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A STUDY OF THE SLOPE STABILITY IN UNSATURATED MARLY CLAY SOIL

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Abstract: The analysis of some experimental field data on an unsaturated unstable slope made of a marly clay soil showed that the swelling and collapse phenomena gave rise to the landslide problem. In the case studied, field investigation data and laboratory tests based on determining the water retention curve were analysed. The recorded pore-water pressure field helped us to identify the hydrological conditions. In fact, wet and dry cycles involve a total suction and saturation changes. To predict the shallow slope failure, a constitutive model taking into account the suction effect as well as its dependence on the degree of saturation is proposed. It is especially remarkable that the collapse phenomenon is well reproduced when the model incorporates suction changes and saturated and unsaturated preconsolidation stresses. The analysis of the slope failure, based on the field data and on the theoretical study, shows the hydraulic and mechanical effects.

1. INTRODUCTION

The landslide cases have occurred more frequently in the north-west Tunisia. Every year the Tunisian government invests large amounts of money to repair the damages caused by the slope failure along the national roads. This area is a semi-arid region, with a mountainous relief, different climatic seasons and an important variation in rainfall intensity (from 6.5 mm in July to 80 mm in January). The rainfall events may lead to unstable slopes, often during the wet season and particularly after the long dry season. Since one of the major geotechnical problems is to design the slopes of safe and economical dimensions and a functional infrastructure of roads, our interest has been mainly focused on hydraulic and mechanical causes of the landslide and its type frequently observed in a given region. The interaction between the hydraulic and the mechanical parameters has been studied (water retention curve, permeability and soil shear strength variation due to the suction changes). Conventional analyses of slope stability using the principles of saturated soil mechanics allowed us to define the safe conditions for the slope (factor of safety ranging between 6.2 and 7.5 at the undrained shear parameters and between 1.17 and 1.43 at the effective shear parameters). These factors of safety values corresponded to an average of 80 kPa of undrained cohesion and 4°

for the undrained friction angle. The effective failure parameters are c'= 4 kPa and ϕ' = 10°. Nevertheless, as the conventional slope stability is based on saturated shear parameters, assuming the soil to be either dry or completely saturated, this approach can lead to the worst case scenario of the slope behaviour (FABIOUS and BAY [5]) and consequently to a conservative analysis. Hence, in this case, the conventional study of slope stability appears to be inefficient in explaining the slope failures observed or leads to an erroneous conclusion (it is the case where the undrained shear parameters are taken into account in the safety factor calculation). Besides, the contribution of matrix suction to an increase in the shear strength may be taken into account in the slope stability, particularly here for the case studied, where the groundwater table is deep and the slip planes are shallow (e.g., the shallow landslide, figure 1). Mechanical effects associated with suction changes appear to be more complex to study if the soil is like a marly clay, which is prone to a collapse or a swelling (with a decrease of suction) and shrinkage (with an increase of suction). This is one of the reason for the present study, in which we try to find a theoretical simple model which allows the better understanding of the landslide problem observed in the marly clayey soils.

The first part of the paper describes the site and field instrumentation data. These results give an overall picture of the landslide phenomenon and the idea of the effect of the hydraulic parameters' variation on the mechanism of slope failure. Total physical and mechanical parameters are also given. In the second part of the paper, our interest is focused first on the collapse response of the marly clay soil and second on an alternative model combining the principle of the Barcelona model (BBM, 1990) with those proposed by other authors (VANAPALLI et al. [8]), FABIUS and BAY [5]).

Fig. 1. Slope profile and collapse of the marly clay after the wet season (at a saturation state)

2. DESCRIPTION OF THE SITE AND INSTRUMENTATION

2.1. SOIL PROFILE AND PROPERTIES

The site is in semi-arid area with an average annual rainfall of 600 mm, the most abundant in the period from September to March (figure 2). For economical reasons, only two boreholes were drilled in the mid-slope of the monitored area and used for sampling and installing a piezometer. In order to describe the eventual movement of ground surface, some landmarks were installed across the profile and a topographic measurement was carried out each month. The physical and mechanical parameters of the soil from the boreholes around mid-slope are given in table 1. These parameters testify to the fine soil character (97% < 80 μm) and its relatively high plasticity (an average value of plasticity index I_p is 30%). The densities (wet, dry and particle specific) are also given. An increase in the dry density is naturally related to the earth weight effect. The shearing tests being performed under undrained conditions show the small values of the friction angles and unimportant cohesion value. The values of the parameters obtained in these tests correspond to a degree of saturation S_r, approaching 92%.

