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Numerical analysis of geosynthetic-reinforced embankments on soft soils

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Abstract. This paper analyzes, through numerical modeling in finite element software, the behavior of an embankment reinforced with geosynthetics on soft soils. The results presented and discussed allowed us to establish conclusions regarding the behavior of settlement, horizontal displacement, excess pore pressure, tension and deformation in the geosynthetic as a function of time, depth and horizontal distance. In summary, the numerical analyses presented satisfactory behavior and the results show that the insertion of geosynthetics does not influence the response of some analyzed variables, except for the horizontal displacement. However, the use of geosynthetics aims to increase the global stability of the soil mass through contact interactions and reduce embankment deformation. The contributions of this work to the understanding of the behavior of geosynthetic reinforced embankments on soft soils are highlighted.

Keywords: geosynthetic, soft soils, embankment, Abaqus, numerical model.

1 Introduction

The intrinsic characteristics of soft soils found on the Brazilian coastline pose great obstacles to the implementation of engineering works so that the insertion of geosynthetics as reinforcement and drainage elements is justified in many cases to ensure stability and accelerate settlements by consolidation.

In road-rail embankments built on soft soils, it is common to insert one or more layers of geosynthetics to provide greater strength and lower deformability (Sieira [1], Lopes [2], Palmeira [3]). Sieira [1] explains that when a reinforced soil mass is loaded vertically, it undergoes vertical compression deformations and lateral deformations, with the lateral deformations being limited by the reduced deformability of the reinforcement. In this case, the geosynthetics absorb and redistribute the efforts of the soil matrix, limiting the lateral deformations of the structures. This reorganization of stresses is controlled by two principles: the tensile strength and the pullout resistance of the geosynthetic.

According to Almeida and Marques [4], the reinforcement of embankments on soft soils reduces the shear strength and thus provides the attenuation of the loading on the foundation and increases the resistant forces. The authors add that reinforced embankments can reach greater heights than unreinforced embankments, or, comparing an unreinforced embankment with a reinforced embankment of the same height, an increase in safety factor is observed with the reinforcement. In addition, Palmeira [3] states that geosynthetics are installed at the base of the embankment on soft soils to maximize the contribution of the reinforcement in stabilizing the embankment against a generalized rupture process.

The stability and performance analysis of embankments on soft soils are usually done by analytical methods, abacuses and instrumentation results. In all cases, knowledge of the soil and geosynthetics properties as well as the interaction mechanism between them is crucial.

Currently, the Finite Element Method (FEM) has been used in a complementary manner to analytical and Limit Equilibrium methods to aid in the stability and performance analysis of geosynthetic reinforced embankments on soft soils. It is worth mentioning that the Shear Strength Reduction method is currently used in Finite Element software to indirectly perform the stability analysis and estimate the factor of safety.

Given the above, this paper evaluates, through numerical simulations in finite element software, the distribution of pore pressures, horizontal and vertical displacements, deformation and mobilized forces in a reinforced embankment on soft soils.

2 Finite Element Model

A two-dimensional plane strain model was established to analyze the performance of a reinforced embankment on soft soil. The numerical model consists of an embankment of granular material, a soft clay layer and geosynthetics embedded in the embankment, as shown in Fig. 1. The embankment is 3.5 m high, 20 m long and has a slope of 1:2 (v:h). The soft clay layer is 10 m thick and 60 m long. The length of the geosynthetics varies with its location, considering that the number of geosynthetic layers varies from 0 to 4. Due to space limitations, the paper emphasizes the comparison between the results of the unreinforced and reinforced embankment with 1 layer of geosynthetic. The model size is large enough to avoid any significant boundary effects on calculated displacement, deformation and load. Due to symmetry, only half of the domain of the model was modeled.

The embankment and soft soil domains have elements of the CPE8RP type (8-node plane strain quadrilateral element, biquadratic displacement, bilinear pore pressure and reduced integration), while the geosynthetic elements are of type B22 – 3 node quadratic beam. Figure 1 illustrates the mesh discretization of the finite elements, with greater refinements in regions where a large concentration of stresses and strains are expected.

