

Research Article

INVESTIGATION OF VERTICAL SETTLEMENT DUE TO CONSOLIDATION ON SOFT SUBGRADES USING GEOTEXTILES

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ABSTRACT

One of the problems in road construction projects is the design and construction of roads on soft and weak subgrades. One of the methods to increase the bearing capacity of weak foundation soils is to reinforce those using synthetic fibers and polymers. Based on geotechnical studies and field tests conducted on the Urmia–Tabriz road by the Road and Transportation Organization of West Azerbaijan Province, the presence of an organic soil layer beneath the embankment was identified. In addition, the groundwater level in this area is high and is considered one of the causes of settlement. In this study, the effect of using geosynthetics to improve the properties of an embankment constructed on the soft subgrade of the Urmia–Tabriz road is investigated. Furthermore, the finite difference method using FLAC software and the Mohr–Coulomb model has been employed in analyzing the settlement of the embankment on the soft subgrade. The results obtained from the embankment analysis showed that reinforcing the model with geotextile leads to a significant reduction in vertical settlements. The performance of geotextile reinforcement in soil layers is both axial and frictional. The performance of the reinforcing layer varies across different soil layers. Overall, acceptable results were obtained.

INTRODUCTION

From the perspective of geotechnical engineers, one of the important issues related to the construction of embankments on soft subgrades is the complex behavior of the underlying soft soil. This complexity is related to the properties of soft soils. One of the characteristics of these materials is their high compressibility, which Janbu demonstrated in his Rankine lecture on soft subgrades using the results of oedometer tests. The oedometer test, or one-dimensional consolidation test, was first proposed by Terzaghi. This test is carried out in a consolidation device called an oedometer. The soil sample is placed inside a metal ring, and two porous stone caps, one on top and one at the bottom, are positioned. The sample diameter is usually 63.5 mm, and its thickness is 25.4 mm. A lever applies loading to the sample, and the amount of compression is measured using a dial gauge micrometer. During the test, the sample is kept submerged in water. Each load increment is maintained for 24 hours. After that, the load is usually doubled. By doubling the load, compression continues and is measured. At the end of the test, the dry weight of the test sample is determined ^[1].

Another characteristic of soft soils is their creep behavior. Buisman was the first to observe that the settlement of soft soil cannot be explained by classical consolidation theory and proposed the creep law. Work on one-dimensional secondary consolidation was continued by other researchers such as Mesri, Garlanger, Bjerrum, and Leroueil. Further mathematical studies on creep were conducted by Adachi and Oka, Sekiguchi, and Borja et al. ^[2]. A three-dimensional creep model should be directly derived from the one-dimensional creep model; however, since the one-dimensional equation had not been formulated as a differential equation, this was not possible. Eventually, three-dimensional validation was carried out using predictions and data obtained from triaxial tests by Neher & Vermeer and Vermeer et al. With the development of software and advanced models for simulating soft soil, numerous studies have been conducted to evaluate the strengths and weaknesses of these models ^[3].

Studies conducted on embankments built on soft subgrades can be divided into two categories: studies comparing numerical analyses with laboratory test results, and studies comparing instrumented embankment data with small-scale model results obtained from centrifuge tests. Almeida et al. investigated the consolidation behavior of an embankment on a soft subgrade using a centrifuge device. This test included a sandy embankment placed on a clayey foundation. During the test, pore water pressure, its rate of dissipation, and embankment deformations were measured. To estimate these parameters, the CRISP software and the Cam-Clay model (due to its similarity to soft soil behavior) were used. Except for a few cases, pore pressure, its dissipation rate, and the maximum horizontal and vertical deformations were predicted well. However, the deformation profile with depth did not match well, which was attributed to modeling the embankment as a linear elastic material ^[4].

Barker et al. modeled reinforced and unreinforced embankments in a centrifuge device and, for comparison, performed finite element analysis once using the Cam-Clay model and once using the Mohr–Coulomb model with GeoFEAP software. The results showed that the compression index, swelling index, and void ratio have little effect on embankment behavior, whereas the preconsolidation ratio is the most sensitive parameter ^[5].

Numerous case studies have also been conducted in this field. For example, Vermeer et al. studied the instability that occurred in the Streefkerk embankment in 1984 and performed back-analysis of settlement using Plaxis software and behavioral models, including Mohr–Coulomb, Soft Soil, and Soft Soil Creep, comparing the results with observed settlements ^[6].

Hunter & Fell analyzed deformation behavior and excess pore water pressure response in 13 instrumented embankments constructed on soft soil. The results showed that lateral deformations at the embankment toe and vertical deformations at the toe and within 5 meters around the embankment are the primary indicators of potential failure^[6].

In recent years, due to the importance of this issue, various countries have developed guidelines to consolidate studies in this field. For example, Northern European countries, including Norway, Finland, Sweden, and Scotland, have established a project called Roadex, aimed at studying the construction and maintenance of embankments on peat soils in Northern Europe. The Indian Ministry of Railways has also issued guidelines for constructing embankments on soft soils, including general concepts and various construction methods^[7].

One of the methods for improving the behavior of embankments on soft subgrades is soil reinforcement. The initial idea of reinforced soil is not new and dates back to ancient times; however, the modern concept and methods of analysis and design were established by a French engineer named Vidal. The French Road Research Laboratory conducted extensive studies on the applicability and benefits of reinforced soil as a construction material, documented by Darbin, Schlosser, and Schlosser & Vidal. In these studies, steel strips were used as reinforcement. Following the success of reinforced soil, modern materials were developed for this purpose. One such category is geosynthetics. Geosynthetics are textiles and coverings made from fibers derived from petroleum products, characterized primarily by their resistance to decay within soil environments. Geosynthetics are a relatively new and continuously evolving class of civil engineering materials used in fields related to soil mechanics, geology, environmental engineering, and other sub-disciplines of civil engineering, as well as interdisciplinary applications^[8].

Geotextiles are remarkably suitable for withstanding stresses and relative mechanical deformations, so they can protect weak layers that should not be affected by large stresses and prevent their destruction. Geotextiles have a very good performance in terms of spreading and distributing stresses or forces over a larger surface and optimally prevent point ruptures. Building and earthworks materials can withstand compressive stresses satisfactorily, while they are weak against tension. By using these materials and geotextiles together, the two mentioned properties can be improved. Another property of geotextiles is reversibility, which means that they deform and settle under the influence of an external load, but return to their original state after the load is removed^[8].

In 1970, only five or six types of geosynthetics existed, whereas today more than six hundred different types of geosynthetics are produced worldwide. In less than 30 years, geosynthetics have undergone tremendous development and, in some cases, have completely replaced conventional construction materials. In many cases, the use of geosynthetics can significantly increase the factor of safety, improve performance, and reduce costs compared to other methods^[2].

Numerous studies have been conducted regarding the application of geosynthetics in embankments. Rowe and Soderman presented a method for determining the short-term stability of reinforced embankments. This method is as simple as the conventional limit equilibrium method, and it also considers the effect of soil–geotextile interaction by accounting for the allowable strain of the geotextile. This allowable strain depends on the stiffness of the foundation, the geometry of the embankment, the depth of the foundation, and the critical height of the unreinforced embankment^[9]. In another study, Rowe and Soderman investigated a geotextile-reinforced embankment on peat soil^[2]. The effect of geotextile reinforcement on

the stability and deformations of an embankment constructed on peat was examined at the end of construction and under long-term conditions. The effect of geotextile was compared with methods such as berm construction or the use of lightweight materials, and then geotextile and lightweight materials were used simultaneously. The results showed that both geotextile and lightweight materials improve embankment performance, but the simultaneous use of reinforcement and lightweight materials has the greatest effect on improving embankment performance ^[2].