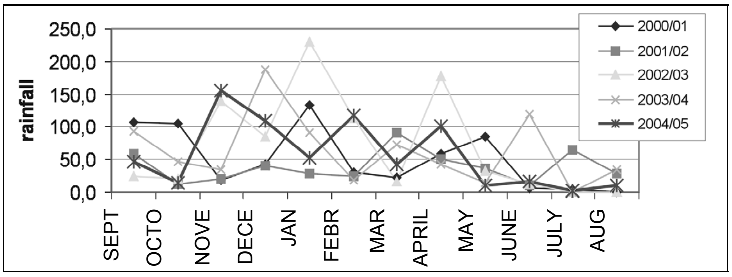

Fig. 2. Rainfall in 2000–2005

Table 1

Physical parameters of the marly clay soil

Depth	Granulometry			Atteberg's Limit		Densities		
(m)	% > 0.42 mm	% < 80 μm	% < 2 μm	ω_l (%)	I_p (%)	γ_h	γ_d	γ_s
1.4–1.9	–	97	34	64	32	1.81	1.37	2.63
3.4–3.9	1	96	28	52	26	1.84	1.51	2.66
5.2–5.7	1	94	20	56	28	1.87	1.45	2.65

2.2. RAINFALL AND PIEZOMETRIC MEASUREMENTS

In 2006, during the period from May to August, an average rainfall was 38.4 mm. However, from November to March, an average rainfall approached 400 mm. The measurement was carried out after a wet season; from April to December the groundwater depth ranged between 0.7 m and 2.0 m. It is observed that when the first rainfall takes place after a long dry season, in November and after December there are no significant changes in piezometric levels. In this sense, the dry shallow slip surface with an expansive marly clay is weakly permeable to water. In fact, the water can infiltrate into the clayey soil essentially through cracks (figure 5) inducing, with a decrease in suction near the saturation, the collapse of soil (figure 6).

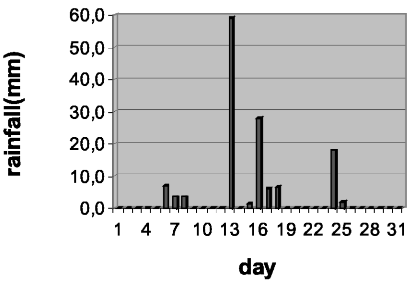

Fig. 3. Rainfall (Dec. 2006)

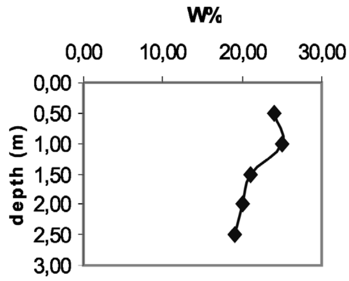

Fig. 4. Water content – depth evolution (Dec. 2006)

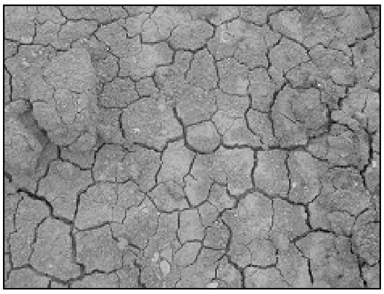

Fig. 5. Pattern cracks after drying

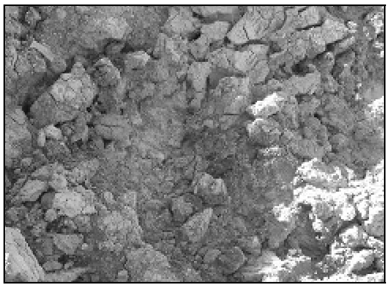

Fig. 6. Behaviour of soil collapse after wetting

3. A MODEL FOR THE SLOPE FAILURE AND THE COLLAPSE STRAINS

3.1. THE PRINCIPLES OF THE MODEL

The model is based on the soil-water characteristic curve as the tool to predict the shear stress function for an unsaturated soil (VANAPALLI et al. [8]). In this paper, using the fitting parameters given by JAMEI et al. [4], the soil-water characteristic curve was obtained (figure 8) based on the particle-size distribution (figure 7).

