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EFFECT OF LARGE DISPLACEMENTS ON THE NUMERICAL ANALYSIS OF AN EMBANKMENT ON SOFT SOILS

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Abstract. This paper intends to clarify the influence of geometric nonlinearity on the behaviour of an embankment built on soft soils, considering the material non-linearity associated with a coupled soil-water formulation. The numerical predictions are compared with the field data in terms of settlements, horizontal displacements and excess pore water pressures. The repercussions of including the large displacements formulation are also studied in terms of the increments of vertical and horizontal effective stresses and of the yield area. It is found that the analysis considering large displacements results in a decrease in settlements and a slight increase in the rate of excess pore pressure dissipation, both of which are related to the reduction of the thickness of a deformable layer.

1 INTRODUCTION

The analysis of most geotechnical problems assumes that the strains are infinitesimal, presuming that the geometry of the elements remains unchanged during the calculation process. However, for structures built on very deformable ground, like very compressible clays and organic soils, this assumption is not completely realistic since these soils are subject to high displacements. The lower permeability and high compressibility of these soils, which are nearly always saturated, means that the analysis should also consider the coupled formulation of the interstitial fluid flow and the deformation of the solid skeleton (Biot's theory).

Several studies about implementations of coupled consolidation theories with finite deformations have been published, considering either linear elastic materials [1-5] or non-linear material behaviour [6-9]. But only a few included applications to real situations, namely to embankments built on very compressive soils, i.e., where the consideration of geometric non-linearity is essential to the improvement in the numerical predictions.

This paper intends to clearly show the importance of considering geometric non-linearity in the numerical analysis of coupled consolidation problems, particularly in problems of embankments on soft soils. In this way, a Lagrangian formulation is used, updating the nodal coordinates at the end of each step of time and/or load; this formulation was described by Zienkiewick [10].

Thus, the case of an embankment built on Portuguese soft soil is studied. The results of the numerical simulation, which considers a non-linear constitutive law (Modified Cam Clay model), with and without the geometric non-linearity phenomenon are compared with the results observed *in situ* in terms of settlements, horizontal displacements and excess pore water pressures. In addition, the influence of the large displacements analysis on the state of stress is studied in terms of vertical and horizontal effective stresses, and in terms of the yield area.

All the numerical analyses used the 2D finite element (FE) code, developed at the University of Coimbra [11], which can perform elastoplastic analyses with coupled consolidation.

2 CHARACTERISTICS OF THE EMBANKMENT

The site studied is located in Portugal, at km 7.775 on the A14 motorway. Three boreholes were performed (S_1, S_2 and S_3) to define the geotechnical profile presented in Figure 1.

The behaviour of the embankment was observed during its construction, with the following instrumentation (Figure 1): (i) a sub-vertical inclinometer tube placed on the vertical of the foot of the main embankment's slope to measure horizontal displacements with depth, (ii) a settlement plate (T) and a electrical piezometer (P) to measure pore pressure [11]. Under the embankment and the additional berm, vertical drains were installed down to the bottom of the soft deposit.

The time history of the construction of the embankment is described with elevations of 1.1, 1.85, 3.45, 4.7, 7.55 and 8.1 metres, applied at times 0, 80, 240, 290, 385 and 420 days, respectively.