Borges & Cardoso investigated the overall stability of geosynthetic-reinforced embankments on soft soils using both finite element and limit equilibrium methods. In this study, three embankments constructed on soft soil were analyzed. The slip circles obtained from both methods were similar for the three embankments, indicating that the limit equilibrium method provides sufficient reliability for stability analysis. Bergado et al. conducted studies on a sample of a geotextile-reinforced embankment on soft soil. The failure mechanism and stability of the embankment under undrained conditions were analyzed using the finite element method, and the critical height of the embankment and the reinforcement strain were determined. High-strength geotextiles reduced plastic deformations in the foundation soil and increased the critical height of the embankment ^[2]. Rowe & Hinchberger, in continuation of their studies, examined the prediction of reinforcement strain at failure and found that failure of reinforced embankments may occur before full mobilization of the ultimate tensile strength. To select an appropriate design strain, the results of finite element analysis were summarized in charts [10]. Rowe & Li reviewed the behavior of reinforced embankments on cohesive soils and peat and briefly described design and analysis methods. In this study, the behavior of reinforced embankments using prefabricated vertical drains (PVD) was investigated, and it was observed that the partial consolidation provided by PVD contributes to embankment stability ^[11].

The slope of the embankment is an influential parameter regarding horizontal displacement at the interface between the embankment and the foundation; the gentler the slope, the smaller the horizontal movement. Regarding embankment settlement, slope is not a significant parameter, but at the end of construction, gentler slopes result in less heaving at the toes. Examination of the slope effect on reinforcement behavior shows that embankment slope is a very important parameter affecting the magnitude of the ultimate tensile force mobilized in the embankment; the gentler the slope, the smaller the axial force generated in the reinforcement ^[12].

The Urmia–Tabriz road, passing through Lake Urmia, has long been of interest to national authorities and remains highly significant both politically and economically. For this reason, this study investigates vertical settlement due to consolidation on soft subgrades using geotextiles along the Urmia–Tabriz road at kilometer 7+800.

Urmia–Tabriz Road

This road has long been a focus of the Ministry of Roads and Transportation, with efforts spanning many years to establish a route across Lake Urmia. Martyr Engineer Kalantari made significant efforts toward constructing this road across the lake. In recent years, with the construction of the Lake Urmia causeway bridge by Sadra Company, the long-standing aspiration of the people in this region has been realized, and the distance between the cities of Urmia and Tabriz has been reduced by approximately 150 kilometers. In addition to benefiting residents, this road shortens the transit route to Europe and is therefore considered a national

project. The total length of the route is approximately 130 kilometers.



Figure 1: View of the route from Tabriz to Urmia

To identify subsurface layers, a series of geotechnical investigations was conducted by the Road and Transportation Organization of West Azerbaijan Province. For this purpose, two boreholes were drilled on the right and left sides of the road. After drilling, geotechnical engineers, with some engineering assumptions, identified the presence of an organic soil layer (peat) near the ground surface and silty clay layers beneath it, which formed the remaining layers. Based on the investigations, the main causes of settlement were identified as the presence of an organic soil layer, a high groundwater level, and silty clay layers. Further studies and local information gathered by engineers indicated that this area had historically been a surface water accumulation zone, and it is still used during rainy seasons for watering local livestock. Based on these findings, the primary cause of settlement can be attributed to the formation of organic soil over time, which is one of the persistent challenges for engineers in constructing embankments on such soils.

MATERIALS AND METHODS

In this study, the main idea is to investigate the consolidation settlement of the embankment, as shown in Figure 2, in which the grid generation in the software, along with the layering of materials under different loading conditions throughout its service life, is considered. The relevant details will be presented in the following sections. First, the properties of the materials used in this study are introduced. Then, the boundary conditions applied in the software are described. Subsequently, the results obtained from the software analysis are briefly presented for the case with geotextile reinforcement, and the numerical results are compared with observed real and field values.

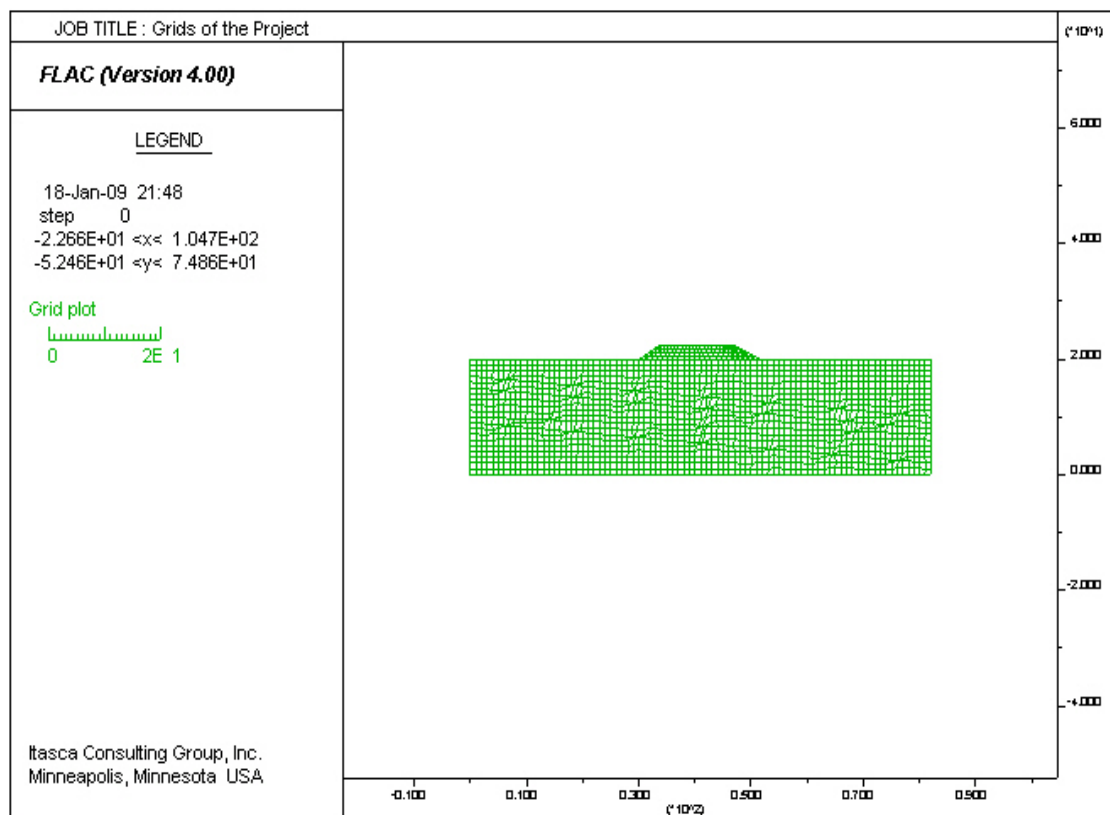


Figure 2: Mesh generation and layering of the embankment investigated in this study