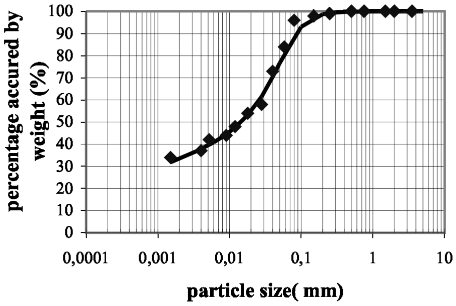

Fig. 7. Particle-size distribution curve

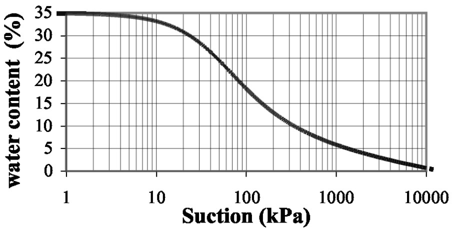

Fig. 8. Soil-water characteristic curve

The fundamental equation relating the suction to the diameter of equivalent particles (JAMEI et al. [4]) is as follows:

$$s_i = \frac{2T_s \cos\theta}{\rho_w g r_i}, \tag{1}$$

where: s_i – the soil-water pressure related to the meniscus at the equivalent particle (i), T_s – the surface tension of water, θ – the contact angle, ρ_w – the density of water, g – the acceleration due to gravity and r_i – the pore radius of particle (i). The model is based on the shear strength function (2a) for unsaturated soil proposed by FREDLUND and XING [6] which, in this paper, has been extended by adding the apparent preconsolidation stress:

$$\tau = c + (\sigma_n - u_a)\tan\phi + s(\overline{\theta}_w)^r \tan\phi, \tag{2a}$$

$$\overline{\theta}_w = \frac{w}{w_{\text{sat}}}, \tag{2b}$$

where: u_a – the air pressure related, σ_n – the total net normal stress, s – the matrix suction, $\overline{\theta}_w$ – the non-dimensional water content defined by (2b), r – the soil parameter being related to the plasticity of the soils, and w_{sat} is the water content under conditions of saturation. In order to introduce the relation between the collapse phenomenon and the preconsolidation stress, equation (2a) is modified as follows:

$$\tau = c + (\sigma_n - u_a)\tan\phi + s[\overline{\theta}_w]^{\frac{p_0}{(p_0)^*}}, \qquad r = \frac{p_0}{(p_0)^*}. \tag{3}$$

The two stresses p_0 and $(p_0)^*$ were given by ALONSO and ROMERO [1]:

$$p_0 = p_{\text{cr}} + p_c\left(\frac{s}{s_{\max}}\right)^n. \tag{4}$$

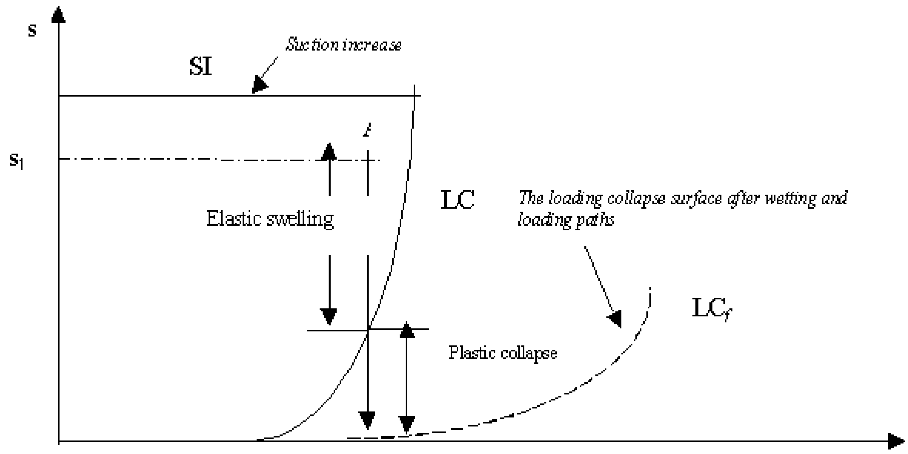

Fig. 9. The principles of the BBM model to include the collapse effect:
loading–collapse (LC) and suction increase (SI) yield curves (ALONSO et al. [2])