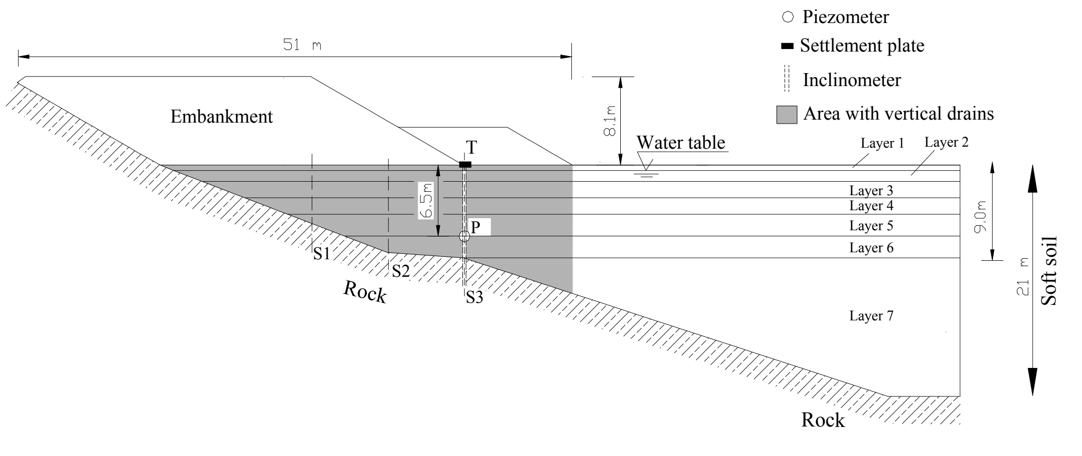


Figure 1: Geotechnical profile of the A14 motorway embankment (Portugal).

The geotechnical characterisation of these soils, carried out by Coelho [12], allowed the foundation soil to be zoned, as shown in Table 1, where the physical and mechanical characteristics of the layers are set forth. The behaviour of the foundation soil is simulated by the Modified Cam Clay (MCC) model. The behaviour of the embankment is simulated by a linear elastic law, with ν' = 0.3 and the deformability modulus varying between 30 MPa (bottom layer) and 2 MPa (top layer), thereby reproducing the reduced containment of the upper layers.

Table 1: Physical and mechanical characteristics of soil layers.

Layer	Depth (m)	γ (kN/m³)	OCR	K_o	e_o	Parameters of MCC model				$k_{y(eq)}$* (m/day) [x 10^{-4}]	k_x/k_y
						$e_{\lambda o}$	λ	κ	M		
1	0.0 - 0.5	15.0	7.0	0.87	2.0	2.58	0.226	0.028		-----	
2	0.5 - 1.5	15.0	5.0	0.76	2.0	2.76	0.226	0.028		15.6	
3	1.5 – 3.0	14.8	3.0	0.62	2.1	3.02	0.282	0.035		62.4	
4	3.0 - 4.5	14.5	1.5	0.47	2.3	3.41	0.374	0.05	1.48	103.6	3.0
5	4.5 - 6.5	14.5	1.0	0.40	2.1	3.10	0.343	0.063		20.8	
6	6.5 - 8.5	15.2	1.0	0.40	1.8	2.37	0.178	0.025		5.1	
7	8.5 - 21.0	15.0	1.0	0.40	1.9	2.76	0.217	0.026		6.2	
Embank.	------	22.0	----	----	-----	-----	-----	-----	-----	-----	-----

* $k_{y(eq)} = 12.\ k_{y(soil)}$

The vertical coefficients of permeability, given in Table 1, correspond to the global equivalent values, thus expressing the drainage conditions of the '*soil-vertical drains'* system [11, 13]. The relationship between the horizontal and vertical coefficients of permeability of the soil is three.

During the calculation, the coefficients of permeability change with the void ratio, in accordance with Taylor [14]:

$$k = k_0 x 10^{\frac{e - e_0}{C_k}} \tag{12}$$

where e_0 represents the initial void ratio, k_0 the coefficient of permeability related to e_0, k the corrected coefficient of permeability related to the current void ratio e, and C_k is a constant equal to $0.5e_0$ [14].

