Effect of soil saturation changes on pressure on tunnel linings

Effet des changements dans la saturation du sol sur les revêtements de tunnels

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ABSTRACT

It is well known that changes in soil degree of saturation have an important influence on mechanical soil properties. Decreasing suction in soil leads to an increase of specific weight and to a decrease of stiffness and strength. These mechanical changes may have an important influence on underground works, particularly on subsurface tunnels. In fact, decreasing soil cohesion due to saturation reduces arching effects above tunnels. Recent developments in unsaturated soil behaviour include numerical models coupling hydro-mechanical phenomena and considering elastoplastic constitutive laws. However, these techniques are seldom used in practical applications. This paper presents a methodology to compute stress and strain changes in a tunnel lining due to changes in soil saturation, using relatively conventional tools. The motivation of this work comes from a real case in Barcelona, where a Metro tunnel received an increment of loading due to loss of cohesion of upper layers after irrigation. The Finite Element programme "PLAXIS" was used. The paper concludes that the effect of soil saturation changes on underground structures can be assessed by using conventional Finite Element codes, if the variation of stiffness and strength with suction is previously known. The analyses presented in the paper show that changes in density and stiffness due to saturation have little influence on the stresses in the sidewalls of a subsurface tunnel. However, reduction of cohesion due to suction changes may reduce arching effects above the tunnel and would generate high stresses in the tunnel lining.

RÉSUMÉ

Il est bien connu que les changements de degré de saturation affectent de manière importante les propriétés mécaniques des sols. Une baisse de succion conduit à une augmentation du poids spécifique et une réduction de rigidité et résistance. Ces changements mécaniques sont susceptibles d'avoir une influence sur les ouvrages souterrains, particulièrement sur les tunnels à faible profondeur. De fait, la baisse de cohésion due à la saturation du sol a pour effet de réduire les effets de voûte au-dessus des tunnels. Les développements récents concernant le comportement des sols non saturés incluent des modèles numériques qui couplent les phénomènes hydromécaniques et considèrent des lois constitutives élastoplastiques. Toutefois, l'application de ces techniques à des cas pratiques est encore rare. Cet article présente une méthodologie pour calculer les modifications de contraintes et déformations provoquées dans un revêtement de tunnel par la saturation du sol, sur la base d'outils relativement conventionnels. La motivation du travail réside dans l'analyse d'un cas réel à Barcelone, où un tunnel de métro a reçu un incrément de charge en raison de la perte de cohésion des couches supérieures de terrain suite à leur irrigation. Le programme Éléments Finis Plaxis a été utilisé. L'article conclue que l'effet des changements dans la saturation du sol sur les ouvrages souterrains peut-être évaluée par un code Éléments Finis conventionnel, si la variation de la rigidité et de la résistance avec la succion est antérieurement connue. Les analyses présentées dans l'article montrent que les changements en densité et rigidité due à la saturation ont une faible influence sur les contraintes dans les flancs d'un tunnel superficiel. Toutefois, la réduction de cohésion due à la baisse de succion est susceptible de réduire les effets de voûte au-dessus du tunnel and pourrait générer de fortes contraintes dans le revêtement du tunnel.

Keywords : Unsaturated soil, suction, tunnel, lining, arching

1 INTRODUCTION

The main load when designing tunnels in soils is the corresponding weight of the soil above the tunnel. It is well known that if soil has enough strength in terms of cohesion, there is an important "arching effect", and the weight above the crown is transmitted towards the sidewalls. Figure 1 presents the principal stresses around a circular tunnel with a lining in both cases: a) when soil does not have cohesion and b) when soil cohesion is important. In Figure 1b the "arching effect" is directly observed following the direction of the major principal stresses.

When unsaturated soils are considered, it is well known that its mechanical properties are quite dependent on its water content or degree of saturation. In fact, any analysis on this type of materials should consider the mechanical and the hydraulic problems in a coupled manner. However, although there are several codes available coupling hydraulic and mechanical

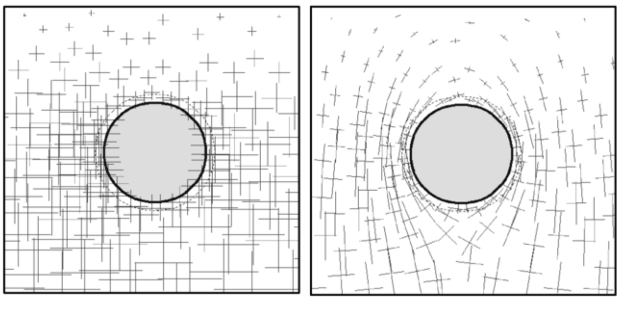

Figure 1. Principal stresses in a soil surrounding a tunnel for a typical case when: left) soil does not have a significant shear strength; right) soil has shear strength and arch effects develop.

