Behavior of an Embankment Built with Evolutive Compacted Material

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1. Abstract

In a research project, an embankment from A10 Motorway in Portugal built with marls was instrumented to record vertical displacements, horizontal displacements and water content in the embankment. With experimental data from an extensive set of tests performed on samples of compacted marls, was possible to model the embankment using program CODE_BRIGHT. For the mechanical behaviour of the compacted marls it was adopted Barcelona Basic Model. The numerical values of the displacements and the water content obtained in the simulation were compared with in situ readings during the construction period and in the two followed years.

2. Introduction

In this paper is analysed the behaviour of a embankments built with evolutive compacted materials. As case study it was adopted an embankment from A10 Motorway in Portugal, which was built with marls.

Marls in general are classified as hard-soil/soft rocks and exhibit evolutive behaviour since their mechanical properties change markedly when exposed to weather conditions, specially wetting-drying cycles that are assumed the main responsible for marls degradation. The degradation of the mechanical properties of the fragments of marl can have strong effect on global behaviour and be responsible for large deformations.

The particularity of the embankment investigated is that the marls used to build the shoulders were treated with lime (3.5% lime, in weight). This treatment was prescribed to reduce the swelling potential of the soil located in this zone in direct contact with the atmosphere and therefore subjected to wetting and drying cycles caused mainly by rain.

The evolution in time of the horizontal deformations, vertical deformations and water content in depth were measured with instruments installed during the construction. Suction was obtained from water content values through the water retention curve. Besides self weight, climate actions from the construction site was considered as input action.

The water retention curve and other useful data were obtained from an extensive set of laboratorial tests performed to characterize the hydro-mechanical behaviour of the marls with and without treatment.

CODE_BRIGHT program (Olivella *et al.*, 1996 and UPC-DLT 2002) was used to model the embankment during its construction and in service conditions in the followed two years. Barcelona Basic Model (BBM), was adopted as constitutive model for the materials. It was necessary to use an unsaturated soil constitutive model to reproduce the deformations of the soil caused by wetting and drying cycles (suction changes).

3. Description of the Embankment

A simplified profile of the embankment studied is presented in Figure 1. As it can be seen, the embankment was built in a slope and is relatively high (near 10m high at the pavement axis).

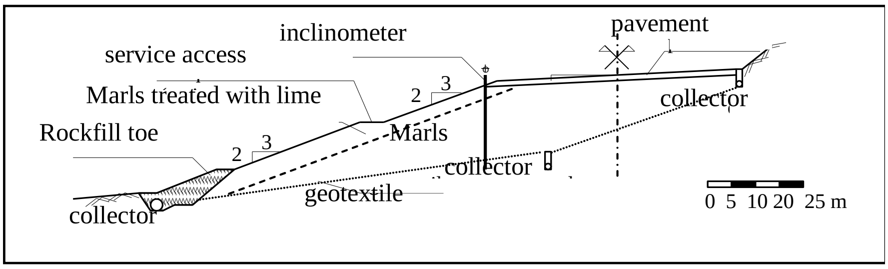


Figure 1 - Embankment profile

The figure also shows the zoned profile adopted with compacted marls in the core (named Solo), and compacted marls treated with lime (named Solo-cal) in the shells (with 5m thickness). Accordingly with the design prescriptions the embakment was compacted with a vibratory sheepstoot roller (equivalent to heavy compaction) and in the wet side of the compaction curve (in the interval $[w_{opt};w_{opt+2\%}]$) to reduce the dimension of the marls fragments. A minimum of 95% of relative compaction was also imposed.

Drainage systems in the foundation and at the toe were included to prevent water access into the embankment core, avoiding this way marls degradation. The lime treatment also reduces the degradation potential of the marls because it reduces the permeability of the soil located on the shoulders.

The instruments installed in the embankment during its construction permitted to collect information concerning to this period and the two years after. In Figure 2 it is possible to see the vertical alignment where the seven sensors used for measuring water content were installed. The one sensor for RH and temperature is also shown. The gutter installed for measuring the displacements was located in a similar profile.