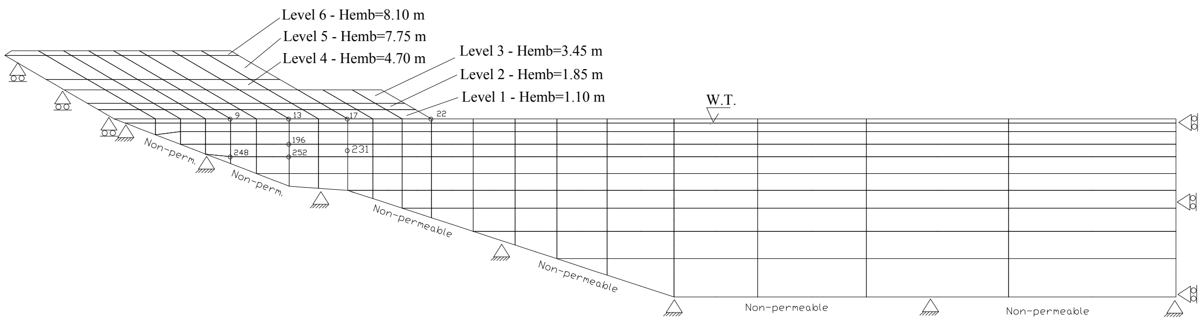


Figure 2: FE mesh.

The FE mesh for the plane-strain analysis is presented in Figure 2. It consists of 679 nodal points and 202 eight-noded isoparametric quadrilateral elements. Elements with twenty nodal degrees of freedom are used below the water table, allowing a coupled analysis of fluid flow and deformation in order to simulate the consolidation phenomenon in the soft soil. These elements provide quadratic interpolation of displacements and linear interpolation of pore pressures; these elements therefore allow the calculation of the displacements in eight nodes and the excess pore pressure in four corner nodes.

The boundary conditions applied to the mesh are such that the right vertical side is restrained from moving in the horizontal direction, while the bottom boundaries are restrained from moving in both directions [12]. In terms of hydraulic conditions, only the top boundary, located at the same level of the water table, is permeable. Above the water table, no water flow was considered in the numerical analyses.

3 ANALYSIS OF RESULTS

The study of the behaviour of this embankment aims to clearly demonstrate the factors inherent in an analysis that involves large displacements. Thus, the results obtained by the two numerical analyses (infinitesimal and large displacements) are compared and also with the behaviour observed *in situ*. The study is carried out with respect to settlements, lateral displacements, excess pore pressures and effective stress state.

3.1 Displacements

The observed and computed time-settlement behaviour measured by plate T is shown in Figure 3. It can be seen that the consideration of geometrical non-linearity (large displacements) tends to reduce the settlements in relation to the infinitesimal analysis (small displacements), with this effect growing with time. This behaviour is consistent with soil mechanics theory, since with large displacements analysis the dependence of the settlements with respect to the real thickness of the compressible layers is considered. Thus, the decrease of the thickness of the soil layer is naturally linked to smaller settlements.