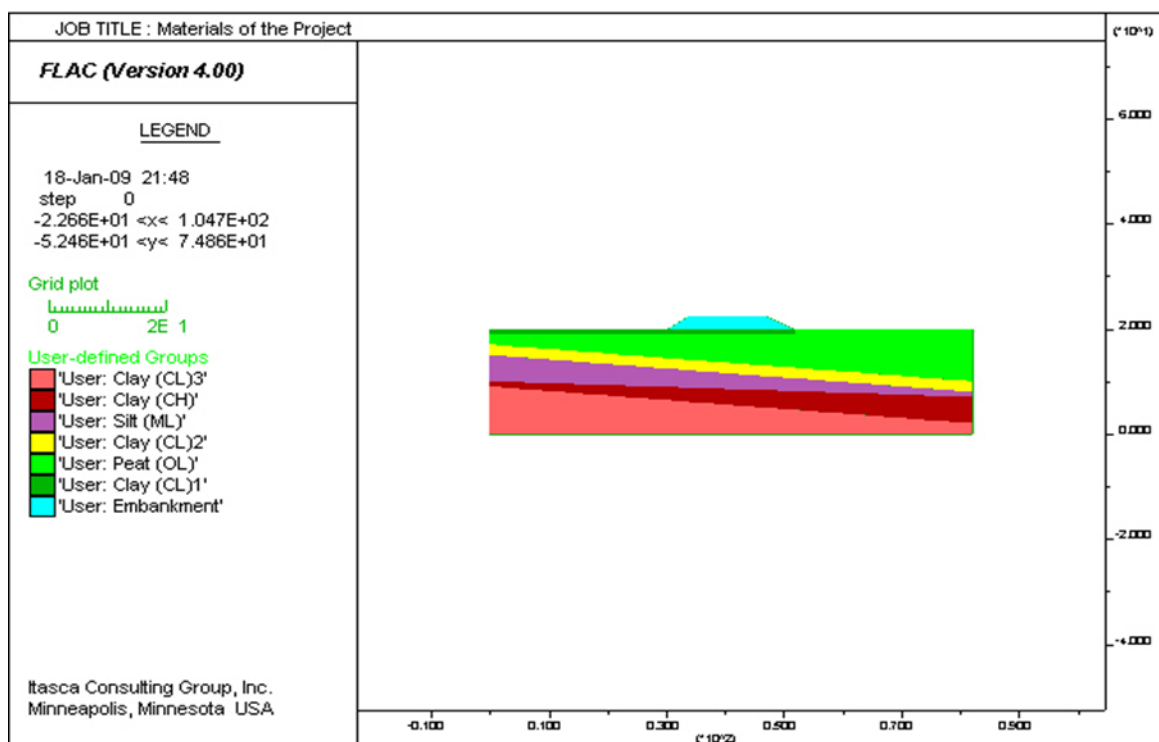


Figure 3: Mesh generation and layering of the embankment investigated in this study

In the upper part of the embankment used for the main road, four layers, each with a thickness of 60 cm, have been constructed over the underlying soil layers. Due to the mechanical properties and strength parameters of the soils, the Mohr–Coulomb constitutive model has been used to represent their behavior in the software. The properties of the materials used in this study are presented in Table 1.

Table 1: Properties of the Materials Used

Soil Type	Cohesion C (Pa)	Internal Friction Angle Φ (degree)	Unit Weight γ (kN/m ³)	Elastic Modulus E (N)	Poisson's Ratio ν	Soil Dilation Angle ψ (degree)
Embankment	1000	34	2100	5e7	0.35	0
Clay (CL(1))	1000	22	1580	2e7	0.3	0
Peat (OL)	5000	30	1508	1e7	0.3	0
Clay (CL2)	10000	20	1580	2e7	0.3	0
Silt (ML)	3000	22	1366	3e7	0.3	0
Clay (CH)	12000	14	1284	7e7	0.35	0
Clay (CL3)	14000	24	1131	1.5e7	0.35	0

As mentioned, the Mohr–Coulomb model has been considered as the constitutive model for the materials.

The permeability coefficients and void ratios of different soil layers are presented in Table 2. To introduce the upper surface of the soil layers as a drainage boundary, the model is first analyzed under its self-weight, and no water flow is considered, although pore water pressure is introduced. In the next stage of analysis, for the upper points of the layers, the pore water pressure is set to zero, and simultaneously, the pore water pressure at these points is fixed at zero. This operation in the software causes the upper layer to act as a drainage layer, similar to a condition in which pore water moves upward. In this way, the consolidation process of the layers under applied loads is simulated in the software. It should be noted that since pore water pressure is assigned to internal points of the layers, all these points in the model and analysis process, except for the uppermost points, are considered saturated, and with continued analysis, the pore water pressure within the layer's decreases.

Table 2: Permeability Coefficient and Void Ratio of Different Soil Layers

Soil Type	Soil Permeability Coefficient (cm/s)	Void Ratio
Embankment	–	0.5
Clay (CL(1))	3e-5	0.6
Peat (OL)	3.5e-4	0.167
Clay (CL2)	1e-4	0.65
Silt (ML)	3.8e-4	0.47
Clay (CH)	6.65e-4	0.58
Clay (CL3)	3.9e-4	0.69

Additionally, the groundwater level is assumed to be exactly at the elevation beneath the

embankment. Therefore, for the upper layer, properties related to water flow are not considered. The finite difference software FLAC has been used to analyze the modeled cases.

FINDINGS

In this study, one layer of geotextile has been used between the third and fourth layers of the upper embankment, which corresponds to the first layer of the model. In a simple and summarized form, the interface elements used in this study have four variables named K_n (normal stiffness), K_s (shear stiffness), c (cohesion), and ϕ (friction angle), and their form in the software is as shown in Figure 4.

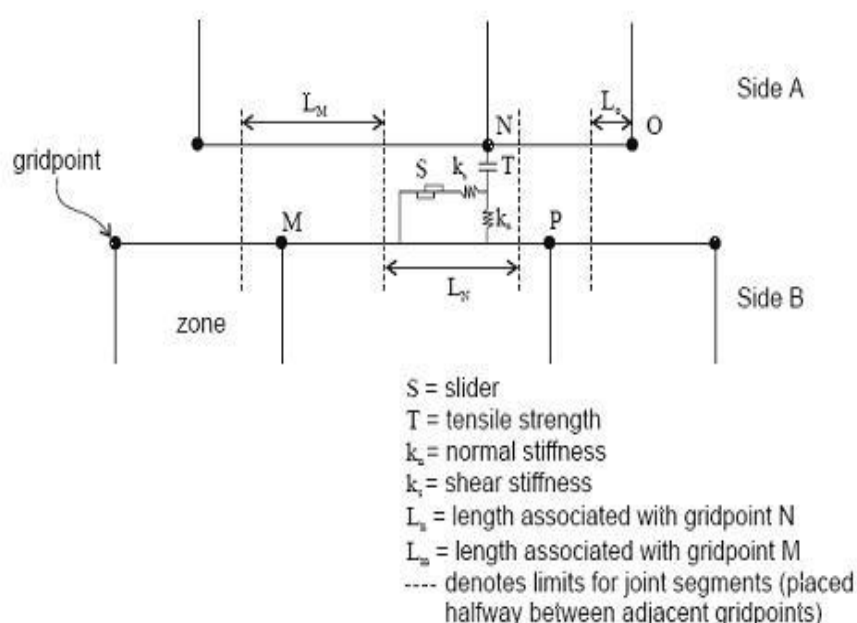


Figure 4: Interface element configuration

Initially, the results related to the vertical settlement of the first layer, in which geotextile has been used, are shown in Figure 5.