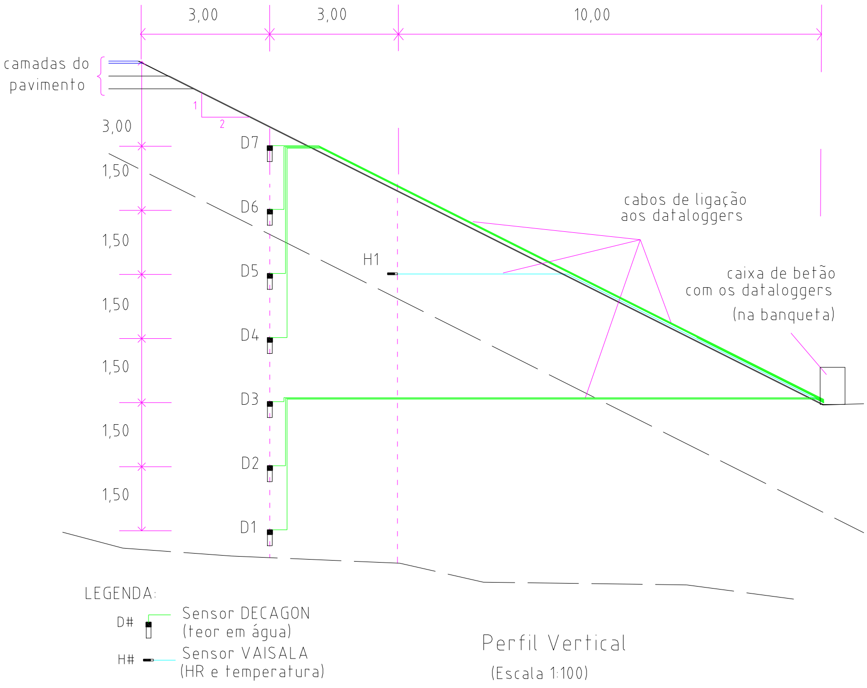


Figure 2 - Location of the instruments: D refers to ECH$_2$0 sensors (water content) and H refers to HMT 337 sensor (relative humidity and temperature)

4. Instrumentation

INCREX instruments (INCRemental EXtensiometers, Interfels, 2004), in Figure 3, were adopted for measuring the vertical deformations. INCREX system was used because large precision was required to detect small deformations due to suction changes.

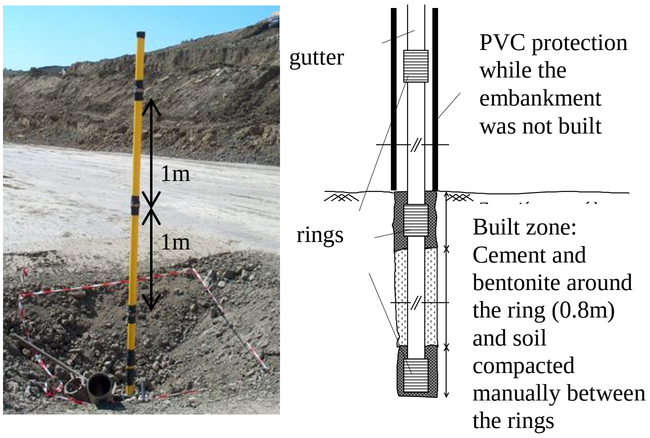


Figure 3 - INCREX sensors

The INCREX system is based on the measurement of the relative vertical displacements through magnetic rings spaced exactly one meter in the installation (Figure 3 left). The rings are installed outside the gutter and are free to slide. Since they are connected to the soil (Figure 3 right) their sliding displacement is equal to the one of the soil. The system required to measure the magnetic field and allows a precision higher than the one obtained when standard measuring systems are used (for INCREX, the precision is ±0.02mm independently from the length of the equipment; for settlement proves, the precision is half of the tape used in the measurement, which is generally ±0.5mm).

The evolution of soil suction during the construction was determined by measuring the water content and the relative humidity of the soil. As previously shown in Figure 2, seven sensors ECH_2O (ECH_2O, 2004) were used to measure water content. One Vaisala HMT 337 sensor was also installed to measure relative humidity and temperature (HMT337, 2004). The ECH_2O sensors were placed in depth, five in the marls and two in the treated marls. Automatic recording of the water content readings was performed and saved in the datalogger.

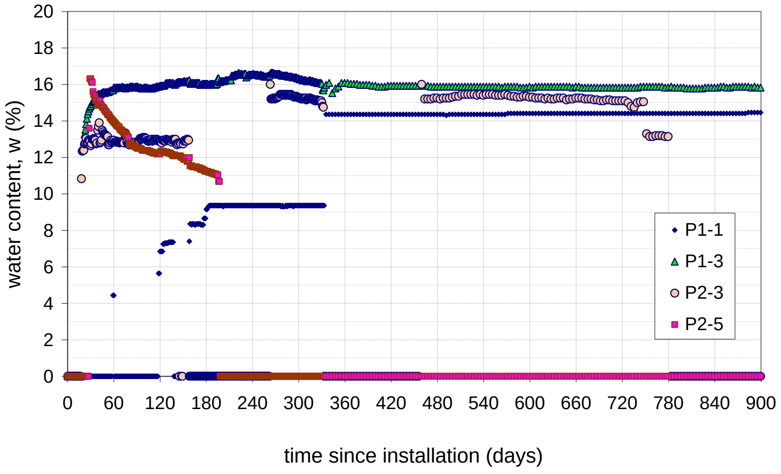


Figure 4 - Measurements of the water content (P1: PK 1+150; P2: PK 1+250)

Data collected from the water content measure sensors, shown in Figure 4 allowed identify an initial period where water content of the soil surrounding the sensor was in equilibrium with the one of the layer where it was installed. After this period it was possible to detect the homogenization in depth of the water content (between 12% and 16%). Two years after the installation, only two ECH$_2$O sensors were working properly.

