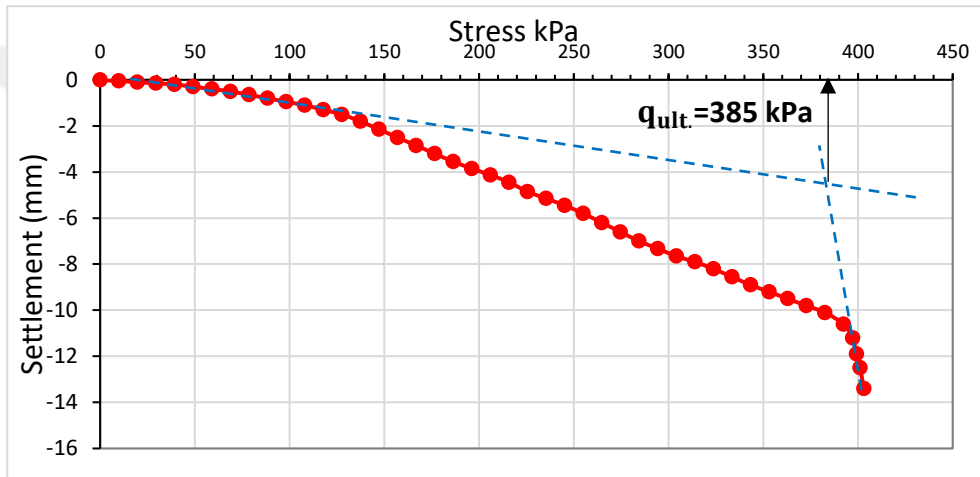


Figure 4.30 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.5B$ for $RD=60\%$ (dry state)

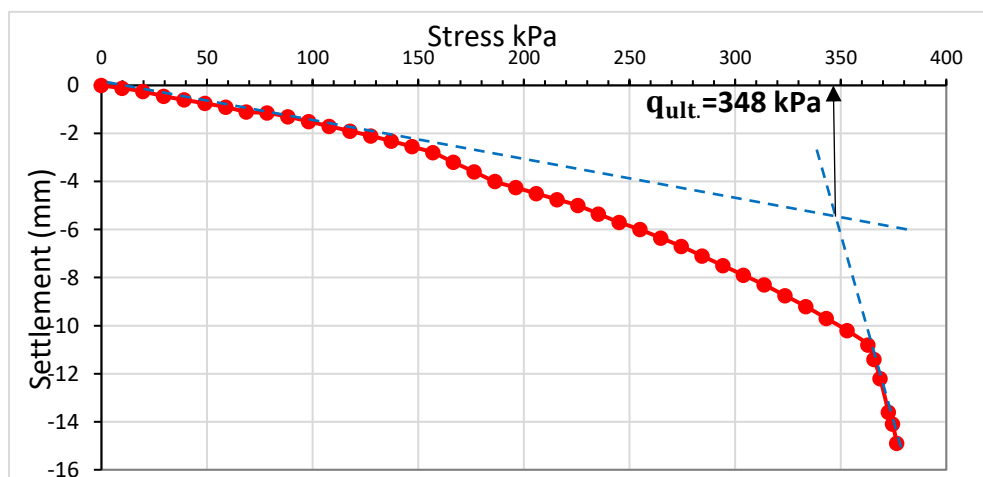


Figure 4.31 Stress - settlement curve for E-glass fiber reinforced soil model at $D=1B$ for $RD=60\%$ (dry state)

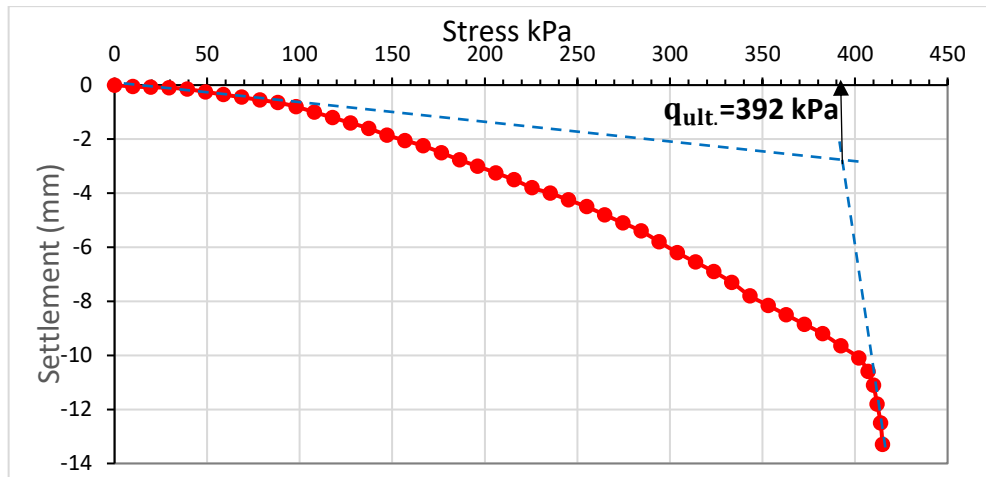


Figure 4.32 Stress - settlement curve for geotextile reinforced soil model at $D=0.25B+0.5B$ for $RD=60\%$ (dry state)

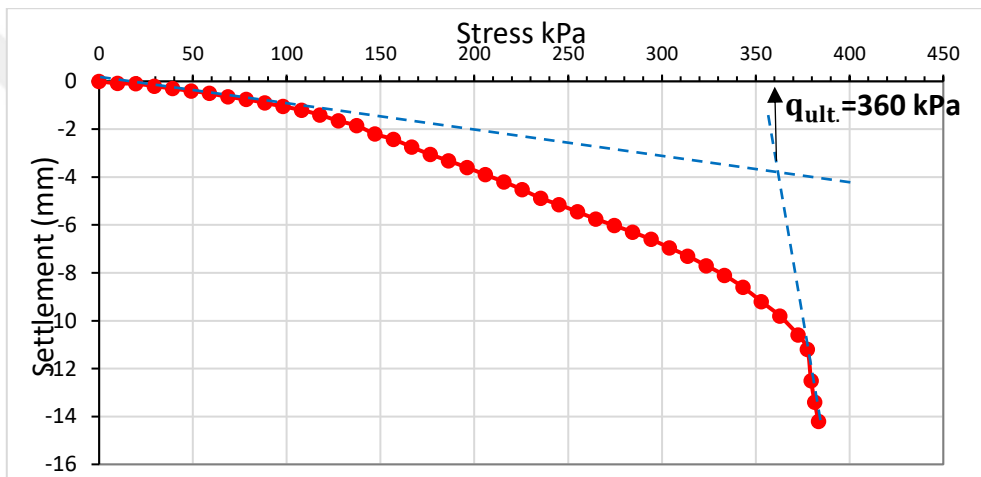


Figure 4.33 Stress - settlement curve for geotextile reinforced soil model at $D=0.5B+1B$ for $RD=60\%$ (dry state)

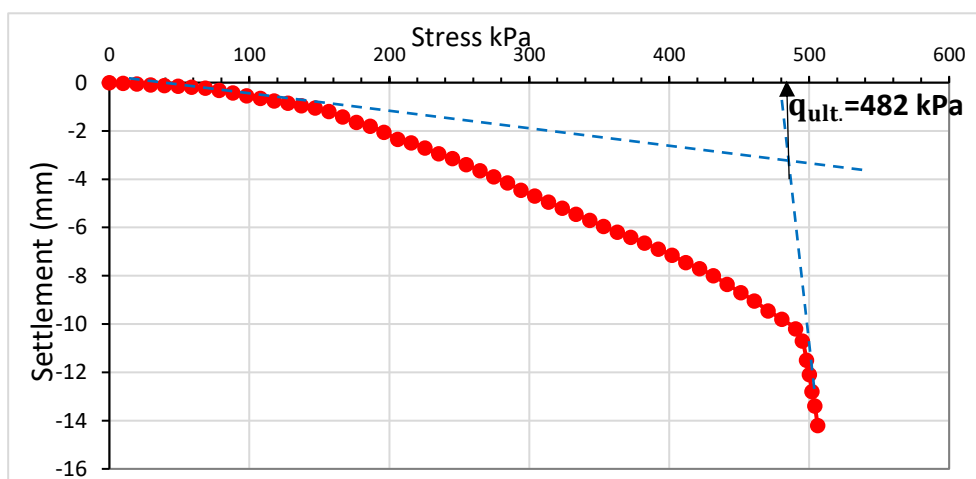


Figure 4.34 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.25B+0.5B$ for $RD=60\%$ (dry state)

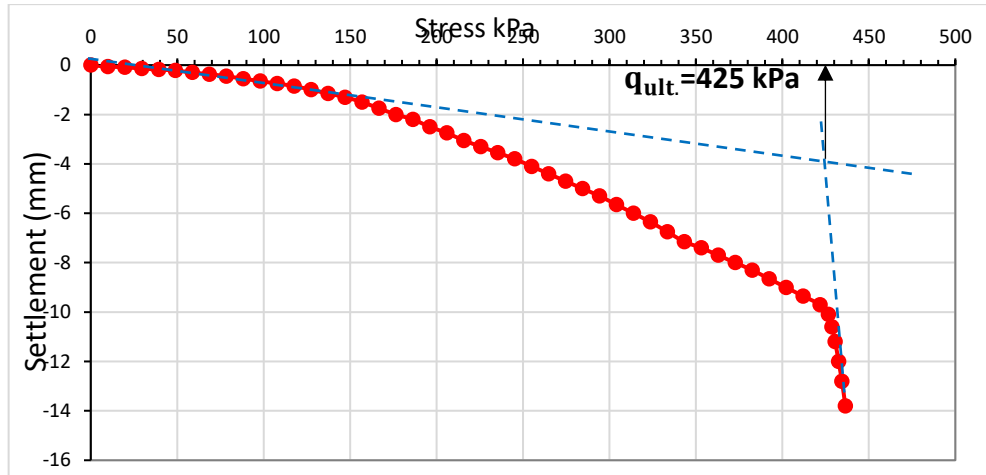


Figure 4.35 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.5B+1B$ for RD=60% (dry state)

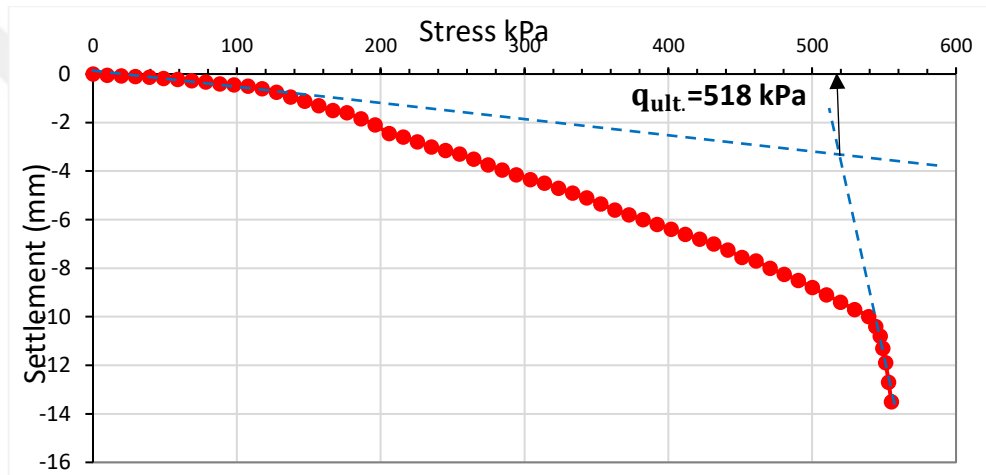


Figure 4.36 Stress - settlement curve for geotextile reinforced soil model at $D=0.25B+0.5B+1B$ for RD=60% (dry state)

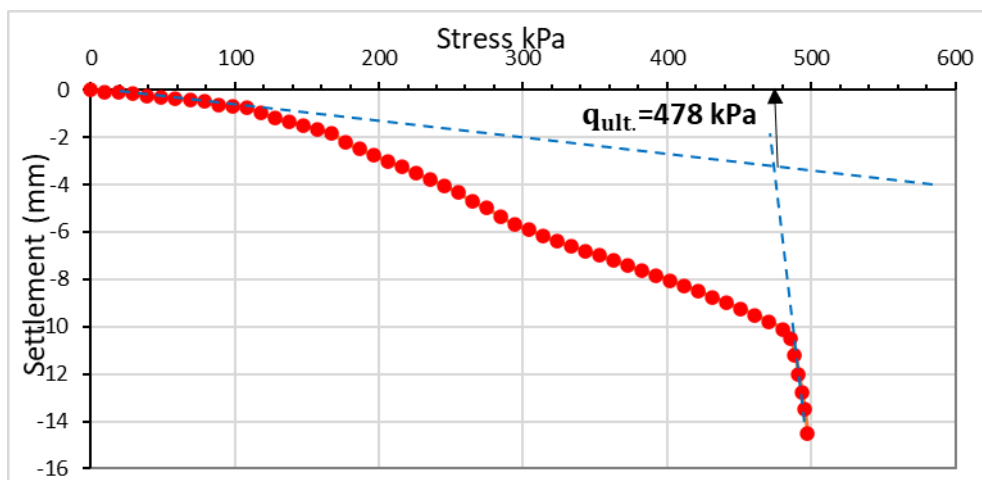


Figure 4.37 Stress - settlement curve for geotextile reinforced soil model at $D=0.5B+1B+1.5B$ for RD=60% (dry state)

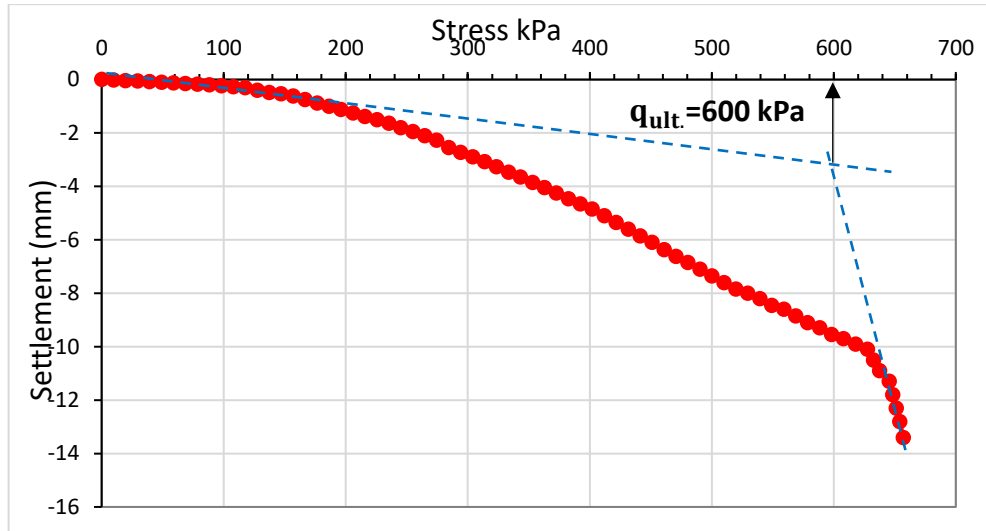


Figure 4.38 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.25B+0.5B+1B$ for $RD=60\%$ (dry state)

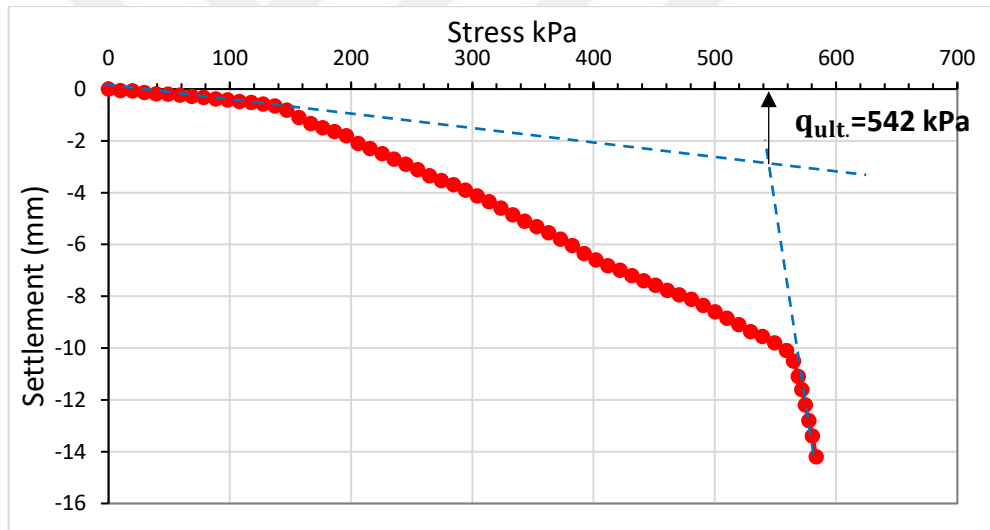


Figure 4.39 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.5B+1B+1.5B$ for $RD=60\%$ (dry state)

Figures (4.40) to (4.42) illustrate the amount of ultimate bearing capacity for using the U-shape reinforcement models and a striate layer of triple layers ($0.25B+0.5B+1B$) at an RD of 30%.

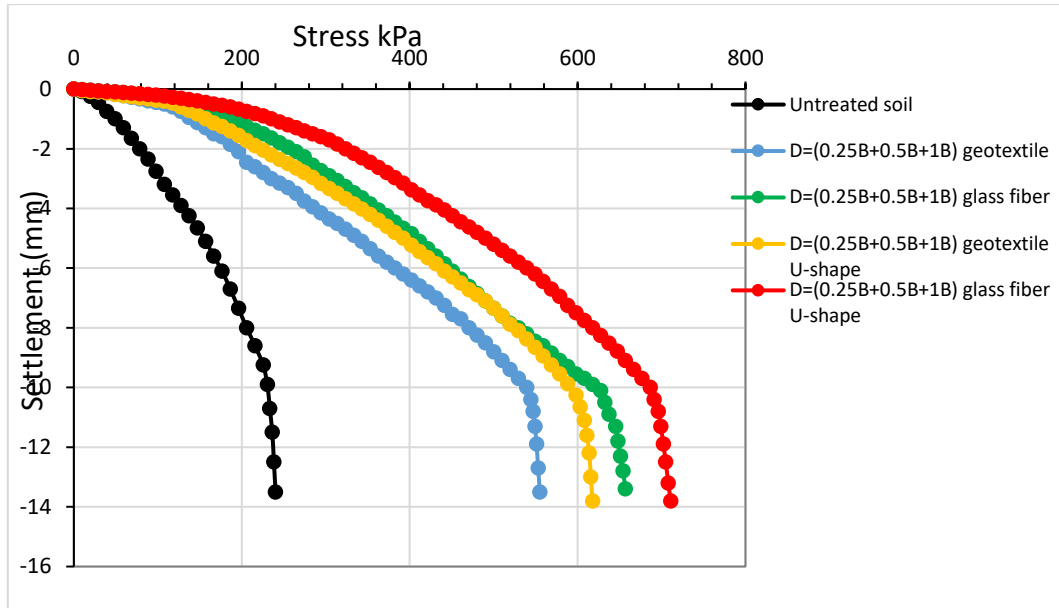


Figure 4.40 Stress-settlement curves for gypseous soil model reinforced by triple layer for RD=60% (dry state)

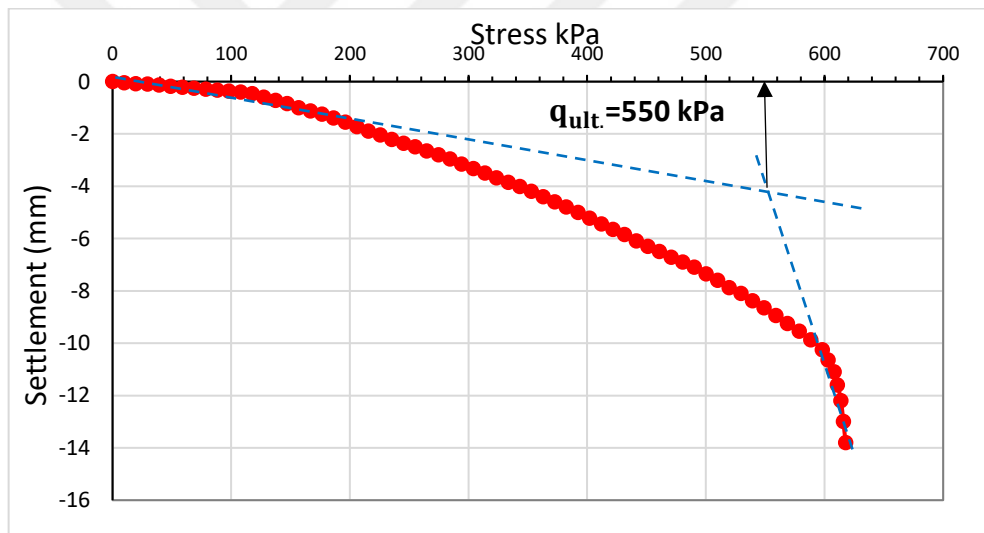


Figure 4.41 Stress - settlement curve for U-shape reinforced soil model at $D=0.25B+0.5B+1B$ (geotextile) for RD=60%

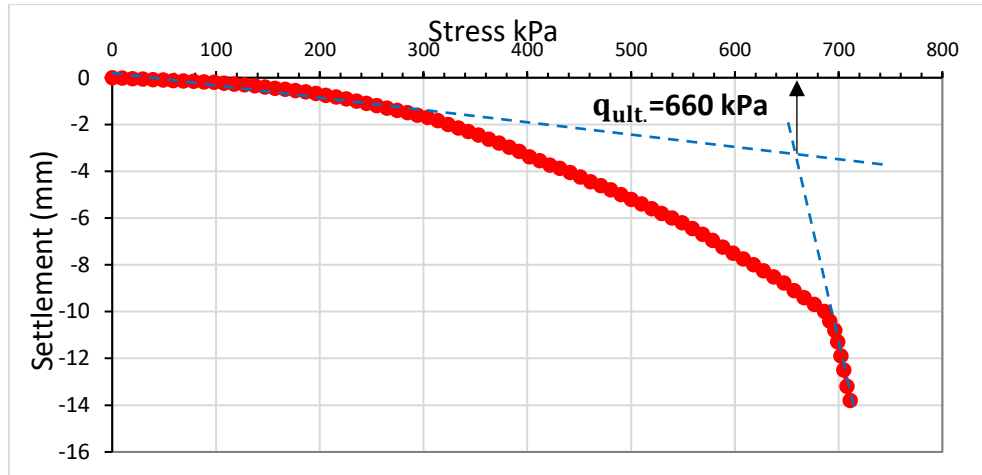


Figure 4.42 Stress - settlement curve for U-shape reinforced soil model at $D=0.25B+0.5B+1B$ (E-glass fiber fabric)

Table 4.1 Values of ultimate and allowable bearing capacity of gypsum soil tested of RD=30% for dry state below the square footing, SF=2

Pattern	Depth of Reinforcement	RD=30% dry state			
		Geotextile		E-glass fiber fabric	
		$q_{ult.}(kPa)$	$q_{all.}(kPa)$	$q_{ult.}(kPa)$	$q_{all.}(kPa)$
Single layers	D = 0.25B	195	97.5	245	122.5
	D = 0.5B	188	94	225	112.5
	D = 1B	164	82	190	95
Double layers	D = 0.25B+0.5B	245	122.5	366	183
	D = 0.5B+1B	200	100	315	157.5
Triple layers	D= 0.25B+0.5B+1B	300	150	431	215.5
	D=0.5B+1B+1.5B	257	128.5	390	195
U-Shape Triple layers	D= 0.25B+0.5B+1B	335	167.5	484	242

Table 4.2: Values of ultimate and allowable bearing capacity of gypsum soil tested of RD=60% for dry state below the square footing, SF=2

Pattern	Depth of Reinforcement	RD=60% dry state			
		Geotextile		E-glass fiber fabric	
		$q_{ult.}(kPa)$	$q_{all.}(kPa)$	$q_{ult.}(kPa)$	$q_{all.}(kPa)$
Single layers	D = 0.25B	330	165	400	200
	D = 0.5B	310	155	385	192.5
	D = 1B	290	145	348	174
Double layers	D = 0.25B+0.5B	392	196	482	241
	D = 0.5B+1B	360	180	425	212.5
Triple layers	D= 0.25B+0.5B+1B	518	259	600	300
	D=0.5B+1B+1.5B	478	239	542	271
U-Shape Triple layers	D= 0.25B+0.5B+1B	550	275	660	330

According to the values in Tables 4.1 and 4.2, Figures 4.43 to 4.50 compare the relationship between ultimate bearing capacity and patterns of geosynthetic reinforced (geotextile and E-glass fiber fabric) in RD of 30% and 60% under dry state.

It was noticed that increasing the value of ultimate bearing capacity for gypseous soil models with E-glass fiber fabric reinforcement was more than the values of the geotextile reinforced models for both RD =30% and 60% in the dry state. The increase in ultimate bearing capacity with using E-glass fiber fabric relative to geotextiles can be attributed to the increase in friction as well as the nature of the material itself, as well for the values of ultimate bearing capacity for models of RD = 60%, were higher compared to the models with a relative density of 30% due to denser of soil and increase the friction between soil particles.

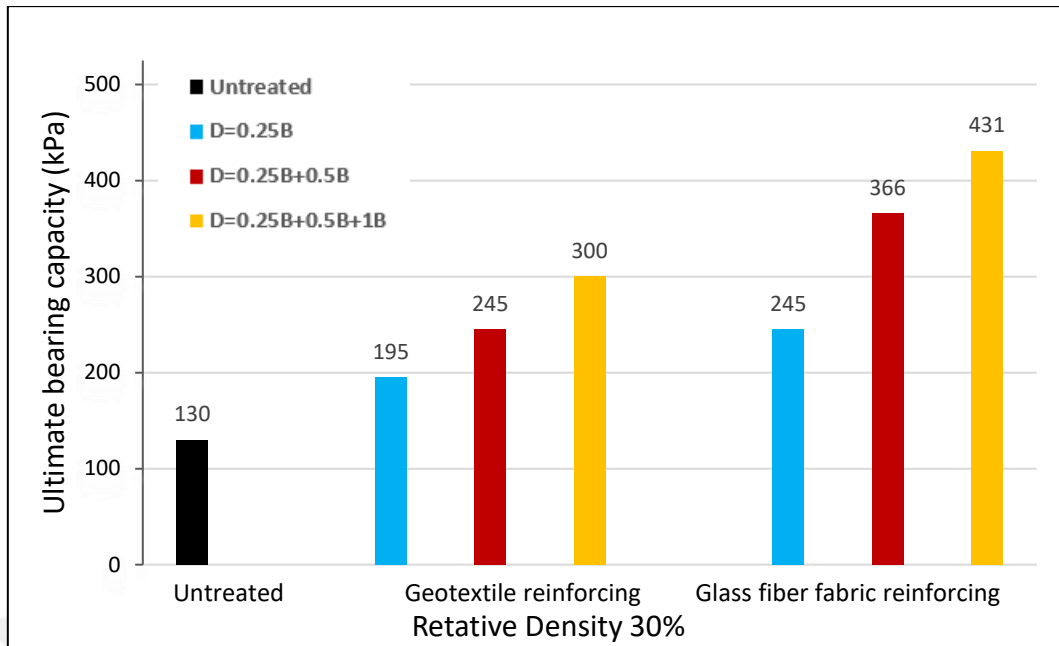


Figure 4.43 Maximum value of ultimate bearing capacity and patterns of geosynthetic reinforced (geotextile and E-glass fiber fabric) at RD= 30% (dry state).

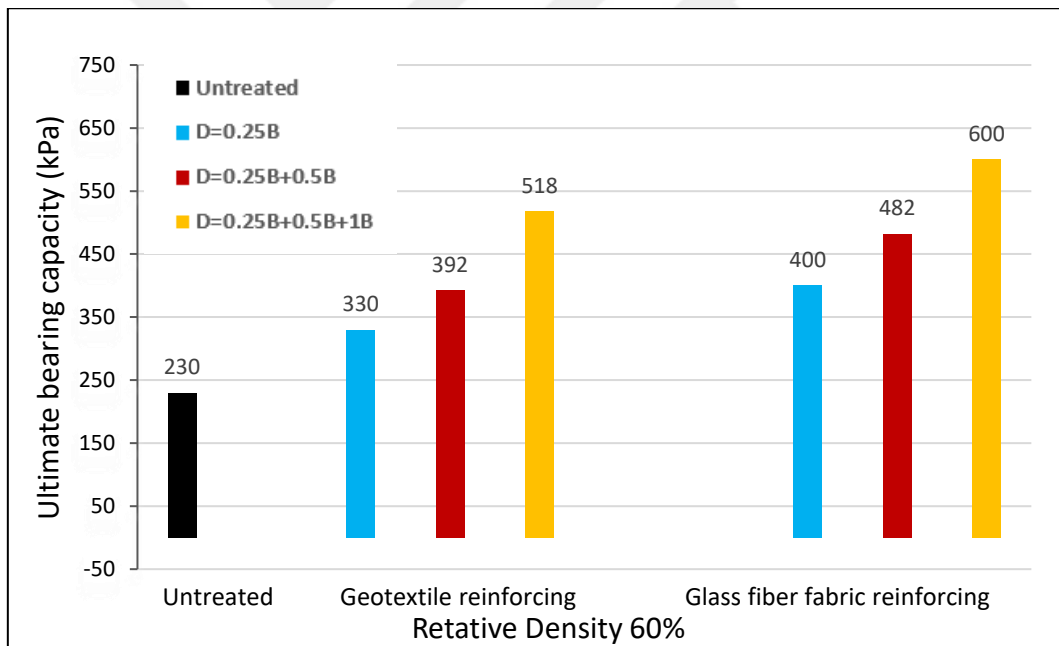


Figure 4.44 Maximum value of ultimate bearing capacity and patterns of geosynthetic reinforced (geotextile and E-glass fiber fabric) at RD= 60% (dry state)

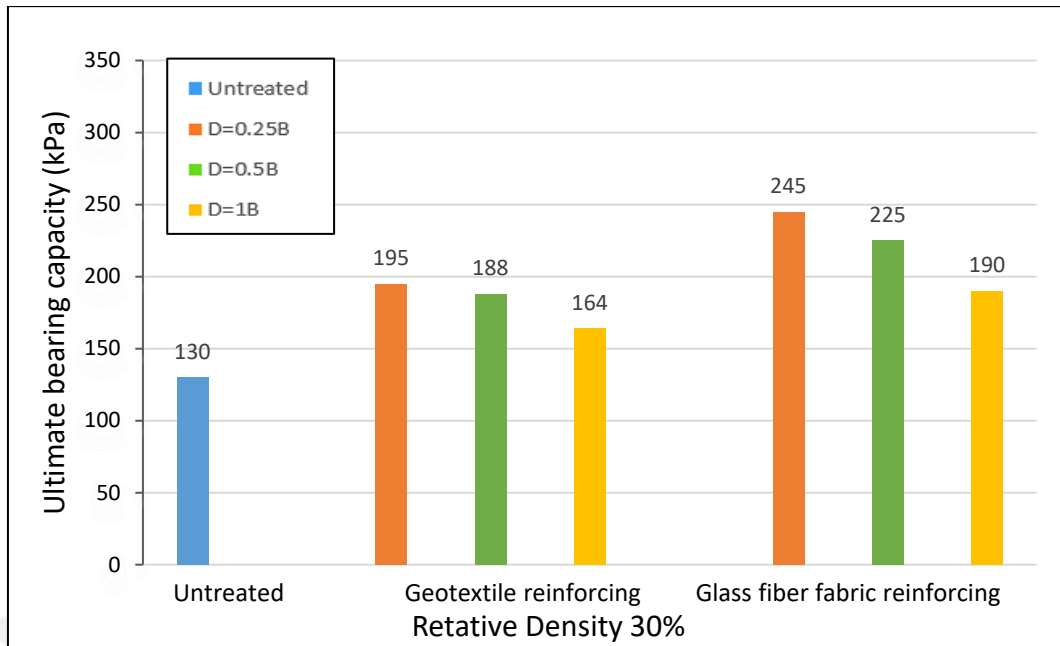


Figure 4.45 Maximum value of ultimate bearing capacity and patterns of single geosynthetic reinforced (geotextile and E-glass fiber fabric) at RD= 30% (dry state)

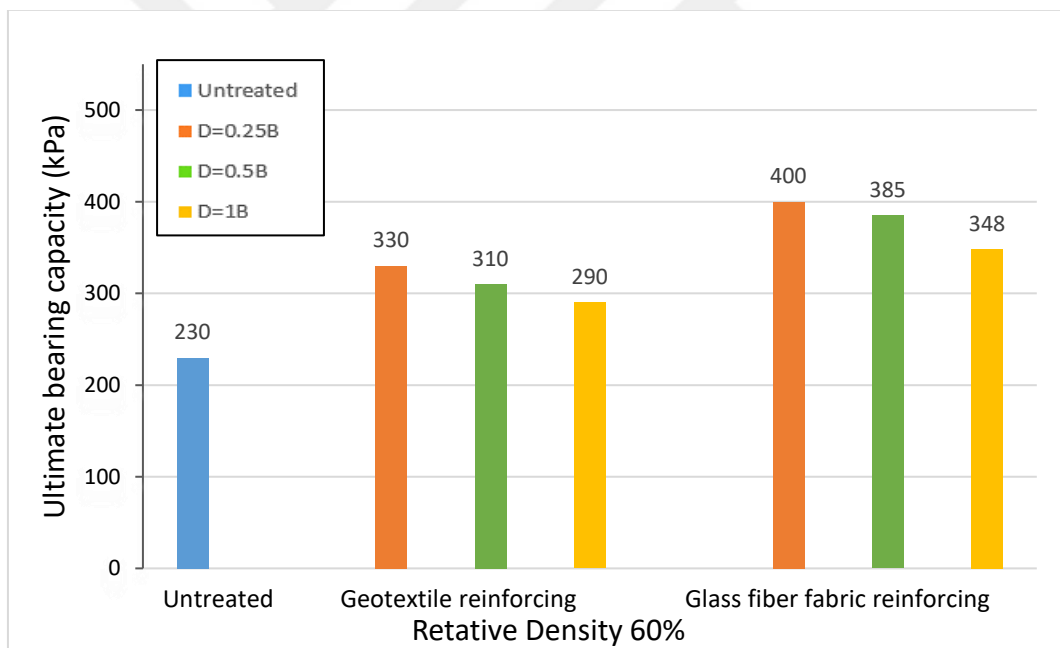


Figure 4.46 Maximum value of ultimate bearing capacity and patterns of single geosynthetic reinforced (geotextile and E-glass fiber fabric) at RD=60% (dry state).