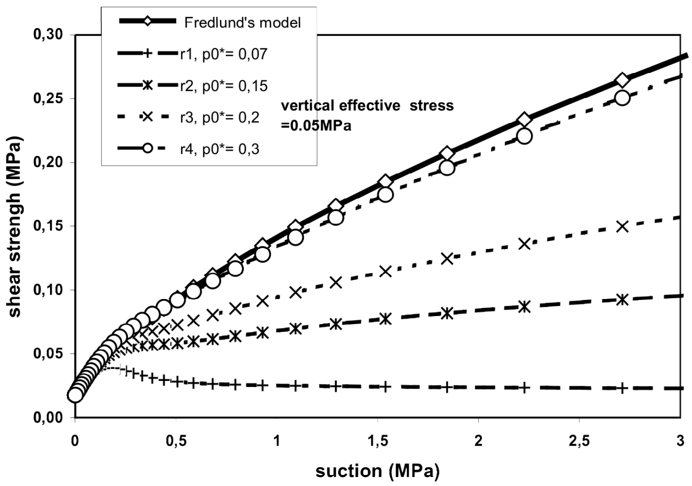

Fig. 10. Shear strength versus suction for different initial saturated preconsolidation stresses

Equation (4) gives the current yield confining stress p_0 for a suction s and a current (actual) saturation confining stress p_{cr}. As shown by ALONSO and ROMERO [1], p_c represents the intensity of the expected collapse. For a given initial (high) suction s_{max} the collapse strains can be predicted. In (4), n is a soil parameter dependent on the LC yield curve (BBM model). The current confining stress p_{cr} can be related to the preconsolidation stress $(p_0)^*$:

$$p_{cr} = (p_0)^* + \bar{p}_0 . \tag{5}$$

Figures (9) and (10) show, respectively, the principles of BBM model (figure 9) and the shear strength vs. suction (figure 10).

3.2. DISCUSSION AND INTERPRETATION OF LIMIT EQUILIBRIUM ANALYSES

The test program included four simulations at some particular initial saturated preconsolidation stresses (figure 10), which led to various values of the ratio *r*. It is shown that the shear strength increases with suction, especially in the samples of soil at a higher initial saturated preconsolidation stress. In fact in this case, the stiffness of soil increases with the increase of suction. However, for the lower initial saturated preconsolidation stress, the shear stress versus suction is not necessarily an increasing function. Comparing our results with those of Fredlund's model tests, it seems that the latter lead to overestimation of the increase in the shear stress with suction. On the other hand, the model of FREDLUND and XING [6] cannot include the effect of preconsolidation due to the decrease of suction or the loading.

It is worth noting that also the safety factor decreases with a decrease of suction, and decreases dramatically from a critical value of suction corresponding to the air-entry value (FREDLUND and XING [6]). The air-entry value is probably influenced by the consolidation state or the compaction of soil. Therefore, this critical value is not the same for the top and the bottom of the slope (figures 12 and 13). The results obtained show (figure 11) that the safety factors corresponding to the shallow circles remain very high, and at full saturation the safety factors are greater than 2. The safety factors are low only for the deep circles which is not in a good agreement with the realistic failure modes.