5. Characterization of the Materials

The marls used in the construction of the embankment are classified as Abadia marls, upper Jurassic in age. Laboratory tests on marls samples with different weathering degrees were performed (Maranha das Neves & Cardoso, 2006). The samples were compacted in conditions similar to those adopted in the field. For all cases, the reconstituted marl (fraction with dimensions D<0.20 mm) can be classified as low plasticity clay (CL), which is in accordance with the nature of the clay minerals found. The Atterberg limits that allowed this classification and other relevant geotechnical properties of Abadia marls are presented in Table 1.

Table 1 - Some geotechnical properties of Abadia Marls

Marls without treatment	
Liquid limit, w_L	36% - 52%
Plasticity index, PI	20%- 25%
Solid weight density (average value)	27.5 kN/m^3
In situ void ratio	0.22-0.55
In situ porosity	18%-33%
Saturated water content, w_{sat}	8%-22%
Marls treated with 3.5% of lime	
Liquid limit, w_L	36%
Plasticity index, PI	7%

Suction was measured in samples prepared with different water content and dry density (Maranha das Neves & Cardoso, 2006) and allowed defining the suction chart presented in Figure 5. In the interval of compaction prescribed (rectangle identified in the figure as construction conditions) the soil has high degree of saturation because low suctions were measured (average value 0.8MPa).

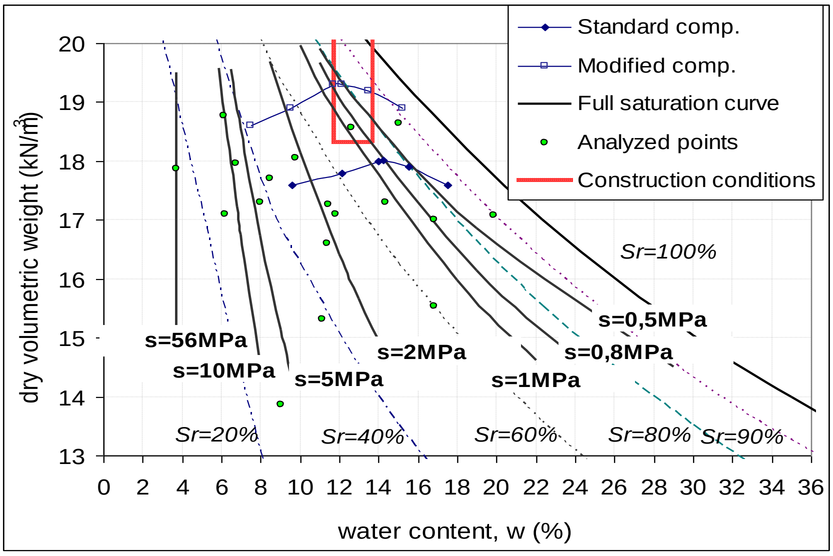


Figure 5 - Suction measured in tests of compacted marls for different water contents and dry densities

The effects of lime addition on the hydro-mechanical behaviour of Abadia marls was investigated by comparing the results of tests performed on samples with and without treatment. The study was extended to different curing periods but this paper only presents the results in tests performed in samples with a curing period of one week, assumed to be valid during the construction of the embankment.

According to Table 1, the treatment reduces the plasticity of the marls (due to the reduction of the w_L thus on PI), improving the workability of the material and changing the classification of the fine fraction from CL to ML.

Swelling tests were performed on samples of compacted marls after the treatment. As expected, the swelling deformations were lower after treatment. The elastic compressibility for suction changes, κ_S, was also reduced with the treatment (from 0.008 to 0.003). Several other tests were performed to compare the hydro-mechanical properties of the compacted marls before and after the treatment (Lynce de Faria, 2007 and Godinho, 2007) and to find the constants for BBM calibration for the marls (Martins, 2009) the treatment decreased the compressibility for isotropic compression, κ (in Table 2) as well as the compressibility measured in oedometer tests. These results can be explained by the formation of cementation minerals after the lime hydration. The presence of these cements is also responsible for the increase of the saturated shear stiffness and strength (Maranha das Neves & Cardoso, 2008).