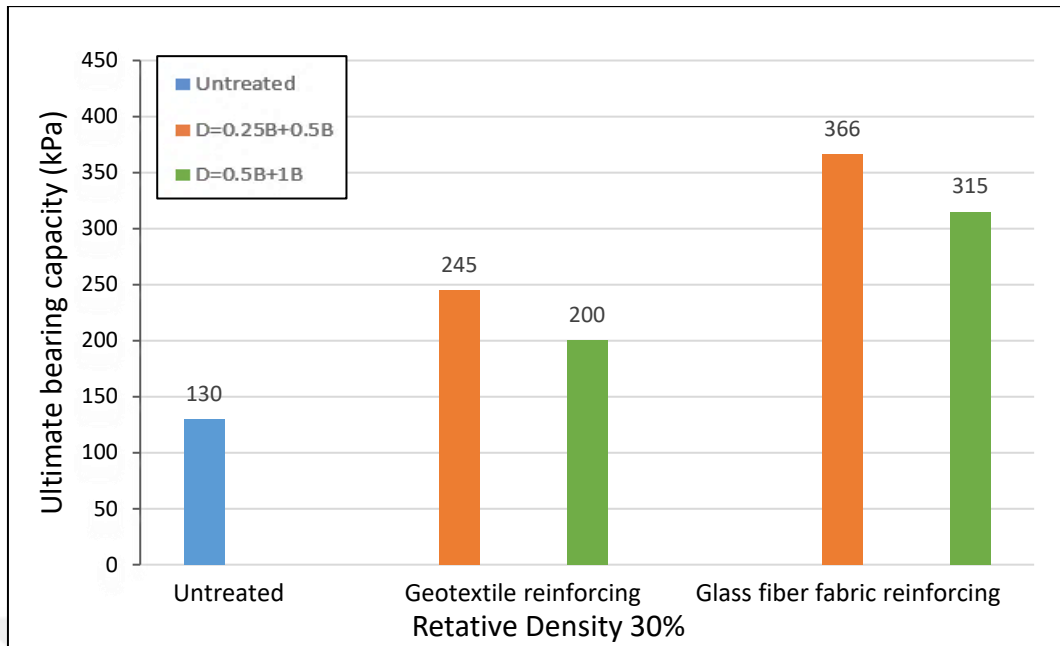


Figure 4.47 Maximum value of ultimate bearing capacity and patterns of double geosynthetic reinforced (geotextile and E-glass fiber fabric) at RD= 30% (dry state).

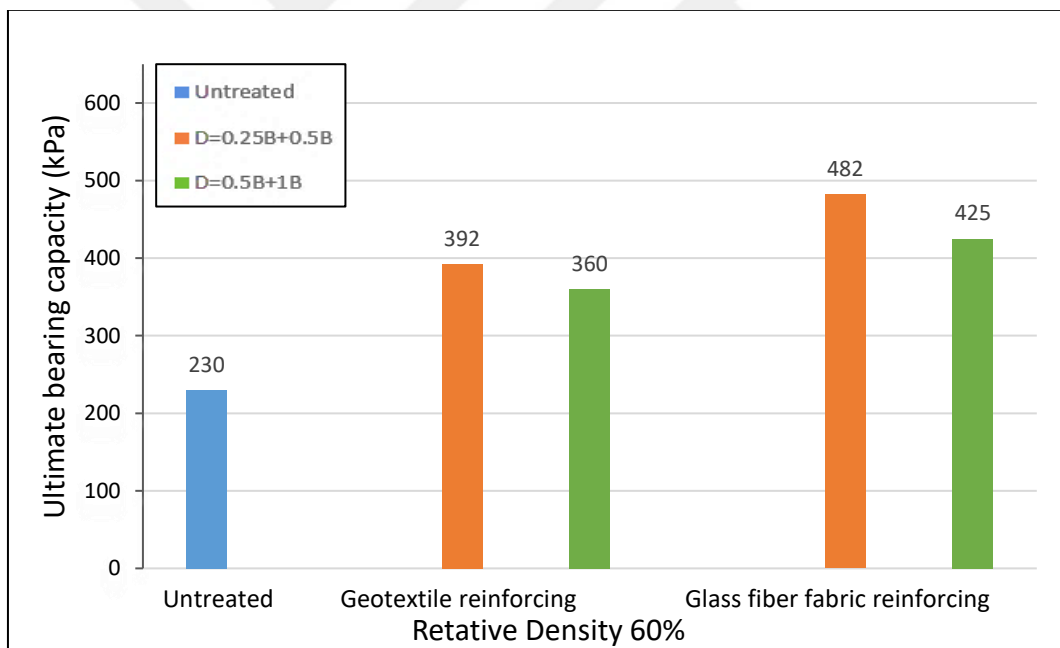


Figure 4.48 Maximum value of ultimate bearing capacity and patterns of double geosynthetic reinforced (geotextile and E-glass fiber fabric) at RD= 60% (dry state).

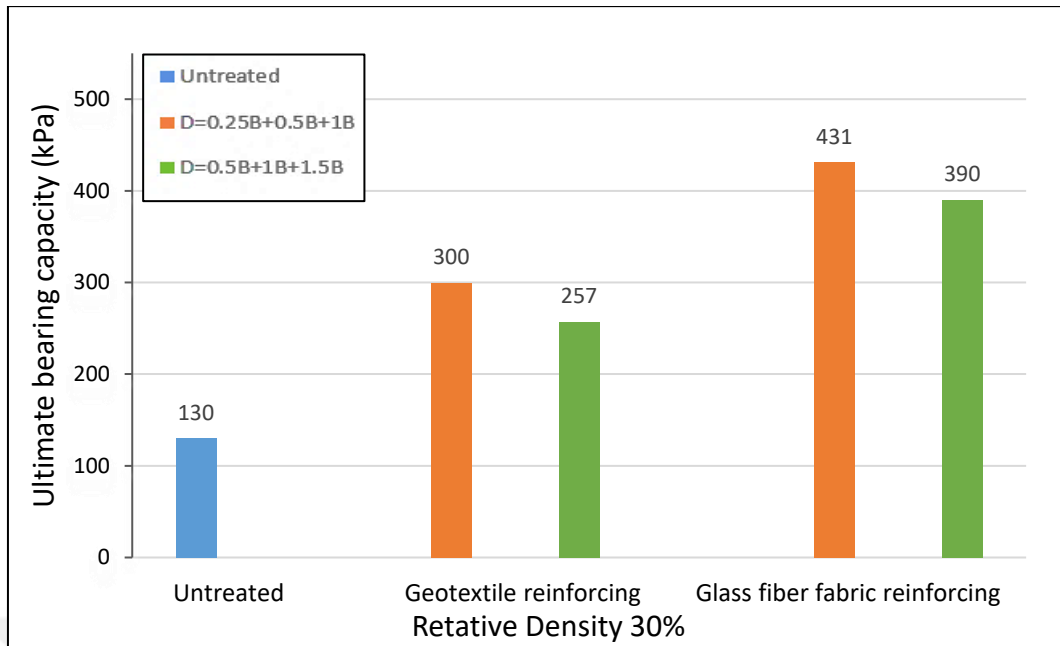


Figure 4.49 Maximum value of ultimate bearing capacity and patterns of triple geosynthetic reinforced (geotextile and E-glass fiber fabric) at RD= 30% (dry state).

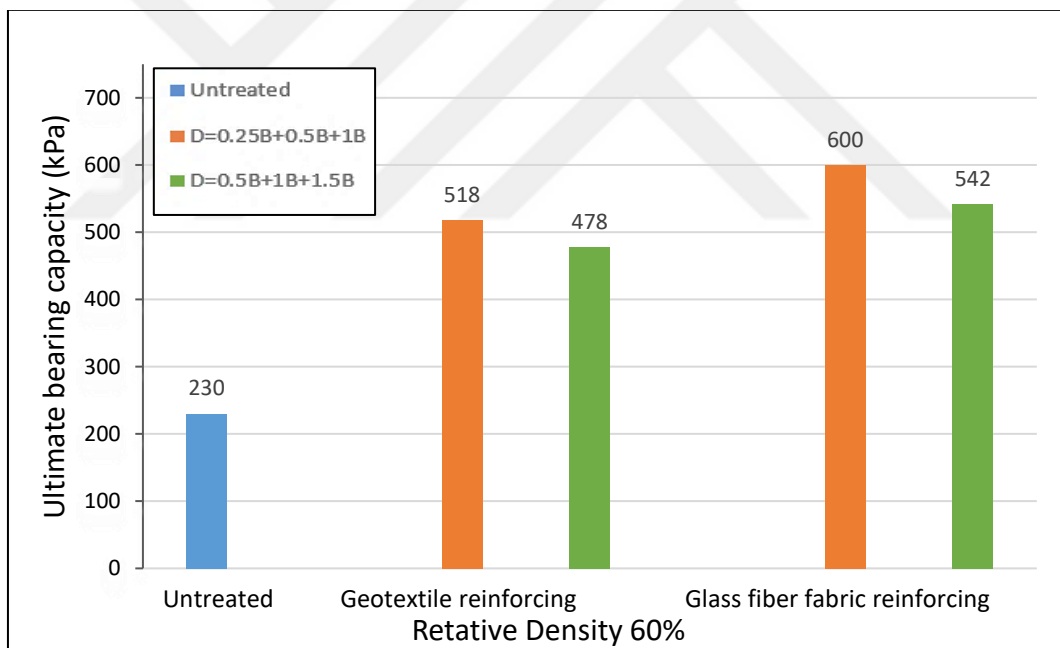


Figure 4.50 Maximum value of ultimate bearing capacity and patterns of triple geosynthetic reinforced (geotextile and E-glass fiber fabric) at RD= 60% (dry state).

Figures 4.51 and 4.52 show the ultimate bearing capacity when using triple reinforcement (0.25B+0.5B+1B) according to the shape of the layer (straight and U-shape), for the relative densities of 30% and 60%, it was noticed increasing the value of ultimate bearing capacity model used U-shape related to straight shape for both the geosynthetic reinforced (geotextile and E-glass fiber fabric). This increase can be attributed to the soil model has

become confined, which leads to an increase in internal friction between the soil particles, as well as an increase in the bonding between the particles.

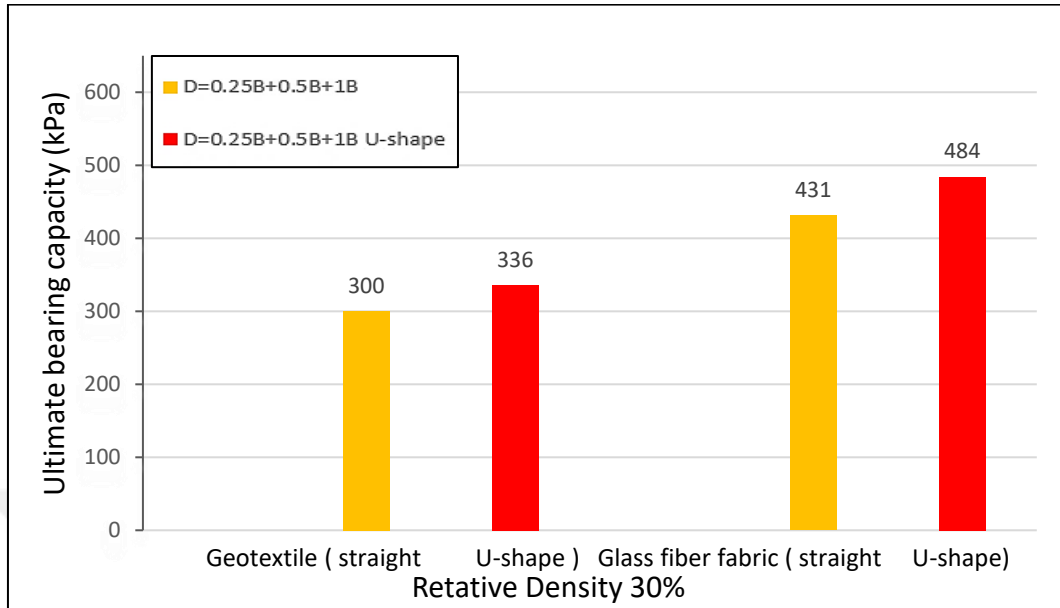


Figure 4.51 Maximum value of ultimate bearing capacity and patterns of triple geosynthetic reinforced (straight and U-shape) at RD= 30% (dry state)

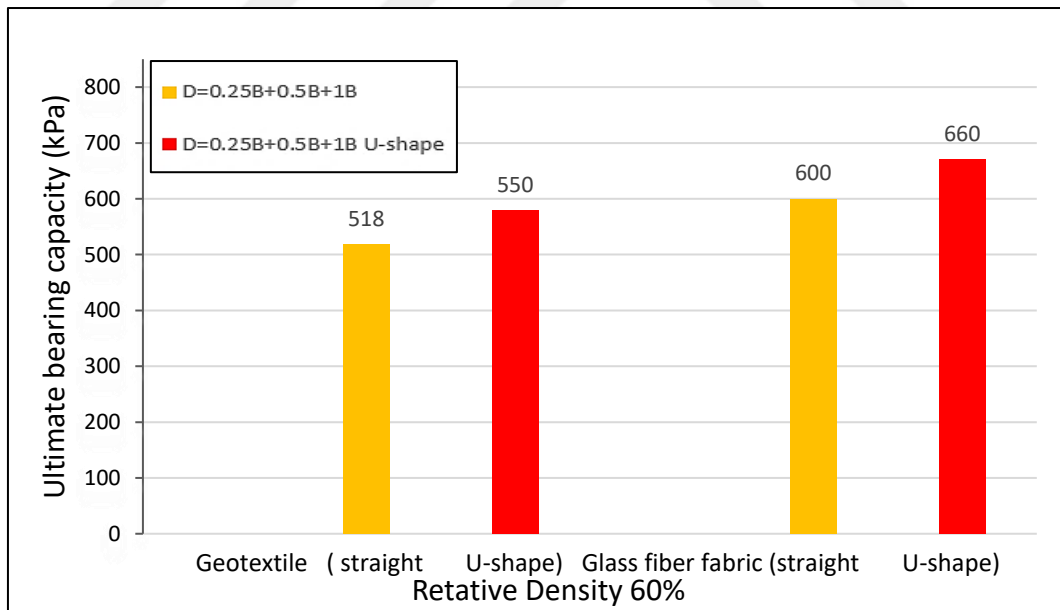


Figure 4.52 Maximum value of ultimate bearing capacity and patterns of triple geosynthetic reinforced (straight and U-shape) at RD= 60% (dry state).

4.2.3 Determine Ultimate Bearing Capacity of Gypsum Soil Models at RD= 30% for Fully Saturation State

Figures (4.53) to (4.75) illustrate the values of ultimate bearing capacity for unreinforced and reinforced models based on the results of experimental work of fully saturated gypseous soil models at an RD of 30% using the method of two tangents intersection, these results demonstrated that the values of the settlement increase as the load increases to the point where the settlement increases while the load magnitude approximately constant. This can be taken as an indication that the soil is starting to fail. Where the final values of the bearing capacity of the soil increased from 62 kN/m² for the unreinforced soil model to (115,97,90) kN/m² and (140,125,115) kN/m² of a single layer reinforcement at a depth (0.25B, 0.5B, 1B), for geotextile and E-glass fiber fabric respectively, while when using the double layer reinforcement at a depth (0.25B+0.5B, 0.5B+1B) the value of ultimate bearing capacity increased to (146, 107) kN/m² for geotextile reinforcement and (195,163) kN/m² for E-glass fiber fabric reinforcement, and triple layers reinforcement at a depth (0.25B+0.5B+1B, 0.5B+1B+1.5B) the value increased to (165, 143) kN/m² for geotextile reinforcement and (230, 205) kN/m² for E-glass fiber fabric reinforcement.

The results indicate that the maximum value of ultimate bearing capacity when using the single layer reinforcement was (115,140) kPa for geotextile and E-glass fiber fabric reinforcement at $D = 0.25 B$, and the minimum value was (90, 115) kPa at $D = 1B$ for geotextile and E-glass fiber reinforced respectively, while the maximum value when using the double layer reinforcement was (146, 195) kPa at $D = (0.25B+0.5B)$ for geotextile and E-glass fiber reinforced respectively, and when using triple layers reinforced the maximum magnitude of ultimate bearing capacity was (165, 230) kPa for geotextile and E-glass fiber reinforced respectively at $D=0.25B+0.5B+1B$.

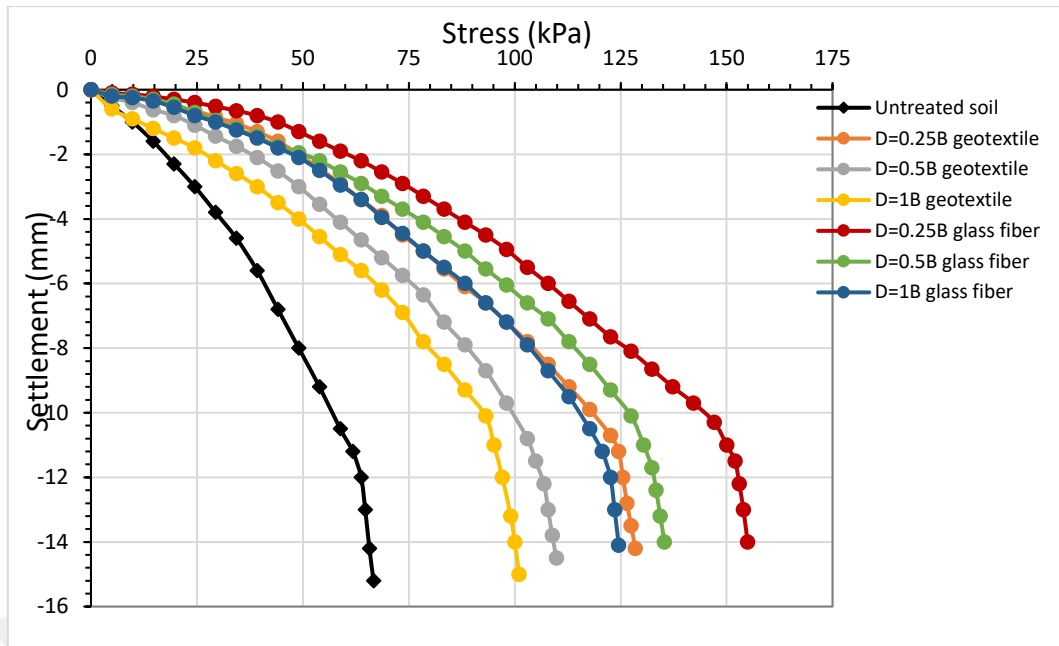


Figure 4.53 Stress-settlement curves for gypseous soil reinforced by a single layer for RD=30% (fully saturation state)

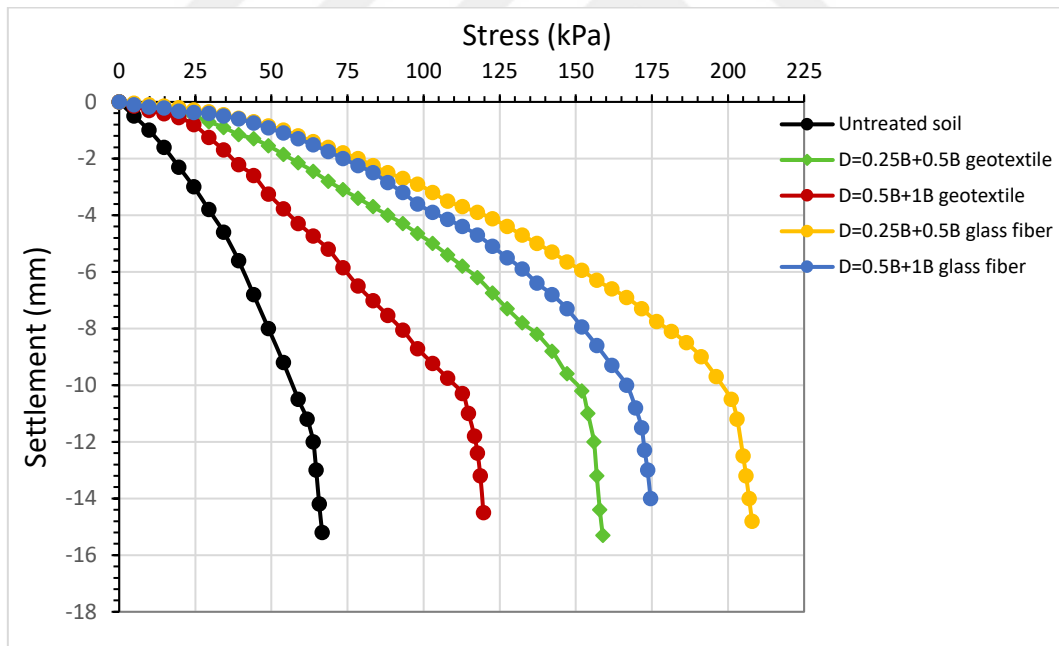


Figure 4.54 Stress-settlement curves for gypseous soil reinforced by double layers for RD=30% (fully saturation state)

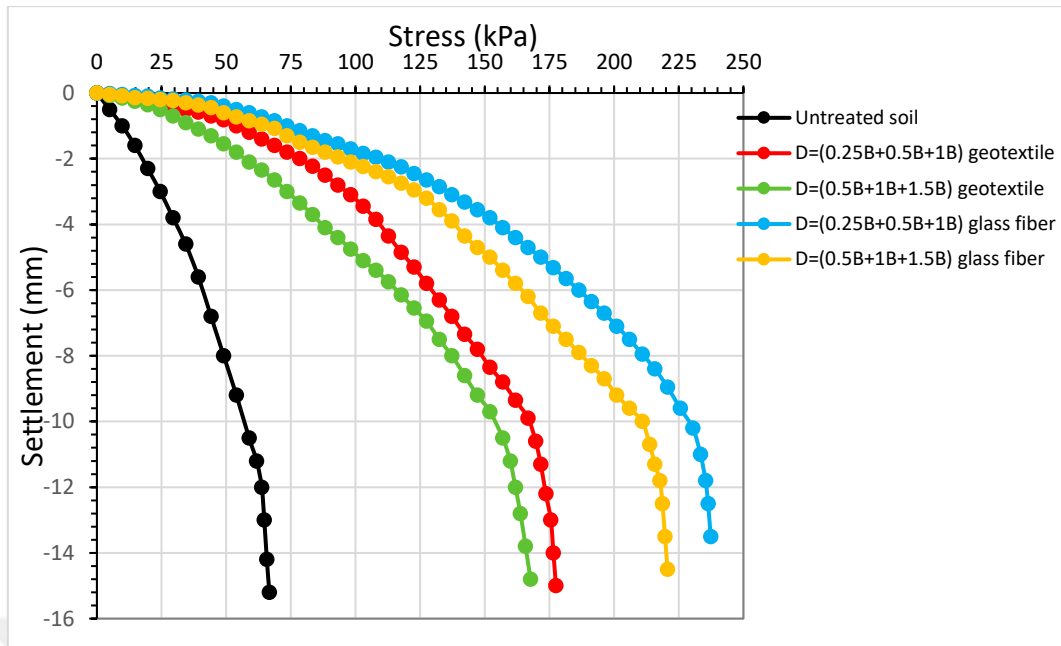


Figure 4.55 Stress - settlement curve for gypseous soil reinforced by triple layers for RD=30% (fully saturation state)

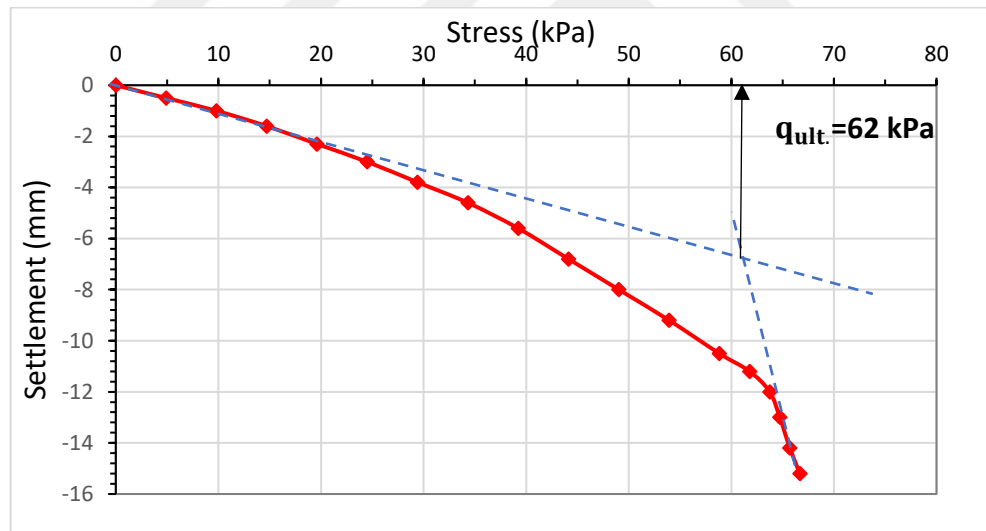


Figure 4.56 Stress - settlement curve for unreinforced soil model for RD=30% (fully saturation)

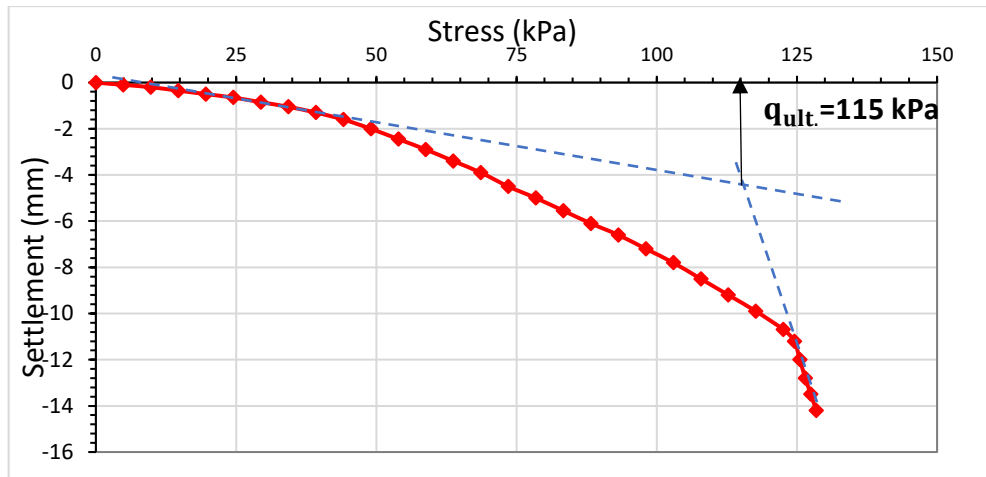


Figure 4.57 Stress - settlement curve for geotextile reinforced soil model at $D=0.25B$ for $RD=30\%$ (fully saturation)

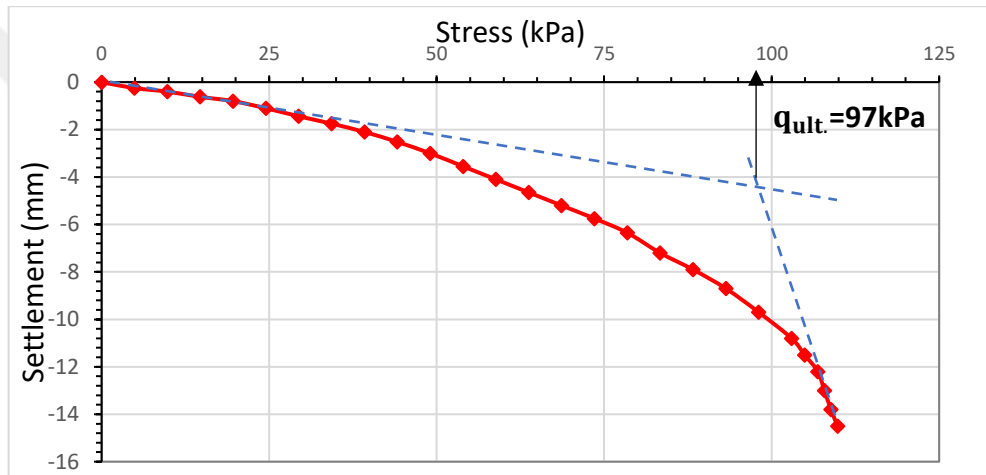


Figure 4.58 Stress - settlement curve for geotextile reinforced soil model at $D=0.5B$ for $RD=30\%$ (fully saturation)

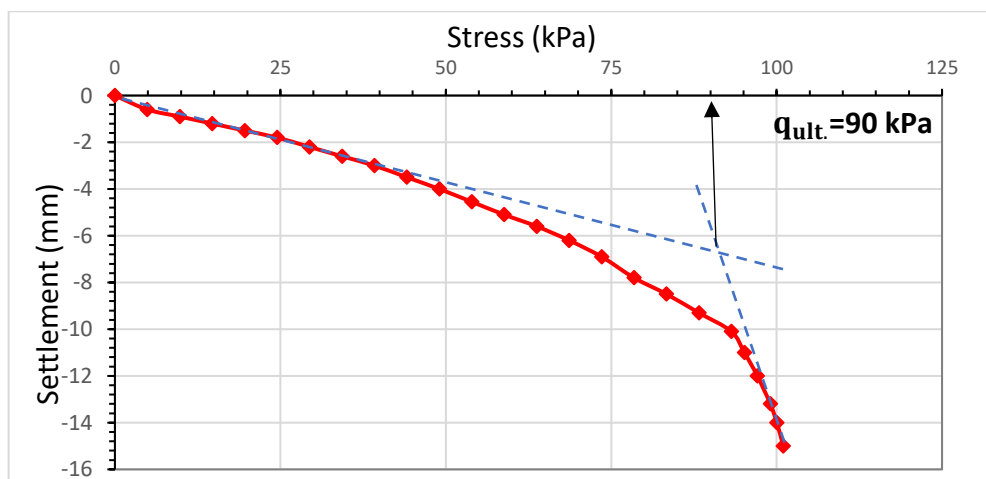


Figure 4.59 Stress - settlement curve for geotextile reinforced soil model at $D=1B$ for $RD=30\%$ (fully saturation)

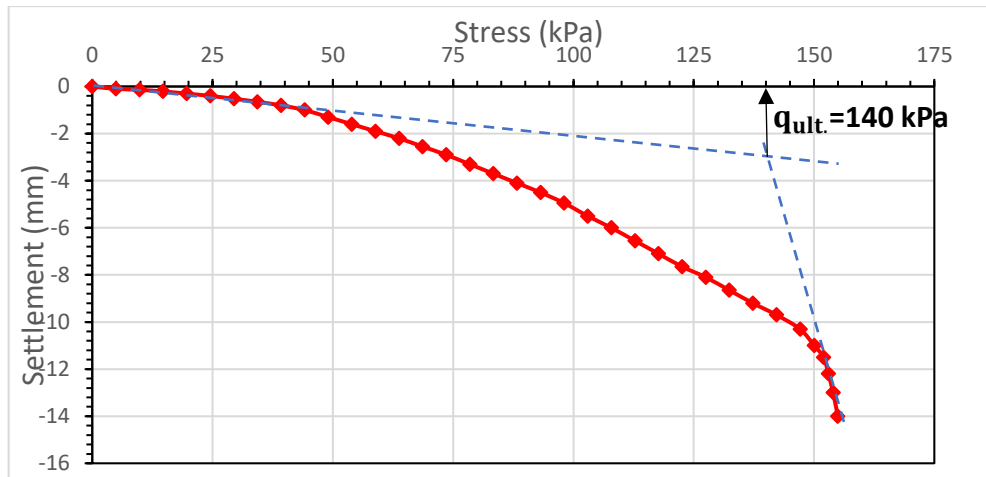


Figure 4.60 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.25B$ for $RD=30\%$ (fully saturation)

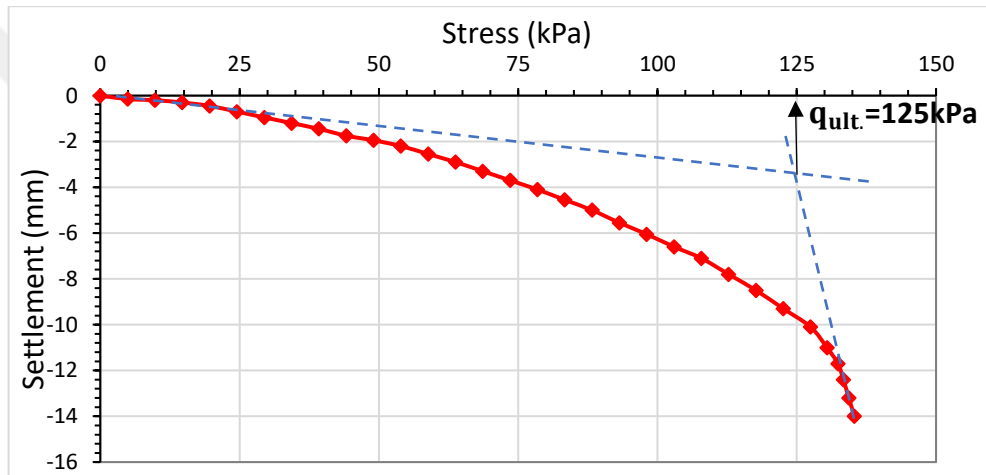


Figure 4.61 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.5B$ for $RD=30\%$ (fully saturation)