behaviour for unsaturated soils, they are seldom used in practical applications. Nevertheless, Finite Element codes for

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-1766

solids and for saturated soils are now available and its use is relatively affordable for many applications. The motivation of this work is related to a real case involving the change of stresses on a tunnel lining from the Barcelona Metro network. The lining increased dramatically its load when the soil above a tunnel section was irrigated due to a garden development at the surface. The increase of weight because of the added water had a marginal influence on the stress distribution, as expected; but, what had more influence was the change of strength of the soil around the tunnel when saturation was increased.

The paper presents a methodology to estimate that change of stress in the lining by using a standard mechanical finite element code without hydraulic coupling (as Plaxis assuming drained conditions). Soil was modelled using elasto-perfect-plastic Mohr-Coulomb constitutive law, changing properties according to the changes in degree of saturation. Several analyses were performed varying specific weight, elastic properties and cohesion. To know the variation of these parameters with suction, some laboratory experiments were considered, including water retention curve obtained using psicrometer and several triaxial tests with suction control. The geometry corresponding to the mentioned Metro tunnel and the soil properties of Barcelona clay were considered.

The results suggest that changes in soil density and stiffness due to saturation have little influence on the stresses of the sidewalls of a subsurface tunnel. However, reduction of cohesion due to soil wetting has a very important influence on the development of high stresses in tunnel lining, because of the reduction of “arching effects”. A set of several simple drained analyses with Plaxis is able to show clearly that effect, and can be used for design purposes if the soil is well characterized.

2 SOIL PROPERTIES REQUIRED FOR THE ANALYSIS

The paper presents the analysis of a particular tunnel geometry in Barcelona clay. Thus the properties of such material are briefly described. It is a low plasticity silty clay (classified as CL) including 43% sand, 41% silt and 16% clay (illite) according to Barrera (2002). The soil is slightly overconsolidated due to chemical cementation. Its basic properties are (Ventayol et al, 2002):

- Natural specific weight (γ_{nat}): 19.5 – 21.0 kN/m^3
- Degree of saturation (Sr): 50% - 80%
- Cohesion (saturated conditions): 20 – 50 kN/m^2
- Friction angle: 28º
- Unconfined strength: 0.25 – 0.50 MPa

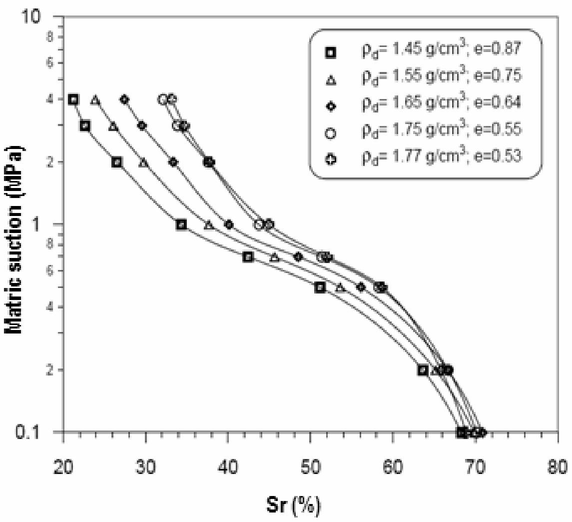

Figure 2. Water retention curves for Barcelona silty clay, the soil considered in the anlyses.

Under unsaturated conditions, mechanical properties depend on suction and therefore the relation between suction and degree of saturation is useful for soil characterization. This relation for Barcelona silty clay is presented in Figure 2, obtained from Barrera (2002), for different dry densities. In the computations considered in this paper, the curve corresponding to a dry density of 1.65 g/cm^3 and void ratio e = 0.64 has been used.

The computational analysis requires a value for the Young modulus of the soil, E, which is strongly dependent on suction. Experimental results from triaxial tests with suction control performed by Barrera (2002) have been used for that purpose. They are presented in Figure 3, where E is plotted against matric suction and net confining stress measured in terms of horizontal stress minus air pressure (σ_3-u_a). In those tests confining pressure is relatively important (0.3, 0.6 and 1.2 MPa), if compared with the average stress at 10 m depth, which is the cover of the tunnel considered in the example below. In order to estimate the variation of E with suction for a confining stress of 0.1 MPa, the following procedure was considered.