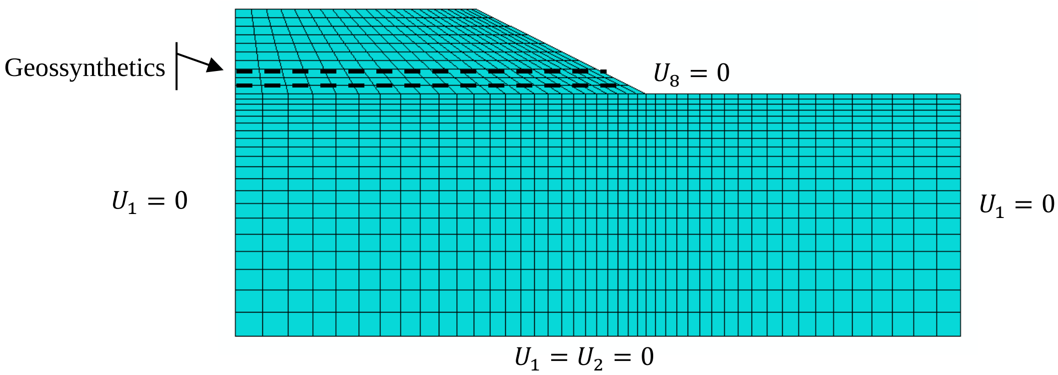

Figure 1. Representation of discretized finite element domain and boundary conditions

The numerical analysis consisted of three steps: (1) geostatic, (2) embankment execution and (3) consolidation. The initial geostatic stresses in the soft soil domain were generated in the first step using the Body Force option. In the second step, the embankment layer with geosynthetics was executed over a period of one month. For this, the embankment load was applied linearly in this period to reach the values of 3.5 m or 35 kPa of effective stress, considering that both soft soil and embankment are saturated. Finally, the consolidation of the clay layer was monitored for 4 years after the completion of the embankment.

Three physical boundary conditions were defined in the first step. On the right side and the symmetry axis, displacement was restricted only in the horizontal direction (U_1). At the bottom of the model, both vertical (U_2) and horizontal (U_1) components of displacement were constrained.

Concerning the permeability boundary condition on the top surface of the soft soil, the pore pressure is equal to 0 (U_8=0) during the first step. At the beginning of the second step, the permeability boundary condition at the base of the embankment was deactivated, so that the pore pressure becomes zero at the crest and the embankment slope lines. This condition did not change until the end of the last step.

The behavior of granular materials of the embankment was modeled as a homogeneous solid, obeying the Mohr-Coulomb failure criterion. The saturated soft soil was modeled as a homogeneous solid with elastoplastic behavior, according to the failure criterion of the Extended Modified Cam Clay model implemented in Abaqus.

To perform later the parametric analysis, the reference values of the parameters of both the embankment and soft clay materials were defined from the parameter range established based on the works of Han [5], Keykhosropur [6], Khabbazian [7], Elsawy [8], Alkhorshid [9], Yapage [10], Fang [11] and Almeida et al. [12]. Tables 1, 2 and 3 present the parameters of the embankment material, soft soil and geosynthetic, respectively.

Table 1. Parameters of the granular material of embankment

Parameter	Reference values	Variation range
Initial void ratio - e_0	0.65	-
Bulk unit weight - γ (kN/m³)	20	18 - 22
Cohesion - c (kN/m²)	2	0 - 5
Internal friccional angle - ϕ (º)	30	25 - 40
Dilatancy - ψ (º)	10	0 - 10
Elastic Module - E (kN/m²)	1000	500 - 80000
Poisson's ratio - ν	0.3	0.3 – 0.35
Permeability coefficient - k (m/s)	0.01	-

Table 2. Parameters of soft soil

Parameter	Reference values	Variation range
Initial void ratio - e_0	1,2	1 - 2
Bulk unit weight - γ (kN/m³)	15	14 - 18
Recompression index - κ	0,05	0.03 – 0.09
Poisson's ratio - ν	0.33	0.35 – 0.45
Compression index - λ	0.2	0.11 – 0.5
Slope of the critical state line - M	1	0.85 – 1.4
Initial size of the yield surface - p'/σ'_{v0}	37.5	-
Size of the yield surface in the wet side - β	1	-
Ratio of the flow stress - K	1	-
Permeability coefficient - k (m/s)	2.50E-08	-
Lateral earth pressure at rest - $K_0 = 1 - \text{sen}\,\phi$	0.58	0.58 – 0.66

Table 3 - Parameters of geosynthetics.