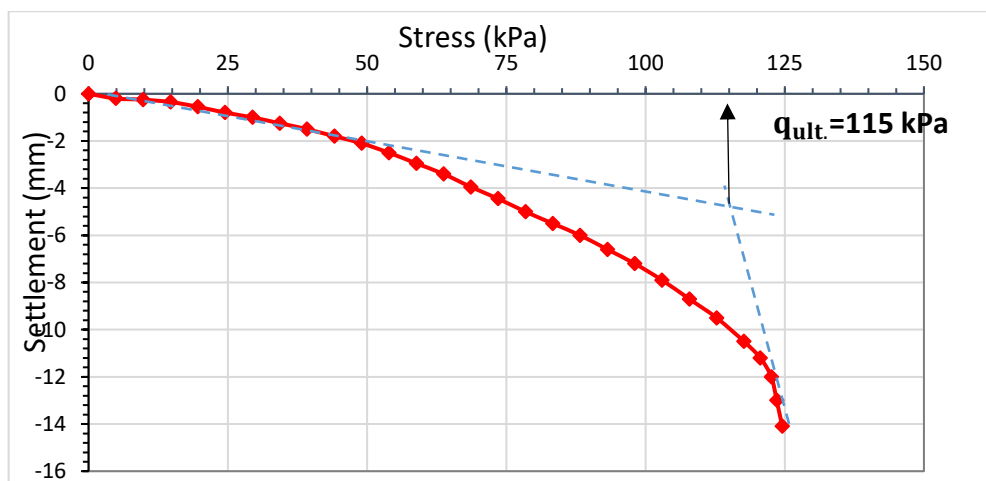


Figure 4.62 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.1B$ for $RD=30\%$ (fully saturation)

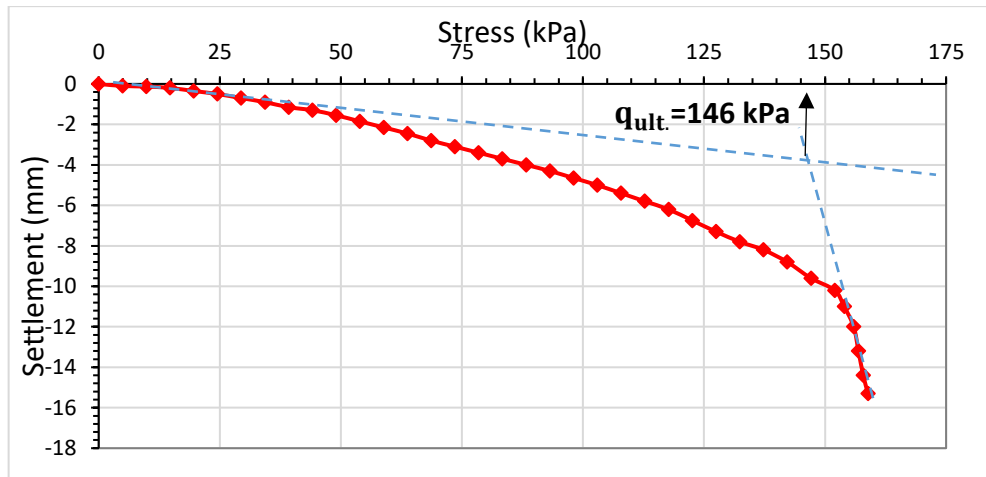


Figure 4.63 Stress - settlement curve for geotextile reinforced soil model at $D=0.25B+0.5B$ for $RD=30\%$ (fully saturation)

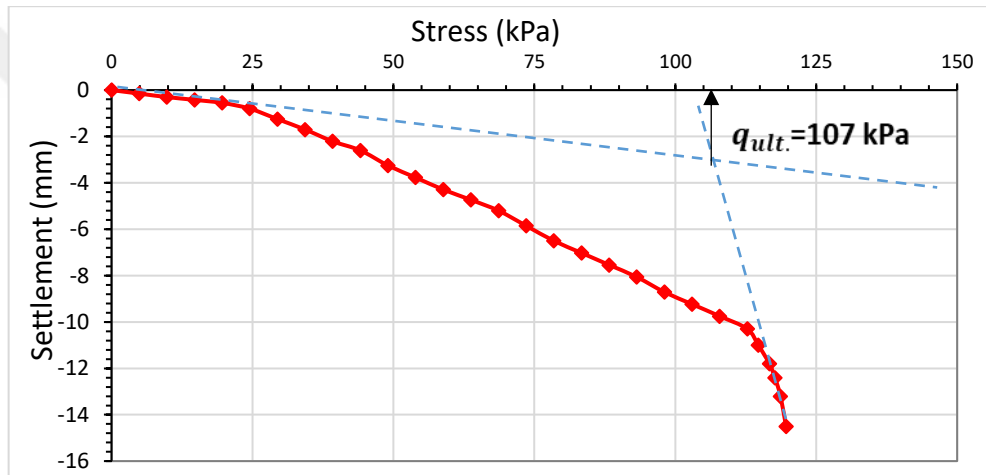


Figure 4.64 Stress - settlement curve for geotextile reinforced soil model at $D=0.5B+1B$ for $RD=30\%$ (fully saturation)

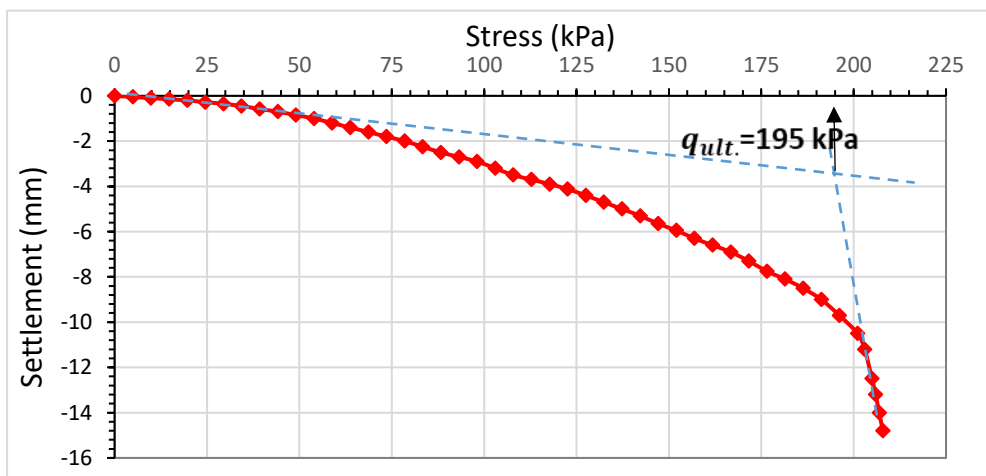


Figure 4.65 Stress-settlement curve for E-glass reinforced $D=0.25B+0.5B$ (fully saturation)

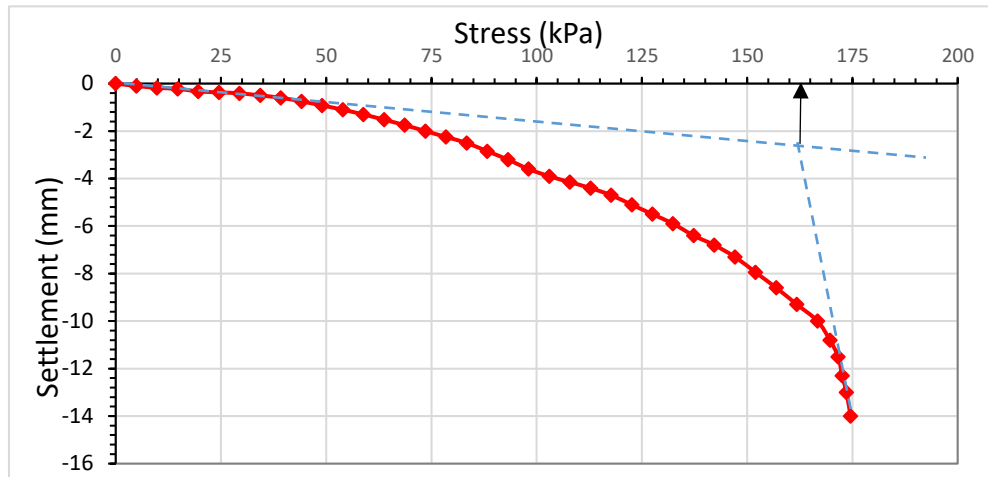


Figure 4.66 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.5B+1B$ for $RD=30\%$ (fully saturation)

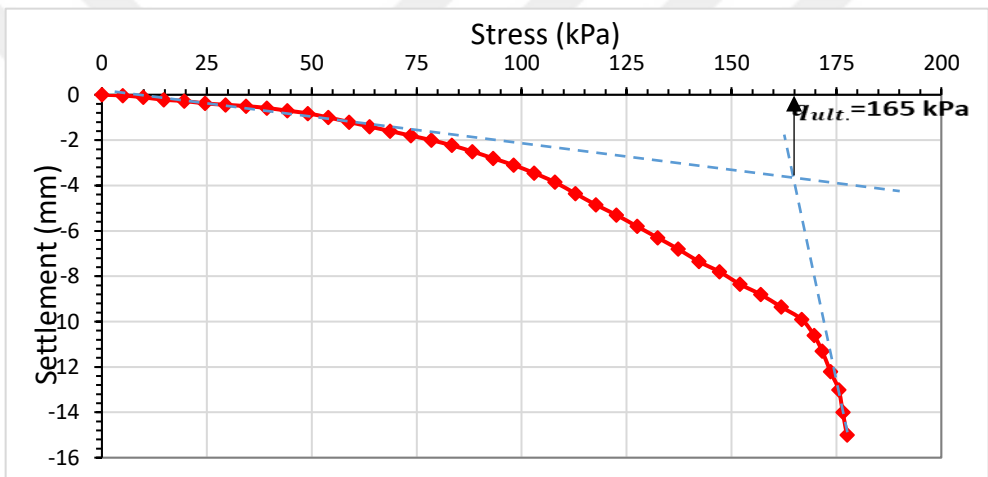


Figure 4.67 Stress - settlement curve for geotextile reinforced soil model at $D=0.25B+0.5B+1B$ for $RD=30\%$ (fully saturation)

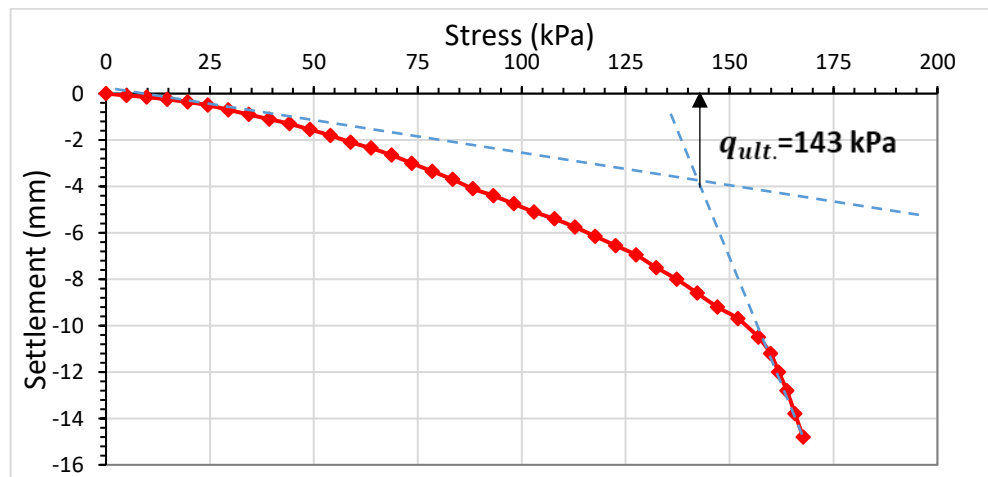


Figure 4.68 Stress - settlement curve for geotextile reinforced soil model at $D=0.5B+1B+1.5B$ for $RD=30\%$ (fully saturation)

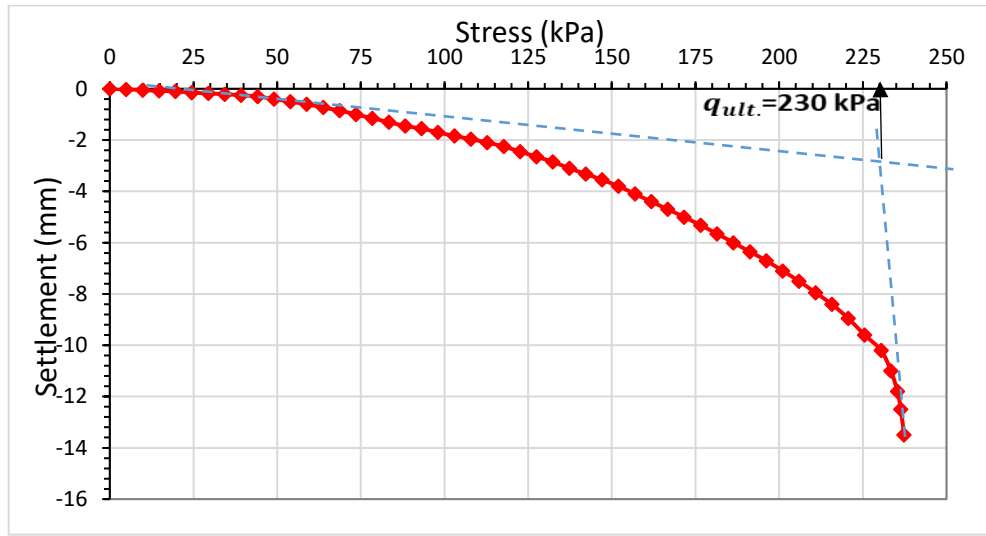


Figure 4.69 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.25B+0.5B+1B$ for $RD=30\%$ (fully saturation)

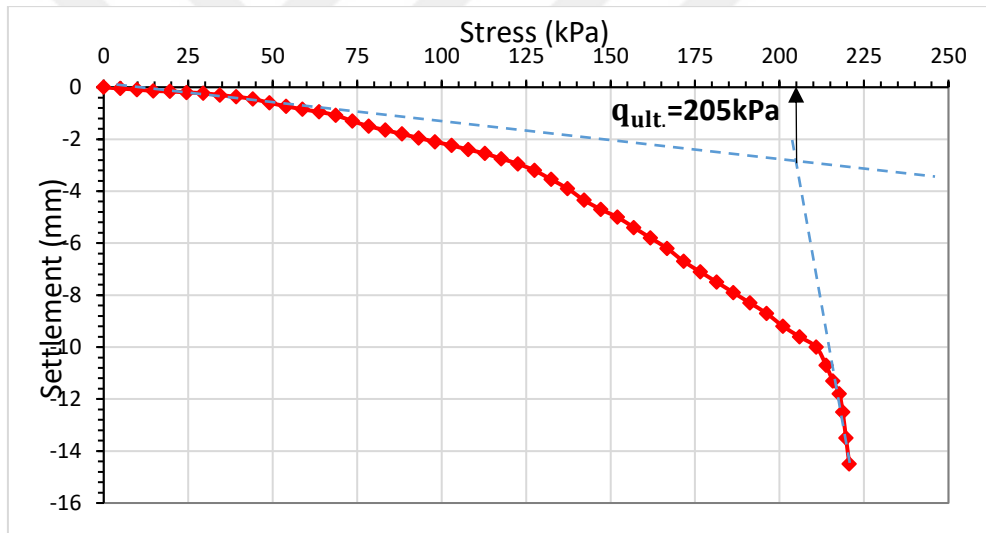


Figure 4.70 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.5B+1B+1.5B$ for $RD=30\%$ (fully saturation)

Figures 4.71 to 4.73 illustrate the values of ultimate bearing capacity for used the U-shape reinforcement models (confined) and striate reinforcement layer of triple layers ($0.25B+0.5B+1B$) at an RD of 30% (fully saturation state).

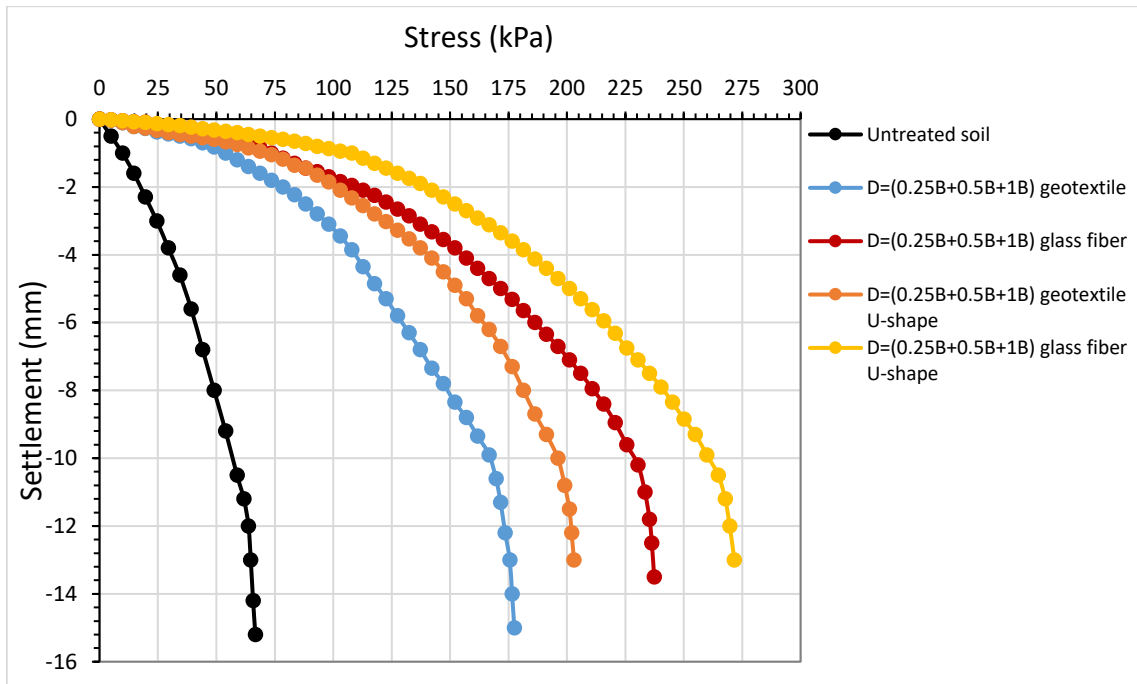


Figure 4.71 Stress-settlement curves for reinforced soil model at U-shape and straight by triple layers for RD=30% (fully saturation)

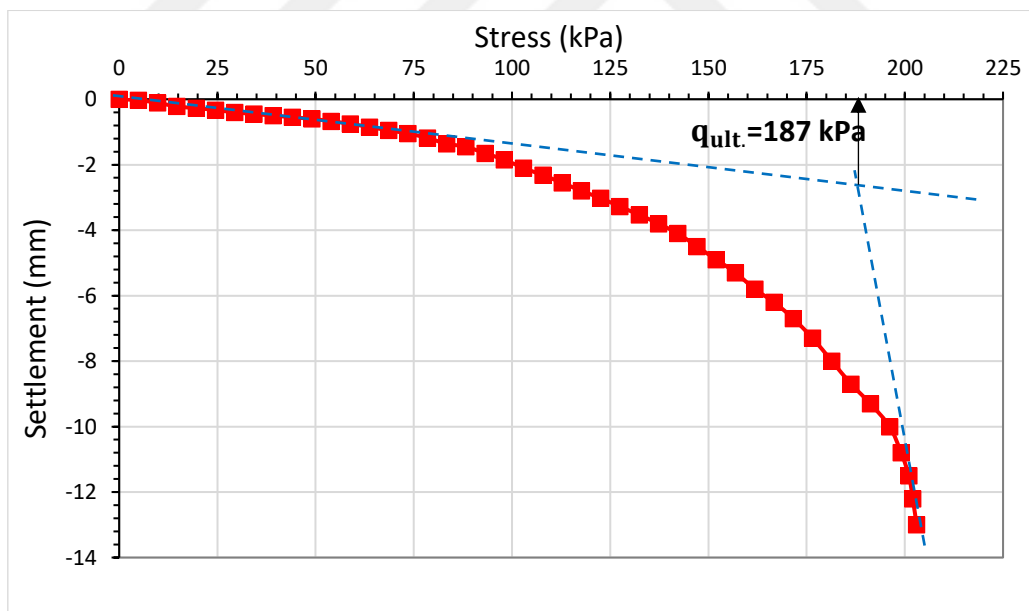


Figure 4.72 Stress - settlement curve for U-shape geotextile reinforced soil model at $D=0.25B+0.5B+1B$ for RD=30% (fully saturation)

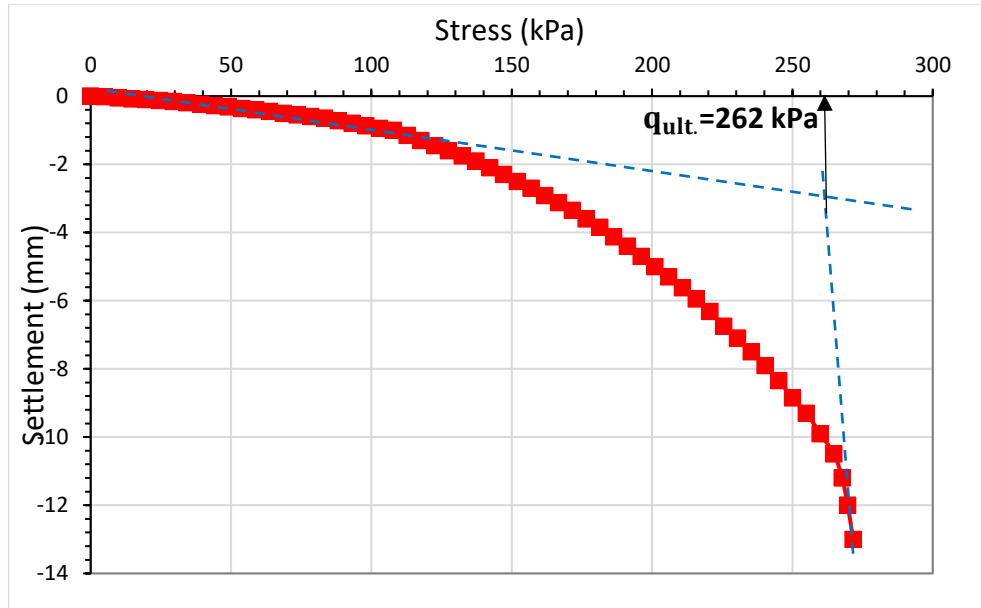


Figure 4.73 Stress - settlement curve for U-shape E-glass fiber reinforced soil model at $D=0.25B+0.5B+1B$ for $RD=30\%$ (fully saturation)

4.2.4 Determine Ultimate Bearing Capacity of Gypsum Soil Models at $RD= (60\%)$ for Fully Saturation State

Figures (4.74) to (4.90) show the values of ultimate bearing capacity for unreinforced and reinforced models based on the results of experimental work of fully saturated gypseous soil models at $RD= 60\%$ using the method of two tangents intersection, these results demonstrated that the values of the settlement increase as the load increases to the point where the settlement increases while the load magnitude approximately constant. Where the final values of the bearing capacity of the soil increased from 110 kN/m² for the unreinforced soil model to (190, 173, 146) kN/m² for geotextile reinforcement and (235, 220, 195) kN/m² for E-glass fiber reinforcement of a single layer reinforced at a depth (0.25B, 0.5B, 1B), while when using the double layer at a depth (0.25B+0.5B, 0.5B+1B) the value of bearing capacity increased to (225, 190)kN/m² for geotextile reinforced and (282, 262) kN/m² for E-glass fiber respectively, and for reinforcement triple layers at a depth (0.25B+0.5B+1B, 0.5B+1B+1.5B) increased the value of the bearing capacity to (240, 113) kN/m² for geotextile and (330, 300) kN/m² for E-glass fiber.

The results indicate that the maximum value of ultimate bearing capacity when using the single layer treated was (190,235) for geotextile reinforced and E-glass fiber reinforced at $D = 0.25 B$, and the minimum value was (146, 195) kPa at $D = 1B$ for geotextile and E-glass fiber reinforced respectively, while the maximum value when using the double layer treated was (225, 282) kPa at $D = (0.25B+0.5B)$ for geotextile and E-glass fiber

reinforced respectively, and when using triple layers reinforced the maximum magnitude of ultimate bearing capacity was (240, 330) kPa for geotextile and E-glass fiber reinforced respectively at $D=0.25B+0.5B+1B$.

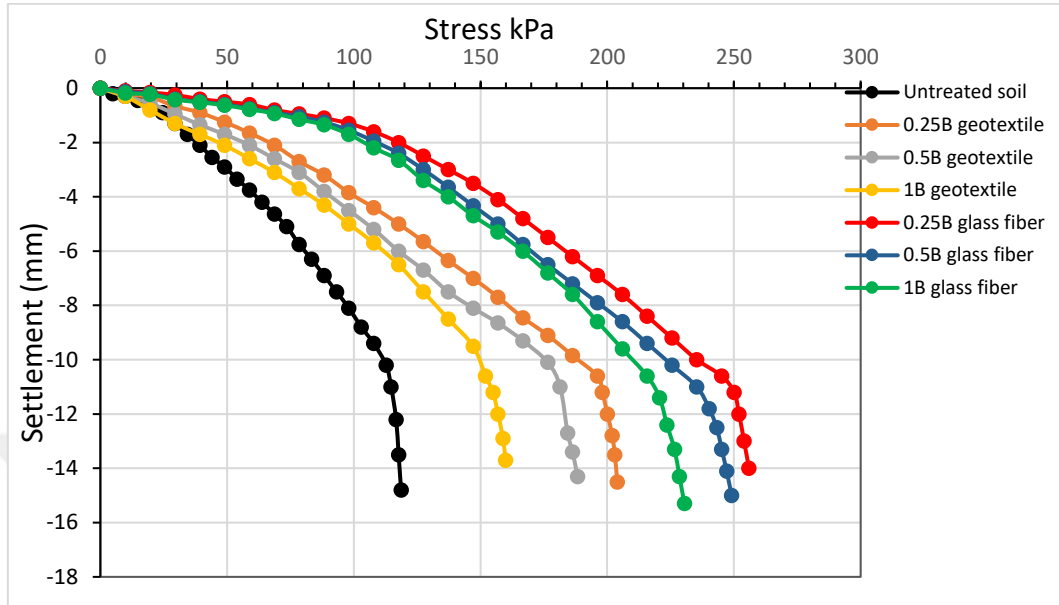


Figure 4.74 Stress-settlement curves for reinforced soil model by single layers for RD=60% (fully saturation)

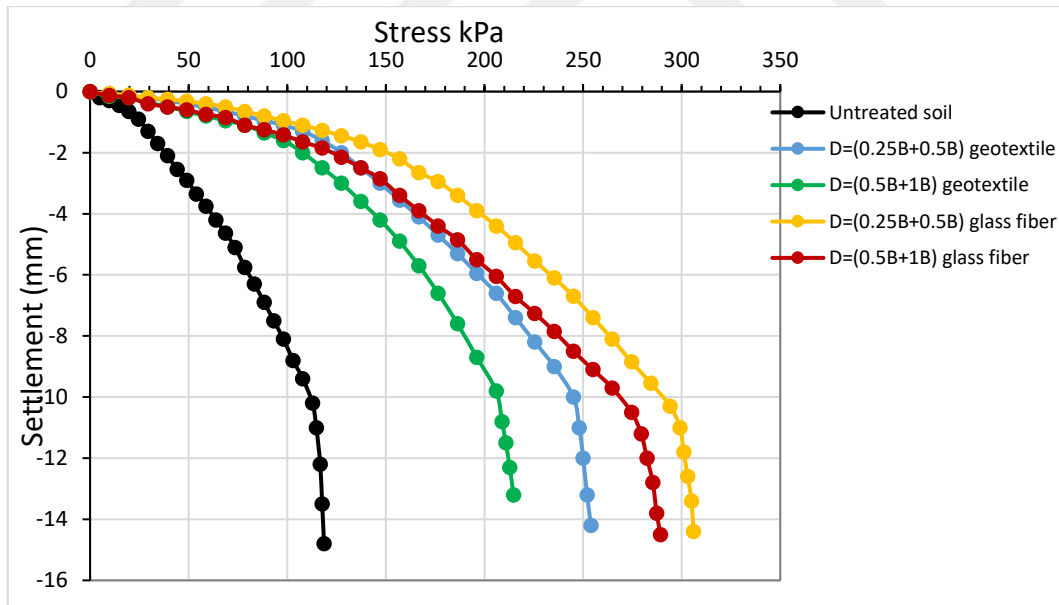


Figure 4.75 Stress-settlement curves for reinforced soil model at double layers for RD=60% (fully saturation)

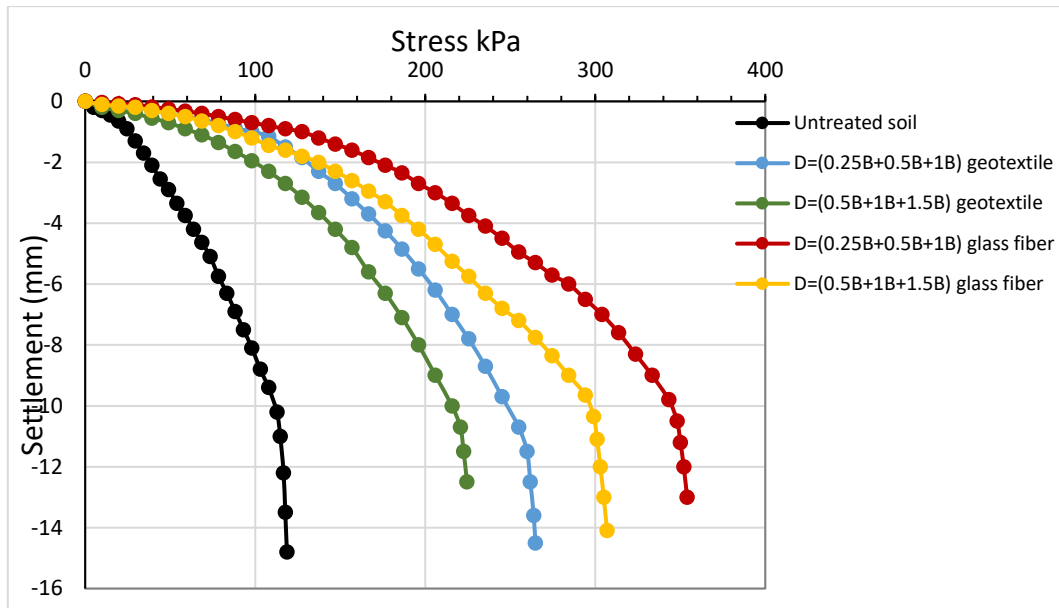


Figure 4.76 Stress - settlement curve for reinforced soil model at triple layers for RD=60% (fully saturation)

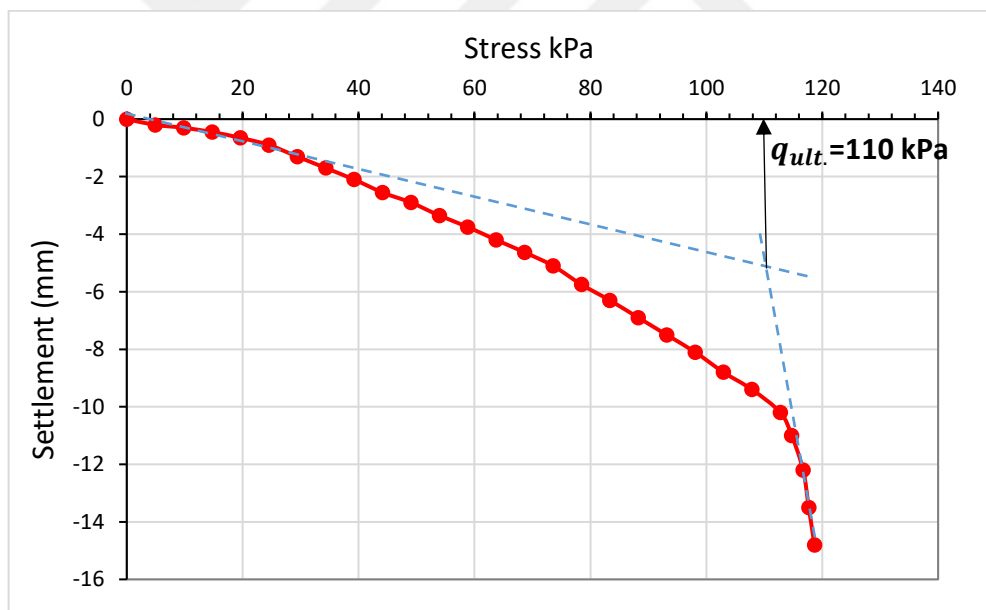


Figure 4.77 Stress - settlement curve for unreinforced soil model for RD=60% (fully saturation)

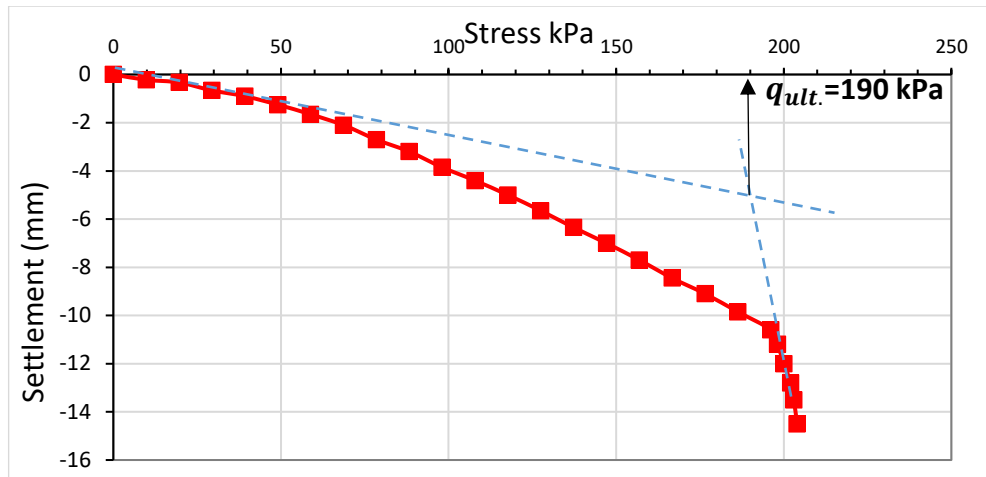


Figure 4.78 Stress - settlement curve for geotextile reinforced soil model at $D=0.25B$ for $RD=60\%$ (fully saturation)