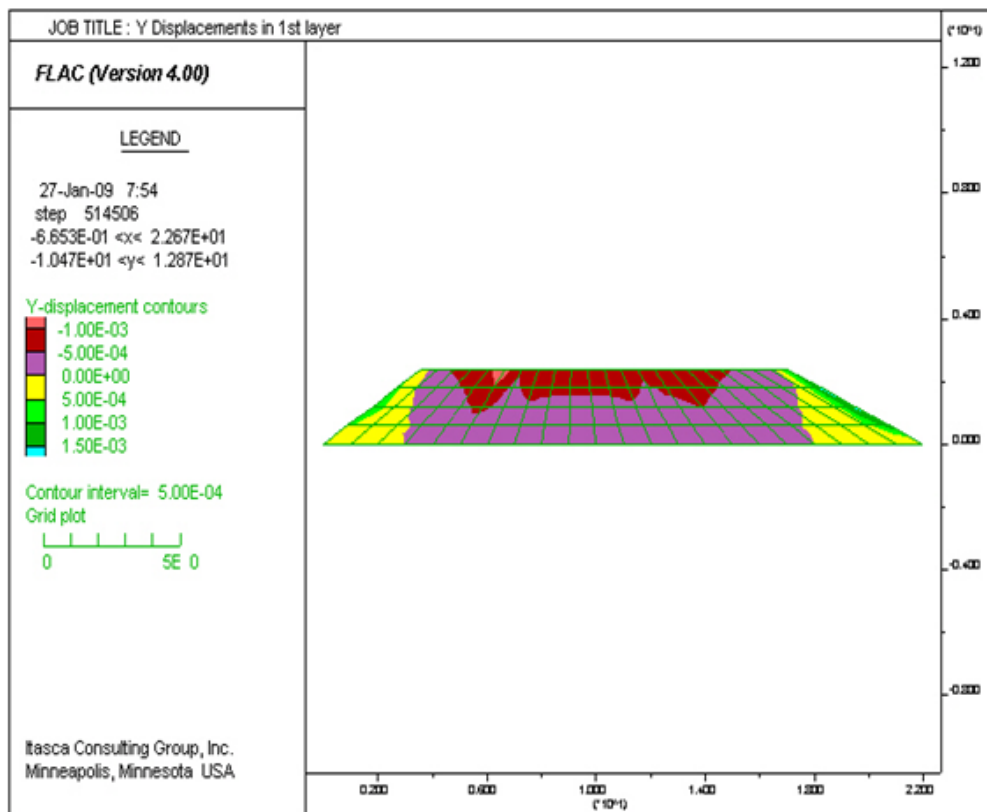


Figure 5: Vertical settlement of the first layer with geotextile

As observed, the use of geotextile has a significant effect on reducing settlement caused by the consolidation of layers under loading. The properties of geotextile under loading conditions are presented below.