Parameter	Reference values	Variation range
layers – n	1.0	0 a 4.0
Poisson's ratio – υ	0.15	0 a 0.45
Thickness – t (mm)	3.0	-
Modulus of rigidity – J (kN/m)	3000	1000 a 5000

To analyze the performance of the numerical model, the numerical results of displacement in the vertical and horizontal directions, pore pressure, effective vertical stress, as well as the maximum strain and stress of the geosynthetics were exported from the Abaqus to Excel. Figure 2 shows the arrangement of the points and lines used to extract the data. In all, 11 points, 3 horizontal lines and 7 vertical lines were defined to extract the data. Data from points were used for analysis over time, while the data collected in the lines allow analysis along depth (vertical direction) or horizontal distance.

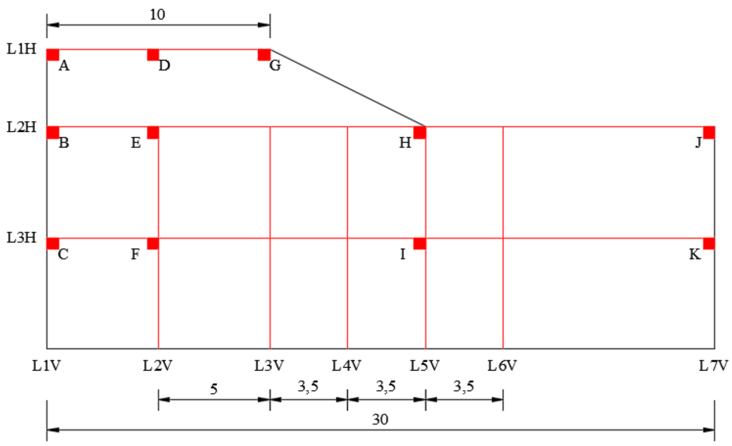

Figure 2. Representation of points and lines where data were collected

3 Results and Discussion

This item presents and discusses the variation of settlement, horizontal displacement, excess pore pressure and tension and deformation in the geosynthetic as a function of time, depth, or horizontal distance.

3.1 Settlement Analysis

An overview of the settlement distribution after 4 years of the execution of the reinforced embankment is shown in Fig. 3. It is observed that the maximum settlement at the top of the embankment was 33.7 cm, while the soil adjacent to the foot of the embankment lifted by 1.4 cm. For comparison, it is worth noting that the maximum displacement observed at top of the unreinforced embankment was 35 cm.

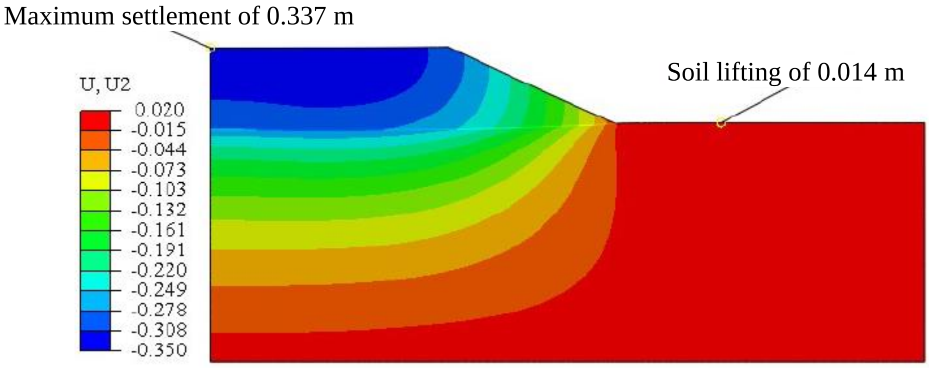

Figure 3. Distribution of the settlement – 4 years

The variation of settlement as a function of time, considering data from points A, B, D, E, G and H, is shown in Fig 4a. Figure 4b illustrates the variation of settlement along the horizontal distance for lines L1H (embankment surface) and L2H (soft soil surface), considering times of 1 month and 4 years.