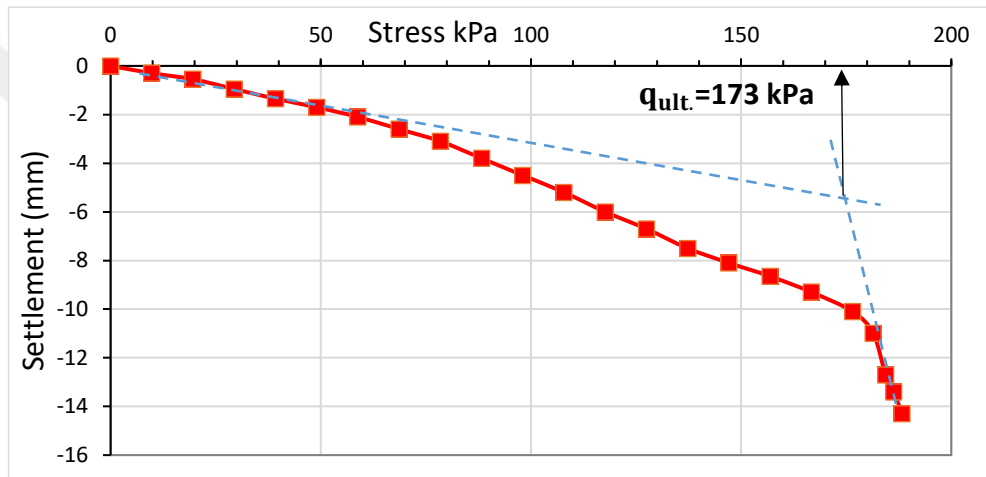


Figure 4.79 Stress - settlement curve for geotextile reinforced soil model at $D=0.5B$ for $RD=60\%$ (fully saturation)

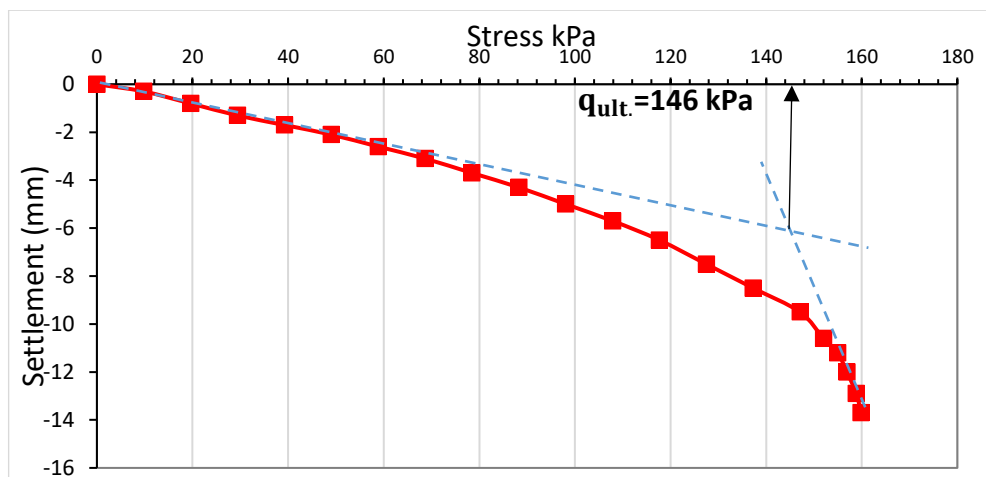


Figure 4.80 Stress - settlement curve for geotextile reinforced soil model at $D=1B$ for $RD=60\%$ (fully saturation)

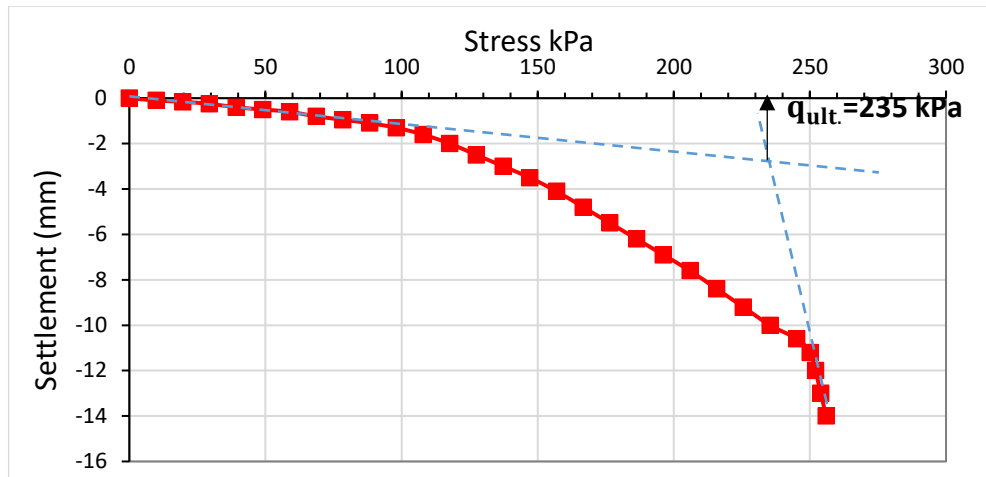


Figure 4.81 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.25B$ for $RD=60\%$ (fully saturation)

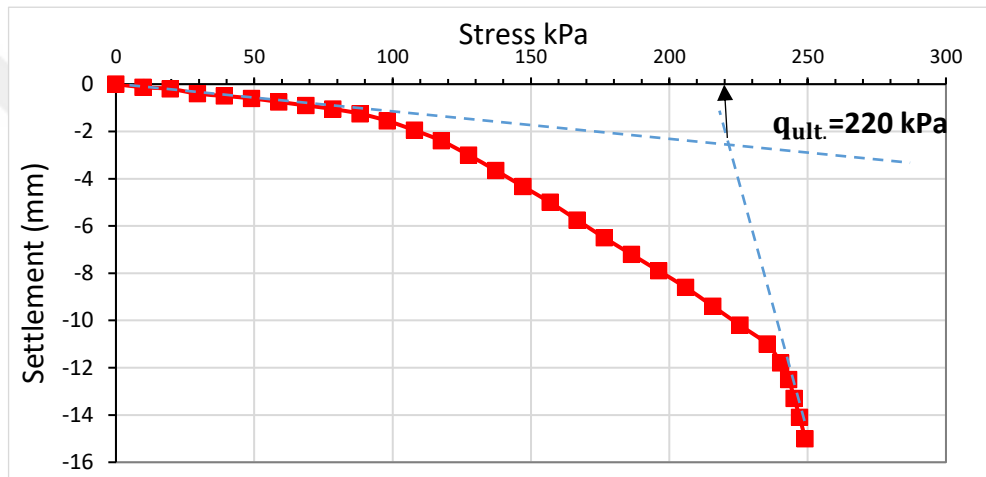


Figure 4.82 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.5B$ for $RD=60\%$ (fully saturation)

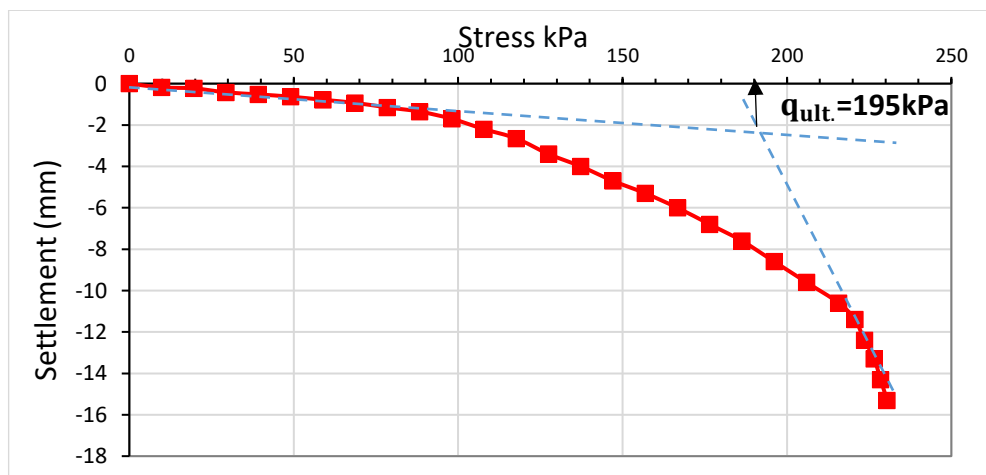


Figure 4.83 Stress - settlement curve for E-glass fiber reinforced soil model at $D=1B$ for $RD=60\%$ (fully saturation)

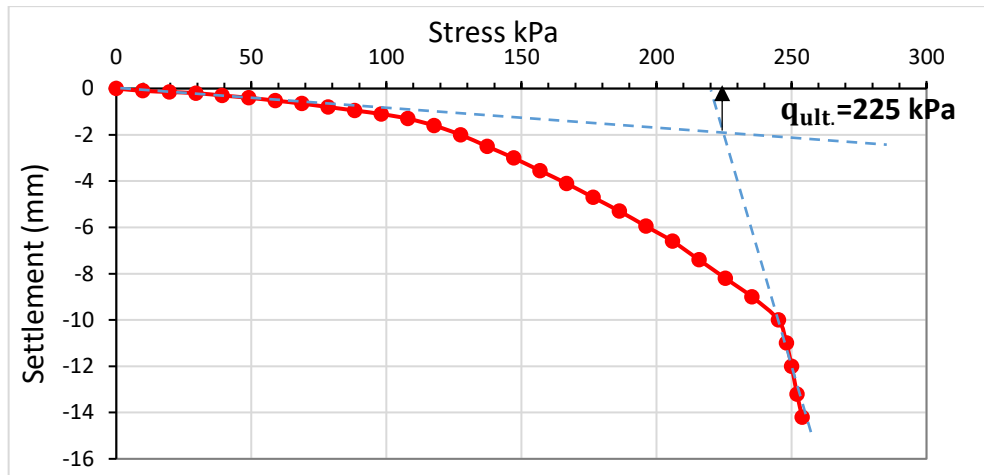


Figure 4.84 Stress - settlement curve for geotextile reinforced soil model at $D=0.25B+0.5B$ for $RD=60\%$ (fully saturation)

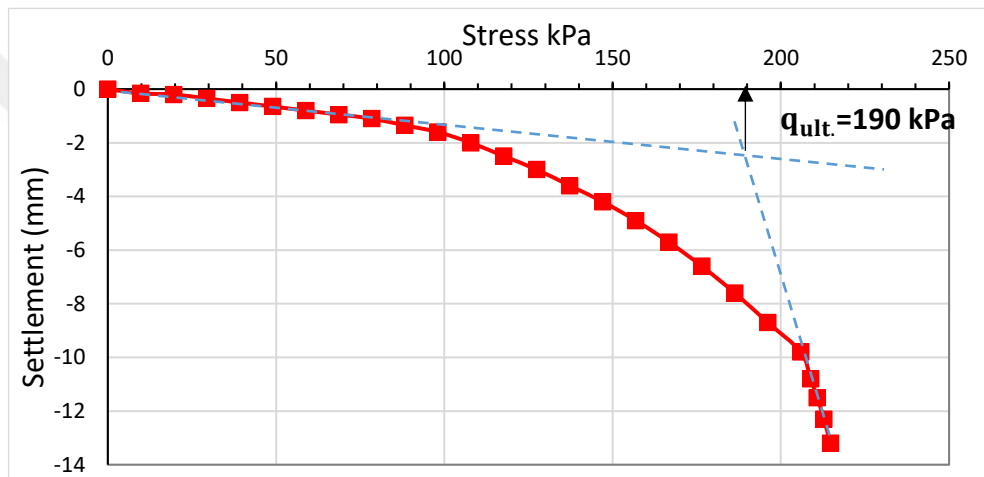


Figure 4.85 Stress - settlement curve for geotextile reinforced soil model at $D=0.5B+1B$ (for $RD=60\%$ (fully saturation)

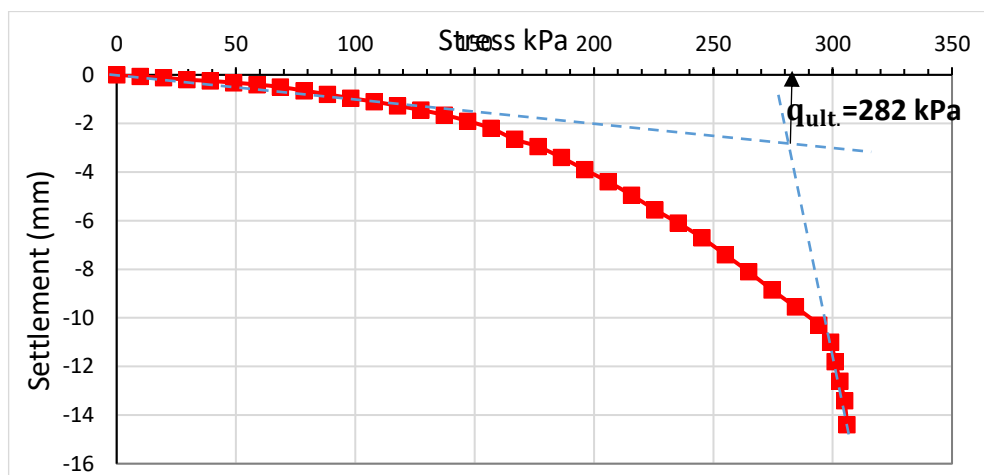


Figure 4.86 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.25B+0.5B$ for $RD=60\%$ (fully saturation)

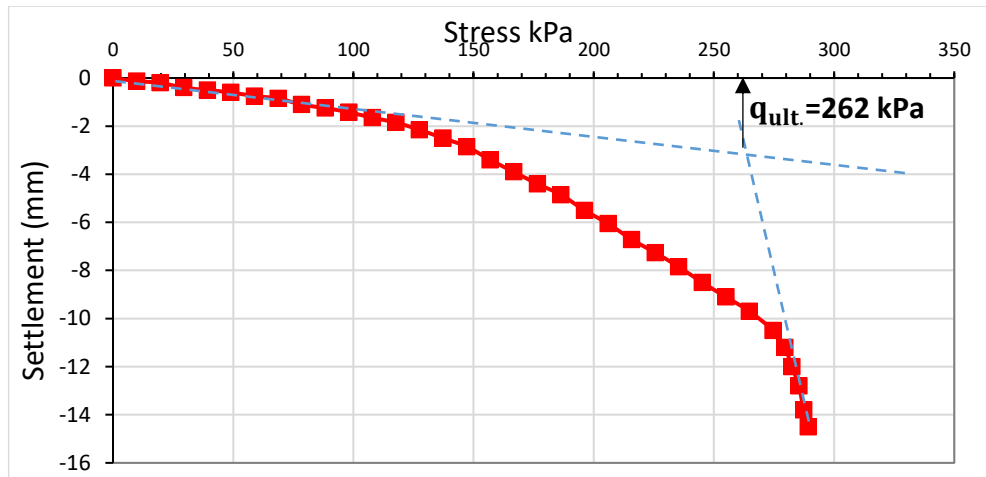


Figure 4.87 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.5B+1B$ for $RD=60\%$ (fully saturation)

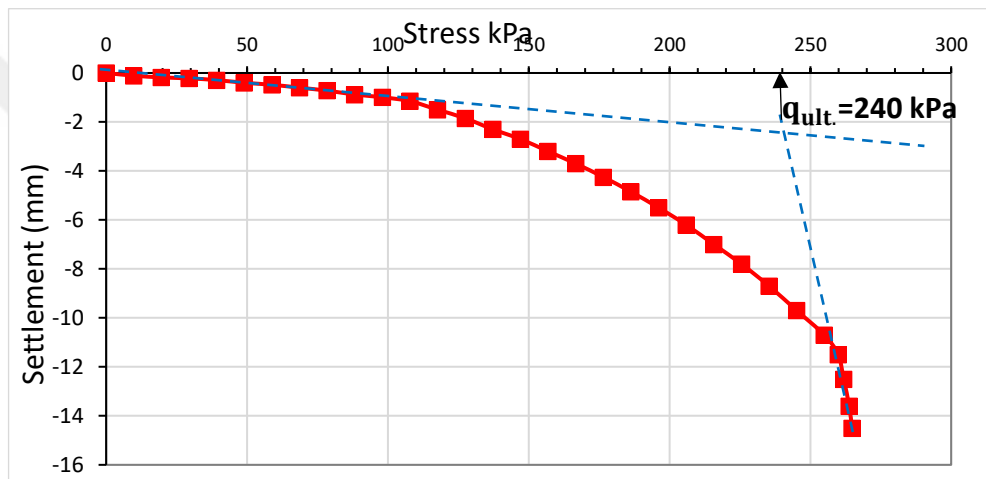


Figure 4.88 Stress - settlement curve for geotextile reinforced soil model at $D=0.25B+0.5B+1B$ for $RD=60\%$ (fully saturation)

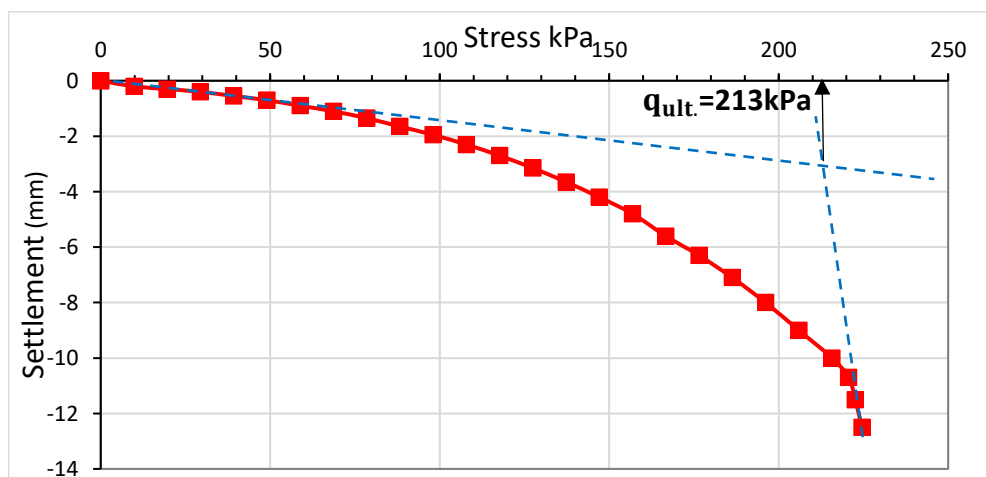


Figure 4.89 Stress - settlement curve for geotextile reinforced soil model at $D=0.5B+1B+1.5B$ for $RD=60\%$ (fully saturation)

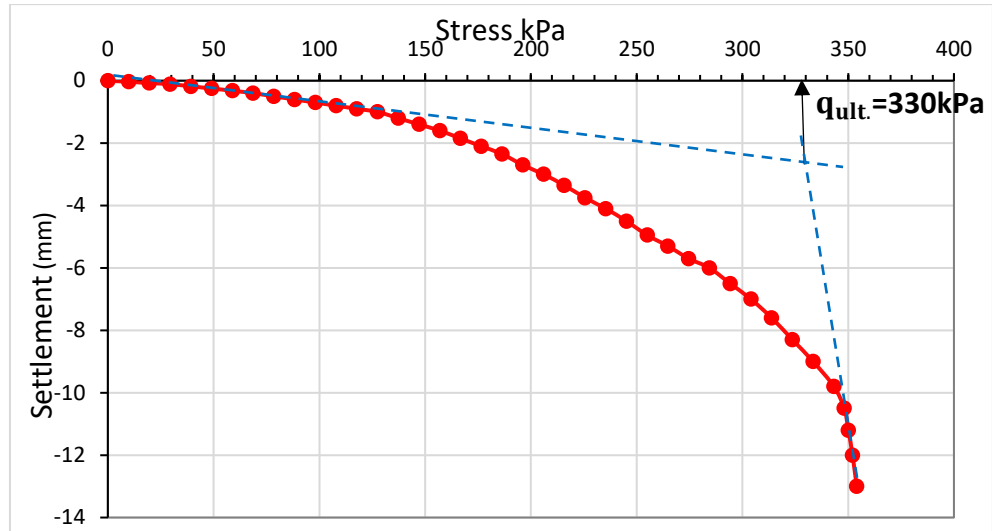


Figure 4.90 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.25B+0.5B+1B$ for $RD=60\%$ (fully saturation)

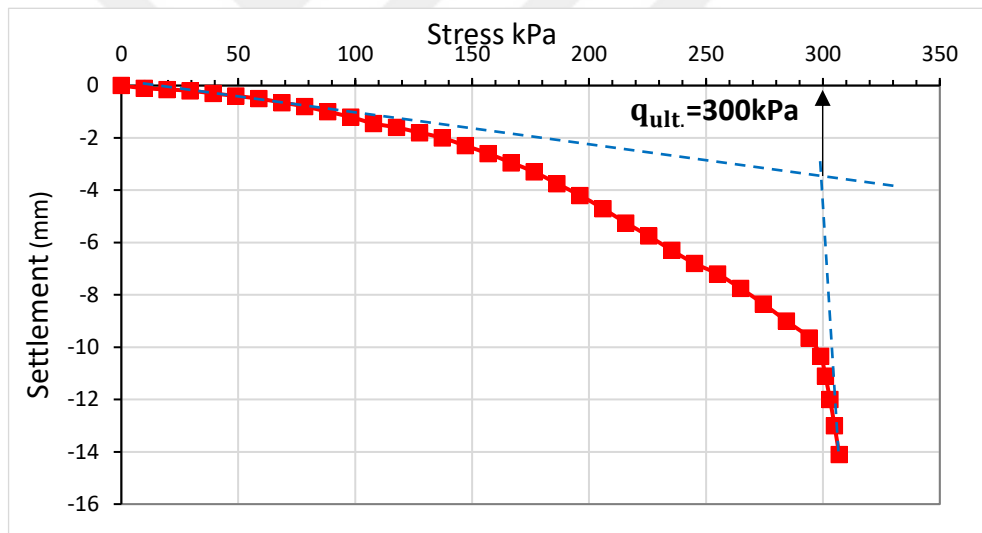


Figure 4.91 Stress - settlement curve for E-glass fiber reinforced soil model at $D=0.5B+1B+1.5B$ for $RD=60\%$ (fully saturation)

Figures 4.92 to 4.94 illustrate the values of ultimate bearing capacity for used the U-shape reinforcement models (confined) and striate reinforcement layer of triple layers ($0.25B+0.5B+1B$) at an RD of 60% (fully saturation state).

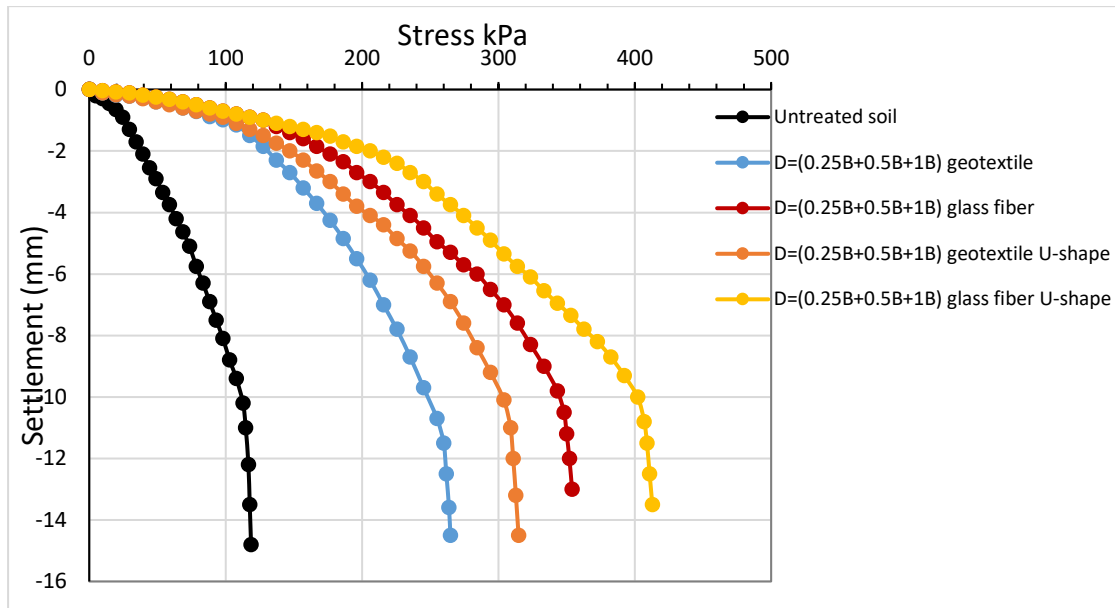


Figure 4.92 Stress - settlement curves for reinforced soil model for U-shape and straight by triple layers at RD=60% (fully saturation)

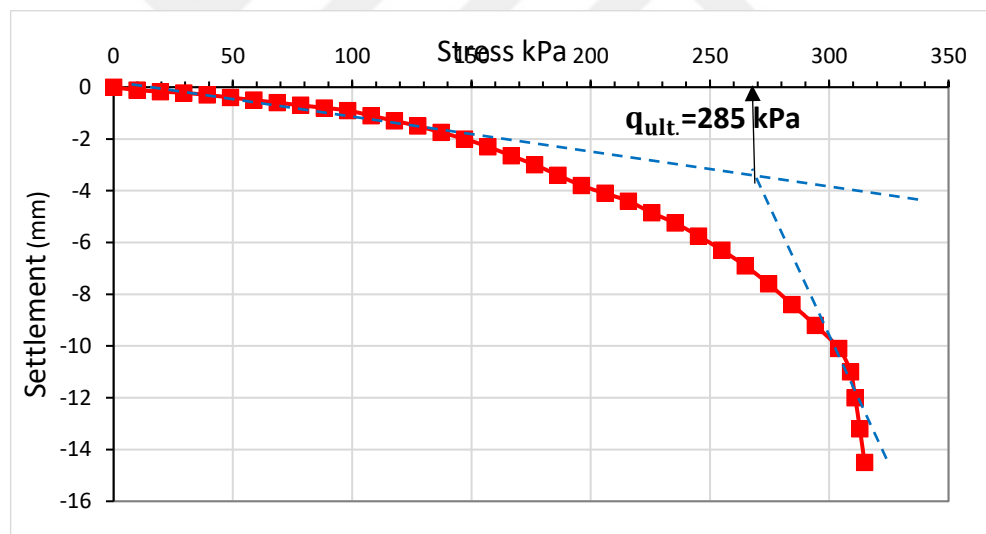


Figure 4.93 Stress - settlement curve for U-shape geotextile reinforced soil model at $D=0.25B+0.5B+1B$ for RD=60% (fully saturation)

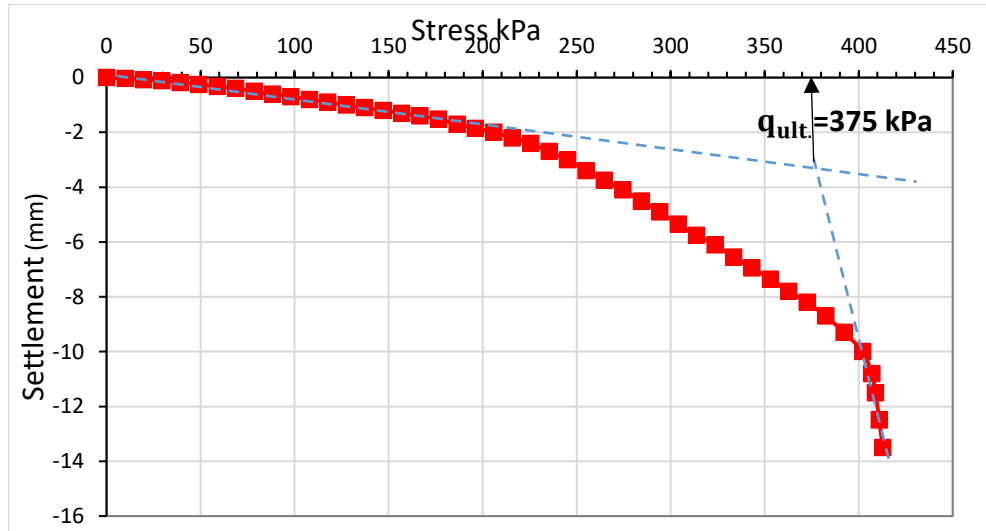


Figure 4.94 Stress - settlement curve for U-shape E-glass fiber reinforced soil model at $D=0.25B+0.5B+1B$ for $RD=60\%$ (fully saturation)

Table 4.3: Values of ultimate and allowable bearing capacity of gypsum soil tested of $RD=30\%$ for wet state below the square footing, $SF=2$

Pattern	Depth of Reinforcement	RD=30% Fully Saturation State			
		Geotextile		E-glass fiber fabric	
		$q_{ult.}(kPa)$	$q_{all.}(kPa)$	$q_{ult.}(kPa)$	$q_{all.}(kPa)$
Single layers	$D = 0.25B$	115	57.5	140	70
	$D = 0.5B$	97	48.5	125	62.5
	$D = 1B$	90	45	115	57.5
Double layers	$D = 0.25B+0.5B$	146	73	195	97.5
	$D = 0.5B+1B$	107	53.5	163	81.5
Triple layers	$D= 0.25B+0.5B+1B$	165	82.5	230	115
	$D=0.5B+1B+1.5B$	143	71.5	205	102.5
U-Shape Triple layers	$D= 0.25B+0.5B+1B$	187	93.5	262	131

Table 4.4: Values of ultimate and allowable bearing capacity of gypsum soil tested of RD=60% for fully saturation state below the square footing, SF=2

Pattern	Depth of Reinforcement	RD=60% Fully Saturation State			
		Geotextile		E-glass fiber fabric	
		$q_{ult.}(kPa)$	$q_{all.}(kPa)$	$q_{ult.}(kPa)$	$q_{all.}(kPa)$
Single layers	D = 0.25B	190	95	235	117.5
	D = 0.5B	173	86.5	220	110
	D = 1B	146	73	195	97.5
Double layers	D = 0.25B+0.5B	225	112.5	282	97.5
	D = 0.5B+1B	190	95	262	131
Triple layers	D= 0.25B+0.5B+1B	240	120	330	165
	D=0.5B+1B+1.5B	213	106.5	300	150
U-Shape Triple layers	D= 0.25B+0.5B+1B	267	133.5	375	187.5

According to the data in Tables 4.3 and 4.4, Figures 4.95 to 4.102 compare the relationship between ultimate bearing capacity and patterns of geosynthetic reinforced (geotextile and E-glass fiber fabric) in RD of 30% and 60% under a fully saturated state.

It was noticed that increasing the value of ultimate bearing capacity for gypseous soil models with E-glass fiber fabric reinforcement was more than the values of the geotextile reinforced models for both RD =30% and 60%. The increase in ultimate bearing capacity with using E-glass fiber fabric relative to geotextiles can be attributed to the increase in friction as well as the nature of the material itself, as well for the values of ultimate bearing capacity for models of RD = 60%, were higher compared to the models with a relative density of 30% due to denser of soil and increase the friction between soil particles.