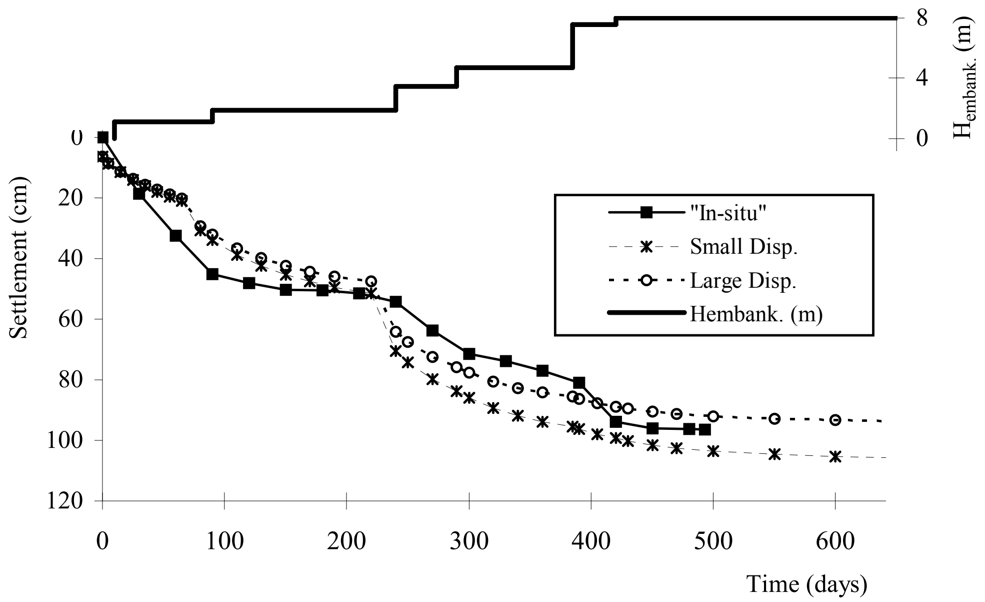
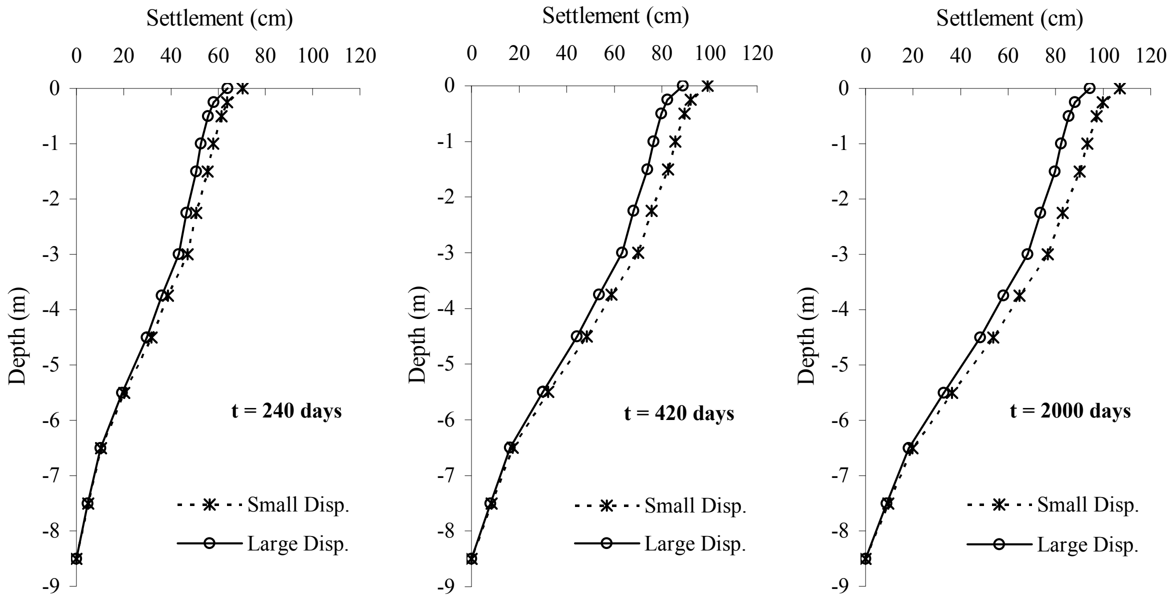


Figure 3: Observed and predicted settlements (plate T).

The comparison of the computed settlements and the field data shows that the consideration of geometric non-linearity improves the numerical prediction. The differences between the numerical analyses and the measured settlements for 100 and 250 days are probably due to the consideration of equivalent coefficients of permeability, which are not the most appropriate to simulate the "real" flow conditions in the soil foundation.

Figure 4 shows the computed settlements under the foot of the embankment, for three times (240, 420 and 2000 days). In line with expected behaviour, it is in the surface area with greater settlements that the greatest discrepancies between the two numerical analyses are found, and these increase from 240 days to 420 days, i.e., with the increment of the settlements. Thus, it was found that the consideration of large displacements has more impact the greater the deformation of the soils involved is.