At the end of the consolidation, Fig. 4a shows the highest normalized settlement (3.37% or 33.7cm of settlement) at points A and D, both located at the top of the embankment. On the other hand, the maximum settlement of the soft soil layer (points B and E) was approximately 27.1 cm (or 2.71% of normalized settlement). In terms of comparison, the maximum normalized settlements at the top of the unreinforced embankment and in the soft soil layer were 3.5% and 2.9%, respectively.

During the construction of the embankment, the soil near point H, located at the foot of the embankment, rises until it reaches the maximum value of about 5,6 cm at the end of 1 month. This positive vertical displacement reduced over time until it stabilized at 1.4 cm at the end of consolidation.

The complementary analyses performed in this study indicate that the magnitude of settlement is not significantly influenced by varying the number of layers and the stiffness of the geosynthetic. This behavior can be justified by the fact that the main function of the geosynthetic is to increase the stability of the embankment and not to decrease the magnitude of the settlements.

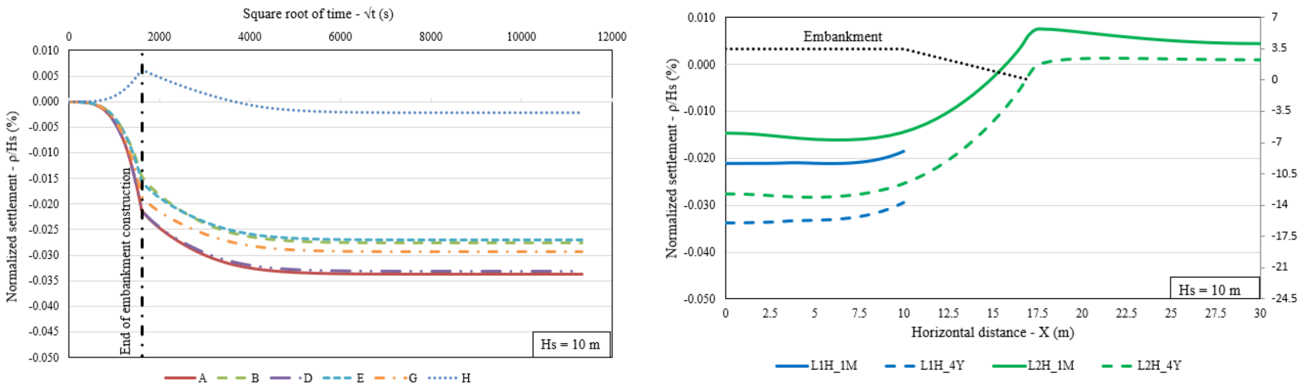

Figure 4. Variation of the settlement – a) versus time, b) versus horizontal distance

Figure 4b illustrates larger settlements near the symmetry axis and the soil lift during the loading stage, and it returns to its initial condition as the soil consolidation advances. The same behavior was observed in unreinforced embankments, but with higher settlement values.

3.2 Horizontal displacement Analysis

The results of the instrumented embankments are useful in analyzing their performance. One of the techniques commonly used to monitor the performance of the embankments consists of installing inclinometers to measure the horizontal displacement of the embankment slope and the soft soil. In this sense, the performance of the numerical model was analyzed from the results of horizontal displacement along the depth, considering unreinforced and reinforced embankments.

The analysis of horizontal displacement along the depth of the soft soil, for 1 month and 4 years, was done for the following vertical lines: L2V, L3V, L4V, L5V and L6V. Figure 5 shows the results of the reinforced embankments. As expected, the reduction of horizontal displacement with depth is observed in all lines. In comparison with the results of the unreinforced embankments, it is worth mentioning that the insertion of geosynthetics reduced the magnitude of horizontal displacement and consequently increased the safety factor.