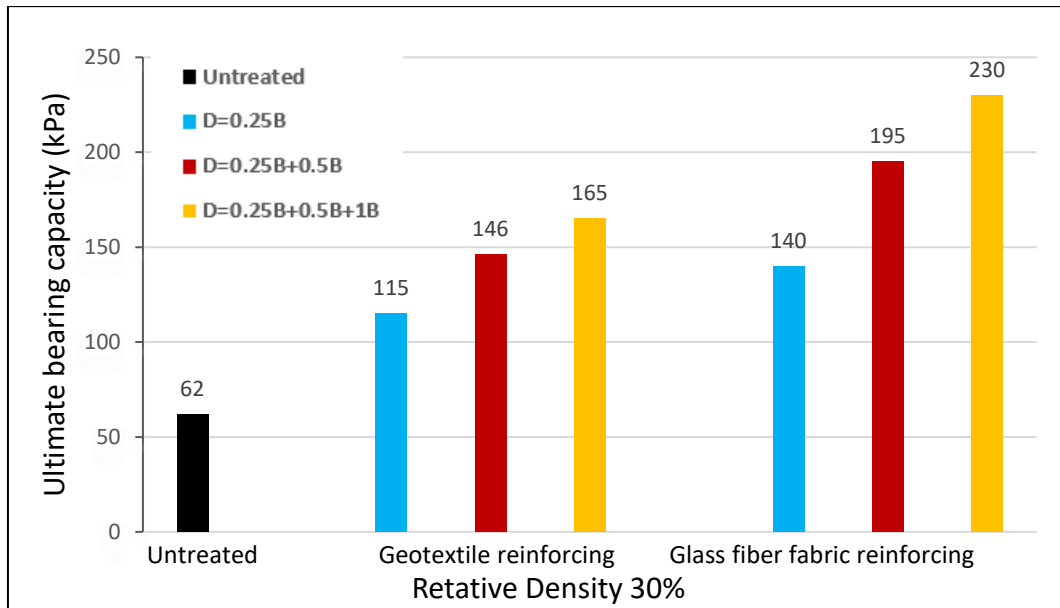


Figure 4.95 Maximum value of ultimate bearing capacity vs. patterns of reinforced (geotextile and E-glass fiber fabric) at RD= 30% (fully saturation)

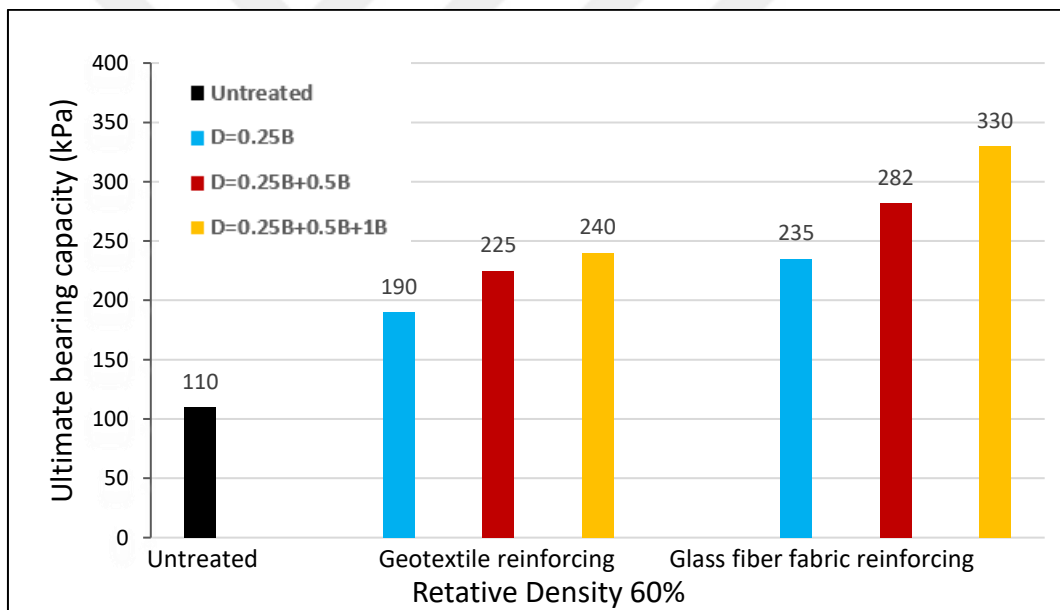


Figure 4.96 Maximum value of ultimate bearing capacity vs. patterns of reinforced (geotextile and E-glass fiber fabric) at RD= 60% (fully saturation)

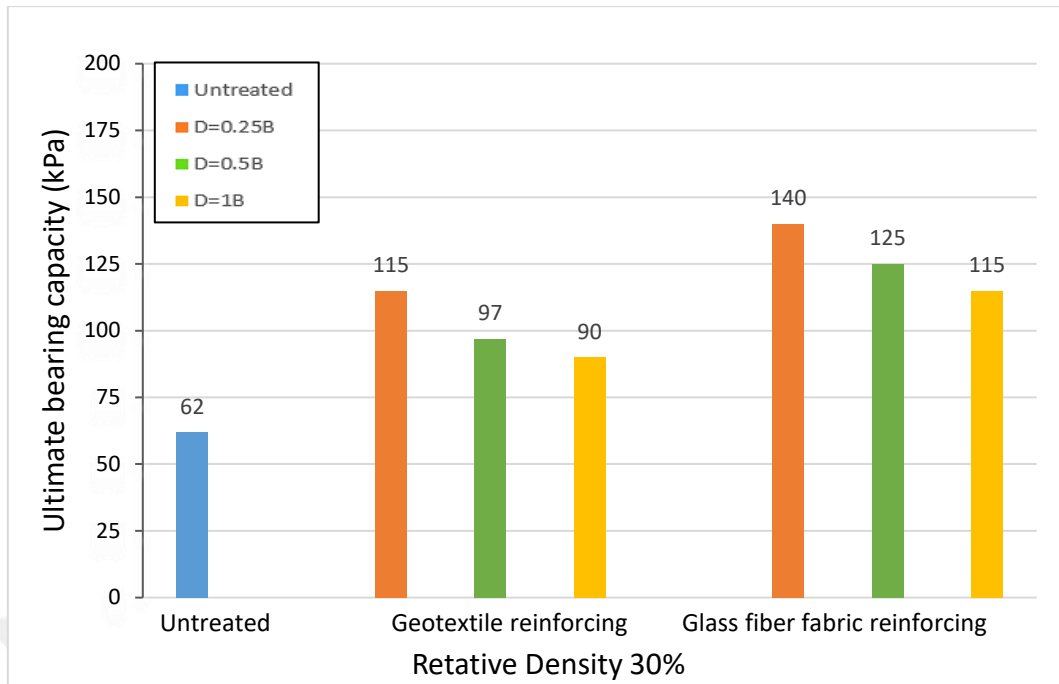


Figure 4.97 Maximum value of ultimate bearing capacity vs. patterns of single layer reinforced (geotextile and E-glass fiber fabric) at RD= 30% (fully saturation)

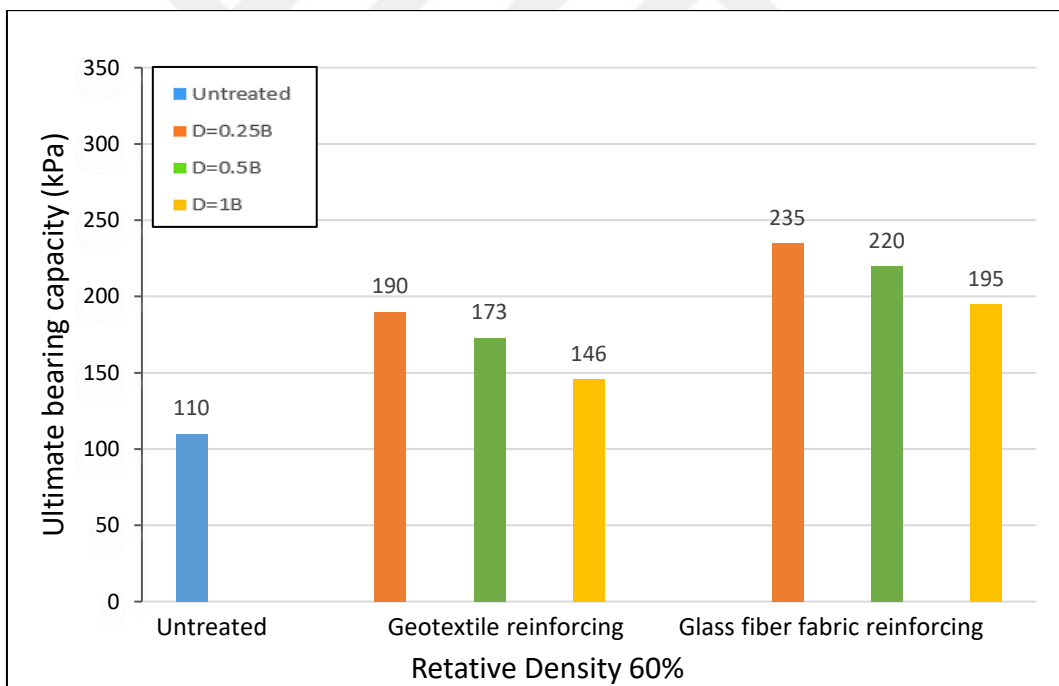


Figure 4.98 Maximum value of ultimate bearing capacity vs. patterns of single layer reinforced (geotextile and E-glass fiber fabric) at RD= 60% (fully saturation)

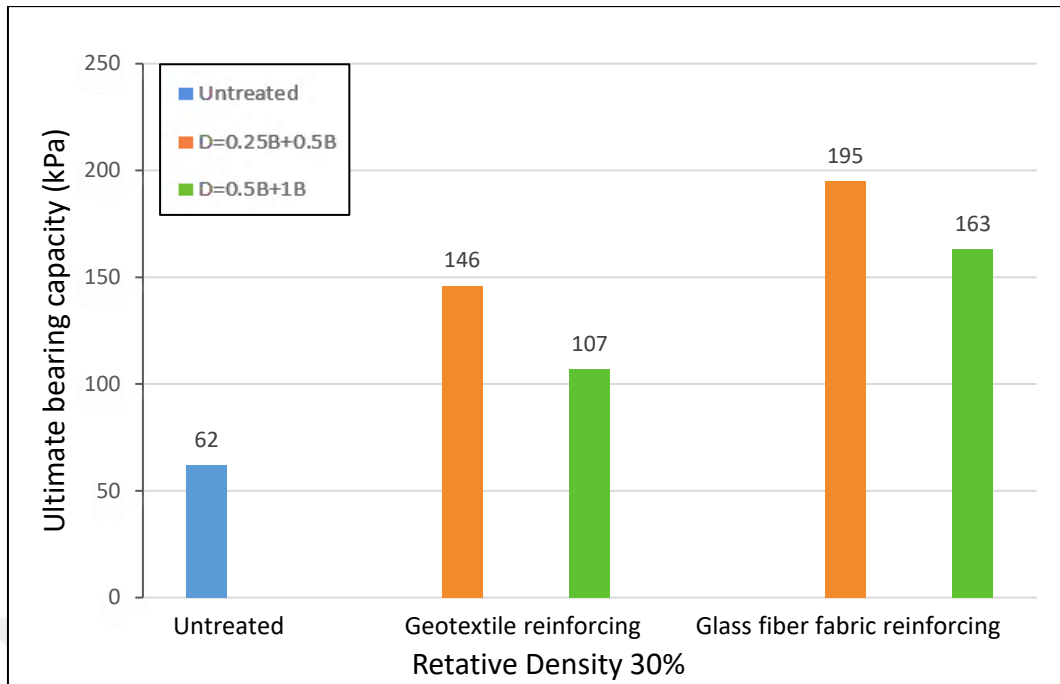


Figure 4.99 Maximum value of ultimate bearing capacity vs. patterns of double layer reinforced (geotextile and E-glass fiber fabric) at RD=30% (fully saturation)

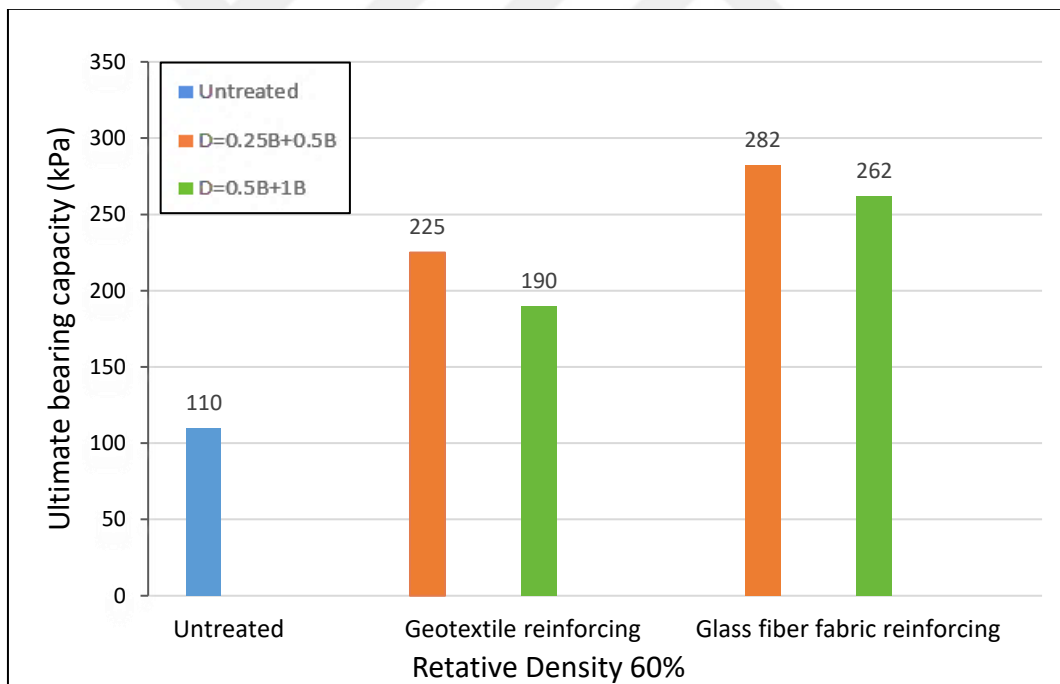


Figure 4.100 Maximum value of ultimate bearing capacity vs. patterns of double layer reinforced (geotextile and E-glass fiber fabric) at RD= 60% (fully saturation)

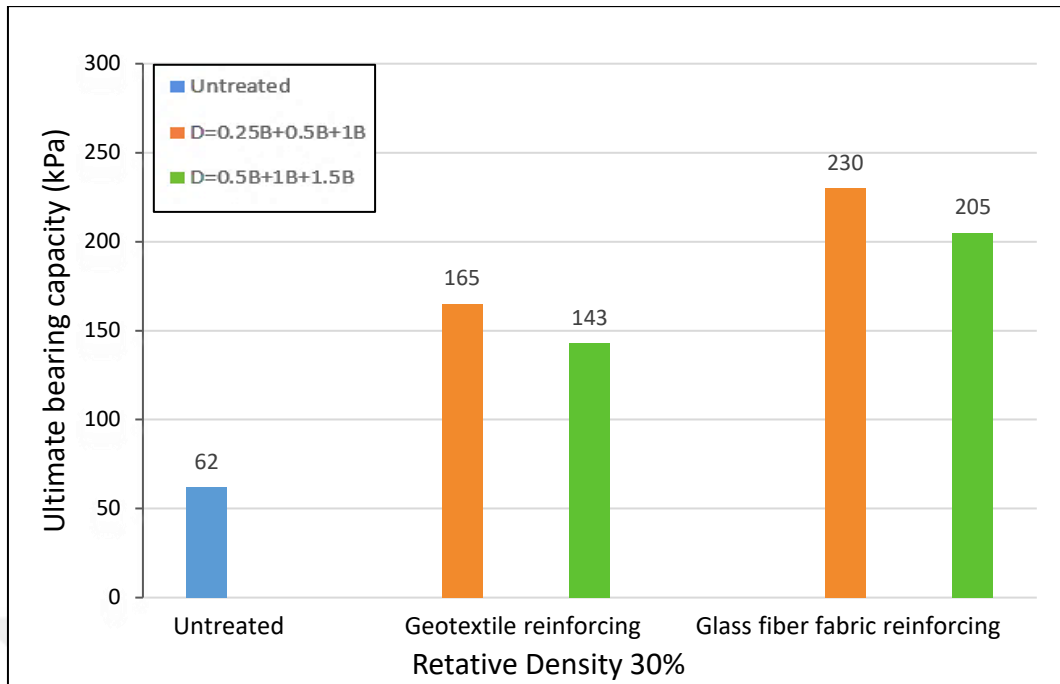


Figure 4.101 Maximum value of ultimate bearing capacity vs. patterns of triple layer reinforced (geotextile and E-glass fiber fabric) at RD= 30% (fully saturation)

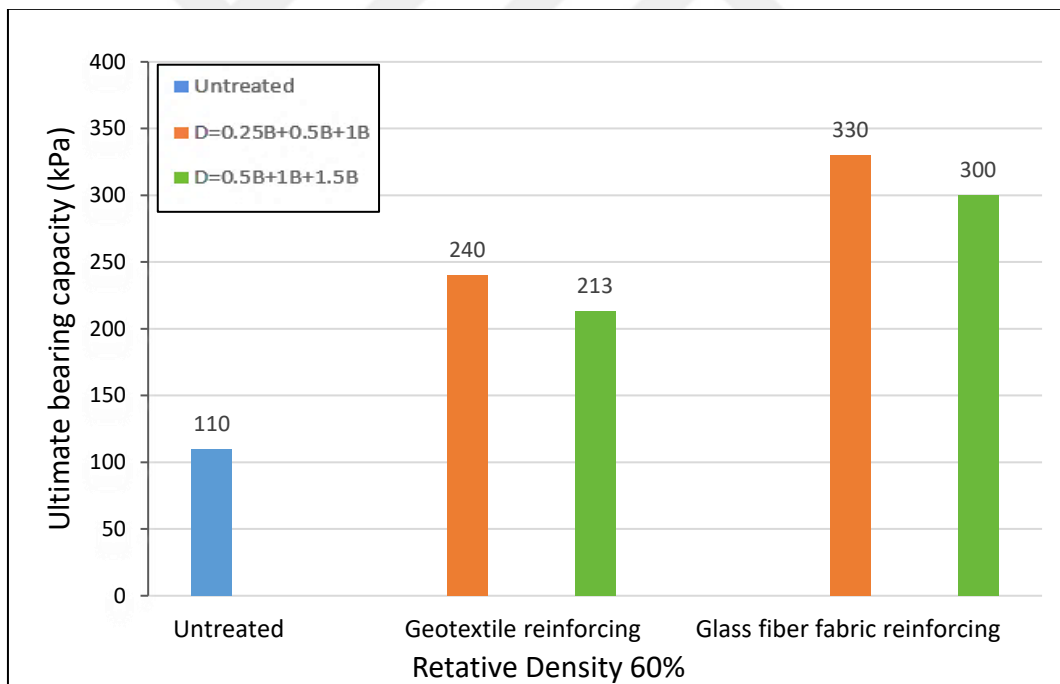


Figure 4.102 Maximum value of ultimate bearing capacity vs. patterns of triple layer reinforced (geotextile and E-glass fiber fabric) RD=60% (fully saturation)

Figures 4.103 and 4.105 show the ultimate bearing capacity when using triple reinforcement (0.25B+0.5B+1B) according to the shape of the layer (straight and U-shape), for the relative densities of 30% and 60%, it was noticed increasing the value of ultimate bearing capacity model used U-shape related to straight shape for both the

geosynthetic reinforced (geotextile and E-glass fiber fabric). This increase can be attributed to the soil model has become confined, which leads to an increase in internal friction between the soil particles, as well as an increase in the bonding between the particles.

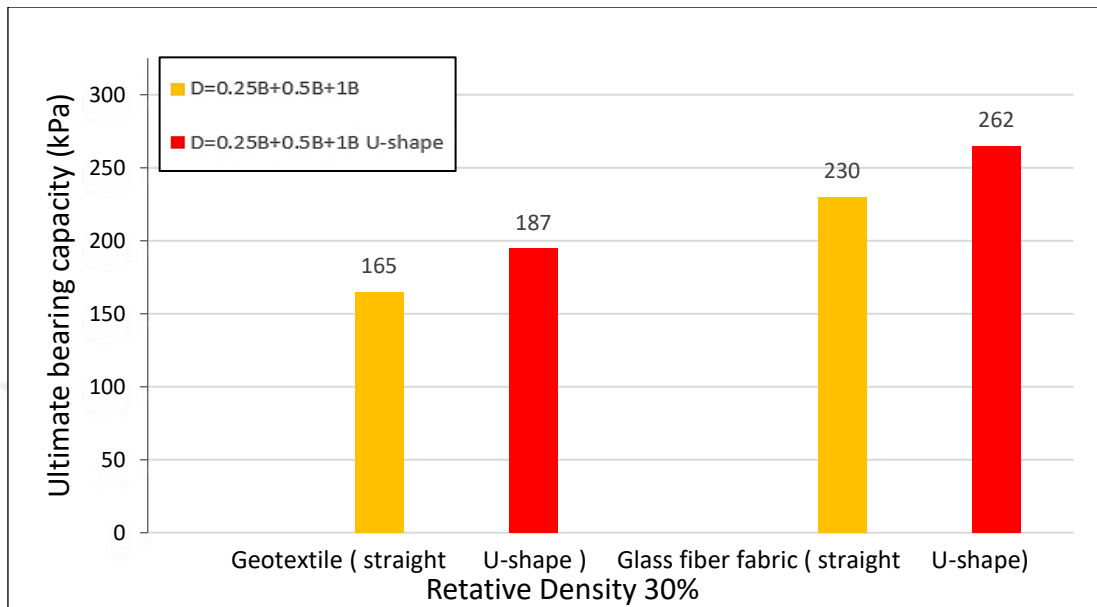


Figure 4.103 Maximum value of ultimate bearing capacity vs. patterns of triple layer reinforced (straight and U-shape) at RD= 30% (fully saturation)

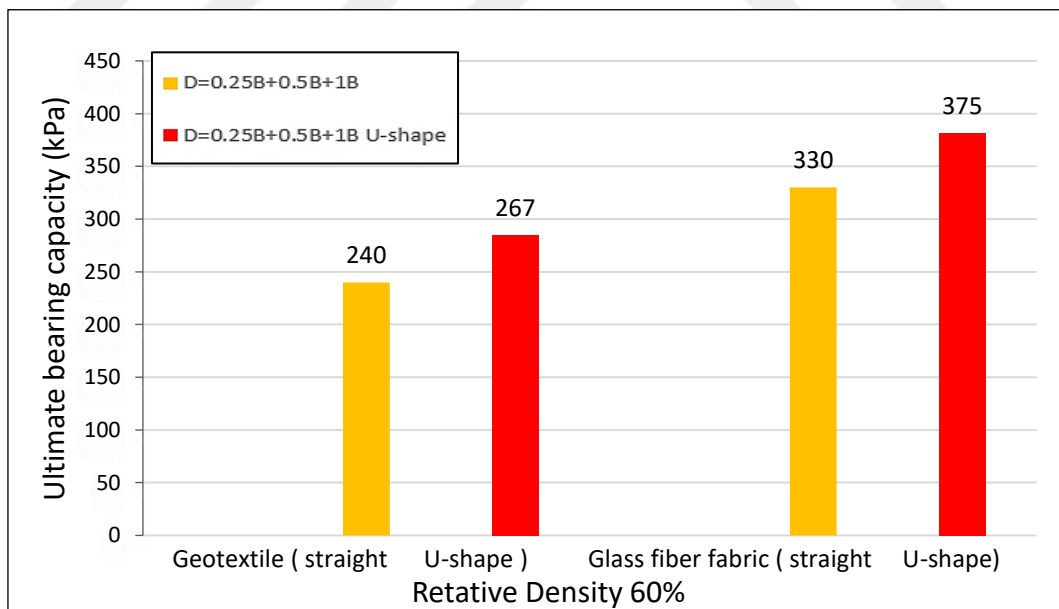


Figure 4.104 Maximum value of ultimate bearing capacity vs. patterns of triple layer reinforced (straight and U-shape) at RD= 60% (fully saturation)

4.3 Improving the BCR % (Ratio of Ultimate Bearing Capacity)

Improving the ratio of bearing capacity BCR% defined the ratio of ultimate bearing capacity of the sample model treated minus the sample untreated model divided by the untreated model as shown in Eq. 4.4 [62]. As it indicates a decrease in settlement by using geosynthetic material (geotextiles) when used in gypsum soils with an increasing the ultimate bearing capacity of the gypsum soil.

$$BCR\% = \frac{q_{tr.} - q_{un.}}{q_{un.}} \times 100 \quad (4.4)$$

Where:

$q_{tr.}$ = Ultimate bearing capacity of soil model treated kPa.

$q_{un.}$ = Ultimate bearing capacity of soil model untreated kPa.

4.3.1 The Effect of Patterns and Depth of Geosynthetic Reinforcing Layers to BCR% of Gypseous Soil Models with Relative Density 30%, and 60% (dry condition)

The improving ratio in bearing capacity (BCR%) for gypseous soil models treated with geosynthetic (geotextile and E-glass fiber fabric) layers of dry conditions at RD=30%,60% for different patterns is shown in Table 4.5. Through the results, the ratio of ultimate bearing capacity BCR% increased by increasing the number of layers for geosynthetic reinforced at relative densities 30% and 60%. The reason for this is the geosynthetic ability to resist the tension resulting from vertical loads and to enable the soil to operate as a unit mass, increasing the soil strength.

According to data from Table 4.5, Figure (4.105) illustrates the relationship between patterns of geosynthetic reinforcing layers (geotextile and E-glass fiber fabric) and the improvement ratio in ultimate bearing capacity (BCR)% at RD = 30% in a dry state.

The results demonstrate that the best improvement (BCR)% of gypsum soil models for single layer patterns of geosynthetic reinforced (geotextile and E-glass fiber fabric) was 50%, and 88.5% at a depth of 0.25B respectively. While the best enhancement (BCR)% in the double layer patterns of geosynthetic reinforced was (88.5%, and 181.5%) at depth (0.25B+0.5B) respectively. whereas for the triple layer patterns, the best enhancement

(BCR%) at depth (0.25B+0.5B+1B) was (130.8%, and 231.5%) when using geotextile and E-glass fiber fabric reinforcement respectively. Also, the maximum improvement ratio of bearing capacity BCR% when using U-shape reinforcement compared with straight reinforced at depth (0.25B+0.5B+1B) was (157.5%, and 270%) when using geotextile and E-glass fiber fabric reinforcement respectively.

The BCR% for gypsum soils when using E-glass fiber fabric reinforcing increases more than compared with using geotextiles. The improvement ratio BCR% is also increased when using U-shape reinforcing layers compared with straight layers, in addition to increasing the improvement ratio of bearing capacity BCR% when increasing the number of geosynthetic layers.

Figure (4.106) illustrates the relationship between patterns of geosynthetic reinforcing layers (geotextile and E-glass fiber fabric) and the improvement ratio in ultimate bearing capacity (BCR)% at RD = 60% in a dry state.

The results demonstrate that the best improvement (BCR)% of gypsum soil models for single layer patterns of geosynthetic reinforced (geotextile and E-glass fiber fabric) was 43.5%, and 74% at a depth of 0.25B respectively. While the best enhancement (BCR)% in the double layer patterns of geosynthetic reinforced was 70.4%, and 109% at depth (0.25B+0.5B) respectively. whereas for the triple layer patterns, the best enhancement (BCR%) at depth (0.25B+0.5B+1B) was (125%, and 160%) when using geotextile and E-glass fiber fabric reinforcement respectively. Also, the maximum improvement ratio of bearing capacity BCR% when using U-shape reinforcement compared with straight reinforced at depth (0.25B+0.5B+1B) was (139%, and 187%) when using geotextile and E-glass fiber fabric reinforcement respectively.

The BCR% for gypsum soils when using E-glass fiber fabric reinforcing increases more than compared with using geotextiles. The improvement ratio BCR% is also increased when using U-shape reinforcing layers compared with straight layers, in addition to increasing the improvement ratio of bearing capacity BCR% when increasing the number of geosynthetic layers.

Table 4.5 BCR% for gypseous soil models after reinforcement of geosynthetic layers in dry conditions for RD= 30% and 60%

NO .	Patter n	Depth of Reinforced	The ratio of Improvement (BCR%)			
			RD=30% Geotextil e	RD=30 % E-glass fiber	RD=60% Geotextil e	RD=60 % E-glass fiber
1	Single layer	D=0.25B	50%	88.5%	43.5%	74%
2		D=0.5B	44.6%	73%	34.8%	67%
3		D=1B	26%	46%	26%	51%
4	Double layer	D=0.25B+0.5B	88.5%	181.5%	70.4%	109%
5		D=0.5B+1B	53.8%	142%	56.5%	85%
6	Triple layer	D=0.25B+0.5B+1 B	130.75%	231.5%	125%	160%
7		D=0.5B+1B+1.5B	97.7%	200%	107.8%	135.5%
8	U- Shape	D=0.25B+0.5B+1 B	157.7%	270%	139%	187%

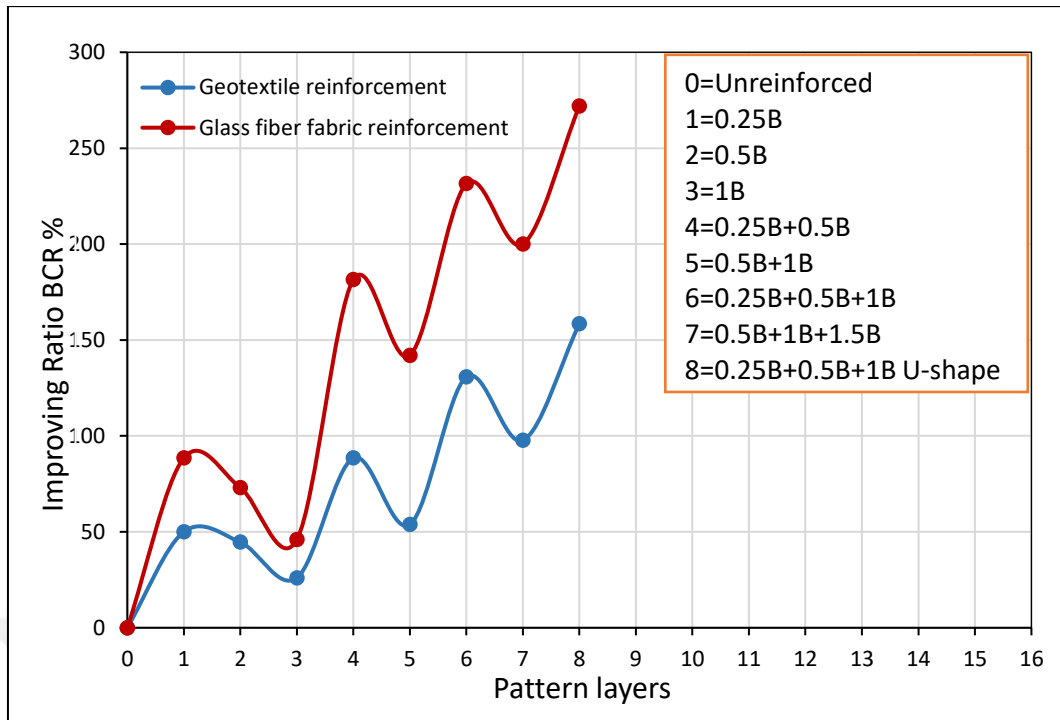


Figure 4.105 BCR% vs. patterns layers for use geosynthetic reinforced (geotextile and E-glass fiber fabric) at RD = 30% dry state

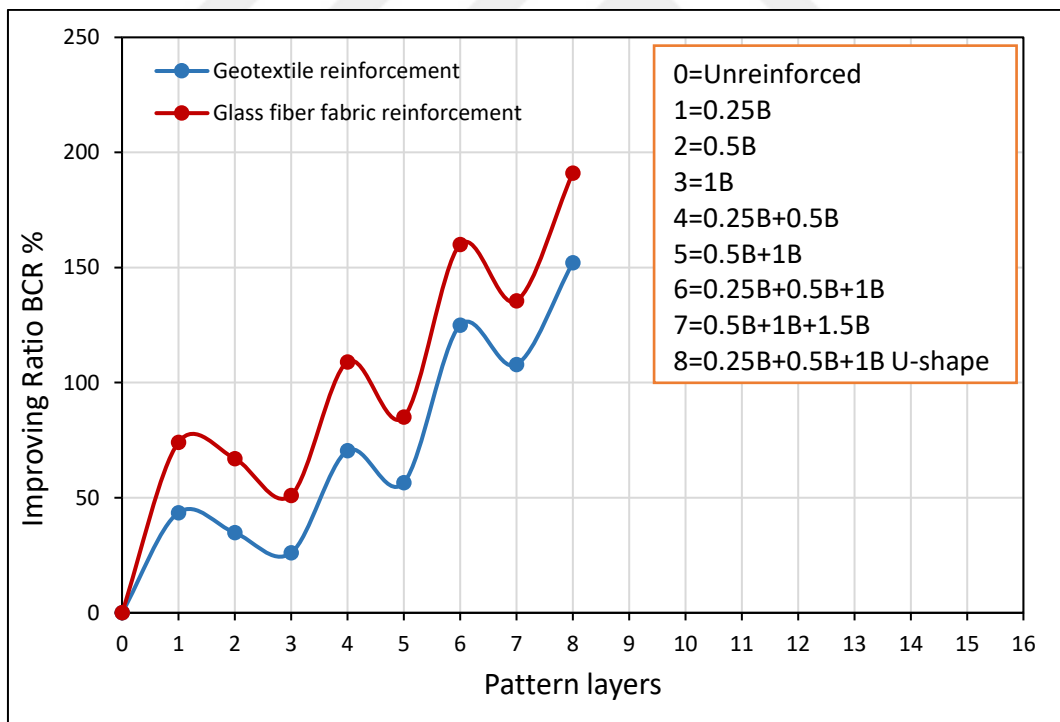


Figure 4.106 BCR% vs. patterns layers for use geosynthetic reinforced (geotextile and E-glass fiber fabric) at RD=60% dry state

According to the data in Table 4.5, Figures (4.107) to (4.116) compare the improvement ratio in ultimate bearing capacity (BCR%) values and patterns RD = 30% and 60% under dry state. The improvement ratio of bearing capacity BCR% can be observed as better for

a relative density of 30% in all patterns of single, double, and triple reinforcing from a relative density of 60%. which may be the reason that the improvement in weak soil expresses more effectively compared to it in strong soil.

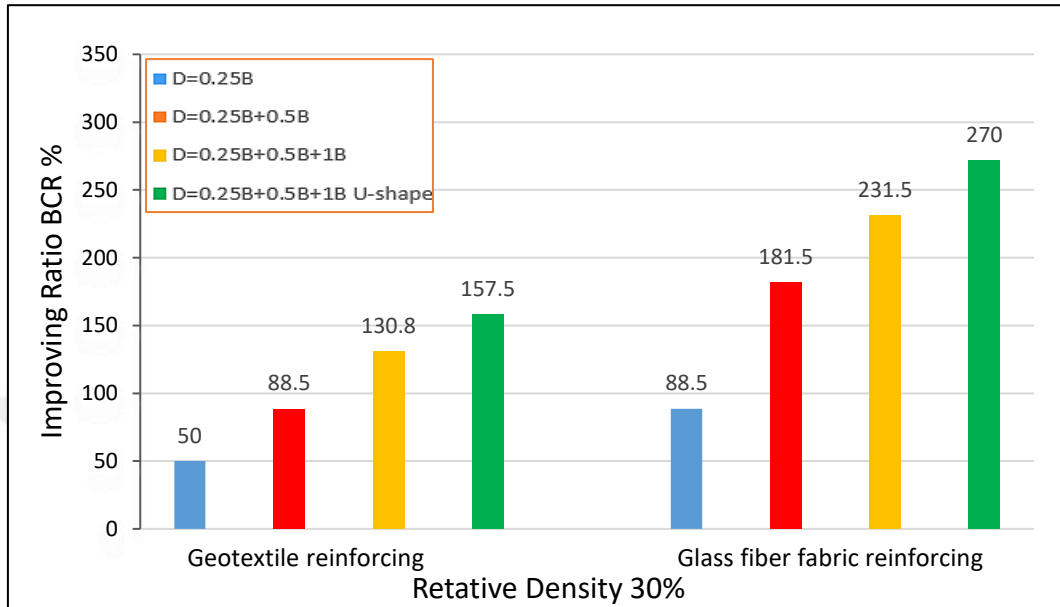


Figure 4.107 BCR% vs. RD =30% of soil models reinforced at different patterns layers geosynthetic

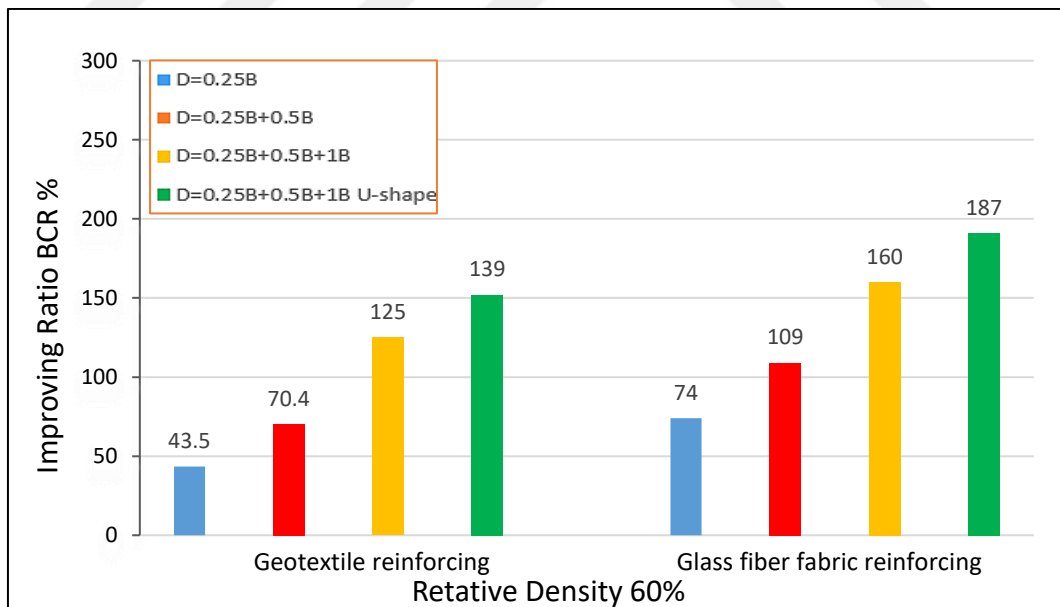


Figure 4.108 BCR% vs. RD =60% of soil models reinforced at different patterns layers geosynthetic

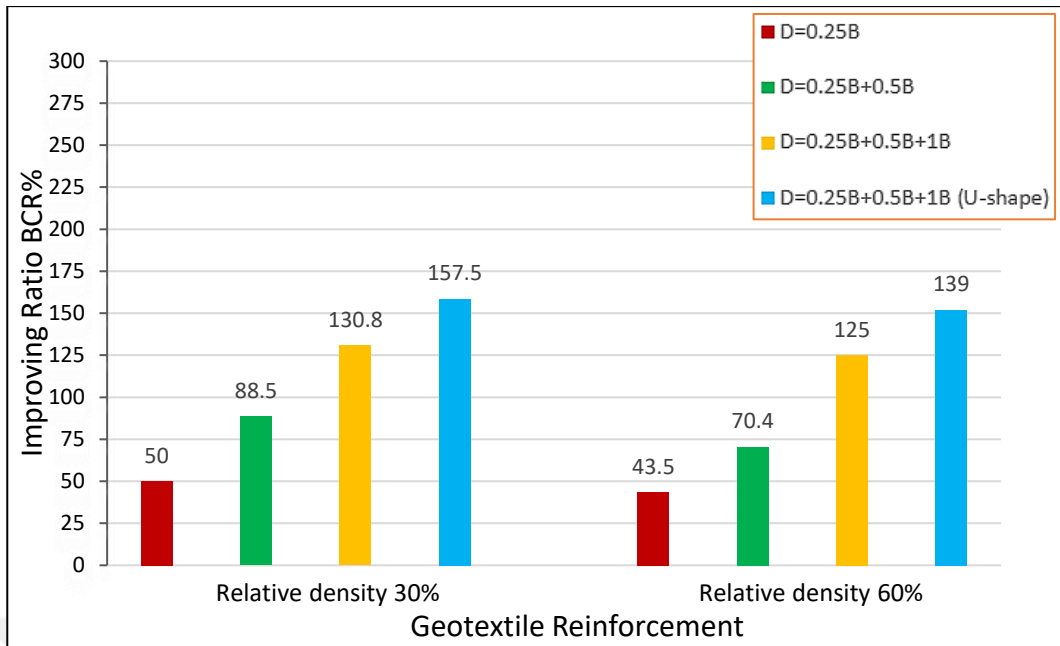


Figure 4.109 BCR% vs. RD =60% and RD =30% of soil models reinforced for different patterns layers of geotextile reinforcement.