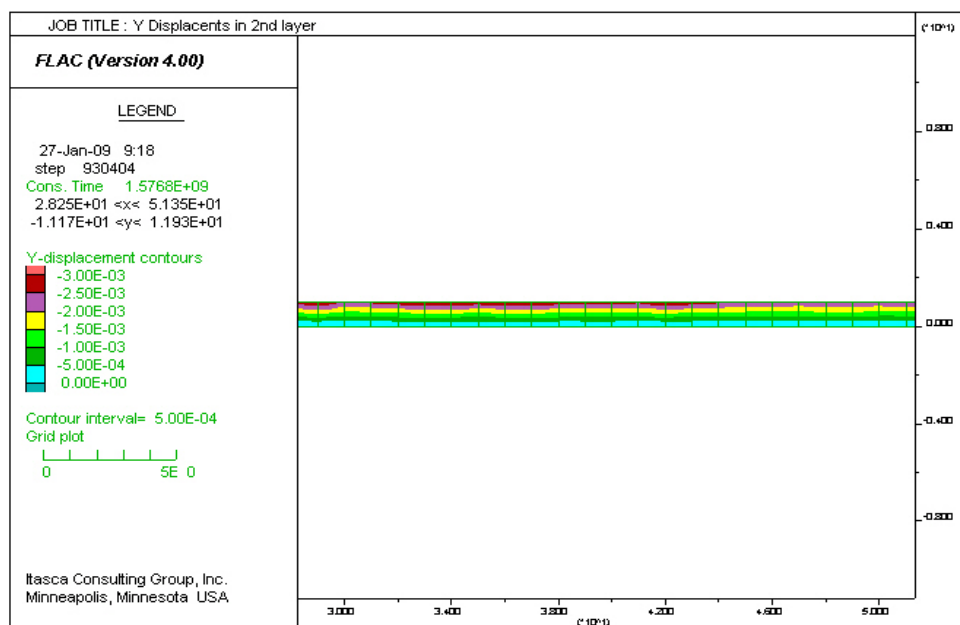


Figure 6: Vertical settlement of the second layer with geotextile

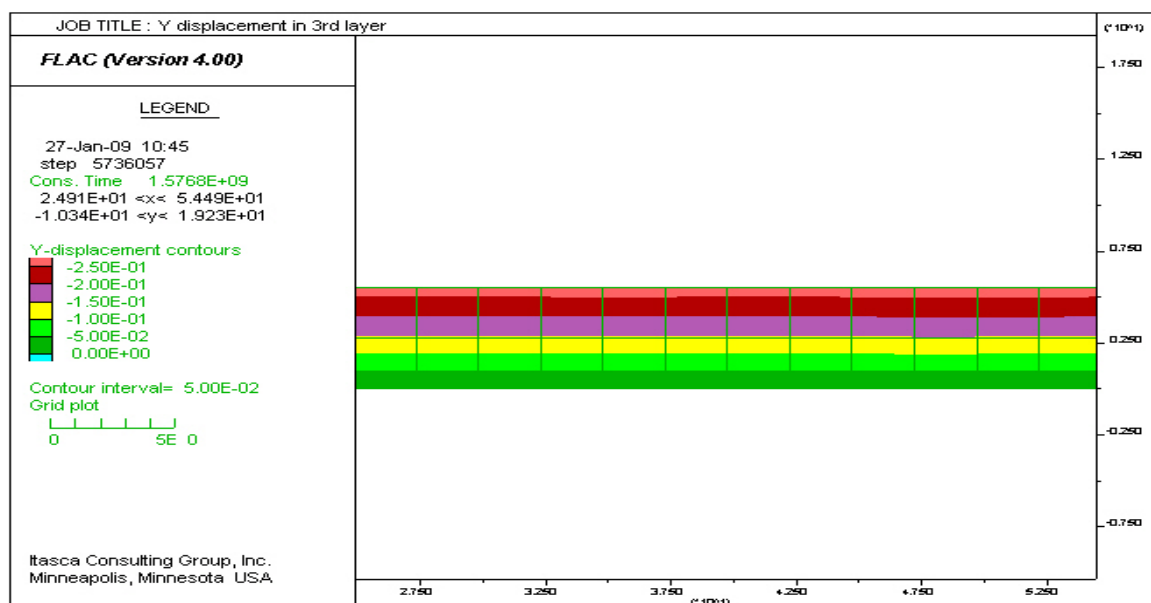


Figure 7: Vertical settlement of the third layer with geotextile

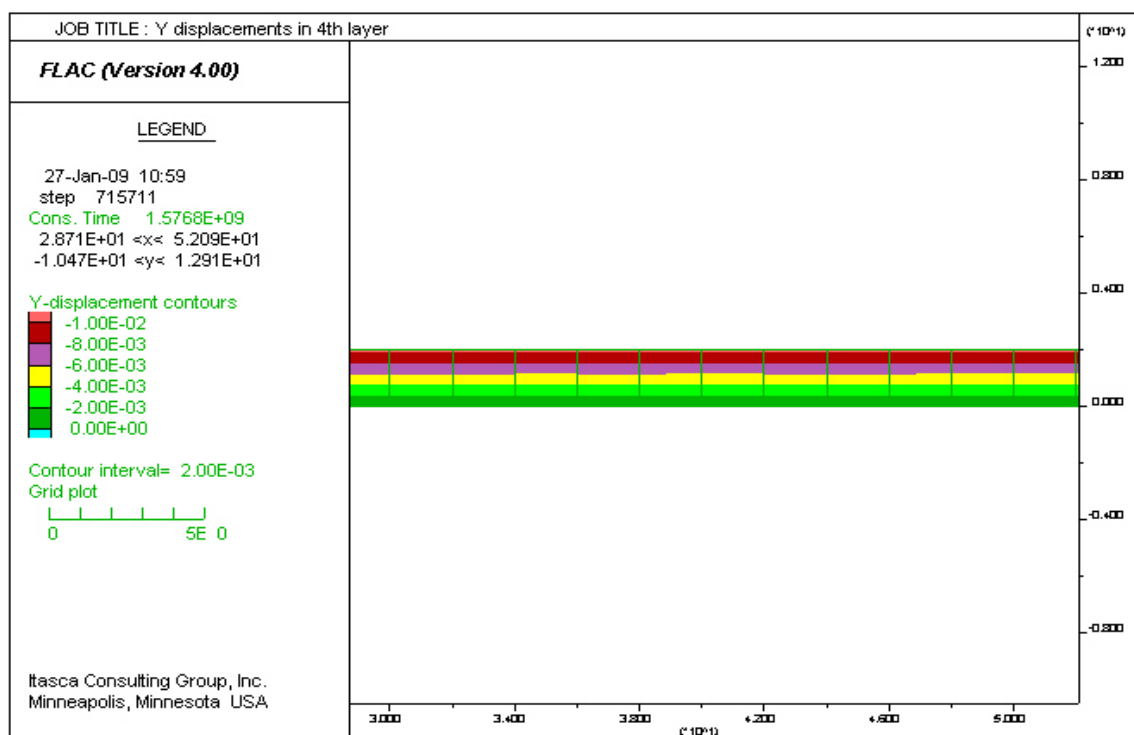


Figure 8: Vertical settlement of the fourth layer with geotextile

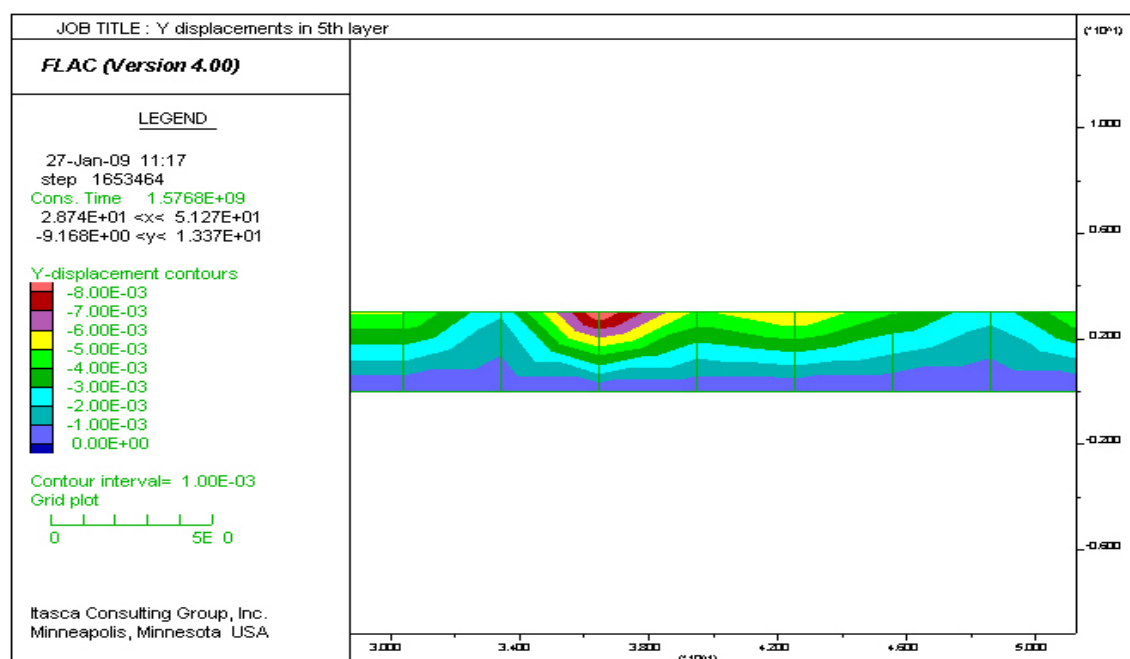


Figure 9: Vertical settlement of the fifth layer with geotextile

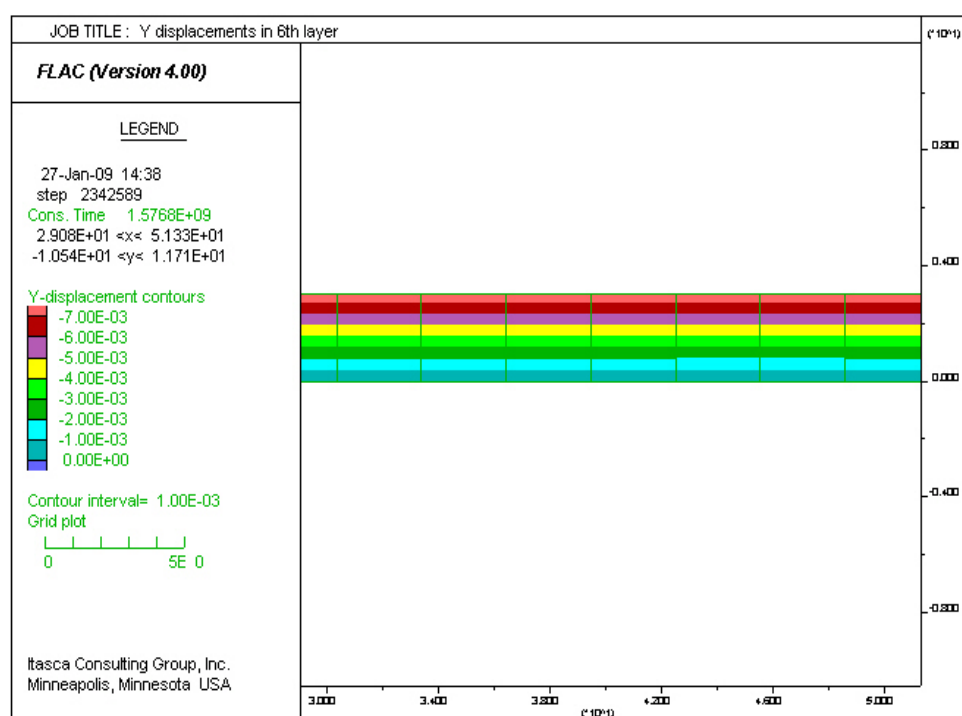


Figure 10: Vertical settlement of the sixth layer with geotextile