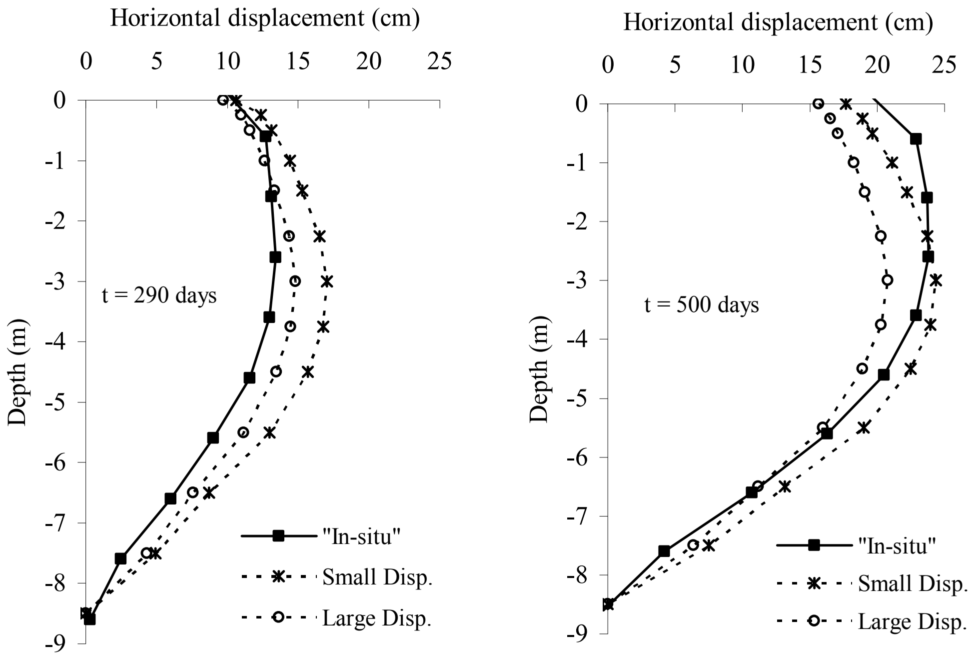
a) Evolution at 240 days. b) Evolution at 420 days. c) Evolution at 2000 days.

Figure 4: Computed settlements under the foot of the embankment.

Figure 5 illustrates the observed and predicted horizontal displacements under the foot of the main embankment at 290 and 500 days. According to the finding for the settlements, the consideration of geometrical non-linearity induces small horizontal displacements relatively to the infinitesimal analysis, and this difference naturally increases with time. The figure also shows that the behaviour of the embankment is qualitatively simulated by both the numerical analyses, albeit with some discrepancies. Thus, at 290 days a better simulation of the behaviour may be observed with the non-linear analysis, while at 500 days, a better agreement is obtained with the infinitesimal analysis.

3.2 Excess pore water pressures

The time evolution of excess pore pressures in piezometer P is given in Figure 6. The consideration of geometrical non-linearity leads to slightly faster dissipation of the excess pore pressure, being this fact linked to the shortening the drainage path length which results from the decreasing of soil thickness. Otherwise, for a time longer than 500 days, the large displacement analysis induces slightly higher u-u_o than the infinitesimal analysis, a fact that is apparently inconsistent. However, these results are due to the fact that the large displacements analysis considers the real nodal coordinates, corrected with the deformations obtained. As the level of the water table does not change and the nodal points are displaced in the vertical, thus, the distance between the nodal points and the water table increases, therefore giving greater equilibrium pore pressure [15].



a) Evolution at 290 days. b) Evolution at 500 days.

Figure 5: Observed and predicted horizontal displacement under the foot of the embankment.