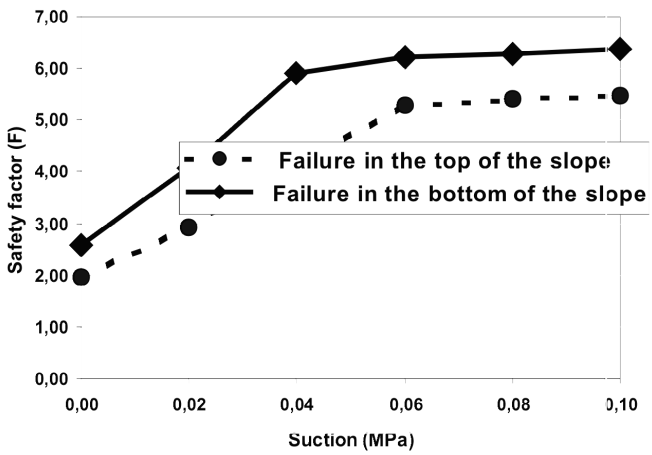

Fig. 11. Predicted safety factor versus suction obtained for the circle failure at the top and the bottom of the slope

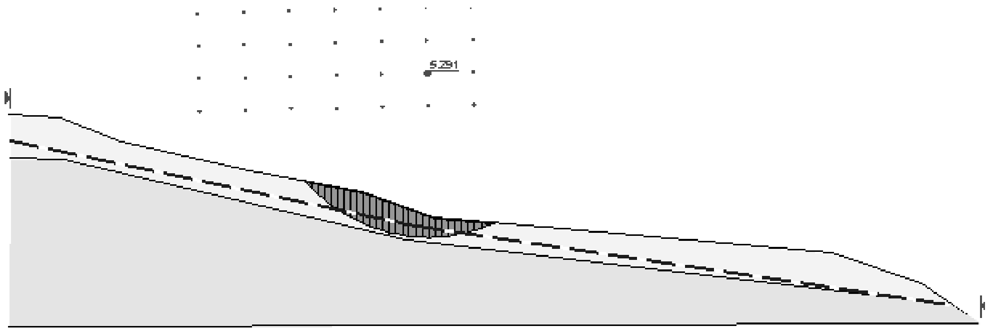

Fig. 12. Local failure circle at the top of slope and for a homogeneous suction s = 60 kPa

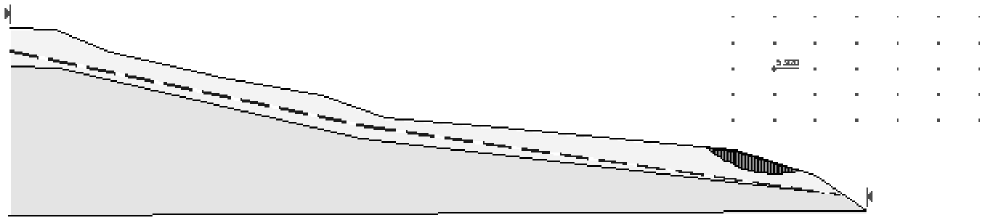

Fig. 13. Local failure circle at the bottom of slope and for homogeneous suction s = 40 kPa

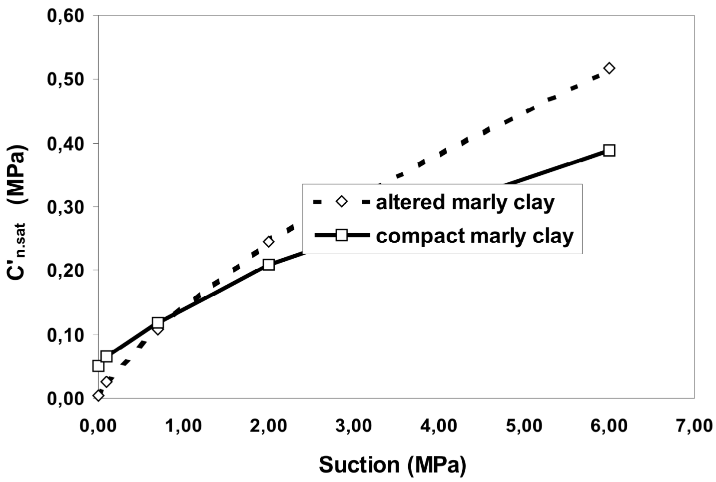

Fig. 14. The effective cohesion for the altered and compact clays

Figure 14 presents effective cohesion versus suction for the two constituent layers (altered and compact marly clay). It is shown that the unsaturated cohesion increases significantly with suction and that the compact marly clay displays a softer behaviour than the altered marly clay. The difference in the behaviours may be attributed to the difference in the effective friction angles for the two soils ($\varphi' = 15°$ for the altered marly clay and $\varphi' = 10°$ for the compact marly clay). It may also be dependent on the difference in the water retention curves. The water retention curve should depend on the initial density and structure of the soil (DUECK [3]).

