A simplified model for collapse using suction controlled tests

Un modèle simplifié d'effondrement, basée sur des essais de succion controlée

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ABSTRACT: Alonso et al. (1990) have presented the most comprehensive theory for partly saturated soils. Their constitutive equations present very complex formulations that rely on a large number of parameters, which are difficult to achieve unless advanced laboratory tests are performed. This paper presents a simple model for predicting the oedometric collapse of soils compacted with low density. The model has a minimum complexity, only needs two parameters, and establishes a linear relationship between log suction and volume change for different vertical pressures, until the moment when suction reaches the field capacity; then volume change remains at a constant value. This linear relationship is controlled by the Instability Index, *Ipt*. Suction controlled oedometer test have been carried out, and the results agree with sufficient degree of accuracy with the proposed model.

RÉSUMÉ : Alonso et al. (1990) on présenté la théorie la plus avancée pour des sols partiellement saturés. Les équations constitutives présentent des formulations très complexes qui dépendent d'un grand nombre de paramètres, qui sont difficiles à évaluer sans des essais de laboratoire très avancés. Cet article présente un modèle simple pour prédire l'effondrement oedométrique du sol compacté avec une faible densité. Le modèle a une complexité minimale, nécessite seulement deux paramètres, et établit une relation linéaire, entre le logarithme de la succion et le changement de volume pour différentes pressions verticales, jusqu'au moment où la succion atteint la capacité de champ ; à partir de ce moment le changement de volume resteconstante. La relation linéaire est contrôlée par l'Indice d'Instabilité, *Ipt*. Les essais oedométriques avec succion contrôlée ont été réalisés, et les résultats sont en accord avec le modèle proposé.

KEYWORDS: unsaturated soil, model, collapse, suction, oedometer.

1 INTRODUCTION.

Expansive and collapsing soils have, generally, the common condition of being partly saturated.

In partially saturated soils with an open structure, the increase in the degree of saturation resulting from environmental or manmade changes can produce irrecoverable volume reductions without any change in the external forces. This phenomenon receives the name of collapse.

The first technical description of the collapse phenomenon may be the one made by Terzaghi and Peck (1948) when they describe the loss of strength and increase in compressibility of loess upon saturation. The word *collapse* to designate this phenomenon was already used by Jennings and Burland (1962). In general terms, a soil will swell or collapse after being flooded, depending upon whether the external pressure is smaller or larger than the swelling pressure. That is the reason why significant collapse may occur in a wide variety of open-structure soils ranging from well-graded sand, gravel and rockfill to plastic clay under high pressure, as long as the degree of saturation is low enough (Justo and Saetersdal 1979). In these soils and under these conditions, collapse is produced as suction decreases. As the external pressure increases, collapse increases up to a maximum; then the particles are so tight that any further decrease in suction produces volume expansion (Booth 1975, Yudhbir 1982, Maswoswe 1985).

During the wetting process in suction-controlled oedometric tests, sometimes swelling has been followed by collapse reached at very low suction values (Escario and Sáez 1973, Cox 1978, Alonso et al. 1987).

Oedometric cells similar to the ones described by Escario (1969), and Escario and Sáez (1973) have been used to investigate swelling, shrinkage and collapse under constant vertical net stress, as well as the loading and unloading behaviour under a constant matrix suction (Balmaceda 1991; Yuk Gehling 1994; Vilar 1995 and Romero 1999).

In the deformational behaviour of partly saturated soils, the soil is sometimes considered elastic and isotropic. Fredlund and Morgenstern (1976), and Justo et al. (1984 a and b) use different elastic moduli with respect to the external stresses and suction. Justo and Saettersdal (1979) present an analysis of expansive and collapsing soils and a revision of calculation methods, including the elastic methods.

Alonso et al. (1987) analyse the volumetric deformations of these soils in the space of net stress and suction. Other authors have continued in this line, generating models that agree with a good approximation to the behaviour of partly saturated, non expansive soils (Josa et al. 1992, Cui et al. 1995, Wheeler and Sivakumar 1995, Habibagahi and Mokhberi 1998, Sheng et al. 2004).

The lattest tendencies in the study of partly saturated soils are addressed to coupling in the same model the expansive and collapsing behaviour of soils (v. Justo and Saetersdal 1979), generating the so called consistent models (Li and Fang 2011). Along this line, it is proposed in this paper a model for open structure collapsing soils based upon two parameters obtained from the relationship between the volumetric deformation (under oedometric conditions), the suction and the vertical pressure.

From the results obtained, it will be observed that the model describes, with sufficient precission, the behaviour of a collapsing mixture of clay, when subject to oedometric conditions, and to a wetting stress path under constant vertical stress.