The water retention curves in Figure 6 were measured by Maranha das Neves & Cardoso (2006). They establish a relationship between water content and suction. The curves were fitted by Equation (1) (von Genutchen, 1980), where *Se* is the saturation degree at the current liquid pressure, P_l, P_g is the gas pressure (assumed to be the atmospheric pressure, 0.1MPa), *P* is the pressure corresponding to the air entry value and λ is a fitting parameter (marls without treatment: P=0.3MPa and λ=0.23 for the drying branch and P=0.18MPa, λ=0.23 for the wetting branch; marls after the treatment: P=0.51MPa, λ=0.25 for the drying branch and P=0.08MPa, λ=0.20 for the wetting branch).

$$S_e = \left[1 + \left(\frac{u_a - u_w}{P}\right)^{\frac{\lambda}{1-\lambda}}\right]^{-\lambda} \qquad (1)$$

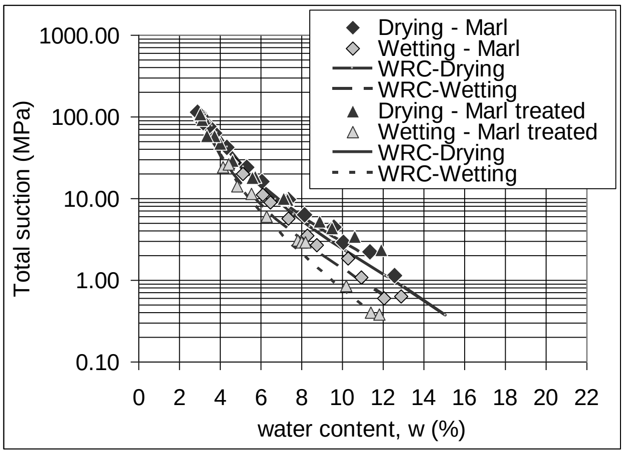


Figure 6 - Water retention curves of the marls with and without the treatment

6. Numerical Model and Results

A model of the embankment was created using CODE_BRIGHT. Thermo-hydro-mechanical coupled analysis was performed to allow the inclusion of climate as input action besides the increment of vertical stress. The inclusion of suction as a state variable requires the use of unsaturated soils constitutive models. Barcelona Basic Model, BBM (Alonso *et al.*, 1990) was adopted. For the marls the complete elastoplastic framework from BBM was used but a viscosity parameter was added to account with creeping effect measured in the field and explained by the degradation of the marls (Cardoso, 2009). Only the elastic part from BBM was used for the marls treated with lime due to the higher yielding stress found in the tests for this material, which are higher than the stresses installed in the field.

Figure 7 presents the geometry adopted defined based on Figure 1. The vertical alignment identifies the points where the vertical displacements and suctions were measured.

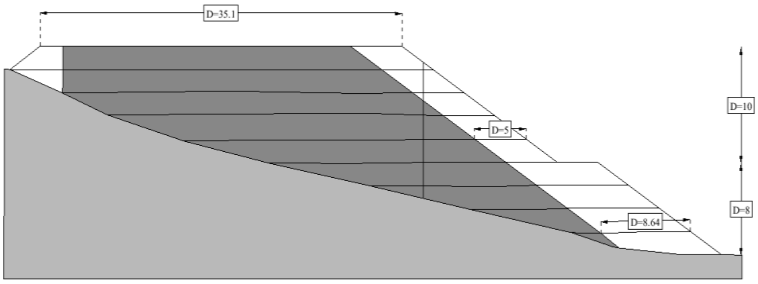


Figure 7 - Model of embankment

The different steps of construction (10 steps in total, corresponding to the construction of 9 layers 2m thick and the construction of the pavement) are also in Figure 7. It was assumed one weak for each construction step. The bed rock for the foundation of the embankment (unweathered rock, grey marl) was also included in the model.

Loading included the weight of rockfill at the toe (50kN/m^2) and of the bituminous pavement (1.2kN/m^2). The bituminous pavement was assumed to be impervious. The initial porosity and suction installed in each construction layer (in Table 2) were defined with the dry unit weight and water content measured in the installation of each ECH$_2$O sensor. Realistic climate data was used measured in a weather station located near the embankment. The parameters necessary for model calibration are presented in Table 3. In the calculation it was assumed only the wetting branch of the water retention curve.

Table 2 – Initial conditions for each construction layer

	Soil									Soil treated
	1	2	3	4	5	6	7	8	9	Identical in all layers
Dry unit weight (kN/m^3)	17.0	17.0	17.0	17.1	15.4	16.2	16.4	16.4	16.4	16.3
Water content (%)	18.9	18.9	18.9	14.4	13.5	13.6	14.0	14.0	14.0	14.5
Void ratio	0.62	0.62	0.62	0.61	0.79	0.70	0.68	0.68	0.68	0.68
Suction (MPa)	0.20	0.20	0.20	0.67	2.15	1.38	1.11	1.11	1.11	1.07

The vertical displacements calculated during the construction are presented in Figure 8a). These values can be compared with the vertical displacements measured in the embankment during the construction presented in Figure 8b).