The limit equilibrium model that takes into account the dependence of shear stress on suction and preconsolidation stress permits us to obtain the safety factors that also depend on these variables. However, neither the geometry of the actual failure of the slope nor the process development with time can be predicted based on this method.

3.3. ELASTOPLASTIC MODEL RESULTS

Alternatively, an elastoplastic model based on the BBM model was applied to further analysis of the slope movements. In this paper, preliminary numerical results are presented (figures 15, 16 and 17). It is shown that, based on the rainfall intensity data, the model has a potentiality for a successful prediction of the collapse phenomenon. The behaviour of the marly clay during the rainfall contrasts with the collapse observed in the slope. After the first dry period of 60 days, a wet period of 120 days was considered. Three sequences are considered during the wet period, the first sequence corresponds to 2 mm/day during 42 days, the second corresponds to the heavy rain of 5 mm/day during 4 days, and the final sequence represents for a normal rain of 1 mm/day during 74 days. The area subjected to collapse is identified and the value of vertical displacement is predicted (475 mm). It is shown (figure 16) that the wetting path leads to the decrease in cohesion and preconsolidation stress because of the wetting of the material. The set of the hydromechanical parameters of the elastoplastic model are summarized in table 2.

Table 2

The set of hydromechanical parameters for the altered and compacted layers

Hydromechanical parameters	Altered marly clay	Compacted marly clay
Saturated friction angle, φ'	15°	10°
Slope of critical state line, M	0.6	0.6
Preconsolidation stress under saturated conditions, P_0^* (kPa)	7	21
Reference stress, P^c (kPa)	25	25
Elastic stiffness coefficient κ for change in net mean stress at suction	0.07	0.07
Virgin compressibility λ (0) under saturated condition (BBM)	0.28	0.28
Intrinsic saturated permeability (m²)	$10^{(-13)}$	$10^{(-13)}$
Unsaturated relative permeability	$10^{(-6)}$	$10^{(-6)}$
Initial porosity	0.5	0.5
Parameter K describing the increase with suction	0.1	0.1