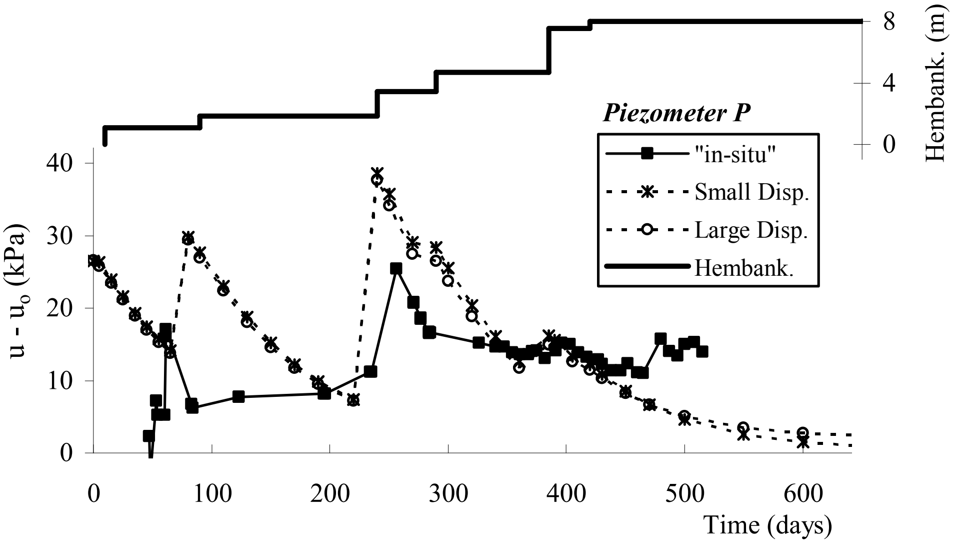


Figure 6: Observed and predicted excess pore pressure in piezometer P.

The contours of the excess pore pressure, shown in Figure 7, illustrate this clearly. At 420 days it can be seen that the non-linear analysis gives rise to an increase in the excess pore pressure close to the surface, reflecting the greatest settlement of the surface points and the corresponding increase in the equilibrium pore pressure. The reduction of the drainage path length associated with the large displacements analysis can also be seen in this figure, since this type of analysis generates smaller excess pore pressure near the bottom boundary.

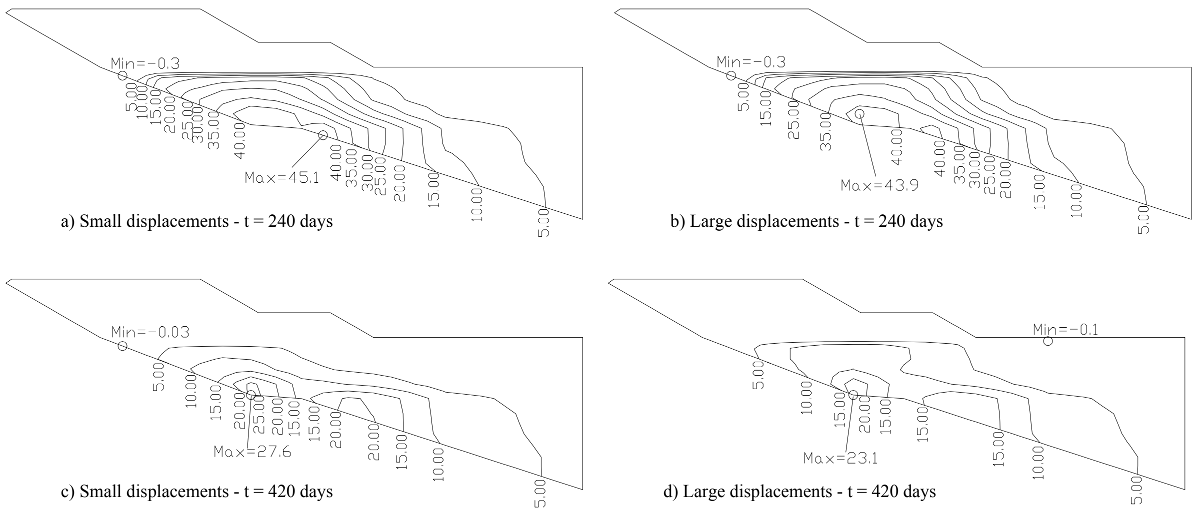


Figure 7: Contours of excess pore pressures at 240 and 420 days.