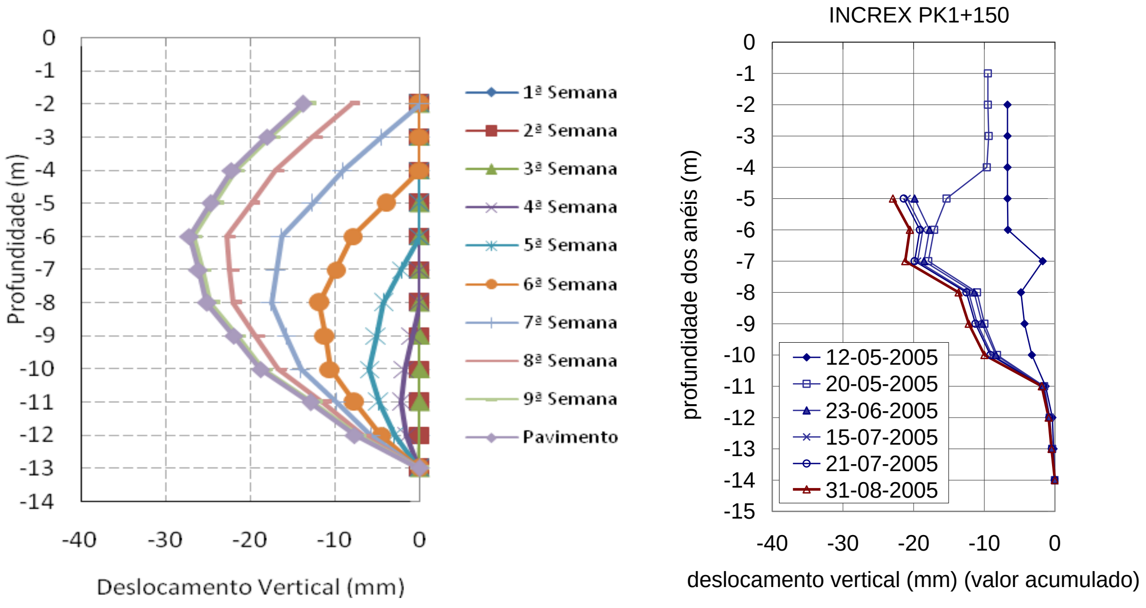
At a certain point the readings were interrupted because of an accident that destroyed the gutters. As consequence, the records of the layers above 5m were considered not valid and that is the reason why in Figure 8b) the values for these layers are not represented. The records from the day 31-08-2005 correspond to the end of the pavement construction.

The major differences found are in the shape of the curves mainly in the construction of the first layers. The smaller displacements measured are explained by the absence of readings because of the process adopted for the installation of the gutters. Nevertheless these differences, the comparison of the plots from

Figure 8 shows that the maximum displacement occurs at the end of the construction, approximately at 5 meters depth. The maximum values are very similar (23mm measured and 27mm calculated).

Table 3 – Calibration of the constitutive models

Parameter	Meaning	Marl	Marl treatead
κ	Elastic compressibility index for isotropic stress changes	0.009	0.003
κ_s	Elastic compressibility index for suction changes	0.0013	0.0003
$\lambda(0)$	Elastoplastic compressibility index for isotropic stress changes		--
r	Parameter defining maximum stiffness with suction	0.20	--
β	Parameter controlling the rate of stiffness increase with suction	0.002 MPa^{-1}	--
p_o^*	Saturated isotropic yielding stress	100	--
p^c	Reference isotropic stress	77	--
K	Parameter describing the increase in cohesion (apparent) with suction	0.001	0.001
c_0	Tension resistance for saturated conditions	0	100kPa
G	Shear modulus	20	70
ν	Poisson coefficient	0.3	0.3
M	Slope of the critical state line	1.0	1.1
λ	Adjustment parameter of the water retention curve	0.23 (wetting)	0.20 (wetting)
P	Adjustment parameter of the water retention curve	0.18MPa	0.08MPa
k_o	Intrinsic permeability (isotropic)	9x10^{-21} m^2	5x10^{-21} m^2
$\lambda_{DRY}=\lambda_{SAT}$	Thermal conductivity in dry and in full saturated conditions	2WmK^{-1}	2WmK^{-1}



a) **b)**

Figure 8 - a) Vertical displacements calculated; b) Vertical displacements measured on PK 1+ 150

The *in situ* values of suction evolution along time in depth inside the embankment during the construction are presented in Figure 9b). These suctions values were calculated based on the water content records, Figure 9a), and using the water retention curves from Figure 6. The calculated suctions are in Figure 10.