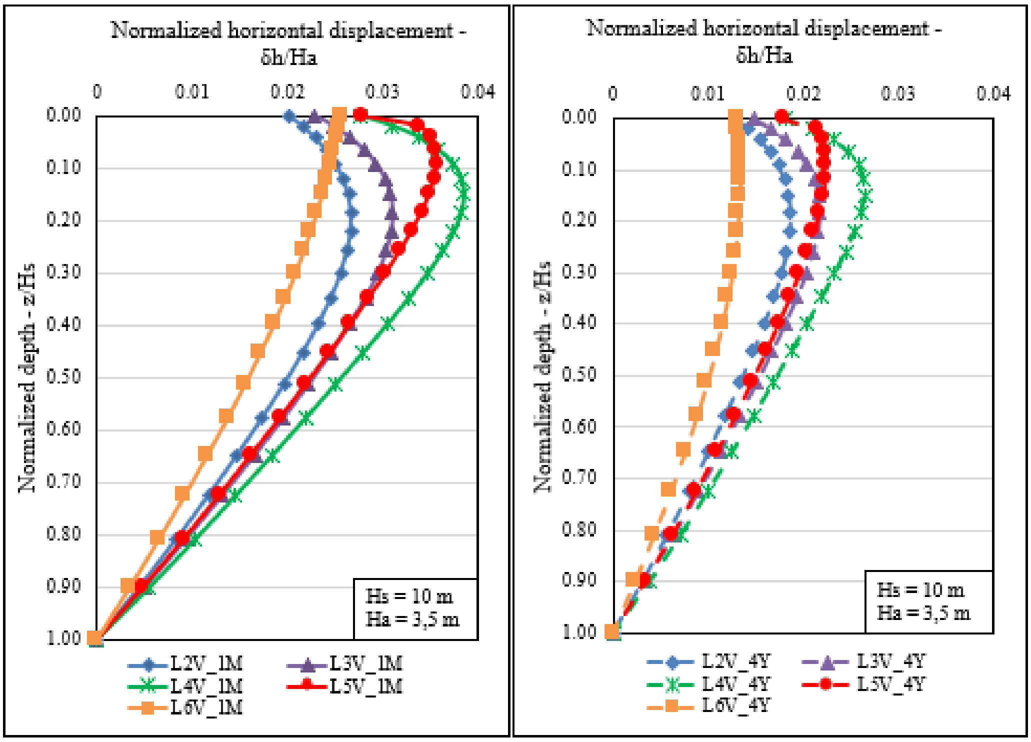

Figure 5. Variation of the horizontal displacement along the depth

In addition, Fig. 5 shows depths near the soft soil surface from which the horizontal displacement ceases to increase and starts to decrease. Depending on the line and time being analyzed, these depths vary between 0.2 m and 2.0 m. Furthermore, the largest and smallest horizontal displacements occur in lines L4V and L6V, respectively. Line L4V passes through the foot of the embankment.

On the other hand, when comparing the curves of 1 month and 4 years, it is evident that the 1-month curves present greater horizontal displacement. The explanation for the regression of the displacement after the completion of the embankment is that, during its construction, the horizontal displacement moves towards the foot of the slope, pushing the soil down because the loading rate is greater than the consolidation rate of soft soil. After the completion of the embankment, the loading rate does not change, however, the consolidation rate continues to exist, so that the soil considerably thickens in the region below the embankment, causing a reversal in the horizontal displacement.

3.3 Pore pressure Analysis

The variation of the excess pore pressure in the middle of the clay layer (horizontal line L3H) was analyzed at the end of the embankment execution (1 month). For this, the excess poro pressure was normalized by the effective vertical stress (q) of 35 kPa applied by the embankment on the surface of the clay layer. Figure 6 compares the results of the reinforced and unreinforced embankments, highlighting the reduction of the excess pore pressure as one moves away from the symmetry axis and the non-influence of the geosynthetic on the behavior of the excess pore pressure.