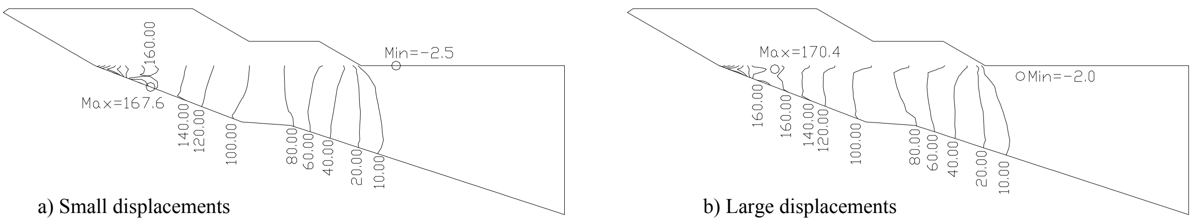


Figure 8: Contours of vertical effective stresses incremernts at 2000 days.

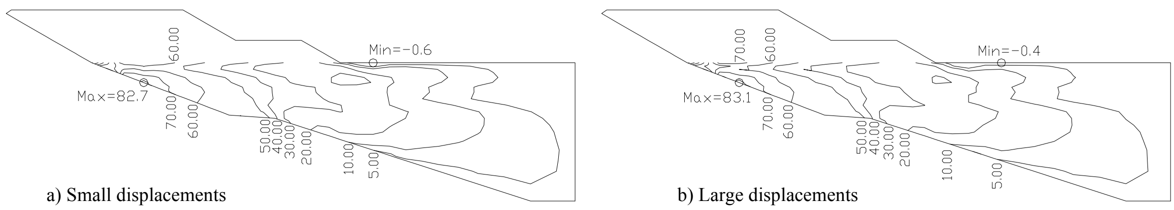
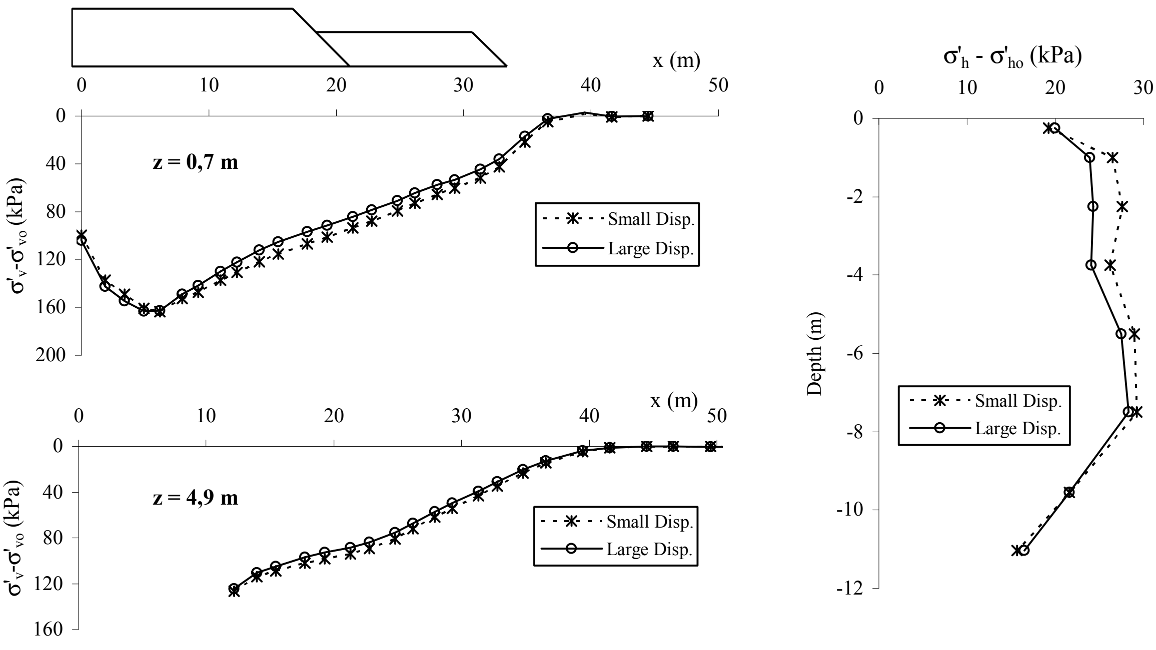


Figure 9: Contours of horizontal effective stresses increments at 2000 days.