The similarity of the measured and calculated values allows concluding that the model reproduces quite well the behaviour of the embankment. Observing the *in situ* and the numerical values is evident that suction distribution in depth tends to a single value. This result indicates that a final homogeneous suction distribution is expected after equilibrium. This is a slow process because of the low permeability of the materials and for this reason equilibrium was not observed at the end of the period studied.

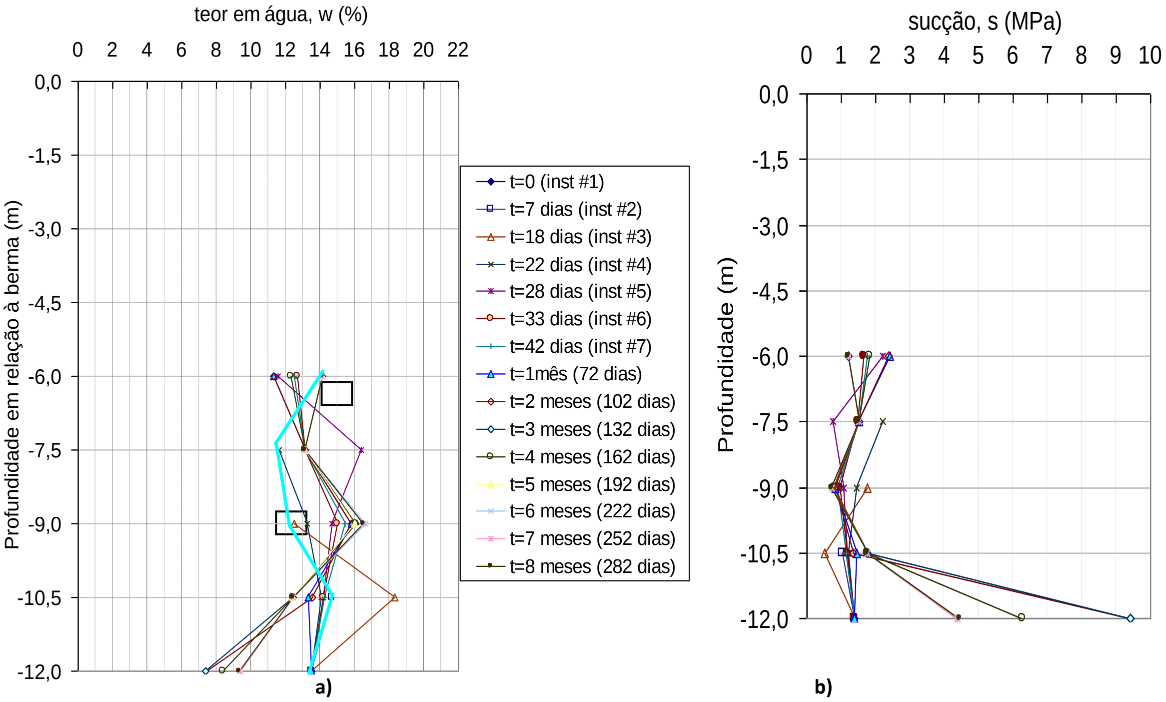


Figure 9 - a) Water content evolution measured since the beginning of the construction until the end of 2005; b) Suction evolution measured since the beginning of the construction until the end of 2005.

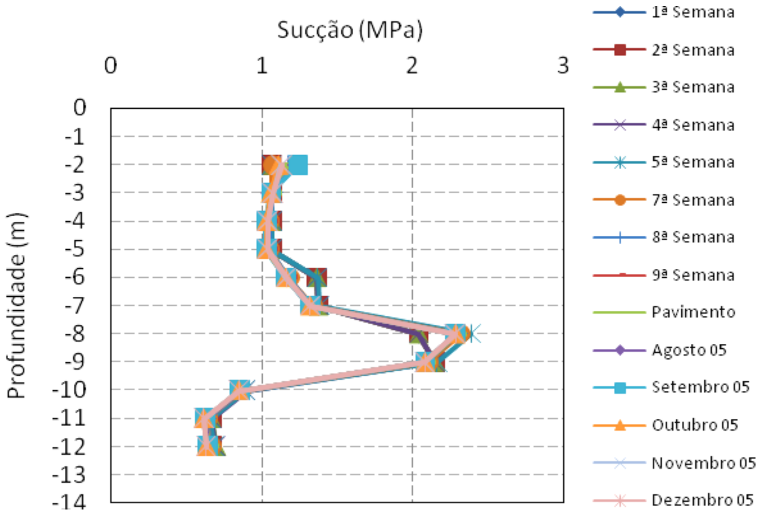


Figure 10 - Suction evolution calculated from the beginning of the construction until the end of 2005

Suction evolution in depth and the vertical displacements were also calculated with the model for the two years after the construction (2006 and 2007). The horizontal displacements were also calculated because they were measured after the construction of the embankment.