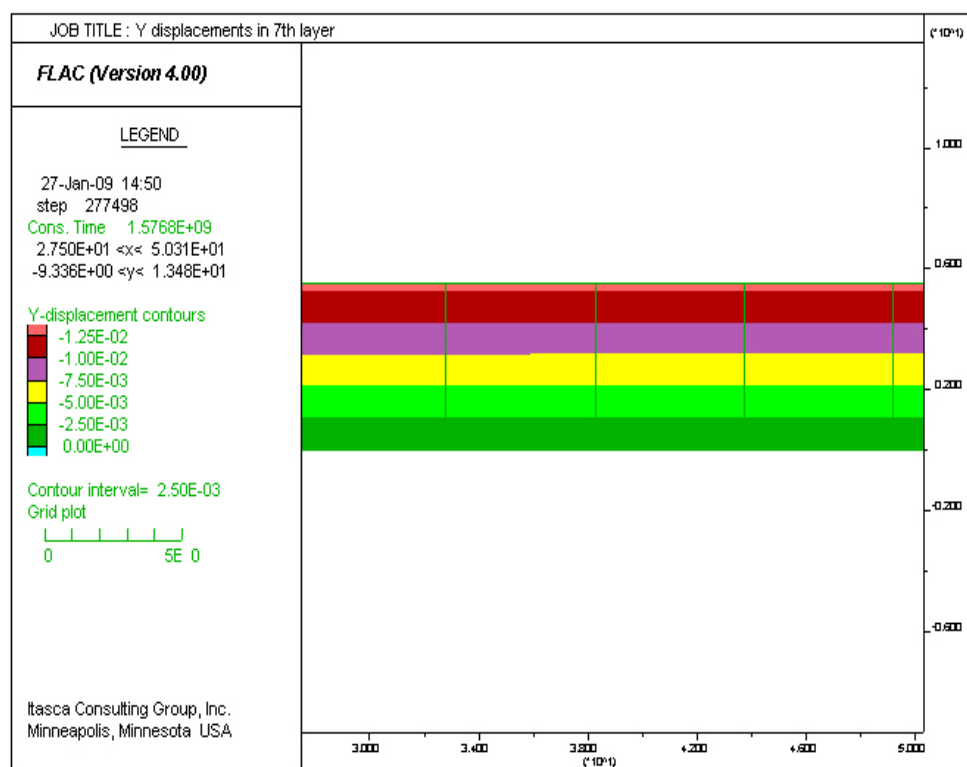


Figure 11: Vertical settlement of the seventh layer with geotextile

It is observed that by using geotextile, the values of vertical settlements are significantly reduced. This is due to the tensile forces being carried by the geotextile layer, resulting in the transfer of lower stress values to the underlying layers. By using geotextile, the stresses generated beneath the layers, which are used to model loading in the lower layers, are also significantly reduced.