3.3 Stress state

The contours of the effective vertical and horizontal stress increments at 2000 days, found with both numerical analyses, are presented in Figures 8 and 9, respectively. In general, it can be seen that the consideration of geometrical non-linearity does not generate qualitative changes in the effective stress state. Figure 10 compares the results of the two analyses in terms of vertical effective stress increments along the embankment section for two depths (Figure 10a) and horizontal effective stress increments under the foot of the additional berm (Figure 10b). The results show that including the large displacement phenomenon in the calculation tends to reduce both the vertical and the horizontal stresses in relation to the infinitesimal analysis, obtaining differences that could be almost 10%. These results are consistent with the fact that the non-linear analysis induces greater equilibrium pore pressure, which naturally corresponds to smaller effective stresses, since the total stresses are unchangeable.



a) $\Delta\sigma'_v$ b) $\Delta\sigma'_h$

Figure 10: Increment of effective stresses at 2000 days.

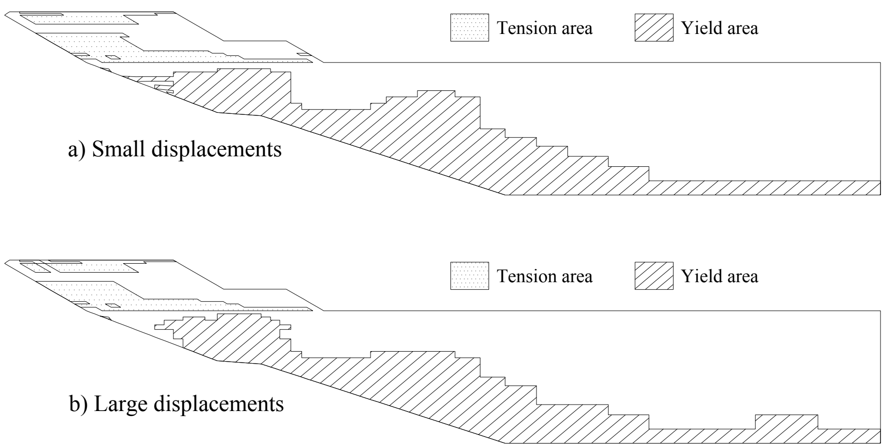


Figure 11: Yield areas at 2000 days.

The reduction of effective stresses indicated by the non-linear analysis, relative to the infinitesimal analysis, results in the shrinkage in the yield area (Figure 11) with special relevance in the layers nearer the surface and under the main embankment, which are initially overconsolidated. This smaller propagation of the yield zones is related to smaller vertical and horizontal displacements.

4 CONCLUSIONS

The analyses performed for this work revealed the following aspects:

- the large displacement analysis leads to a reduction of settlements in relation to the infinitesimal analysis. This fact can be explained by the proportion of the settlements in relation to the thickness of the deformable soil, i.e., when the soil settles, the thickness of the soil layer decreases, which induces the reduction of the settlements in the subsequent phases of the calculation.
- The geometrical non-linearity tends to reduce the horizontal displacements on the side of the embankment, which is also naturally associated with the reduction of settlements.
- The evolution of pore pressure is not particularly affected by the kind of analysis, although the pore pressure dissipates slightly faster as time passes when geometrical non-linearity is considered. This is because the progressive decrease of the soil layer thickness leads to a shorter drainage path length. However, the results do not show this clearly enough, since it can be masked by the increase in equilibrium pore pressure, due to the greater elevation difference between the nodal points and the water table, which is unchanged.
- The increase of equilibrium pore pressure in the points nearer the surface, due to the adjustment of the coordinates (obtained from the inclusion of geometrical non-linearity), contributes to the decrease of effective stress increments, since the total stress is independent of these kinds of analysis. This reduction of effective stresses gives rise to the shrinkage of the yield area. This fact is naturally linked to lesser displacements generated.

ACKNOWLEDGMENTS

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