Suction evolution after the construction is shown in Figure 11. The values vary from 0,5MPa and 2,5MPa. Considering Figure 7, that shows in situ readings, it is possible to see that the water content varies between 14% and 17% which corresponds to suction values between 0,5MPa and 2MPa, which is a good approximation from the numerical model. A unique value of suction for the embankment was not possible to achieve due to the extreme low permeability of the soil.

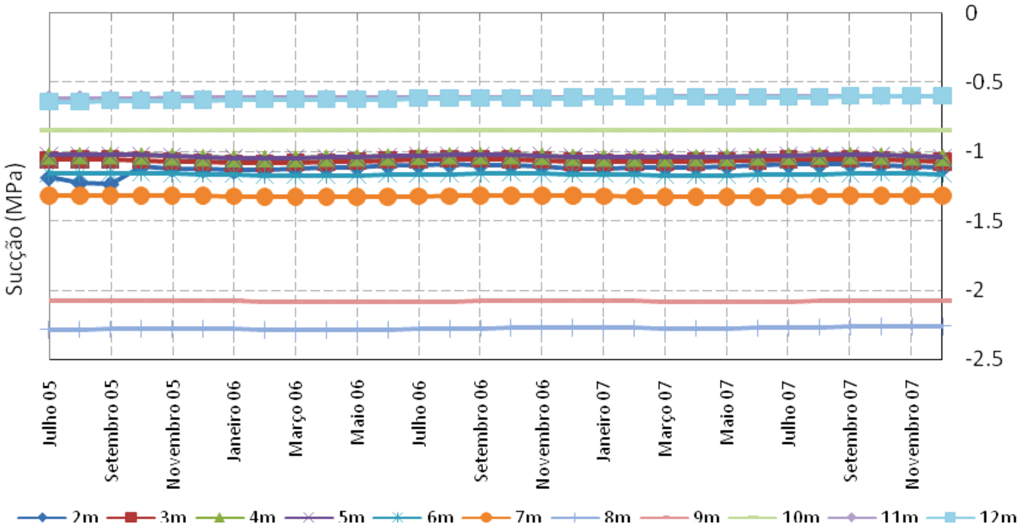


Figure 11 - Suction evolution calculated

The vertical displacements in 2006 and 2007 obtained in the calculation are presented in Figures 12a) and 12b), respectively.