Results Related to Pore Water Pressure Variations in Model Analysis Using Geotextile

In this section, in order to compare pore water pressure values with the model without a geotextile, the pore water pressure values at the end of the analysis for each layer are presented. Figures (12) to (17) show the pore water pressure values at the end of each analysis stage with geotextile for layers two to seven.

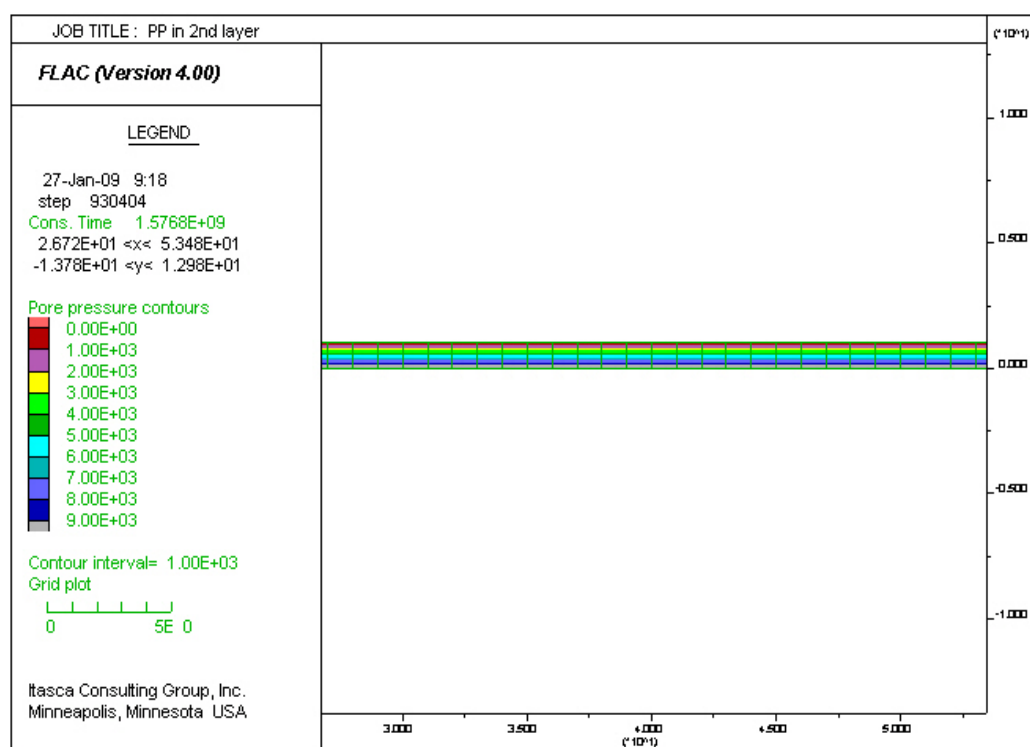


Figure 12: Pore water pressure values using geotextile for the second layer

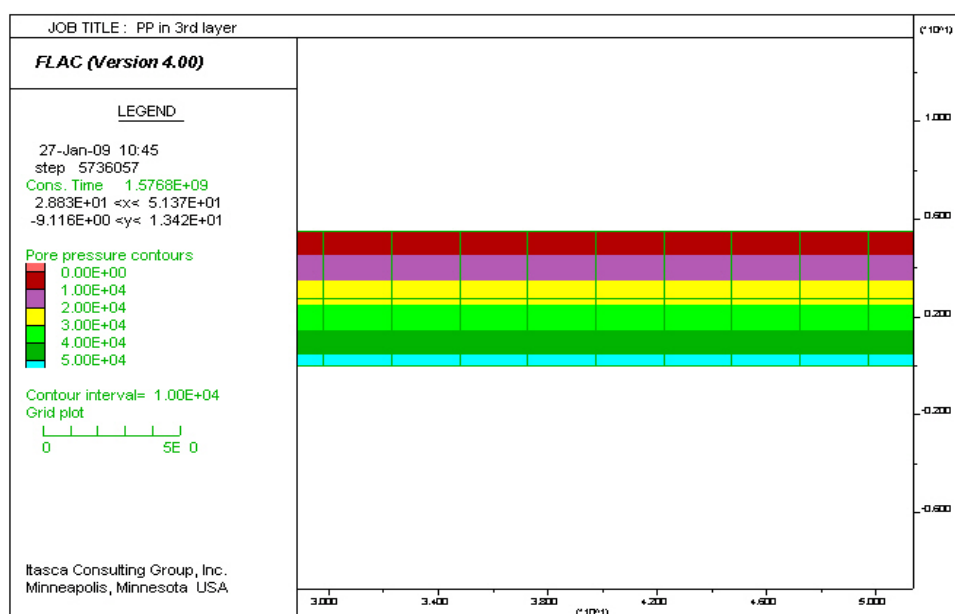


Figure 13: Pore water pressure values using geotextile for the third layer

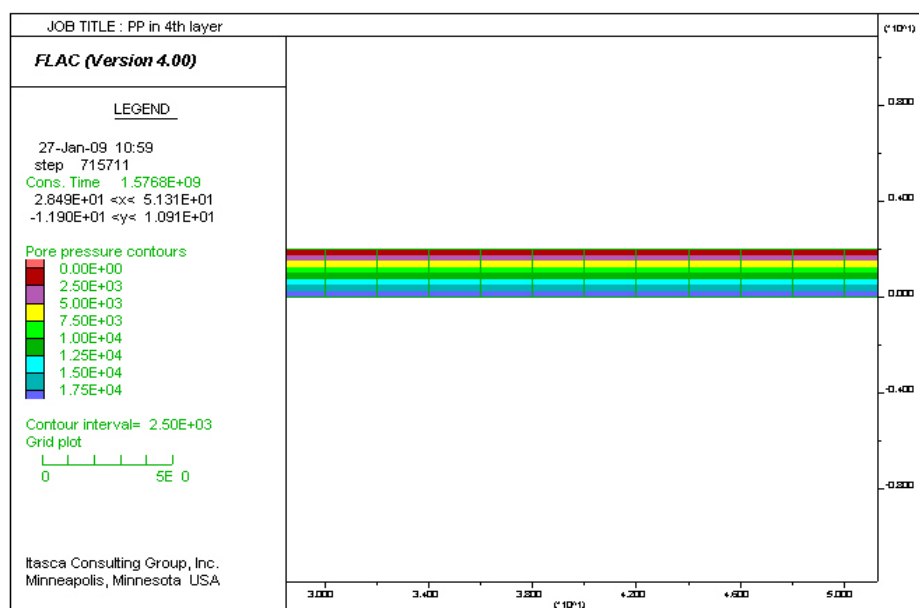


Figure 14: Pore water pressure values using geotextile for the fourth layer

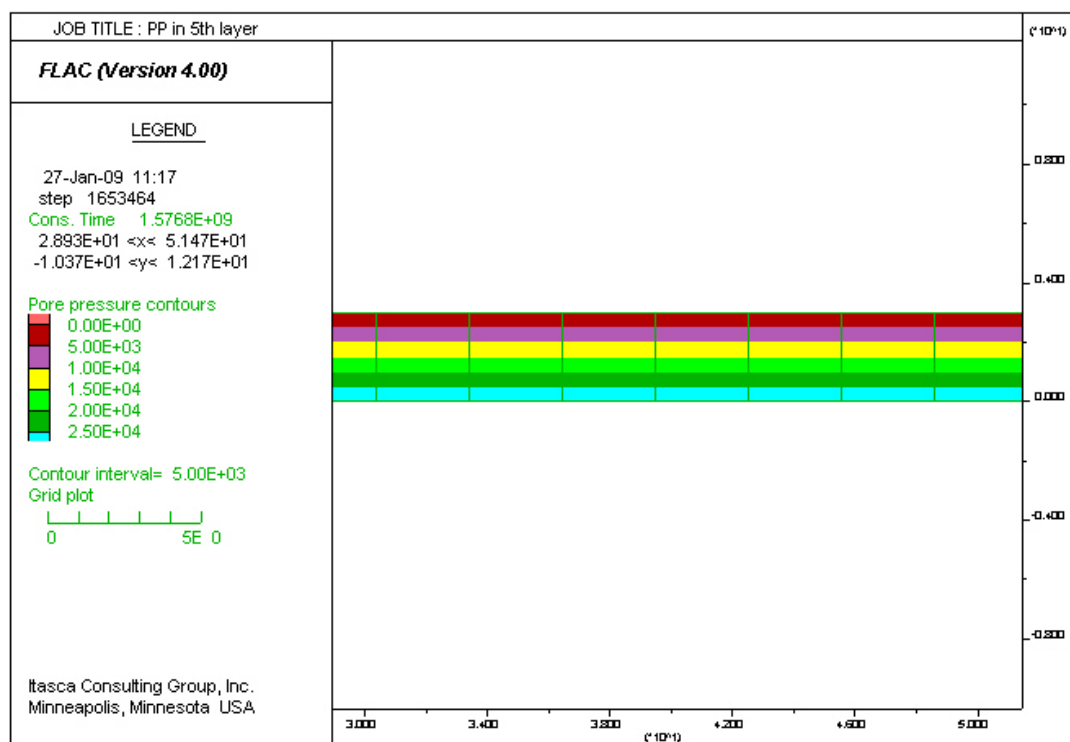


Figure 15: Pore water pressure values using geotextile for the fifth layer

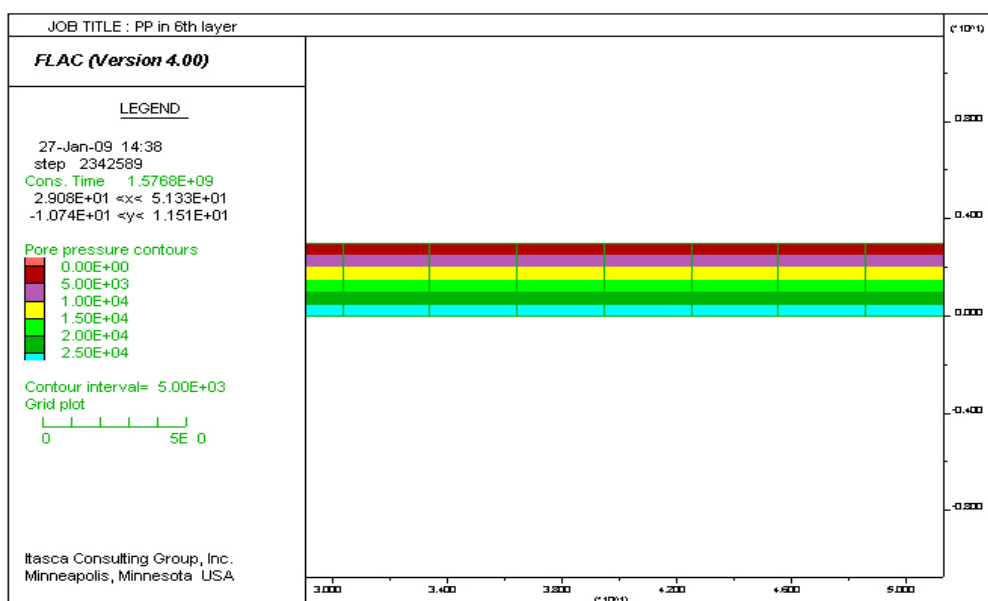


Figure 16: Pore water pressure values using geotextile for the sixth layer

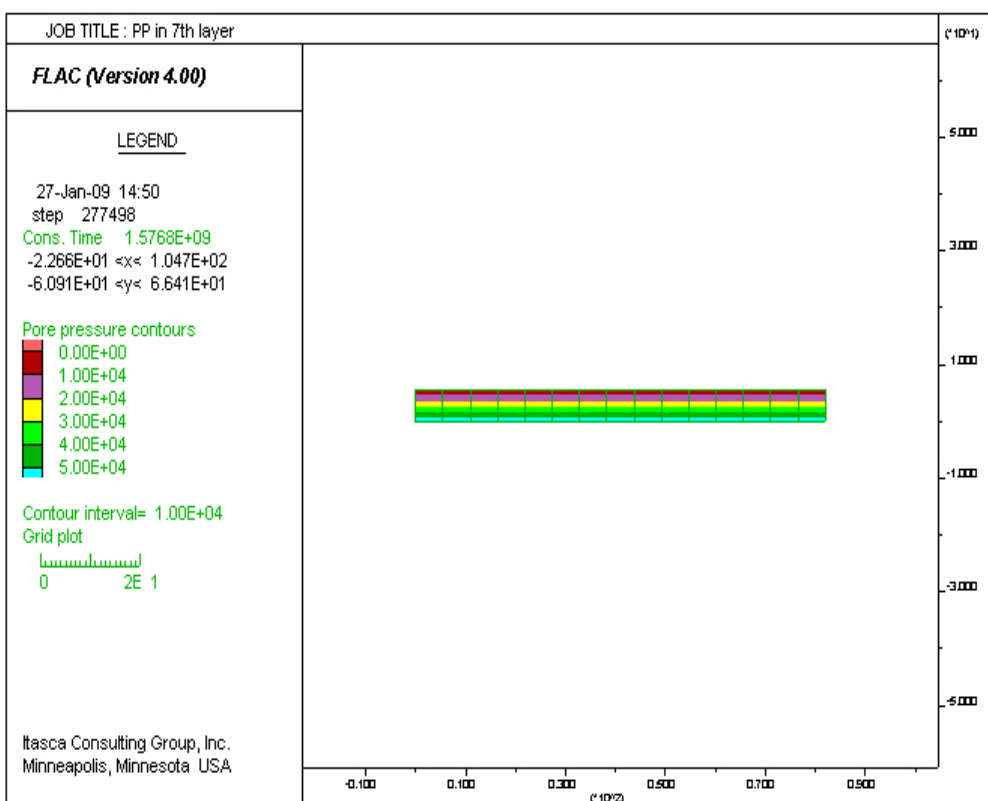


Figure 17: Pore water pressure values using geotextile for the seventh layer

In general, by observing the values of pore water pressure in the case of the model reinforced with geotextile compared to the unreinforced state, it is observed that the pore water pressure in the reinforced state is significantly reduced compared to the unreinforced state. The reason

for this is due to the reduction in the stress values in the layers in the reinforced state compared to the unreinforced state. This stress reduction is due to the performance of the geotextile in the tensile and frictional states, and these characteristics are prominent examples of geosynthetics. This reduction in pore water pressure in the reinforced state compared to the unreinforced state causes a reduction in settlement in the embankment.

Total Vertical Settlements in Model Analysis Using Geotextile

In this section, similar to the unreinforced case, the results of the total vertical settlement of the model are presented separately and cumulatively for comparison in Figures 18 and 20, respectively.