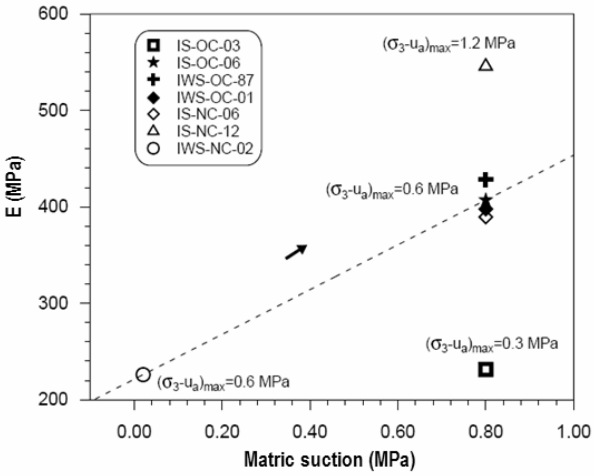

Figure 3. Young modulus versus matric suction for different tests on Barcelona silty clay. The effect of net confining stress is also indicated.

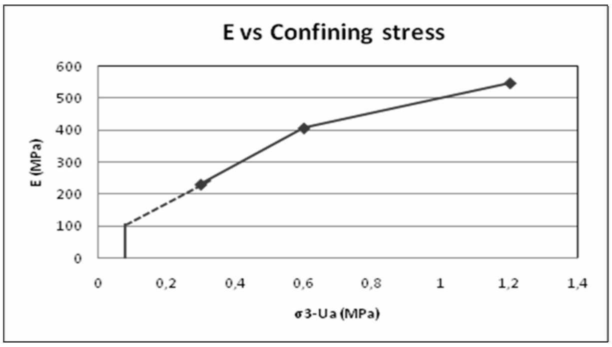

Figure 4. Young modulus versus net confining stress obtained for a constant suction of 0.8 MPa. The tendency has been extended for low confining stresses.

First, the plot E versus confining stress, for a constant suction 0f 0.8 MPa was plotted from the data presented in Figure 3. That plot is presented in Figure 4, including an extension of the tendency of the relationship for low confining stresses. A value of E = 100 MPa is obtained for a confining stress of 0.1 MPa and 0.8 MPa of suction. Then, to obtain the dependency with suction of that value, the same linear trend found in Figure 3 has been considered. In this manner, the values suction – Elastic modulus presented in Table 1 have been obtained. Posson’s ratio was assumed 0.35 and constant.

Secondly, the soil strength was defined for unsaturated conditions. The criterion considered follows the proposal by Fredlund et al (1978):

$$\tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \quad (1)$$

where τ is the shear strength, σ is the normal total stress, u_a is the air pressure, u_w is the water pressure, c' the cohesion, ϕ' the friction angle and ϕ^b the friction angle for suction changes. Expression (1) is a linear relationship in terms of net stress and suction, $s = u_a - u_w$, and recovers Mohr-Coulomb criterion for saturated conditions. The terms not including the net normal stress may be considered as an apparent cohesion depending on suction, c(s):

$$c(s) = c' + (u_a - u_w)\tan\phi^b \quad (2)$$

Laboratory experiments from Escario and Sáez (1986) showed that shear strength followed a nonlinear law, which may be reproduced by assuming a nonconstant value of ϕ^b in (2). Gan et al (1988) proposed a relation between ϕ^b and suction depicted in Figure 5. For Barcelona silty clay the value of ϕ^b was obtained considering the same trend depicted in that Figure 5. The values indicated in Table 1 were finally employed in the analyses. Then, from equation (2) it is possible to obtain the variation of the apparent cohesion with suction, as presented in Table 1. That Table includes also the values of natural specific weight computed for each degree of saturation.