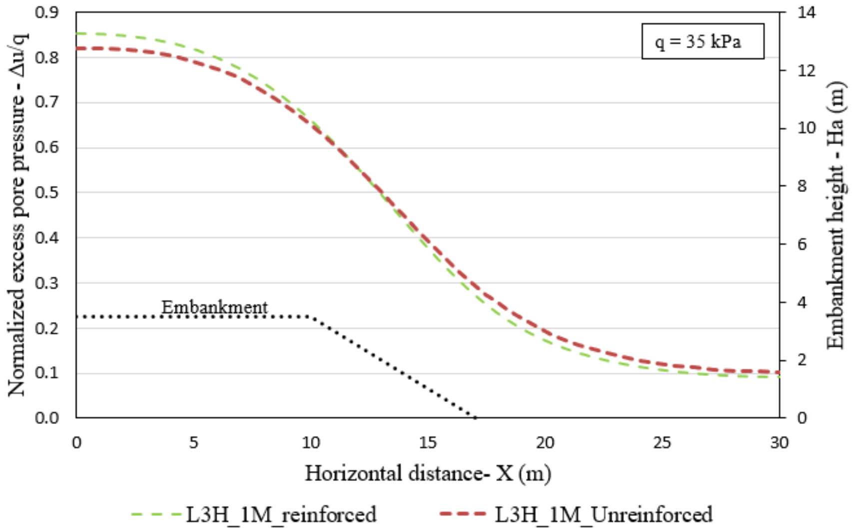

Figure 6. Variation of excess pore pressure versus horizontal distance

Complementary analyzes showed that there is some influence of the number of layers and the stiffness of the geosynthetics on the behavior of the normalized excess pore pressure. In general, at greater depths, the excess pore pressure tends to increase with both increasing number of layers and increasing geosynthetic stiffness.

3.4 Analysis of tension and deformation in the geosynthetic

For a better understanding of the influence of geosynthetics on the performance of embankments on soft soils, Figure 7 illustrates the variation of deformation and mobilized tension along the length of the first geosynthetic layer, considering embankments reinforced with one (1L), two (2L), three (3L) and four (4L) geosynthetic layers with the same stiffness.

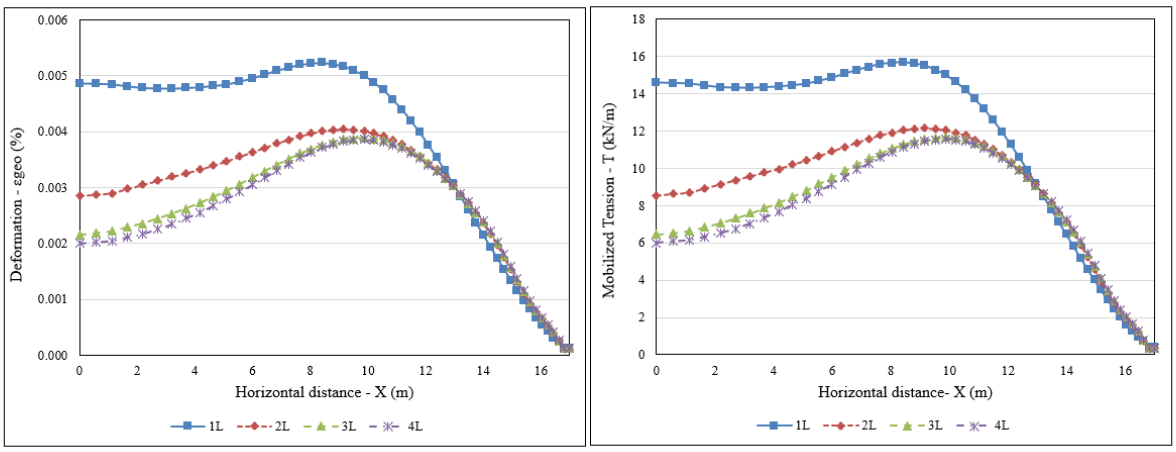

Figure 7. Variation deformation and mobilized tension along the length of the 1st geosynthetic layer

Two different behaviors can be highlighted in Fig. 7. The first is related to the decrease in both deformation and forces mobilized in the central region of the embankment with the increasing number of geosynthetic layers. This trend is not linear, since the results of the embankments with 3 and 4 layers are almost identical. The second behavior occurred in the slope region of the embankment, where the curves overlap, indicating no influence of the number of layers on the values of deformation and tensile force.

4 Conclusions

The paper presents and discusses the results of numerical analysis to evaluate the performance of geosynthetic-reinforced embankments. The results are satisfactory and show that the insertion of geosynthetics contributes to the reduction of horizontal displacement and settlement. The reduction in horizontal displacement is closely related to the increase in the safety factor. On the other hand, the insertion of geosynthetics has virtually no influence on the magnitude of excess pore pressure. Finally, it is worth noting that the insertion of more than three layers of geosynthetics does not contribute to the reduction of deformation and mobilized forces in geosynthetics near the soft soil surface.

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