2 MATERIAL USED IN THE RESEARCH

2.1 *Composition and characterization of material*

The material used is a mixture of sand (30%), silt (32%) and clay (38%) (v. Figure 1). The analysis by X-ray diffraction indicates that the soil mixture consists of quartz, calcite, dolomite and vermiculite.

Figure 1. Soil mixture

Table 1 summarizes the results obtained from the analysis of the major chemical compounds present in the samples tested by the method of quantitative Pyrite.

Table 1. Major compounds present in the sample

SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	K_2O
47.9%	6.0%	2.8%	1.5%	9.8%	1.3%

Calcination loss	Others
19.0%	1.72%

Table 2 summarizes the characterization tests of the soil mixture. The initial suction (Ψ_0), was obtained with a sphygmomanometer T5x-UMS.

Table 2. Characterization tests of soil mixture

T200 (%)	w_{opt} (%)	ρ_{max} (kg/m^3)	ρ_s (kg/m^3)	e_0	S_r (%)
73.49	14.5	1795	2700	0.68	45

w_L	I_P	Ψ_0 (kPa)
31	13.6	95.4

To obtain a more open structure that guarantees a collapsing behavior, the sample was compacted to 90% of the Proctor standard maximum dry density (1615 kg/m^3). As the moisture content (8.8%), corresponding to this density in the Proctor curve, prevented obtaining acceptable handling conditions (it crumbled when removed from the compaction ring), it was finally compacted to a moisture content of 11.3% and ρ_d=1615 kg/m^3.

2.2 *Soil water characteristic curve (SWCC)*

The techniques used to implement and control the suction in the different samples may be grouped by ranges as indicated below:

1. Pressure membrane for suctions less than 500 kPa.
2. Vapour equilibrium in vacuum desicator, with saline solutions (NaCl, $CaCl_2$) for suctions ranging from 500 kPa to 150 MPa.
3. Vapour equilibrium in vacuum desicator, with acid solution (H_2SO_4) for suctions exceeding 150 MPa.

The time required to reach equilibrium under the imposed suction was determined before performing the experimental tests scheduled. In test specimens in the pressure membrane apparatus, a suction of 400 kPa was applied for several days. Every two days the samples were weighed and it was found that the weight stabilized in eight days.

In the experimental phase stabilization times were greater, at least ten days for all samples tested, thus ensuring that suction equilibrium was reached.

Figure 2 shows the SWCC for the drying paths from the initial suction and the subsequent wetting paths.

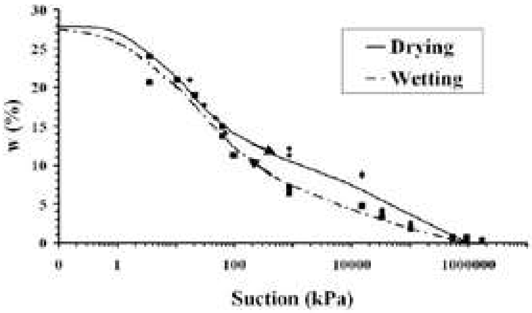

Figure 2. Soil water characteristic curve

3 EQUIPMENT AND EXPERIMENTAL METHODOLOGY

3.1 *Experimental techniques*

Oedometer tests have been performed on cells that control the suction of the soil mixture, using the technique of axis translation and keeping constant the vertical pressure (see Figure 3).

All tests have been carried out in a room with controlled temperature (20±1 ºC) and relative humidity of 65±2%.

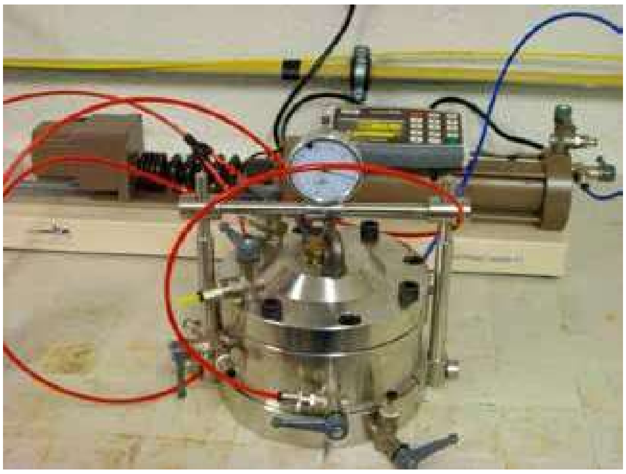

Figure 3. Suction controlled oedometric cell.

3.2 *Experimental results.*

The experimental program intends to simulate the behaviour of a collapsing soil when it is progressively wetted until saturation. The wetting process is carried out decreasing progressively the suction until zero.