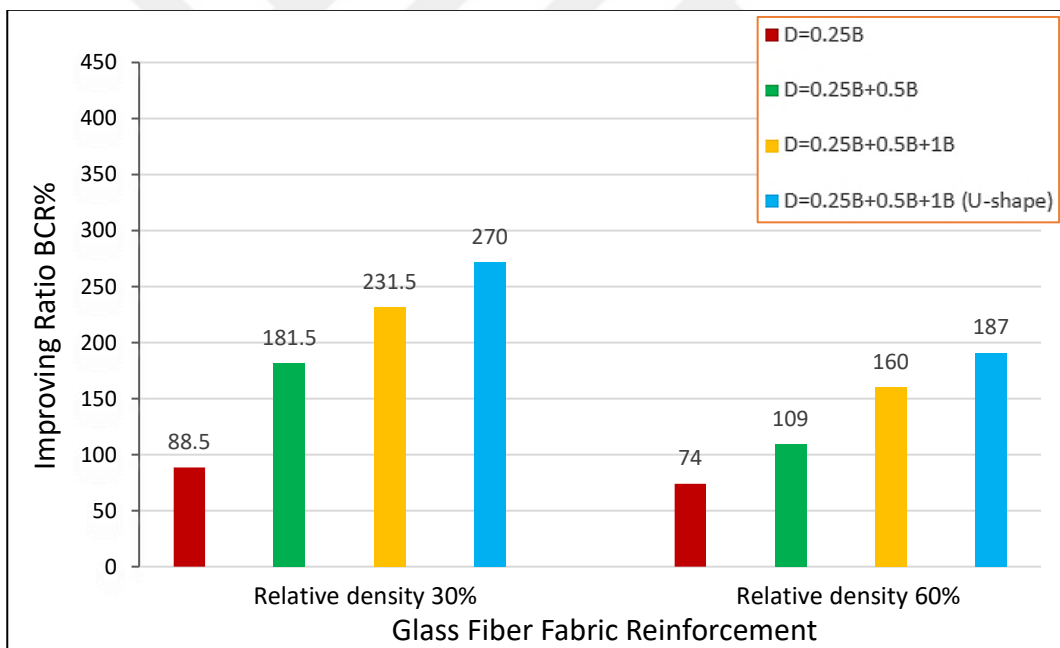


Figure 4.110 BCR% vs. RD =60% and RD =30% of soil models reinforced for different patterns layers of E-glass fiber reinforcement

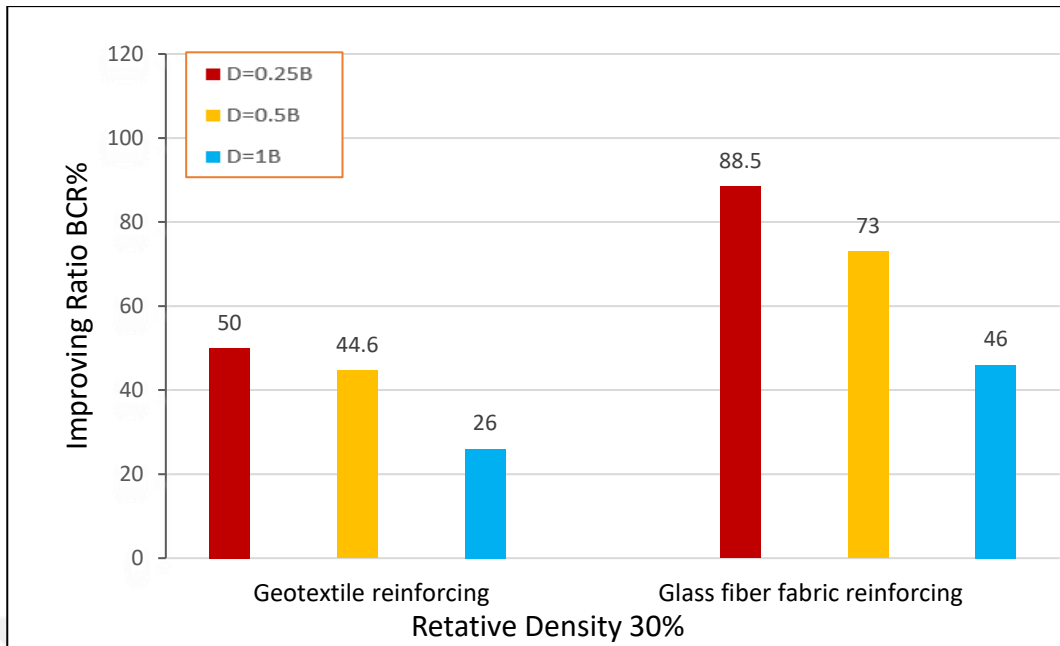


Figure 4.111 BCR% vs. RD =30% of soil models reinforced by single layer (geotextile and E-glass fiber fabric).

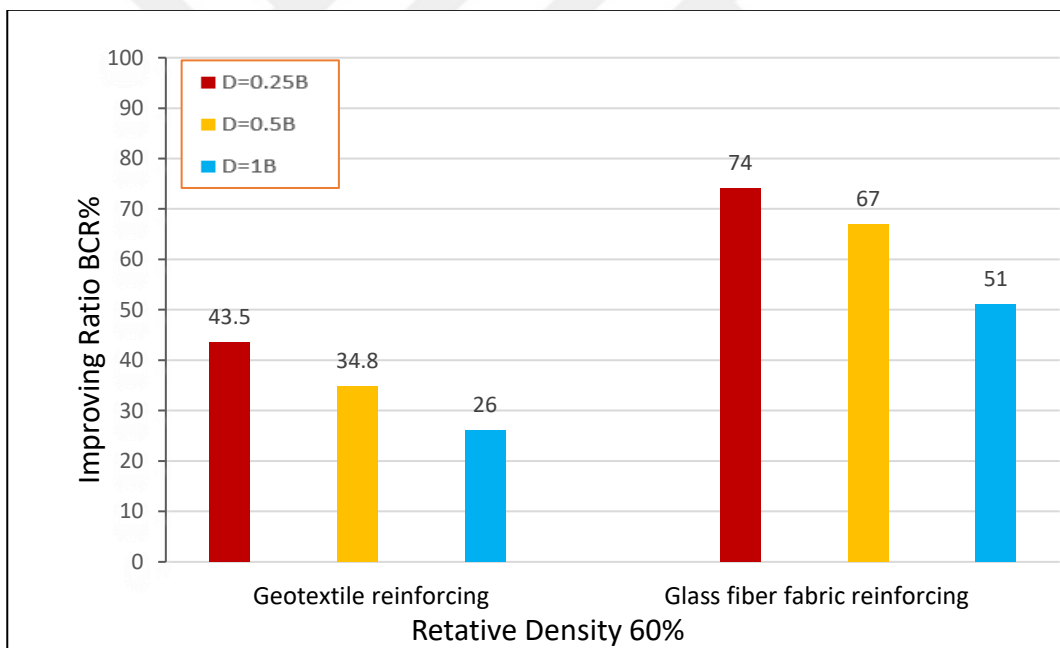


Figure 4.112 BCR% vs. RD =60% of soil models reinforced by single layer (geotextile and E-glass fiber fabric).

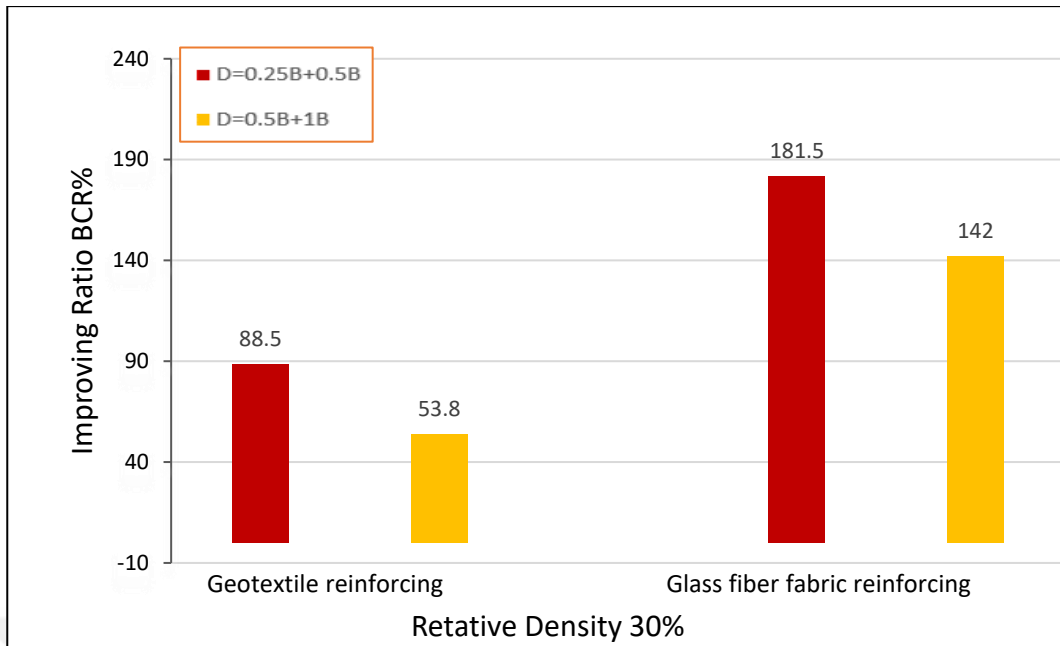


Figure 4.113 BCR% vs. RD =30% of soil models reinforced by double layer (geotextile and E-glass fiber fabric).

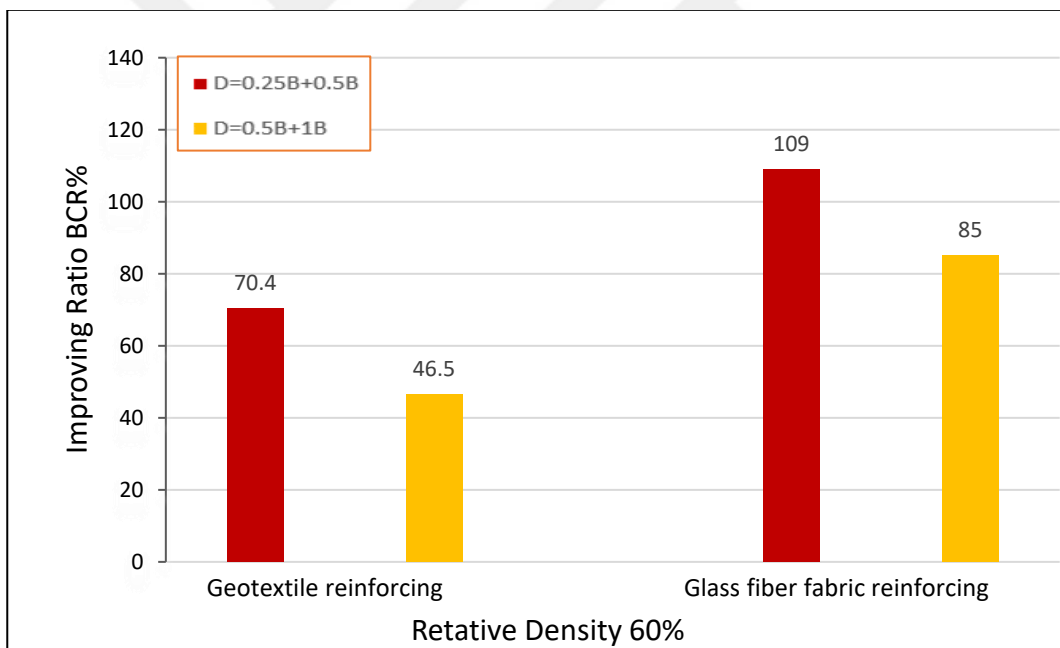


Figure 4.114 BCR% vs. RD =60% of soil models reinforced by double layer (geotextile and E-glass fiber fabric).

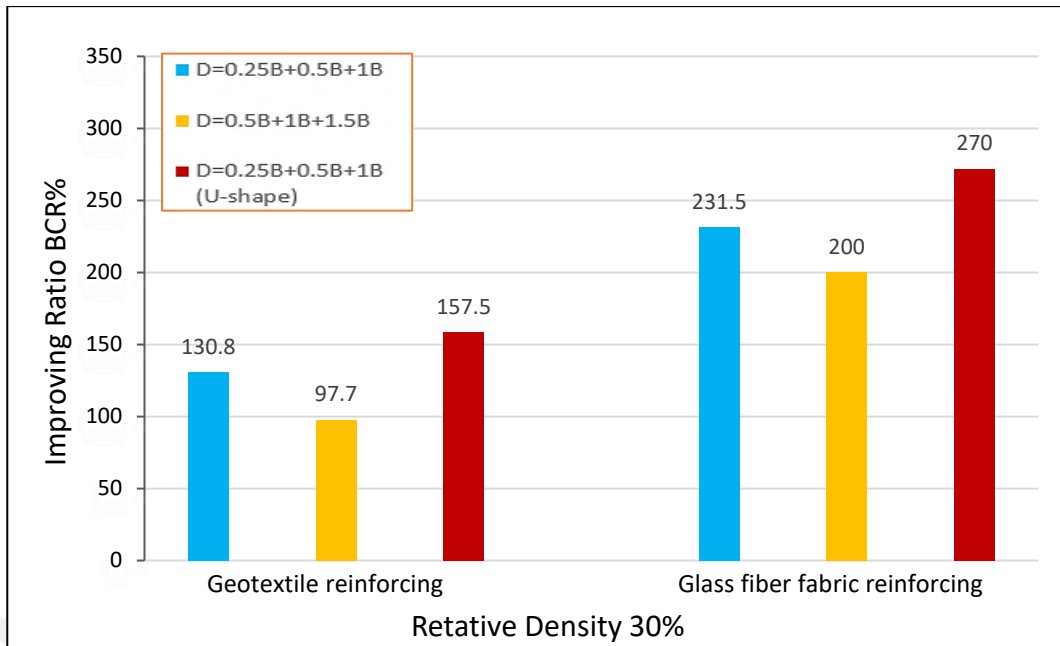


Figure 4.115 BCR% vs. RD =30% of soil models reinforced by triple layer and U-shape reinforcement (geotextile and E-glass fiber fabric).

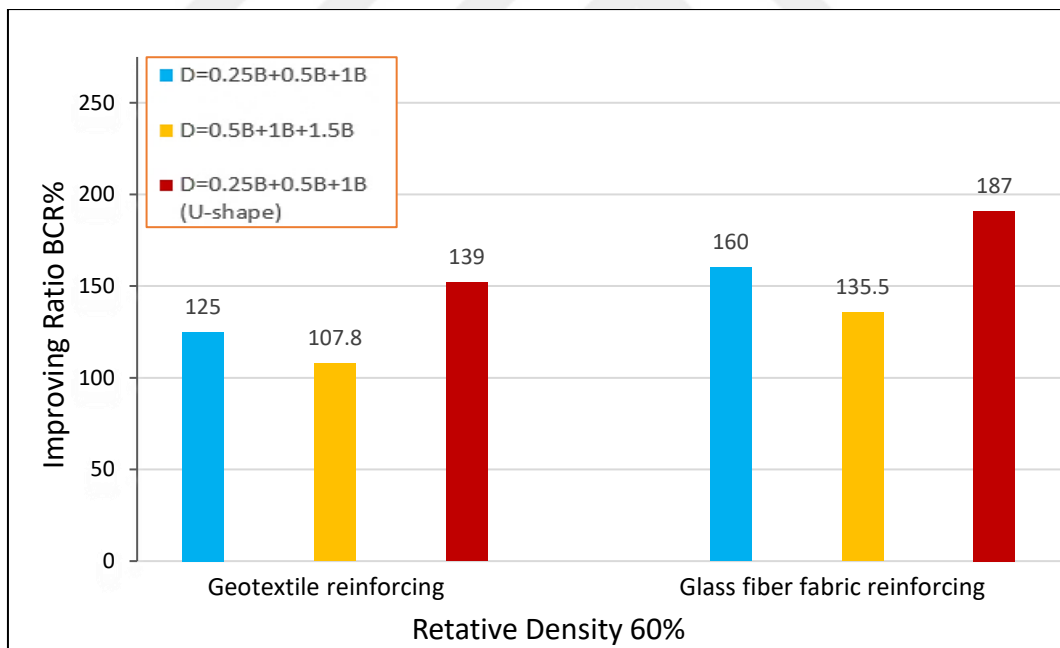


Figure 4.116 BCR% vs. RD =60% of soil models reinforced by triple layer and U-shape reinforcement (geotextile and E-glass fiber fabric).

4.3.2 The Effect of Patterns and Depth of Geosynthetic Reinforcing Layers to BCR% of Gypsum Soil Models with Relative Density 30%, and 60% (Fully Saturation State)

The improving ratio in bearing capacity (BCR%) for gypseous soil models treated with geosynthetic (geotextile and E-glass fiber fabric) layers of wet conditions at RD=30%,60% for different patterns is shown in Table (4.4). Through the results, the ratio of ultimate bearing capacity BCR% increased by increasing the number of layers for geosynthetic reinforced at relative densities 30% and 60%. The reason for this is the geosynthetic reinforcing layers, which serve to stabilize the soil and prevent sudden collapse by reducing particle sliding and increasing friction forces between them. According to data from Table 4.6, Figure (4.117) illustrates the relationship between patterns of geosynthetic reinforcing layers (geotextile and E-glass fiber fabric) and the improvement ratio in ultimate bearing capacity (BCR)% at RD = 30% in full saturation.

The results demonstrate that the best improvement (BCR)% of gypsum soil models for single layer patterns of geosynthetic reinforced (geotextile and E-glass fiber fabric) was 85.5%, and 125.8% at a depth of 0.25B respectively. While the best enhancement (BCR)% in the double layer patterns of geosynthetic reinforced was (135%, and 214.5%) at depth (0.25B+0.5B) respectively. whereas for the triple layer patterns, the best enhancement (BCR%) at depth (0.25B+0.5B+1B) was (166%, and 271%) when using geotextile and E-glass fiber fabric reinforcement respectively. Also, the maximum improvement ratio of bearing capacity BCR% when using U-shape reinforcement compared with straight reinforced at depth (0.25B+0.5B+1B) was (201%, and 322.5%) when using geotextile and E-glass fiber fabric reinforcement respectively.

The improvement ratio of bearing capacity BCR% for gypsum soils when using E-glass fiber fabric reinforcing increases more compared to an increase in the improvement ratio of bearing capacity BCR% using geotextiles. The improvement ratio BCR% is also increased when using U-shape reinforcing layers compared with straight layers, in addition to increasing the improvement ratio of bearing capacity BCR% when increasing the number of geosynthetic layers.

Figure (4.118) illustrates the relationship between patterns of geosynthetic reinforcing layers (geotextile and E-glass fiber fabric) and the improvement ratio in ultimate bearing capacity (BCR)% at RD = 60% in a saturation state.

The results demonstrate that the best improvement (BCR)% of gypsum soil models for single layer patterns of geosynthetic reinforced (geotextile and E-glass fiber fabric) was 72.7%, and 113.5% at a depth of $0.25B$ respectively. While the best enhancement (BCR)% in the double layer patterns of geosynthetic reinforced was 104.5%, and 156% at depth $(0.25B+0.5B)$ respectively. whereas for the triple layer patterns, the best enhancement (BCR%) at depth $(0.25B+0.5B+1B)$ was (118%, and 200%) when using geotextile and E-glass fiber fabric reinforcement respectively. Also, the maximum improvement ratio of bearing capacity BCR% when using U-shape reinforcement compared with straight reinforced at depth $(0.25B+0.5B+1B)$ was (142%, and 241%) when using geotextile and E-glass fiber fabric reinforcement respectively.

The improvement ratio of bearing capacity BCR% for gypsum soils when using E-glass fiber fabric reinforcing increases more compared to an increase in the improvement ratio of bearing capacity BCR% using geotextiles. The improvement ratio BCR% is also increased when using U-shape reinforcing layers compared with straight layers, in addition to increasing the improvement ratio of bearing capacity BCR% when increasing the number of geosynthetic layers.

Table 4.6 BCR% for gypsum soil models after reinforcement of geosynthetic layers in fully saturation state for RD= 30% and 60%

NO:	Pattern	Depth of Reinforcement	The ratio of Improvement BCR%			
			RD=30% Geotextile	RD=30% E-glass fiber	RD=60% Geotextile layers	RD=60% E-glass fiber
1	Single Layers	$D = 0.25 B$	85.5%	125.8%	72.7%	113.5%
2		$D = 0.5 B$	56%	101.5%	57%	100%
3		$D = 1 B$	45%	85.5%	32.7%	77%
4	Double	$D=0.25B+0.5B$	135%	214.5%	104.5%	156%
5	Layers	$D=0.5B+1B$	72.5%	163%	72%	138%
6	Triple	$D=0.25B+0.5B+1B$	166%	271%	118%	200%
7	Layers	$D=0.5B+1B+1.5B$	130.6%	230.5%	93.5%	172.7%
8	U-shape	$D=0.25B+0.5B+1B$	201%	322.5%	142%	241%

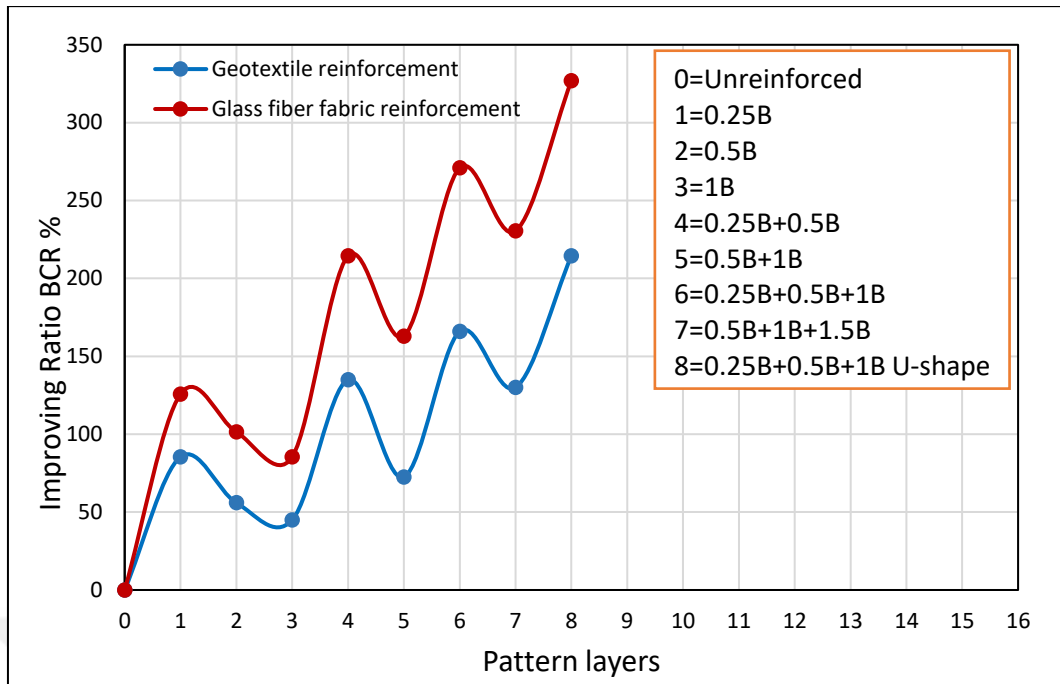


Figure 4.117 BCR% vs. patterns layers for use geosynthetic reinforced (geotextile and E-glass fiber fabric) at RD=30% of full saturation

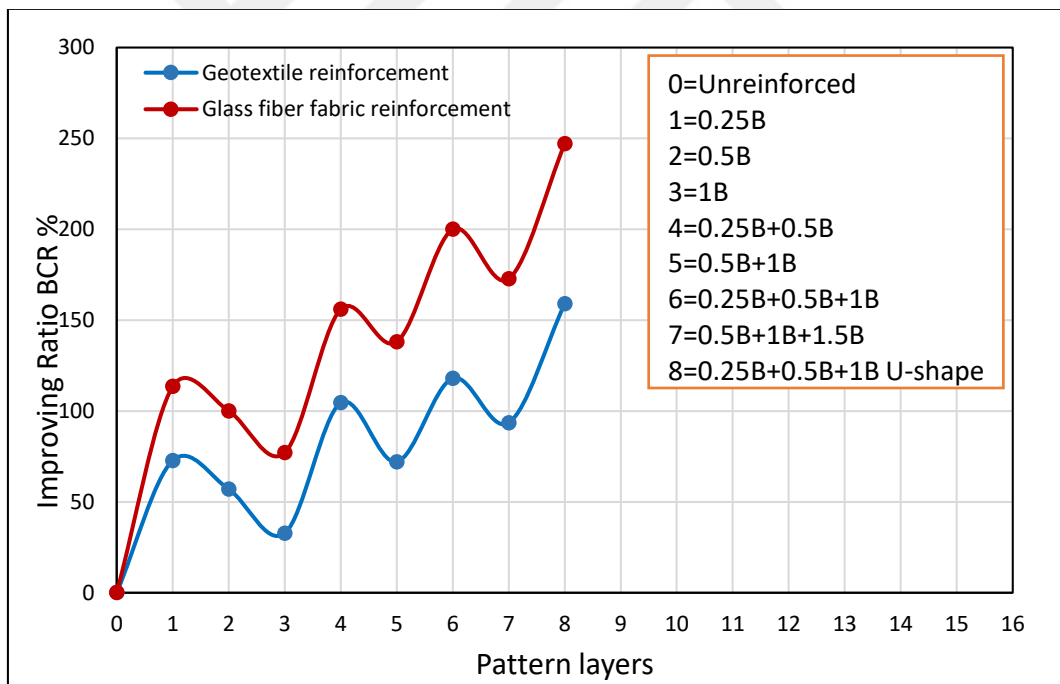


Figure 4.118 BCR% vs. patterns layers for use geosynthetic reinforced (geotextile and E-glass fiber fabric) at RD=60% of full saturation

According to the data in Table 4.6, Figures (4.119) to (4.128) compare the improvement ratio in ultimate bearing capacity (BCR%) values and patterns RD = 30% and 60% under fully saturation.

The improvement ratio of bearing capacity BCR% can be observed as better for a relative density of 30% in all patterns of single, double, and triple reinforcing from a relative density of 60%. which may be the reason that the improvement in weak soil expresses more effectively compared to it in strong soil.

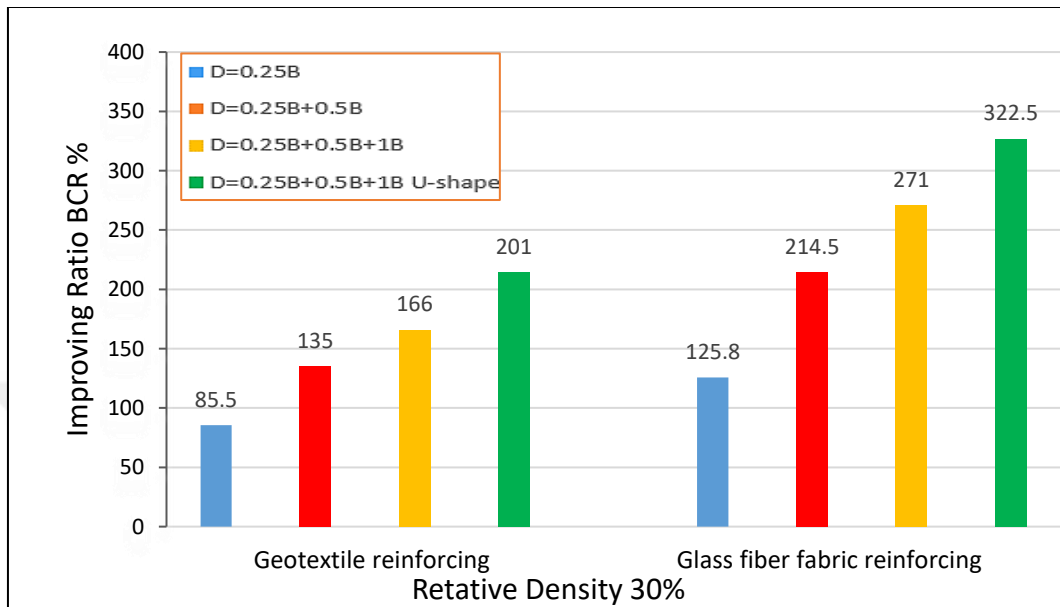


Figure 4.119 BCR% vs. RD =30% of soil models reinforced at different patterns layers geosynthetic

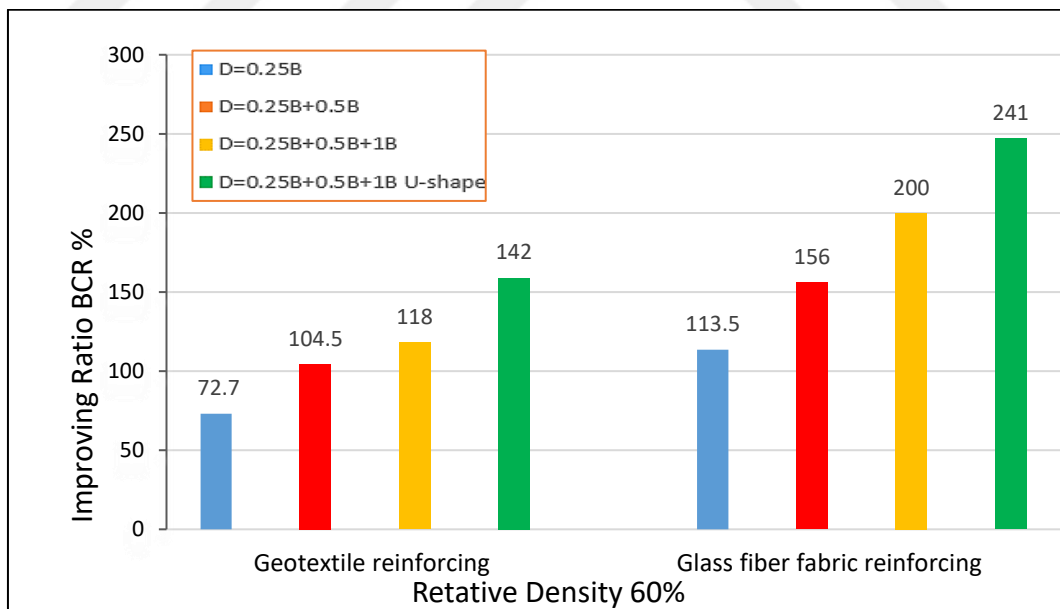


Figure 4.120 BCR% vs. RD =60% of soil models reinforced at different patterns layers geosynthetic