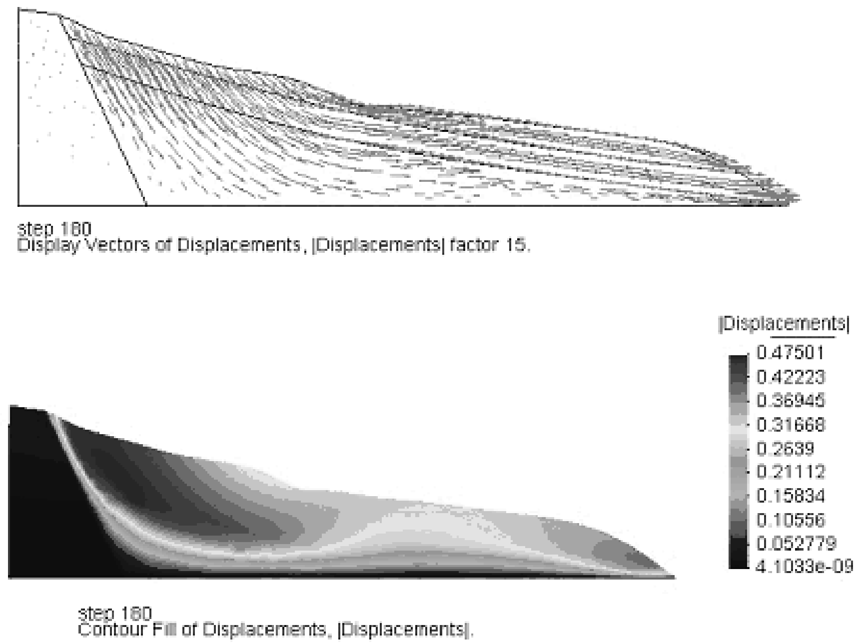

Fig. 15. Numerical results for the field of displacement

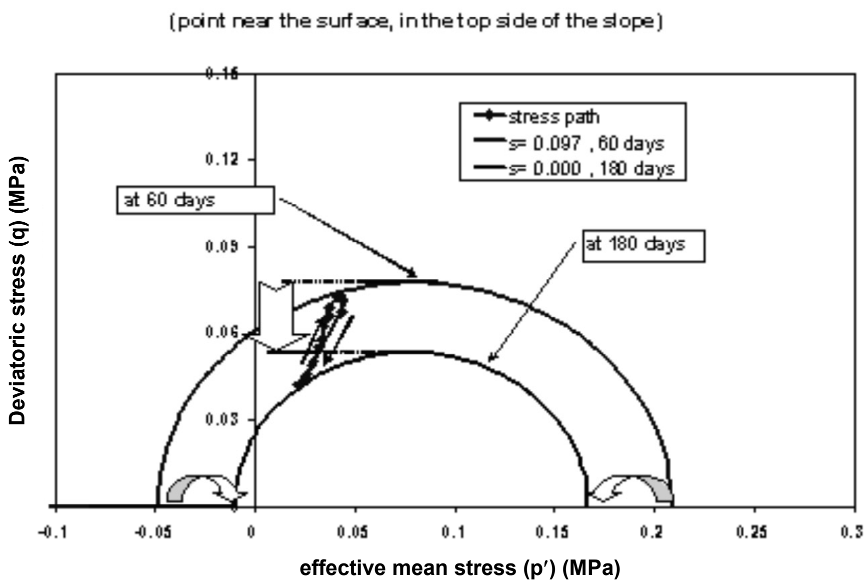

Fig. 16. The yield surface evolution with the wetting path

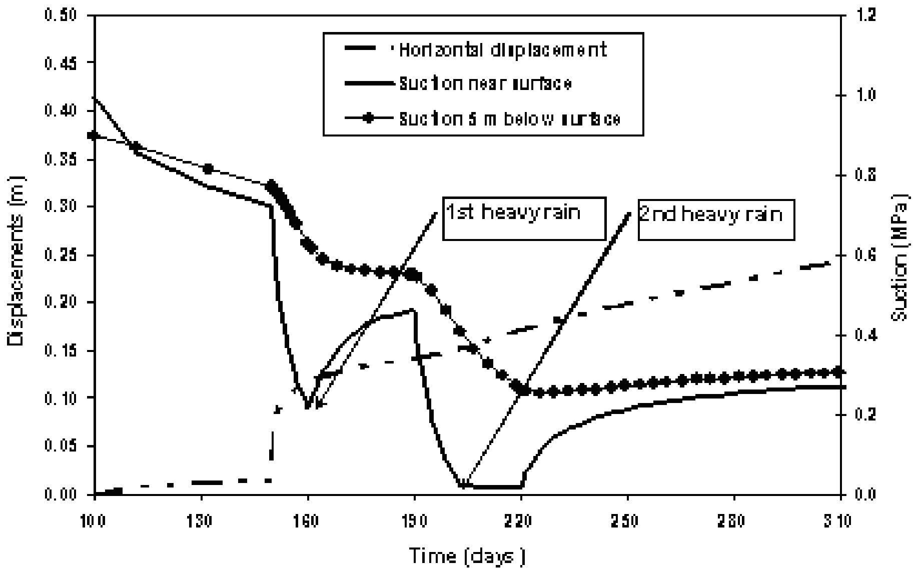

Fig. 17. Horizontal displacement and suction evolutions with time

4. CONCLUSIONS

The study presents the case of unsaturated shallow slope failure due to the decrease of suction and principally due the wetting and drainage cycles. The experimental site data gives an idea of this phenomenon. The limit equilibrium model proposed in this paper includes the suction changes and preconsolidation stress effects, based on the water retention curve data. It provides a quantitative variation of the soil shear strength. The model may allow the slope failure to be predicted, based on the safety factor versus suction. Unfortunately, such a model is not efficient for the prediction of the actual shallow failure and cannot include the collapse phenomenon. In the paper, an alternative methodology based on elastoplastic modelling using finite elements is applied. It gives a comprehensive explanation for the occurrence of rainfall intensity and collapse strains, and for the influence of wetting path on the marly clay behaviour.

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