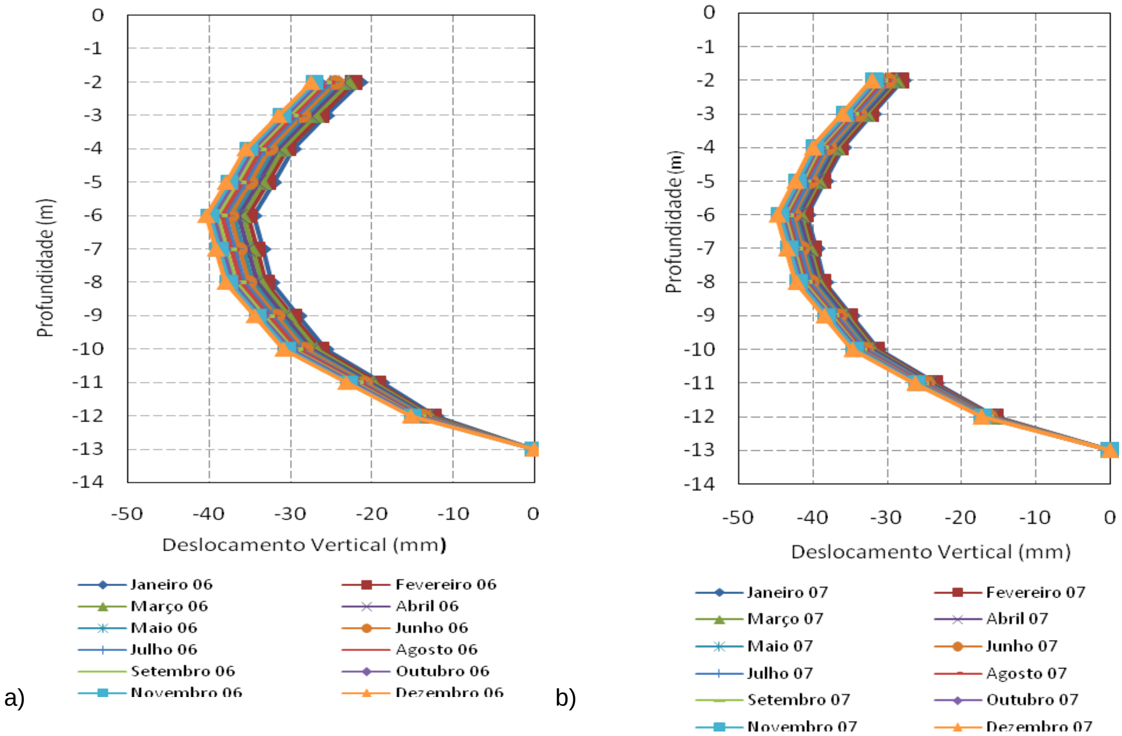


Figure 12 - a) Vertical displacements calculated for 2006; b) Vertical displacements calculated for 2007

In the comparison of the vertical displacements from Figures 12a) e 12b) with the measured values, not shown, it is possible to observe that the numerical values are higher than the measured values (calculated and measured values respectively of 40mm and 28mm at the end of 2006 and 47mm and 37mm at the end of 2007). This difference was studied and it was concluded that the model captured the tendency of *in situ* records. The differences are due to the calibration of the viscosity parameter that was done only for the construction stage but was needed to be done also for the period after the construction.

Finally, concerning the horizontal displacements, the model is also able to reproduce their values after a small correction necessary to account with introduced to account with different horizontal stiffness between the soil and model and the real soil.

7. Conclusions

Suction evolution and the vertical deformations of the embankment during its construction calculated with the model were relatively well predicted as they were similar to those measured in the field. During the two years after the construction, the model was also able to reproduce suction evolution and the vertical displacements in an acceptable manner, as well as the horizontal deformations.

The vertical displacements calculated after the construction were larger than the values measured. The difference is explained by the value adopted for the viscosity parameter. Its value was calibrated to fit well the results for the construction period but a different value should have been adopted for the two years after. This explains the better results found during the construction. An alternative to the adoption of a viscosity parameter is the use of more adequate models for evolutive compacted materials. Nowadays they are being study (Cardoso, 2009) and they should be used in the future to reproduce the behaviour of the embankment presented.

8. References

Alonso, E., Gens, A. & Josa, A. (1990) – A Constitutive Model for Partially Saturated Soils. Géotechnique 40, No. 3, pp 405-430.

Cardoso, R. (2009) – Hydro-Mechanical Behaviour of Compacted Marls. Dissertação para a obtenção do Grau de Doutor, Instituto Superior Técnico, Lisboa, Portugal.

Godinho, N. (2007) – Determinação do Comportamento Hidro-Mecânico das Margas Tratadas com Cal. Dissertação para a obtenção do Grau de Mestre, Instituto Superior Técnico, Lisboa, Portugal.

Lynce de Faria, F. (2007) – Influência da Molhagem após Compactação no Comportamento de um Aterro da Auto-Estrada A10 (BRISA). Dissertação para obtenção do Grau de Mestre, Instituto Superior Técnico, Lisboa, Portugal.

Maranha das Neves, E. & Cardoso, R. (2008) – Projecto de Investigação Relativo ao Comportamento Estrutural de aterros com Materiais não Saturados – Aplicação aos Aterros da Auto-Estrada A10, Sublanço Arruda dos Vinhos/Carregado. Relatórios ICIST nº EP nº 13/08.

Maranha das Neves, E. & Cardoso, R. (2006) – Projecto de Investigação Relativo ao Comportamento Estrutural de aterros com Materiais não Saturados – Aplicação aos Aterros da Auto-Estrada A10, Sublanço Arruda dos Vinhos/Carregado. Relatório ICIST nº 23/06.

Martins, M. (2009) – Influência do tempo de cura no comportamento de um Aterro tratado com cal. Dissertação para obtenção do Grau de Mestre, Instituto Superior Técnico, Lisboa, Portugal.

Olivella, S., Gens, A., Carrera, J. & Alonso, E. (1996) – Numerical Formulation for Simulator (CODE_BRIGHT) for Coupled Analysis of Saline Media. Engineering Computations, Vol. 13, No 7, pp 87-112.

UPC-DLT (2002) – CODE_BRIGHT – User's Guide. Departamento de Ingeniería del Terreno, E.T.S. Ingenieros de Caminos, Canales y Puertos de Barcelona, Universitat Politècnica de Catalunya, Barcelona, Espanha.

Van Genutchen, M. (1980) – A Closed-Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. Soil Sci. Soc. Am. J. 44, pp 892-898.