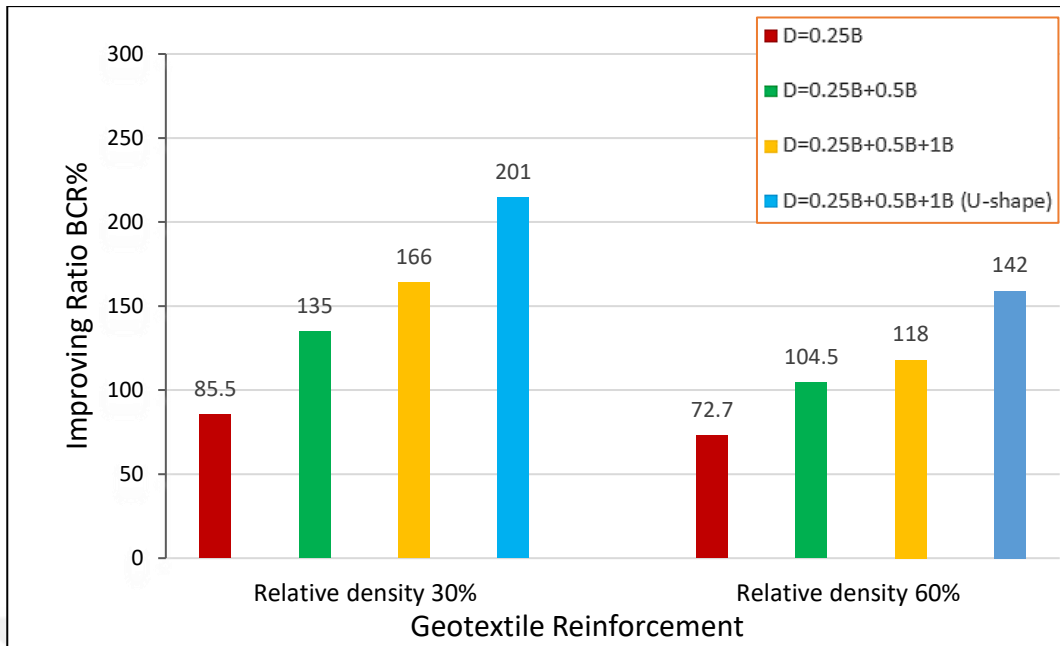


Figure 4.121 BCR% vs. RD =60% and RD =30% of soil models reinforced for different layers of geotextile reinforcement

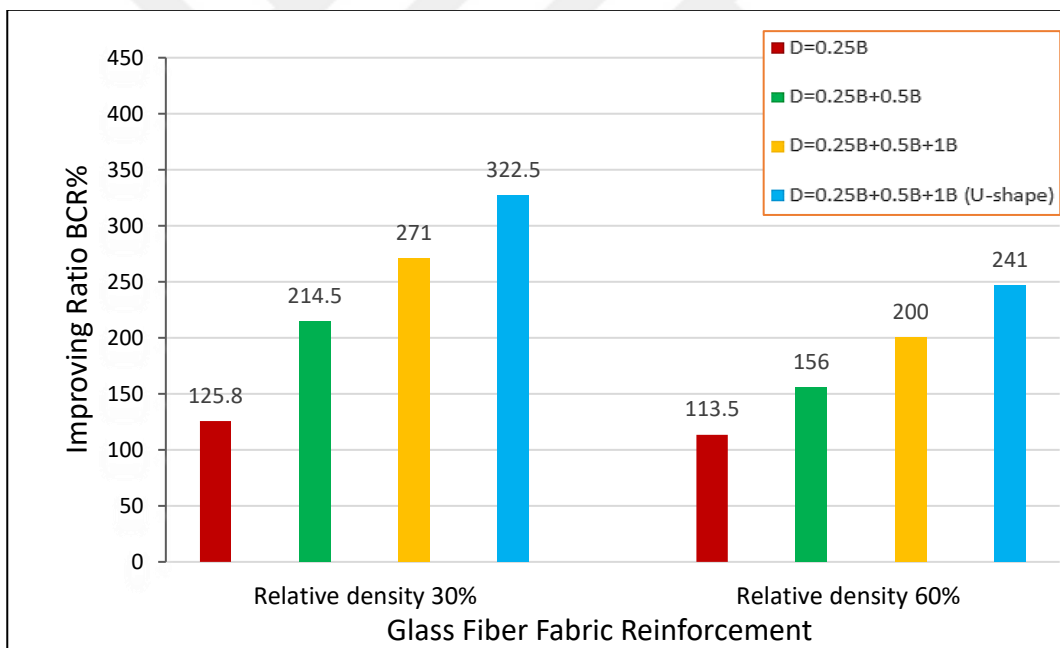


Figure 4.122 BCR% vs. RD =60% and RD =30% of soil models reinforced for different patterns layers of E-glass fiber reinforcement

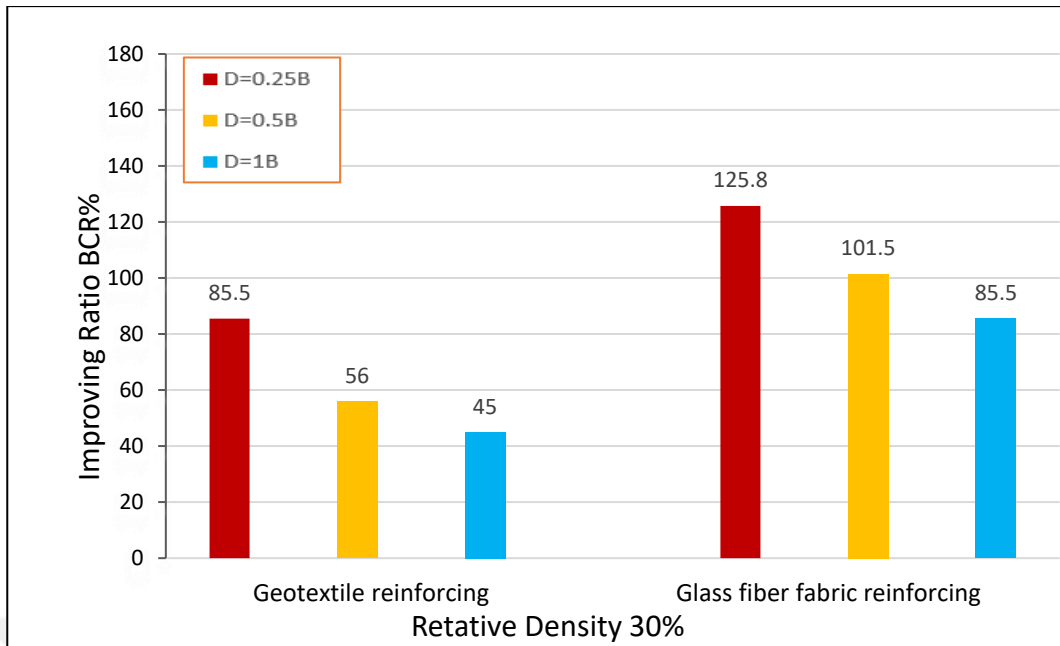


Figure 4.123 BCR% vs. RD =30% of soil models reinforced by single layer (geotextile and E-glass fiber fabric)

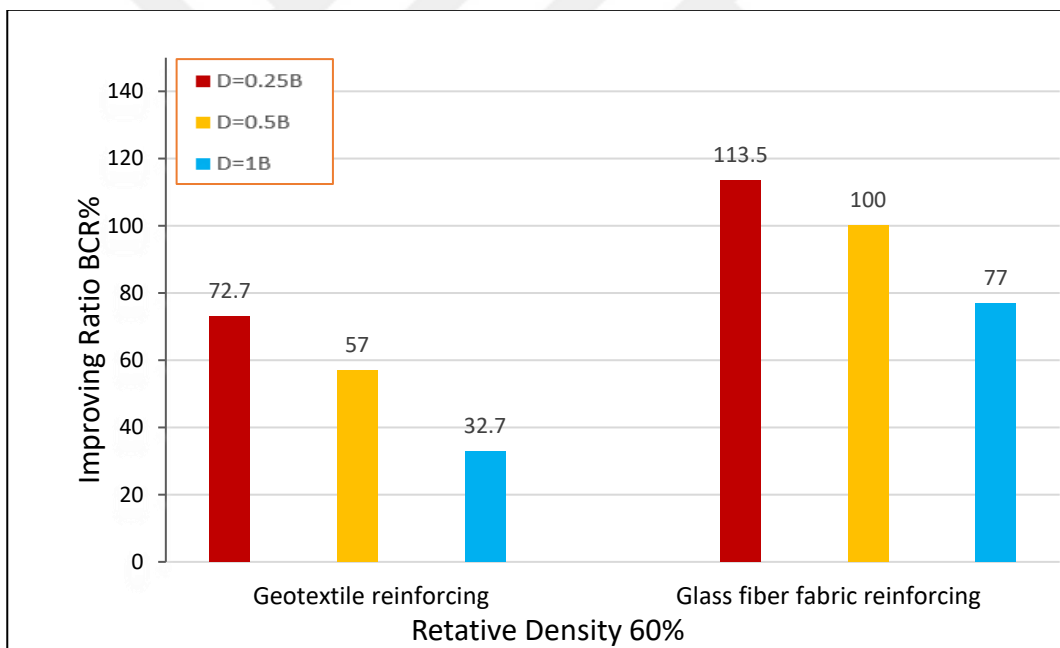


Figure 4.124 BCR% vs. RD =60% of soil models reinforced by single layer (geotextile and E-glass fiber fabric)

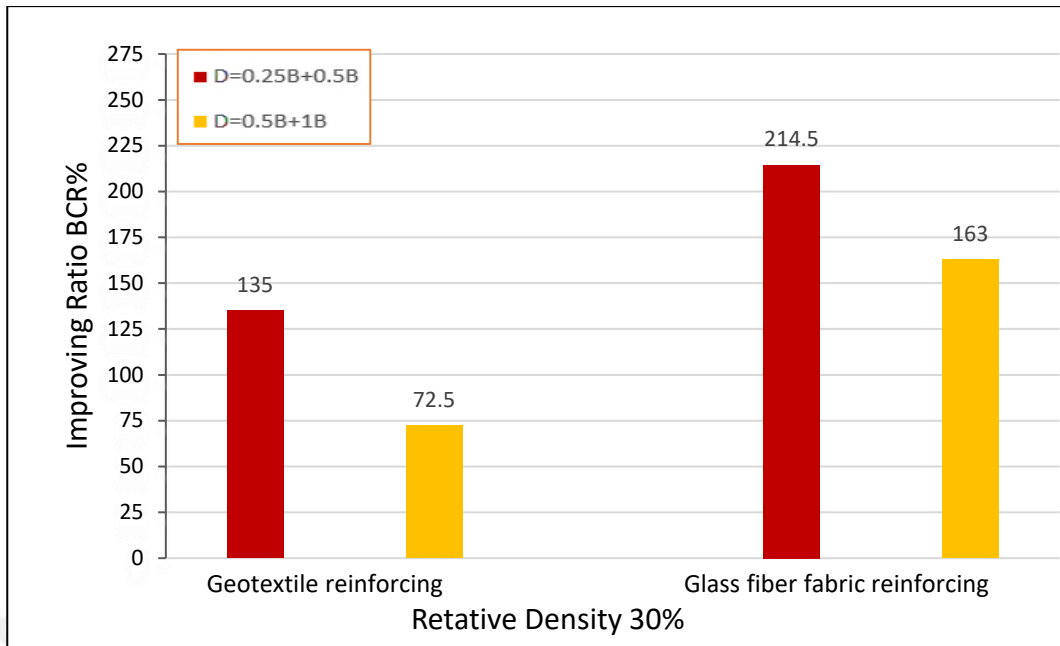


Figure 4.125 BCR% vs. RD =30% of soil models reinforced by double layer (geotextile and E-glass fiber fabric)

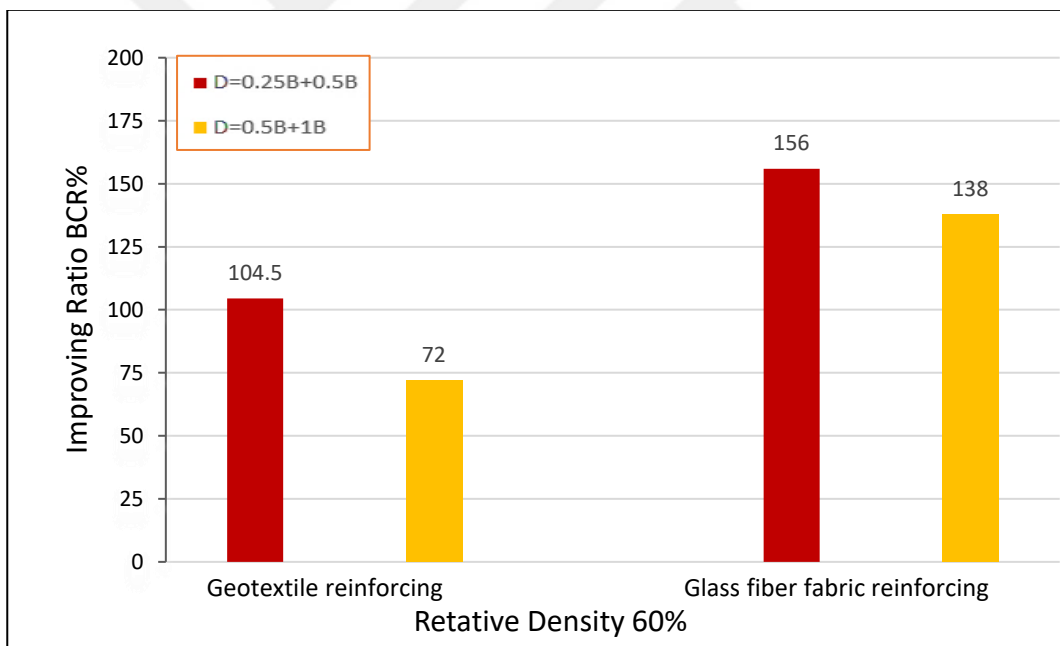


Figure 4.126 BCR% vs. RD =60% of soil models reinforced by double layer (geotextile and E-glass fiber fabric)

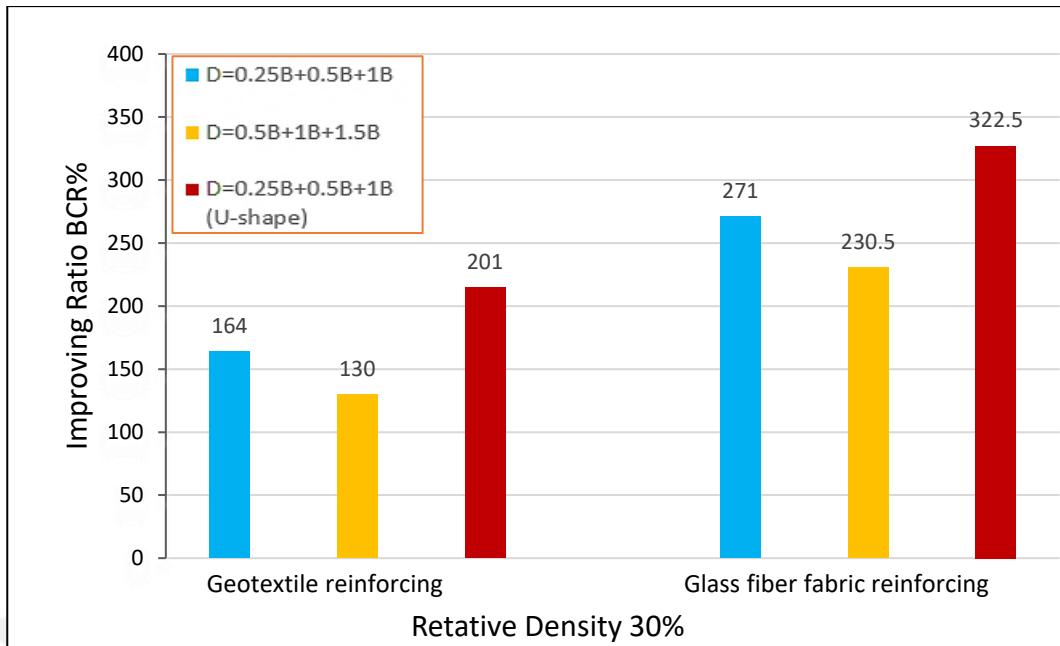


Figure 4.127 BCR% vs. RD =30% of soil models reinforced by triple layer and U-shape reinforcement (geotextile and E-glass fiber fabric)

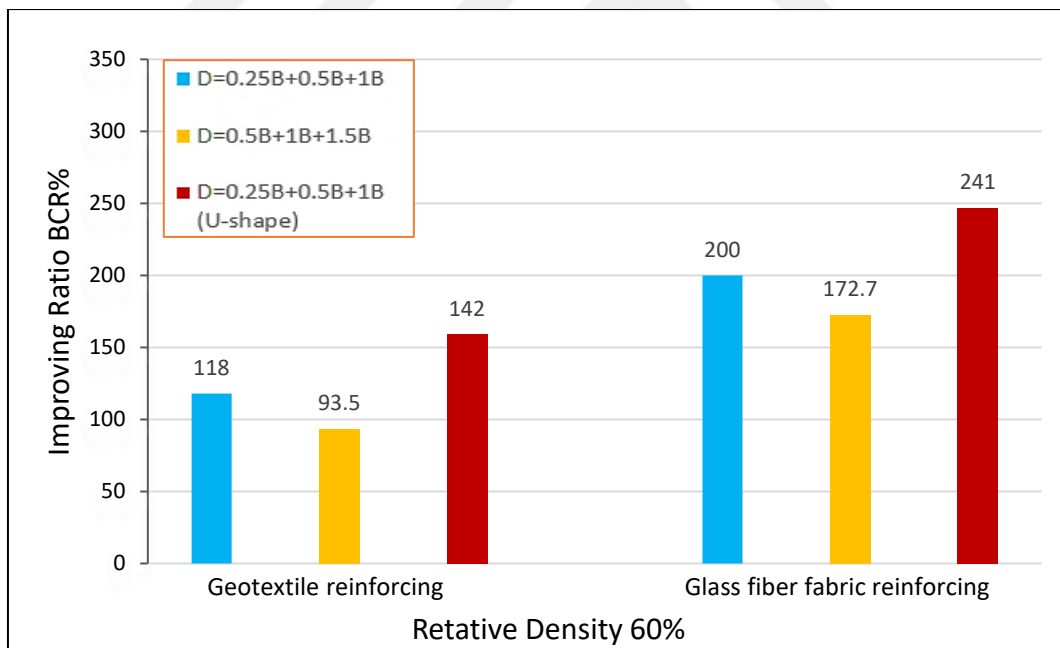


Figure 4.128 BCR% vs. RD =60% of soil models reinforced by triple layer and U-shape reinforcement (geotextile and E-glass fiber fabric)

4.4 Numerical Analysis

The PLAXIS 3D program utilized the (FEM) to analyze the results of a gypseous soil model with a relative density of 30% under both dry and wet conditions.

The soil model was reinforced with geosynthetic materials (geotextile and E-glass fiber fabric) in different patterns, such as a single layer at a depth of $0.25 B$ and a double layer at a depth of $0.25B+0.5B$.

The results were compared to experimental work for the soil model at $RD=30\%$.

The model was verified in two ways as presented in chapter three. Where the results are as follows.

4.4.1 Numerical Results of Soil Model (Dry State)

4.4.1.1 Unreinforcement Soil Model

Numerical results by PLAXIS 3D of the gypsum soil model. The simulation was conducted in a dry state with a relative density of 30%. The results obtained from the simulation before reinforcing were presented in Figure 4.129.

Figure 4.130 illustrates the comparison of the results between the numerical analysis with the experimental work of the soil model unreinforced case. The results were very close.

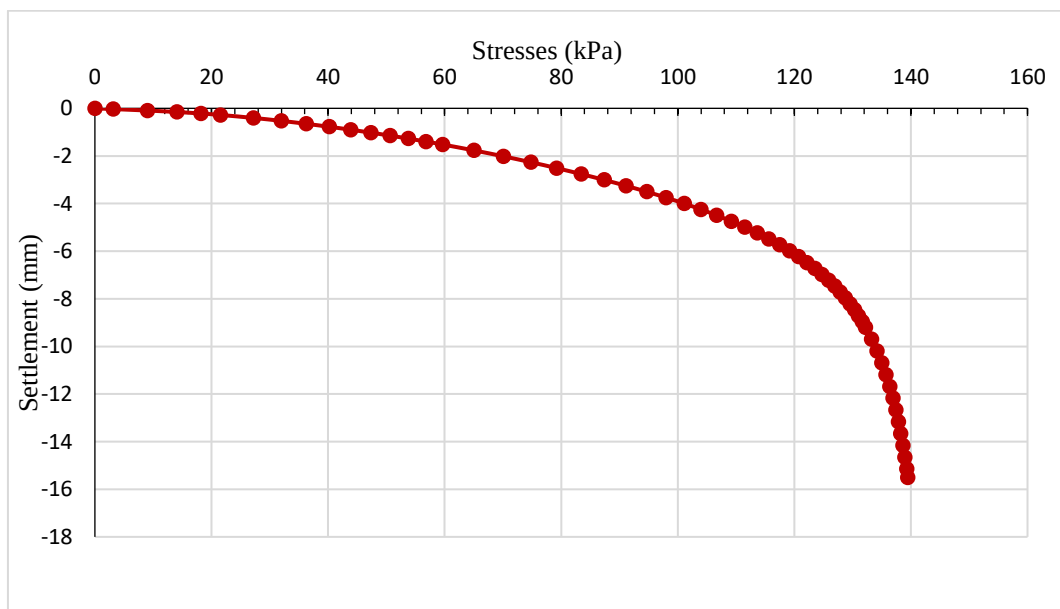


Figure 4.129 Numerical result of unreinforced soil model at dry state by Plaxis 3D

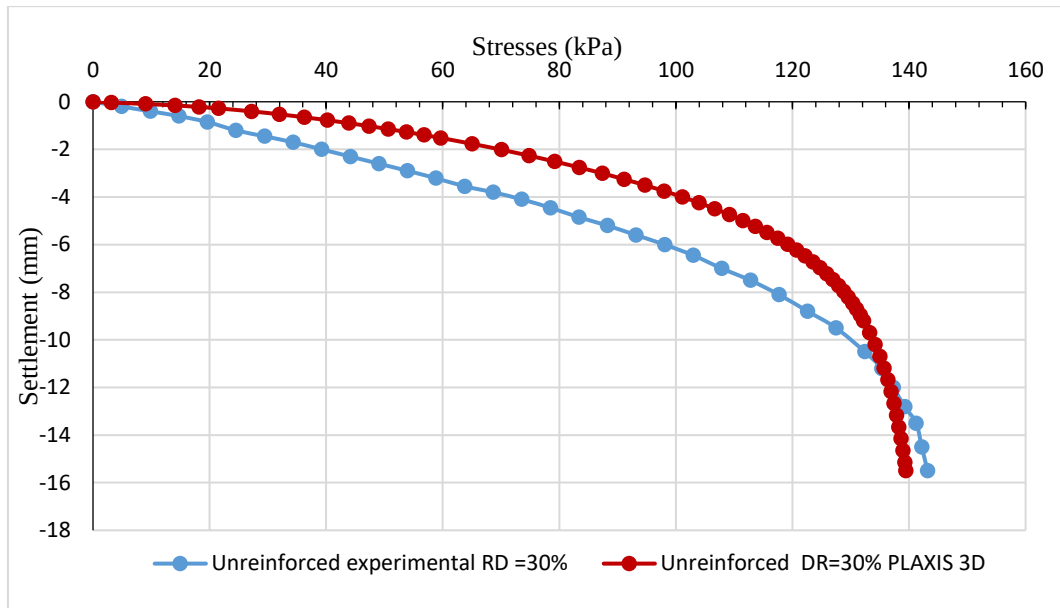


Figure 4.130 Numerical and experimental result of unreinforced soil model at RD = 30%

4.4.1.2 Reinforcement Soil Model

Numerical results for the reinforced soil model when using geosynthetic materials (geotextile and E-glass fiber fabric) as shown in Figures 4.131 to 4.135.

Figures 4.136 to 4.140 show numerical and experimental results for the gypsum soil model reinforced by geotextile and E-glass fiber fabric at RD=30%. The results were close between the numerical analysis and the experimental work, which confirms the reliability of the work.

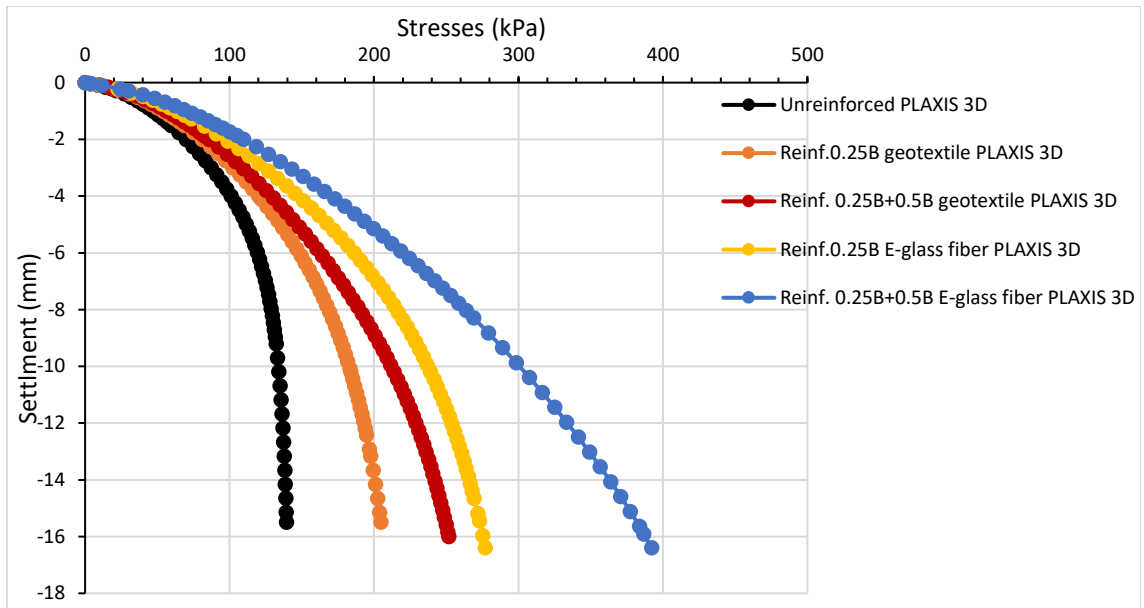


Figure 4.131 Numerical result for unreinforced and reinforced soil model with a single and double layer at dry state by Plaxis 3D

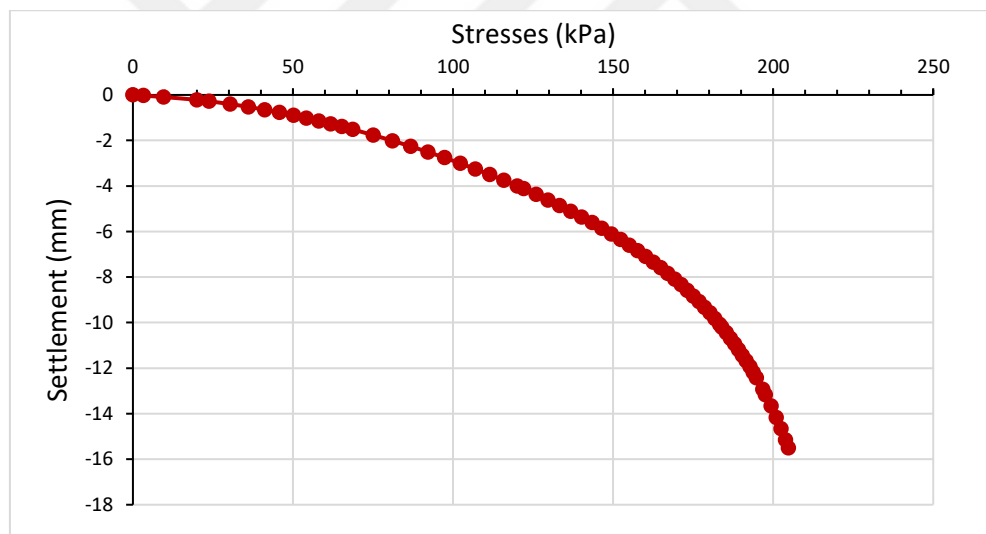


Figure 4.132 Numerical result for geotextile reinforced soil model at D=0.25B

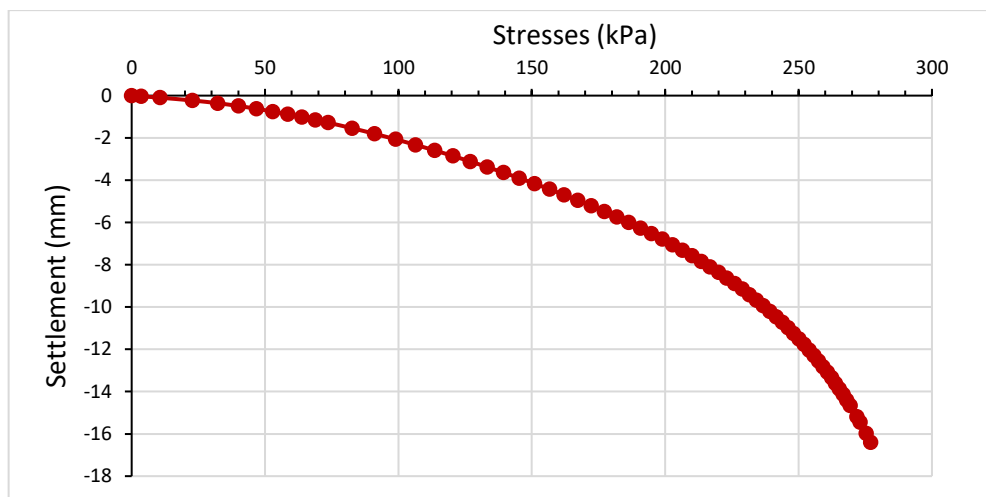


Figure 4.133 Numerical result for E-glass fiber reinforced soil model at $D=0.25B$

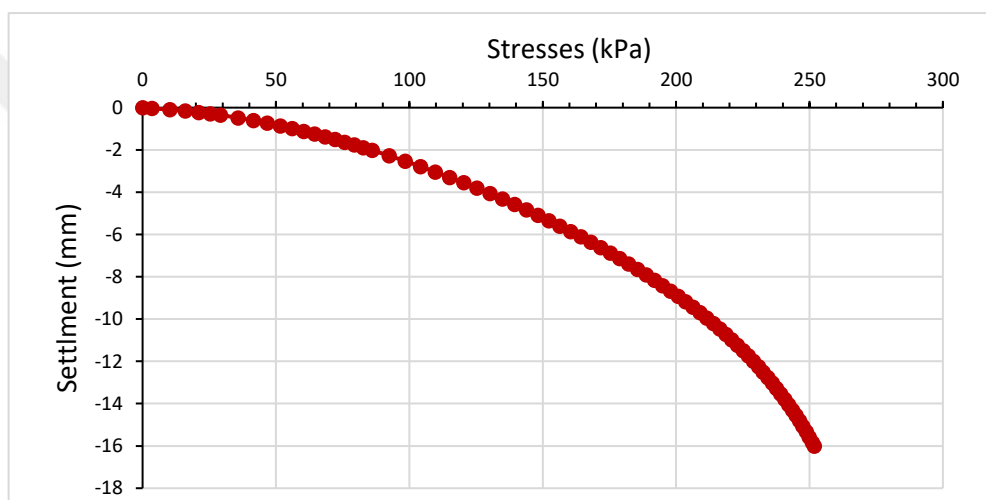


Figure 4.134 Numerical result for geotextile reinforced soil model at $D=0.25B+0.5B$

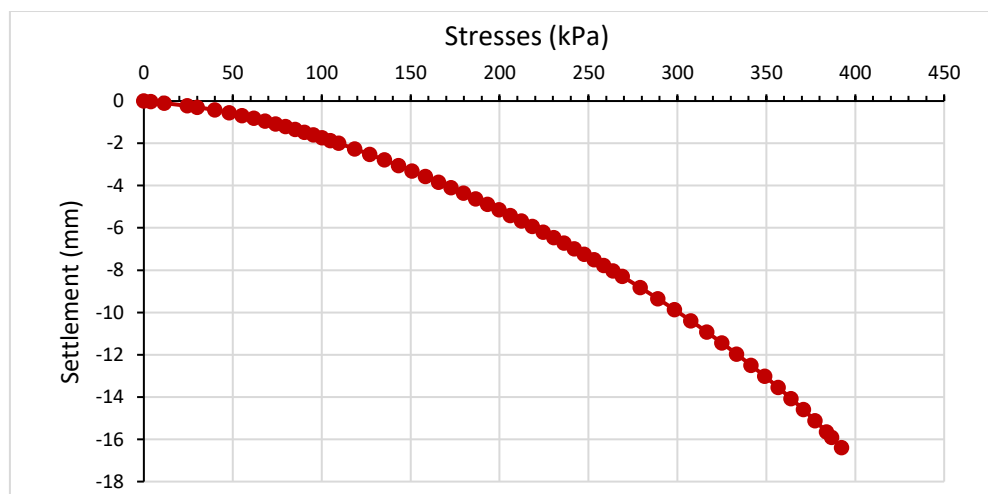


Figure 4.135 Numerical result for E-glass fiber reinforced soil model at $D=0.25B+0.5B$

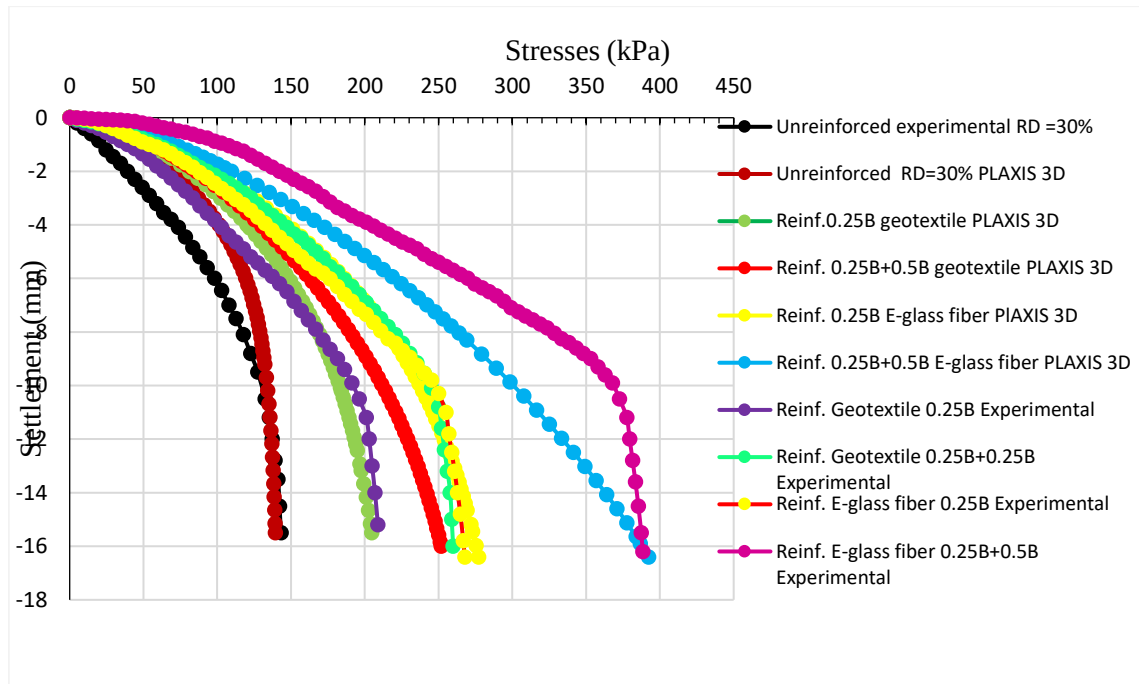


Figure 4.136 Numerical and experimental result of soil model at RD=30% for different reinforcement layer