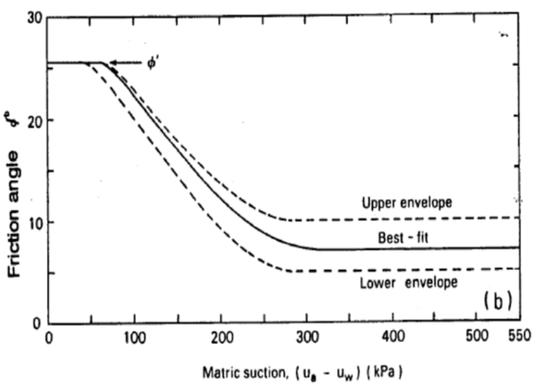

Figure 5. Variation of ϕ^b with respect to suction, after Gan et al. (1988).

Table 1. Parameters of the Barcelona silty clay used in the analyses.

Sr (%)	s (MPa)	E (MPa)	ϕ^b (º)	c(s) (KPa)	γ_{nat} (KN/m^3)
40	1	110	10	196.3	18.09
45	0.8	100	10	161	18.28
52	0.6	88	10	125.8	18.55
59	0.4	76	10	90.5	18.84
67	0.2	65	15	73.6	19.14
100	0	54	28.94	20	20.4

3 NUMERICAL MODEL

The code PLAXIS in 2D was used to represent the geometry of a tunnel of 10 m diameter and with its axis at 15 m depth below ground level on an homogeneous soil with the abovementioned properties. The lining was defined by means of structural elements of concrete (thickness = 0.1 m, E = $4\cdot10^7$ kPa). The steps of the analysis involved first the excavation of the tunnel, then the construction of the lining, and finally a set of substeps changing the soil properties according to the values of suction represented in Table 1, starting from s = 1 MPa and ending with saturation (s = 0). By using this procedure, the saturation process is simulated as a sequence of uncoupled analyses for decreasing suctions.

A linear elastic – perfect plastic (Mohr-Coulomb) model was assumed in the calculations (drained conditions without water table assumed). Three basic analyses were performed with the aim of studying the effect of cohesion, Young modulus and density on the stresses in the lining.

3.1 *Effect of cohesion changes*

Figure 6 shows the evolution of the normal stress in the sidewalls of the tunnel for different suctions, from the initial value of 1 MPa to saturation. As it can be observed, the stress increases from 92 KPa to 3974 KPa when saturation is reached. As a reference value, the total weight of the soil above the tunnel, if the soil would not have any strength, would produce a normal stress on each sidewall of about 10017 KPa for unsaturated soil (s = 1 MPa) or 11296 KPa for saturated soil (s = 0). The apparent cohesion available for unsaturated states generates an arch effect above the tunnel and thus decreases substantially the normal stress in the lining sections.

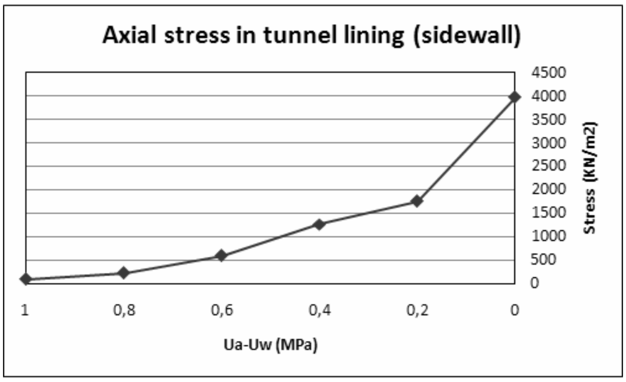

Figure 6. Axial stress in the sidewall of tunel lining obtained in the analyses for each value of suction.

3.2 *Effect of Elastic modulus*

The elastic modulus seems to have small influence on the sresses in the lining. Figure 7 presents the results of two types of analyses, one assuming a constant E for all suctions and another one changing E according to the suction in each substep. The results where similar for both cases.

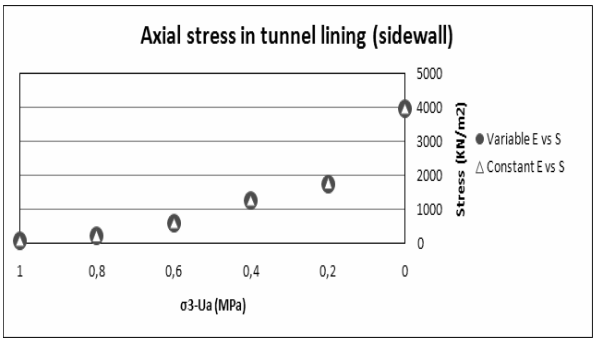

Figure 7. Axial stresses in the sidewalls of tunnel lining for different suctions considering a constant or a variable Elastic modulus.