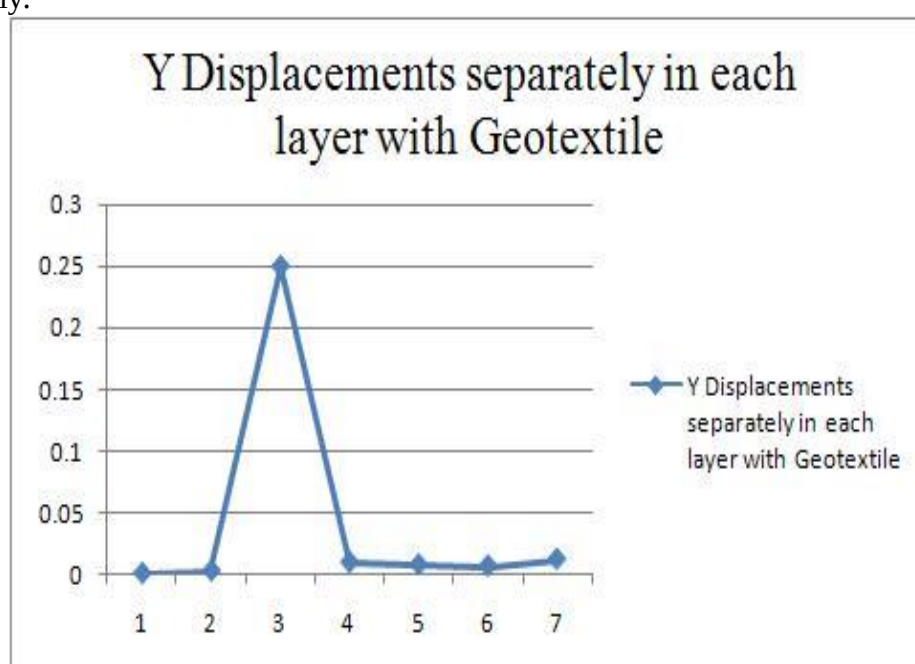


Figure 18: Settlement of layers (vertical axis) versus different layers (horizontal axis) at the end of 50 years (in meters) in modeling with geotextile

The overall comparison of settlements in different layers in the reinforced model can be observed in a single figure (as shown in Figure 19).

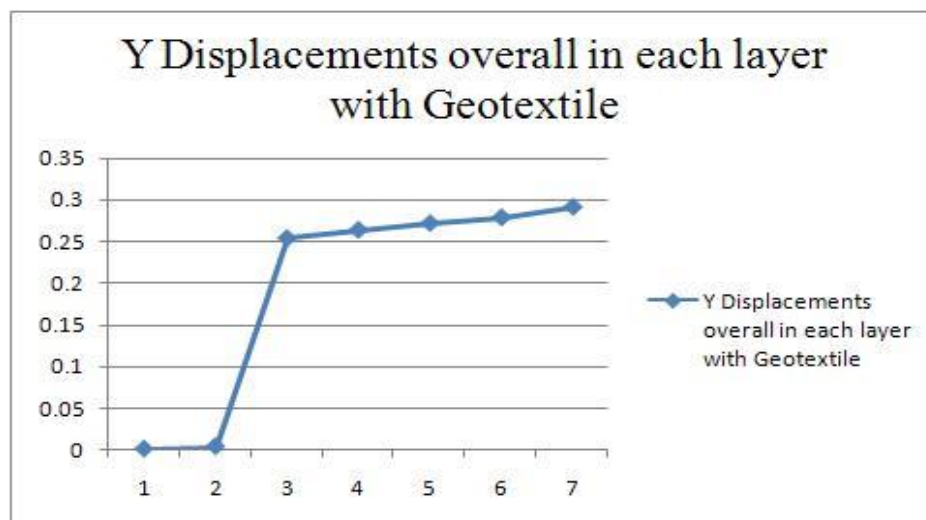


Figure 19: Cumulative settlement of layers (vertical axis) versus different layers (horizontal axis) at the end of 50 years (in meters) in modeling with geotextile

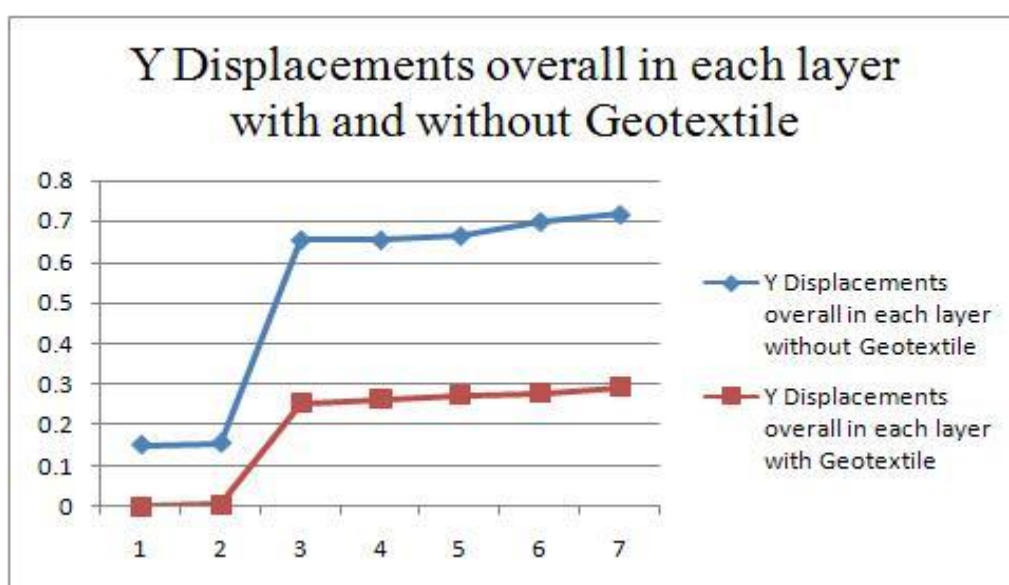


Figure 20: Comparison of cumulative settlement of layers (vertical axis) versus different layers (horizontal axis) at the end of 50 years (in meters) in reinforced and unreinforced modeling

Comparison of settlement values of the reinforced model (0.2915 m) with the vertical settlement of the unreinforced model (0.71704 m) shows that reinforcing the model with geotextile reduces the vertical settlement by approximately 60% on average, which is highly significant. Of course, this value varies for different layers depending on the type of material. For example, for the third layer it is about 50%, and for the first layer it is very large (1 mm compared to 15 cm). Therefore, it can be concluded that reinforcing the model with these materials varies depending on the type of material, distance from loads, and other factors.

Reinforcing the model also leads to a reduction in pore water pressure values. Since the reduction in pore water pressure depends on various factors, is time-dependent, and varies by layer with elevation, it is not possible to provide an exact and definitive value for this parameter. This factor also depends on many variables. Determining a precise value for pore water pressure reduction in this study would require further research.

CONCLUSION

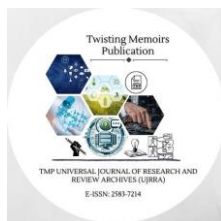
The results obtained from the analysis of the embankment in the unreinforced condition showed good agreement with the observed settlement values. Reinforcing the model with geotextile leads to a significant reduction in vertical settlements. The performance of geotextile reinforcement in soil layers is both axial and frictional. The performance of the reinforcing layer varies across different soil layers. Overall, acceptable results were obtained.

It is recommended that, before constructing embankments on such subgrades, appropriate geotechnical tests should first be carried out on these types of foundations. Suitable measures should also be provided to maintain and stabilize the embankment during and after construction. If soft and muddy soils are encountered along the embankment route, the behavior of the foundation under embankment loading should be considered. For this purpose, the behavior of the foundation can be analyzed using numerical analyses and computer programs such as PLAXIS, GEO SLOPE, or FLAC.

Additionally, the use of piles in the foundation, analysis of embankment behavior using piles, comparison of results with the present study, and the use of vertical and horizontal drains, along with analysis of embankment behavior during and after construction, are recommended.

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