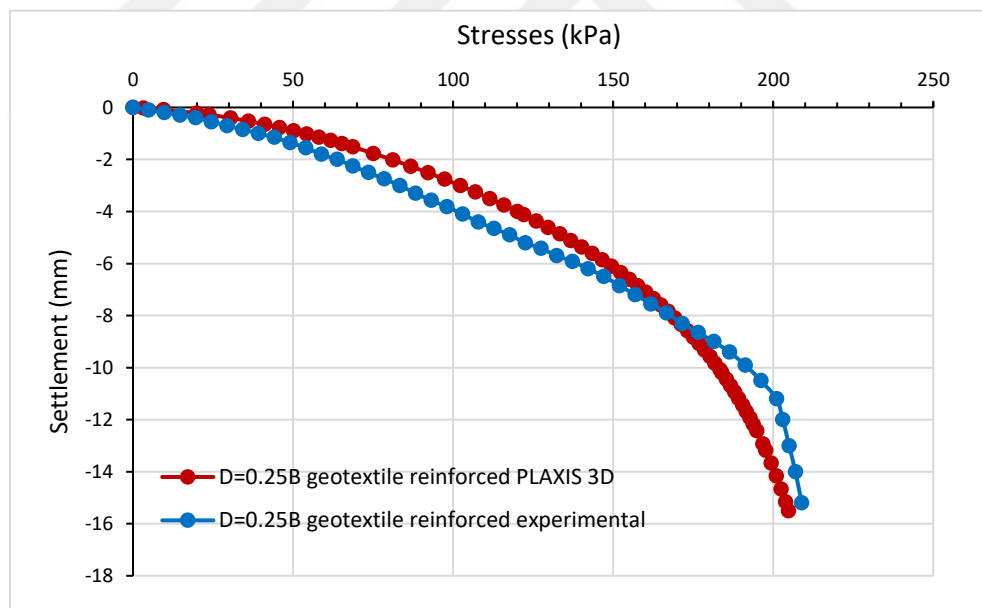


Figure 4.137 Numerical and experimental result for geotextile reinforced soil model at D=0.25B

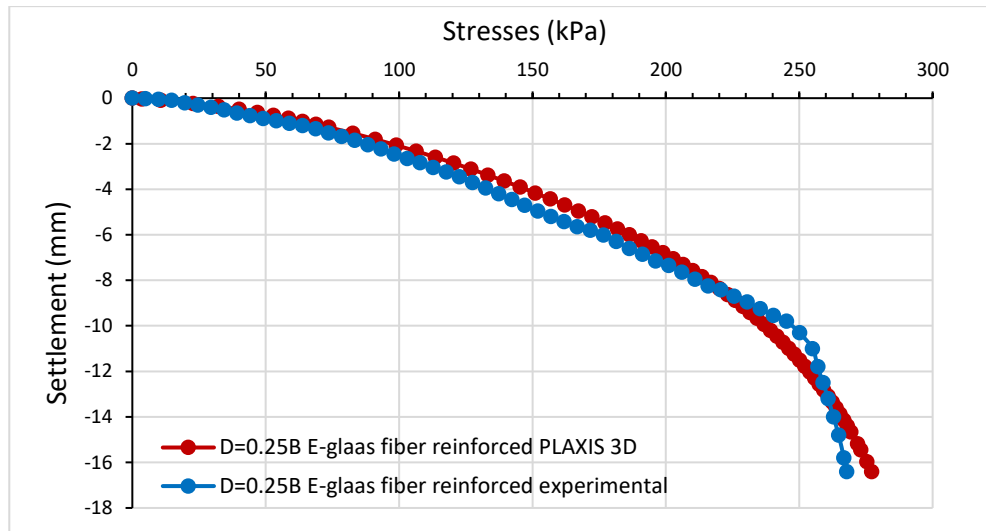


Figure 4.138 Numerical and experimental result for E-glass fiber reinforced soil model at $D=0.25B$

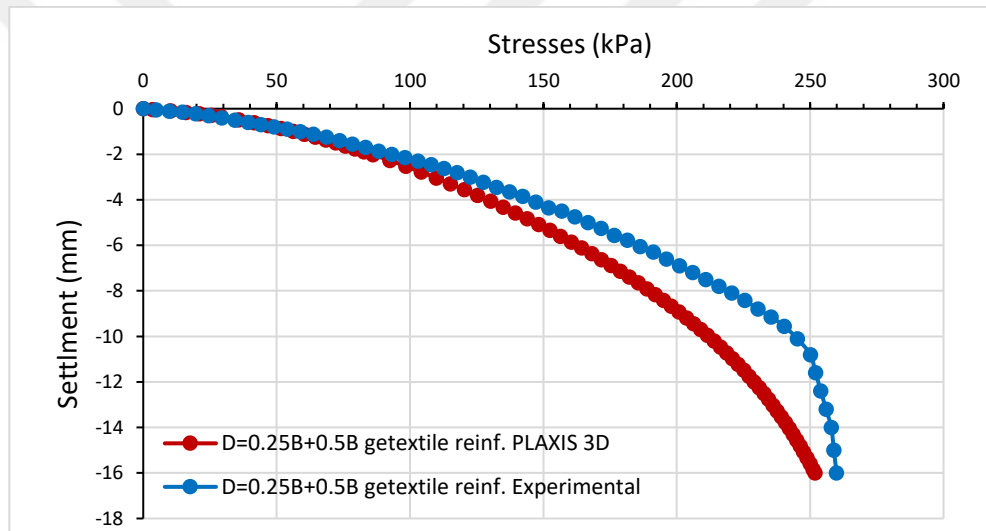


Figure 4.139 Numerical and experimental result for geotextile reinforced soil model at $D=0.25B+0.5B$

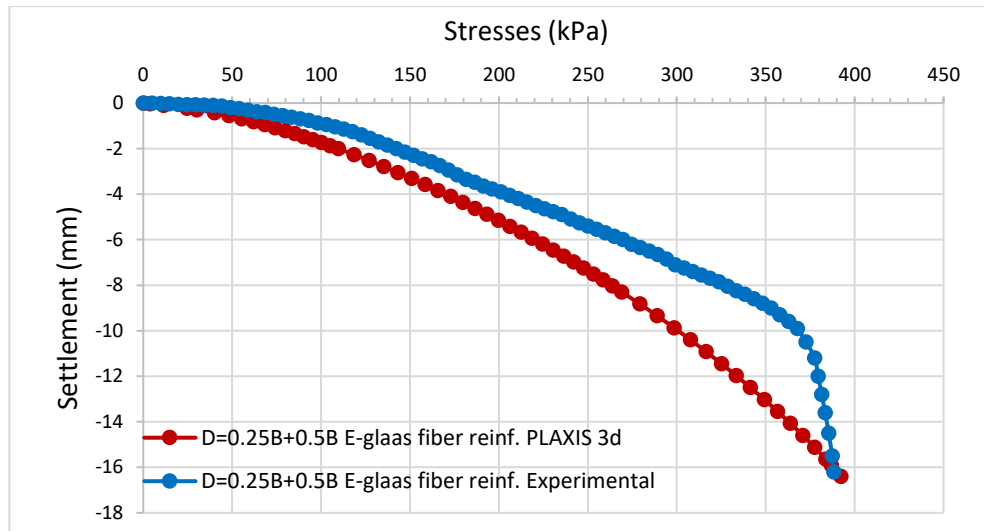


Figure 4.140 Numerical and experimental result for E-glass fiber reinforced soil model at $D=0.25B+0.5B$

4.4.2 Numerical Results of Soil Model (wet State)

4.4.2.1 Unreinforcement Soil Model at $RD=30\%$

Numerical results by PLAXIS 3D of the gypsum soil model. The simulation was conducted in a fully saturation state with a relative density of 30%. The results obtained from the simulation before reinforcing were presented in Figure 4.141.

Figure 4.142 illustrates the comparison of the results between the numerical analysis with the experimental work of the soil model unreinforced case. It can be seen the results were very close.

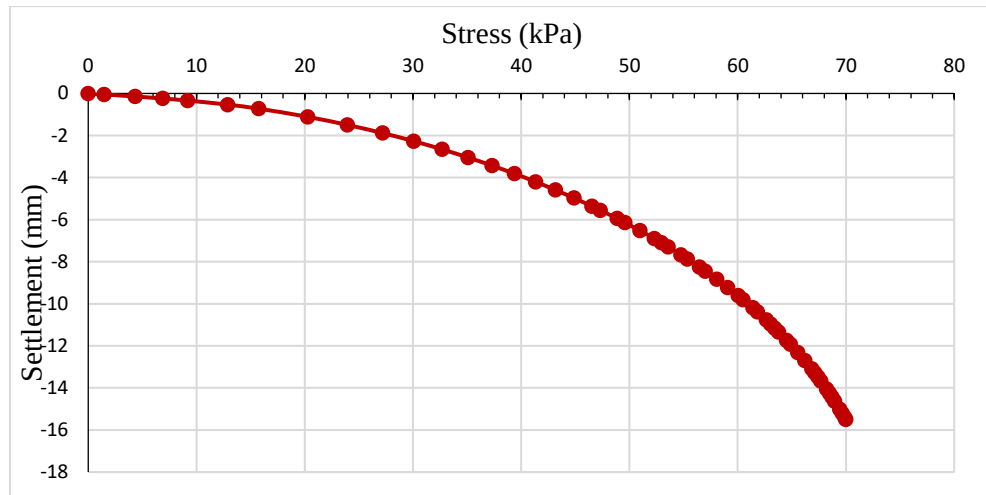


Figure 4.141 Numerical result of unreinforced soil model at fully saturation state by Plaxis 3D

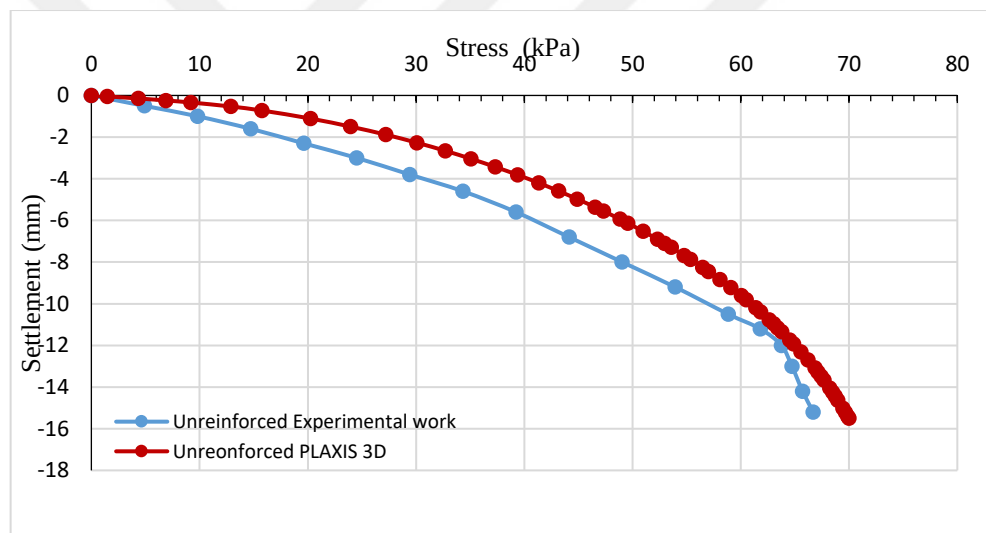


Figure 4.142 Numerical and experimental result of unreinforced soil model at RD = 30%

4.4.2.2 Reinforcement Soil Model

Numerical results for the reinforced soil model when using geosynthetic materials (geotextile and E-glass fiber fabric) as shown in Figures 4.143 to 4.147.

Figures 4.148 to 4.152 show numerical and experimental results for the gypsum soil model reinforced by geotextile and E-glass fiber fabric at RD=30%. The results were close between the numerical analysis and the experimental work, which confirms the reliability of the work.

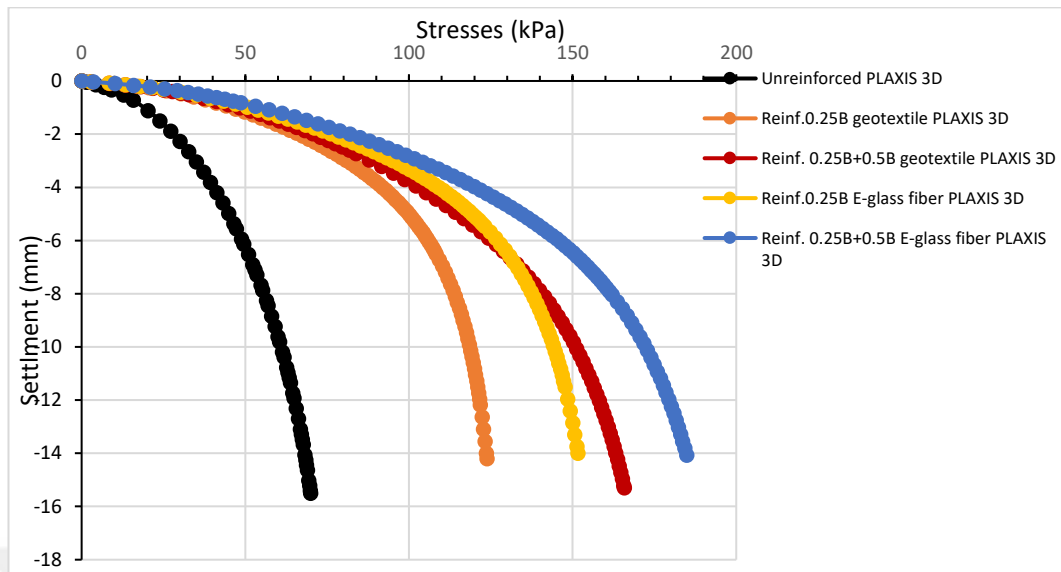


Figure 4.143 Numerical result for unreinforced and reinforced soil model with a single and double layer at dry state by Plaxis 3D

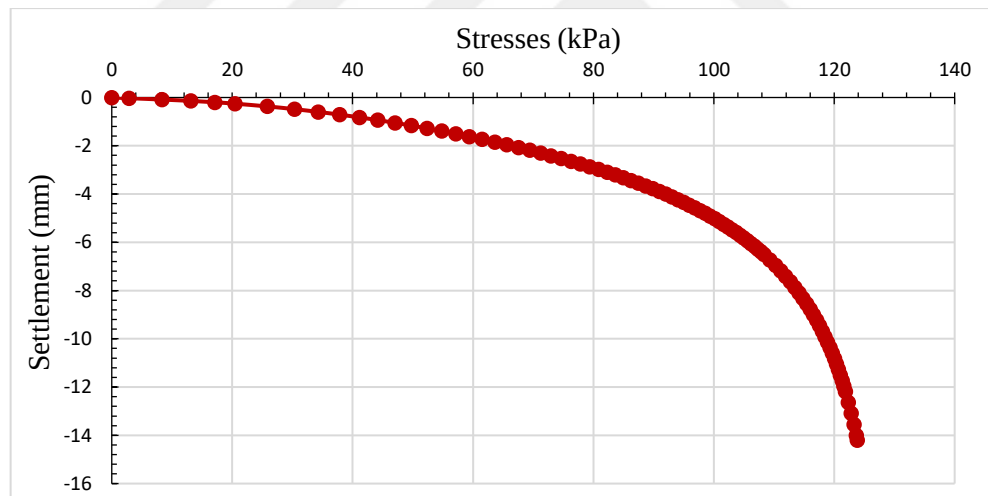


Figure 4.144 Numerical result for geotextile reinforced soil model at D=0.25B

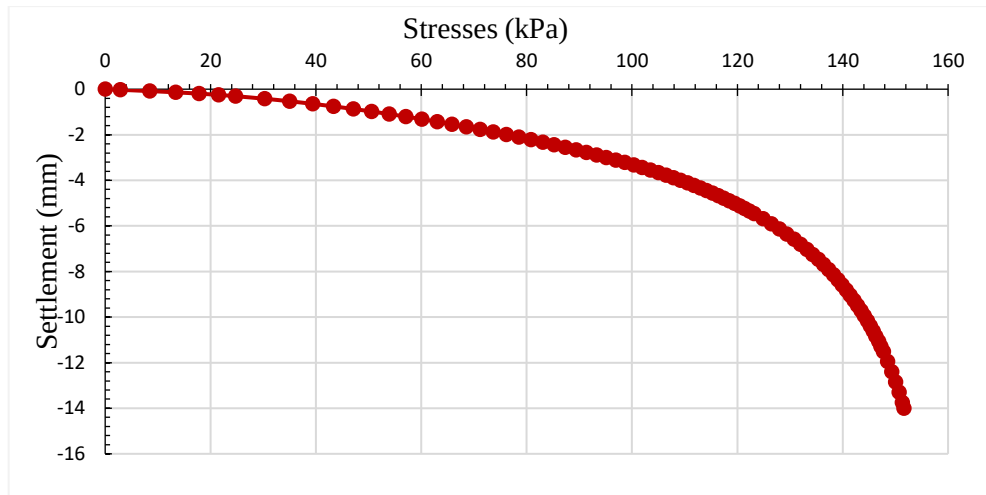


Figure 4.145 Numerical result for E-glass fiber reinforced soil model at $D=0.25B$

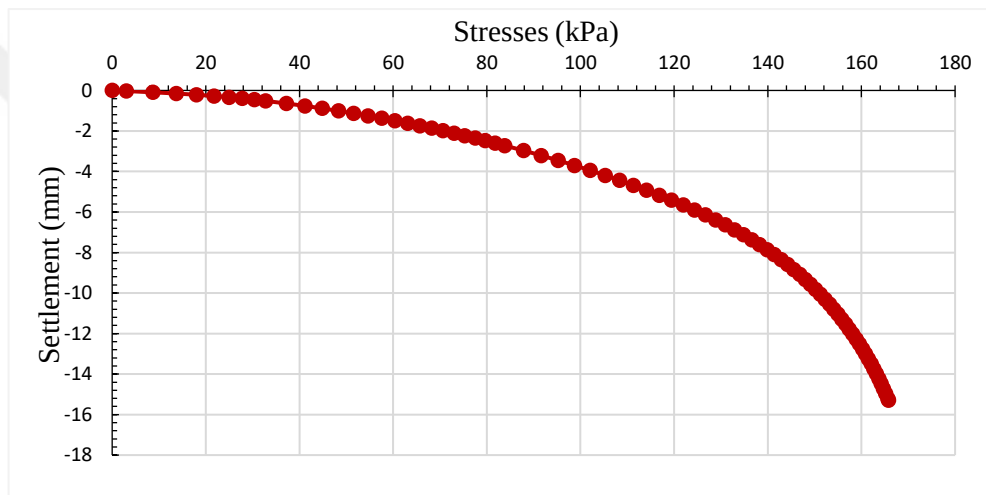


Figure 4.146 Numerical result for geotextile reinforced soil model at $D=0.25B+0.5B$

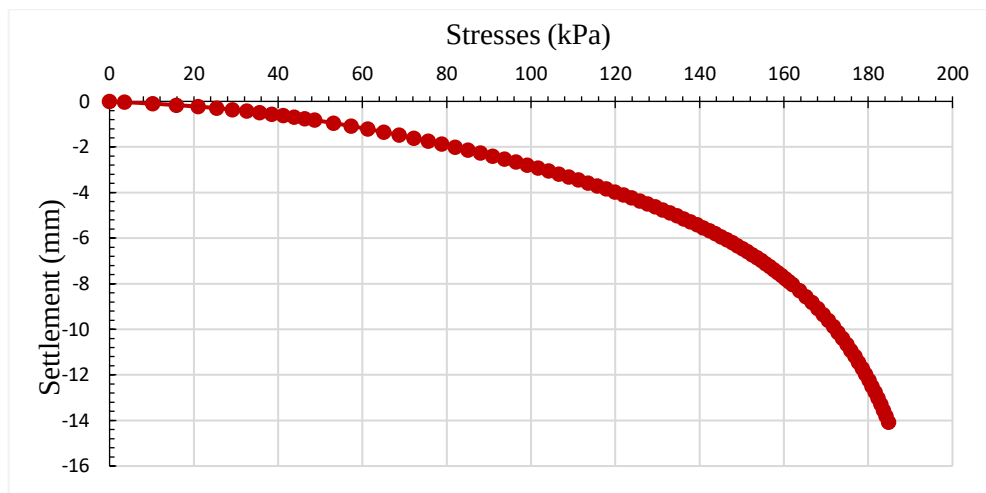


Figure 4.147 Numerical result for E-glass fiber reinforced soil model at $D=0.25B+0.5B$

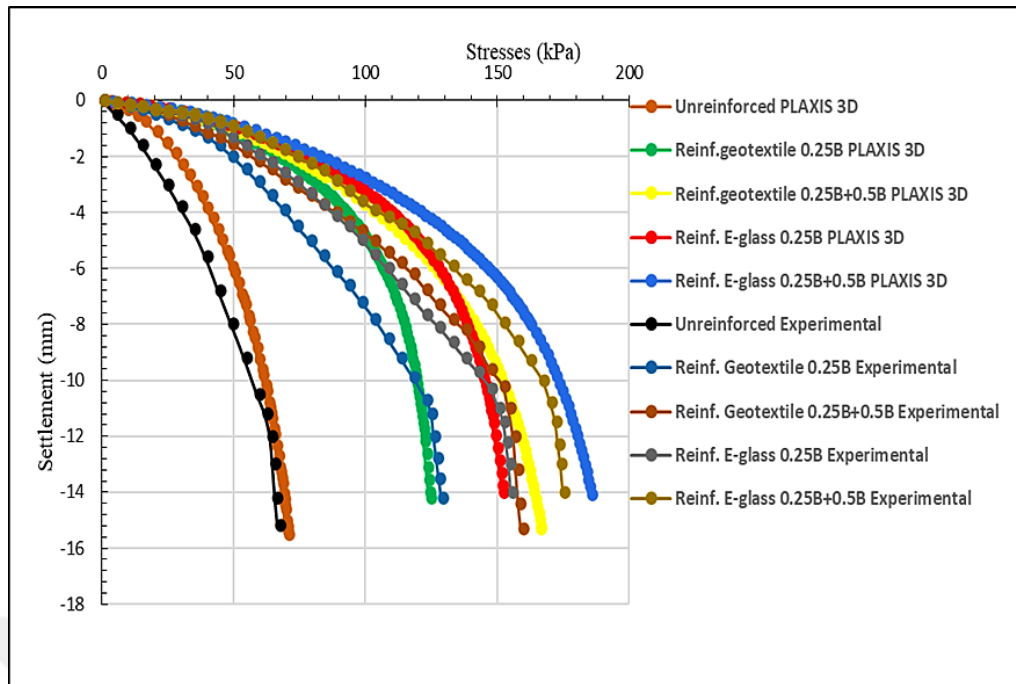


Figure 4.148 Numerical and experimental result of soil model at RD=30% for different reinforced layer

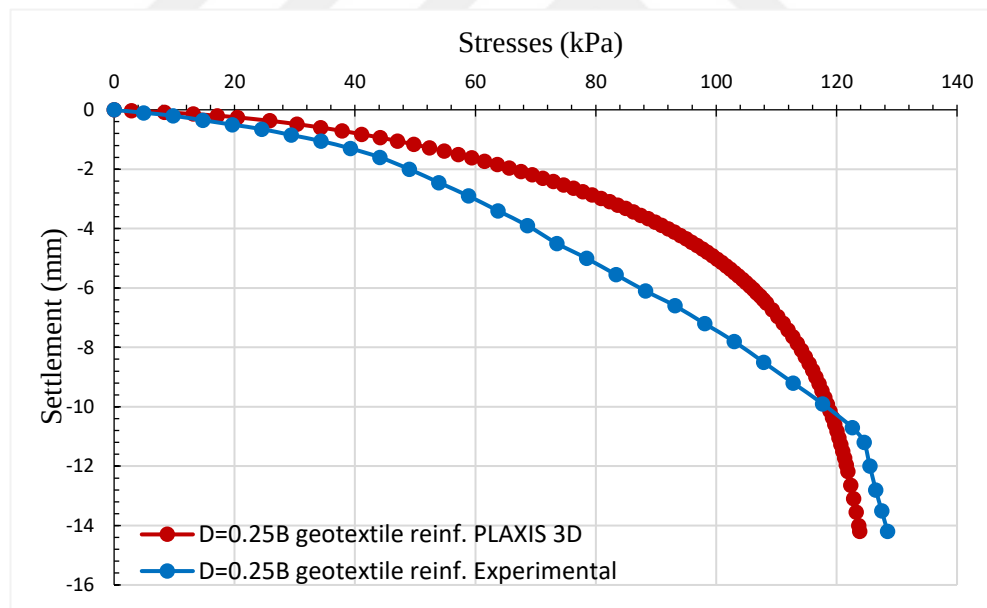


Figure 4.149 Numerical and experimental result for geotextile reinforced soil model at D=0.25B

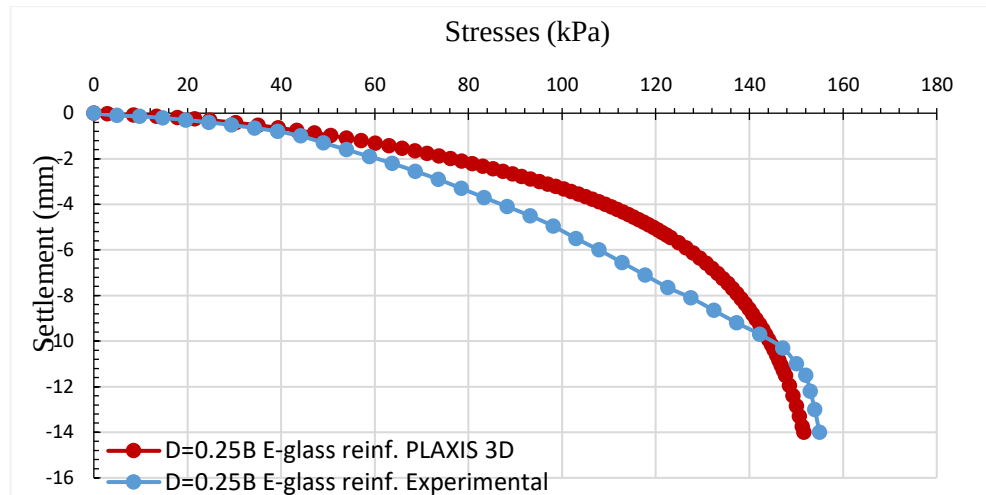


Figure 4.150 Numerical and experimental result for E-glass fiber reinforced soil model at $D=0.25B$

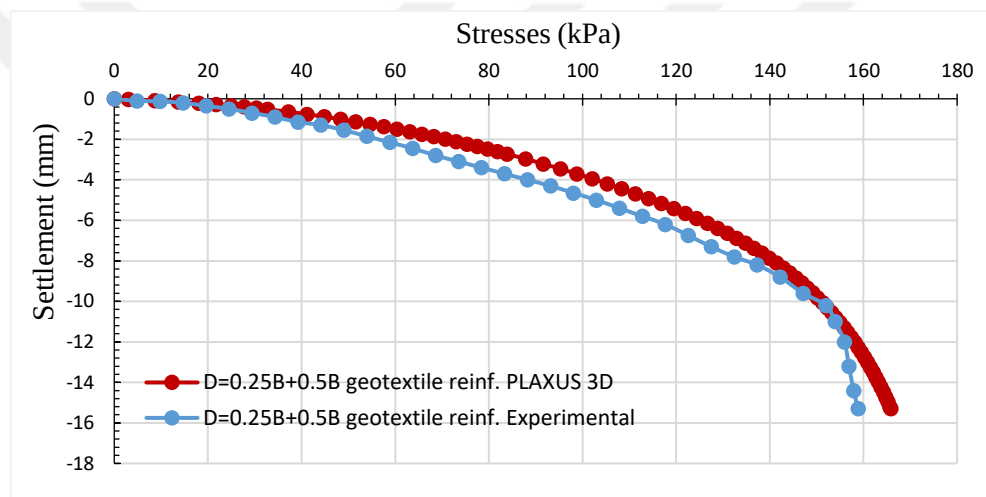


Figure 4.151 Numerical and experimental result for geotextile reinforced soil model at $D=0.25B+0.5B$

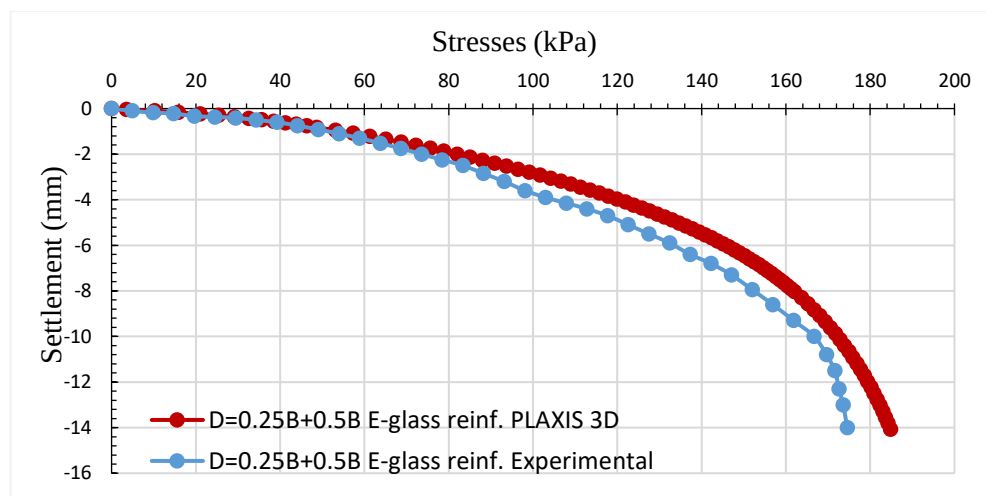


Figure 4.152 Numerical and experimental result for E-glass fiber reinforced soil model at $D=0.25B+0.5B$

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

1. The Two Tangent Intersection Method was used to achieve the ultimate bearing capacity values of the gypsum soil model, where the values in the dry state were greater than the saturated state.
2. The ultimate bearing capacity of the gypseous soil reinforced with two types of geosynthetic material has been increased, Where the final values of bearing capacity increase from 130 kPa for the unreinforced model to (300, 431) kPa for the reinforced model at $D = 0.25B + 0.5B + 1B$ by (geotextile and E-glass fiber fabric) respectively for dry state at $RD = 30\%$. while the ultimate bearing capacity increased from 230 kPa for the unreinforced model to (518, 600) kPa for reinforced model at $D = 0.25B + 0.5B + 1B$ by (geotextile and E-glass fiber fabric) respectively for dry state at $RD = 60\%$.
3. The ultimate bearing capacity of the gypseous soil reinforced with two types of geosynthetic material has been increased, Where the final values of bearing capacity increase from 62 kPa for the unreinforced model to (165, 230) kPa for the reinforced model at $D = 0.25B + 0.5B + 1B$ by (geotextile and E-glass fiber fabric) respectively for wet state at $RD = 30\%$. while the ultimate bearing capacity increased from 110 kPa for the unreinforced model to (240, 330) kPa for the reinforced model at $D = 0.25B + 0.5B + 1B$ by (geotextile and E-glass fiber fabric) respectively for wet state at $RD = 60\%$.
4. The percentage increase of bearing capacity when using E-glass fiber fabric was 38.5% higher than geotextile reinforcement at a single layer with depth $D = 0.25B$. While the percentage of increase was 93% and 100% for $D = 0.25B + 0.5B$ at double and $D = 0.25B + 0.5B + 1B$ at triple reinforcement respectively, for dry state at $RD = 30\%$. while the percentage increase in bearing capacity for the soil model at $RD = 60\%$ was 30.5% when using E-glass fiber fabric compare with geotextile at depth $D = 0.25B$ and was 37% and 35% when used $D = 0.25B + 0.5B$ at a double and $D = 0.25B + 0.5B + 1B$ at triple reinforcement respectively.

5. For a wet state the percentage increase of bearing capacity when using E-glass fiber fabric was 40.3% higher than geotextile reinforcement at a single layer with depth $D=0.25B$. While the percentage of increase was 79.5% and 105% for double and triple reinforcement respectively, at $RD=30\%$. while the percentage increase in bearing capacity for the soil model at $RD=60\%$ was 40% when using E-glass fiber fabric compare with geotextile at depth $D=0.25B$ and was 51.5% and 82 % when used $D=0.25B+0.5B$ at a double layer and $D=0.25B+0.5B+1B$ at a triple layer reinforcement respectively.
6. The ultimate bearing capacity increased when using the U-shape reinforcement at triple layer $D=0.25B+0.5B+1B$ by about 11.6% and 12.3 %when using the straight layer reinforced (geotextile and E-glass fiber) respectively, for dry state at $RD=30\%$. It increased by 5.8% and 10% when using the straight layer reinforced (geotextile and E-glass fiber) respectively, for dry state at $RD=60\%$.
7. The ratio of ultimate bearing capacity BCR% increased by increasing the number of layers for geosynthetic reinforcement, also the increase for the saturated model is more than for the dry model at relative densities 30% and 60%.
8. The results of the numerical analysis using the finite element program PLAXIS 3D for the soil model with a relative density of 30% were very close to the results of the experimental work, which indicates that it is possible to use the numerical analysis to simulate the reality of the situation.

5.2 Recommendations

1. Investigation of the impact of using a dynamic load on gypseous soil models and compare the results with those obtained in this study.

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PUBLICATIONS FROM THE THESIS

Conference Papers

1. A. A. Waleed, M.E. SELÇUK, M. K. Mohsen," Investigation behavior of gypsum soil reinforced by geosynthetics supported square footing-an experimental study" in IOP Conference Series: Earth and Environmental Science.