The reason for that may be related to the plastification of many points around the tunnel, particularly close to the sidewalls, as saturation progresses. The results from PLAXIS suggest that reduction of cohesion due to saturation is so important that points in the elastic domain at the beginning, reach the Mohr-Coulomb criterion easily, thus making the whole analysis less sensitive to E changes.

3.3 *Effect of natural specific weight*

Figure 8 shows a chart including the normal stress (as percentage with respect to maximum) in the sidewalls for two similar analyses, but using a constant specific soil weight for one case and a variable specific soil weight for the other. Note that the results are very similar. That is, considering the increase on density of the soil due to saturation only increases 5% the stresses in the lining. It becomes evident that this effect is not relevant and it is usually not considered in geotechnical applications.

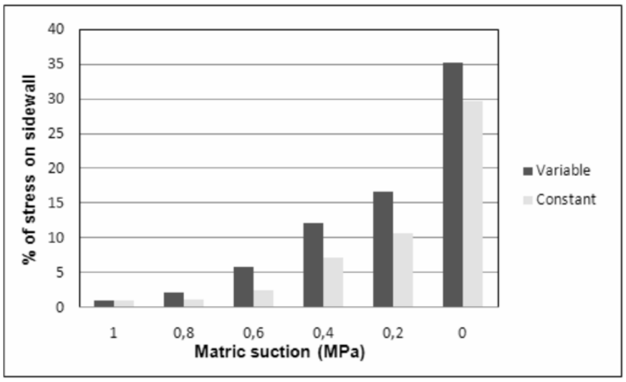

Figure 8. Stress change for different suctions when natural density is assumed constant or variable with degree of saturation.

3.4 *Key parameters*

It becomes evident from the results presented that apparent cohesion is the most relevant parameter in this type of problems. Therefore, it is worth to devote some effort to its measurement in the laboratory.

Finally, Figure 9 presents the evolution of the vertical displacements on the crown of the lining for different suctions.This Figure corresponds to the case where all parameters are considered suction dependent. The final step from suction = 0.2 MPa to saturation involves a vertical movement of 5 mm and seems to be the most important step in terms of movements. In fact, this last step corresponds to a large change in degree of saturation: from 67% to 100%.

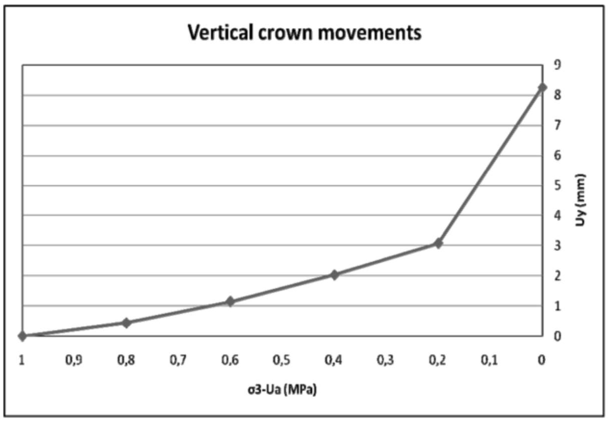

Figure 9. Vertical crown movements for each suction.

4 CONCLUDING REMARKS

The paper shows how the effect of soil saturation changes on underground structures can be assessed by using a conventional finite element code (not prepared for unsaturated soils). The basic requirement refers to the knowledge of the soil properties related to suction changes. In urban areas, it is feasible to have changes in soil saturation due to irrigation developments or loss of water from broken pipelines. In that case, the apparent cohesion of the soil is decreased dramatically and the arching effect is progresively lost, increasing the effective loads on underground structures. The paper shows also that Young modulus variations with suction, or density variations with suction, have a marginal influence on those effective loads. A practical case involving the changes in stresses in the lining of a circular tunnel in Barcelona silty clay when saturated is described. Due to the low sensitivity of the stresses in the lining to the elastic modulus or the changes in density, the crucial parameter in this type of problems becomes the apparent cohesion. As triaxial tests with suction control are rather scarce, in practice it is possible to obtain that apparent cohesion from direct shear tests with control of suction. Then a conventional finite element code could be used for this type of analysis.

ACKNOWLEDGEMENTS

This work is part of a research project on ageing of underground structures financed by the Spanish Ministry of Science and Technology (Project BIA2006-27031-E) directly related to a research project from the Eurocores Program (European Science Foundation).

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