Oedometer tests have been performed in the prepared specimens maintaining suction values in the range initial suction-zero. Specifically, the suction steps applied were: 95.4 kPa, 50 kPa, 15 kPa, 10 kPa y 0 kPa (suction for saturation). Figure 4 shows the test results.

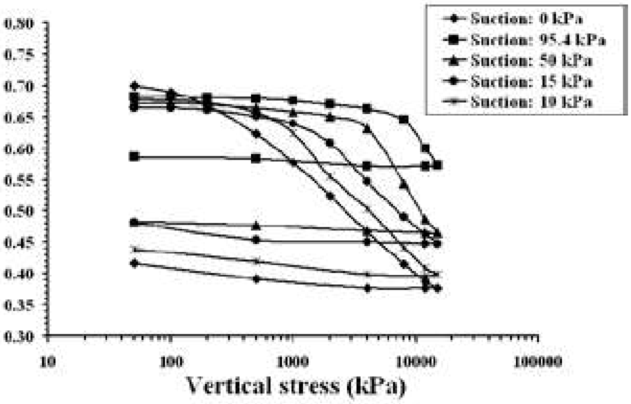

Figure 4. Results from oedometer test

Figure 5 shows the volume increase in samples tested at different external pressures when suction is decreased from the initial value.

3 SIMPLIFIED COLLAPSE-SUCTION MODEL.

Following the results extracted from oedometer tests, a relationship has been sought between volumetric strain under oedometric conditions, suction and applied external vertical stress.

Tests carried out on expansive soils indicate that for constant external pressure there is a linear relationship between volumetric strain and log of suction (Meintjes 1992, Gordon 1992).

The model proposed in this paper is associated to the behaviour of a collapsing soil instead of an expansive soil, but uses the same linear relationship between volume strain (ε_v) and log relative suction (Eq. 1).

$$\varepsilon_v = I_{pt} \cdot log\left(\frac{\Psi}{\Psi_0}\right) \tag{1}$$

where Ψ_0 is the initial suction and I_{pt} is the “Instability Index”, proposed by Aitchison et al. (1973) for swelling and shrinking test son soils.

The Instability Index is a function of the vertical stress applied.

The proposed relationship is valid until suction arrives to a low value, corresponding to the field capacity, when volumetric strain becomes constant (v. Figure 6). Water is not absorbed anymore by the soil.

In Figure 5, the Instability Index is the slope of the regression line relating volumetric strain and log (Ψ/Ψ_0) for every vertical pressure.

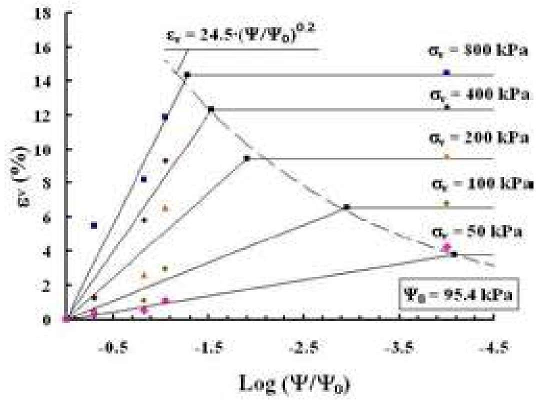

Figure 5. Volumetric strain versus relative suction.

Figure 6 indicates a linear relationship between Instability Index and vertical pressure drawn in semilog scale.

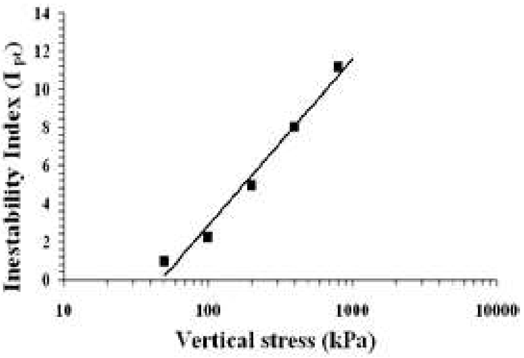

Figure 6. Instability Index versus log vertical stress.

This relationship can be expressed by equation Eq. 2.

$$I_{pt} = C \cdot log(\sigma_v) \tag{2}$$

Substituting Eq. 2 into Eq. 1, a relationship between vertical stress and suction with vertical strain is obtained.

$$\varepsilon_v = C \cdot log(\sigma_v) \cdot log\left(\frac{\Psi}{\Psi_0}\right) \tag{3}$$

Figure 7 is a 3D picture of the experimental relationship between vertical strain, relative suction and vertical pressure. The lines corresponding to constant σ_v values may be approximated by straight lines as indicated by equations (1) and (3). The picture includes the line when the field capacity is reached and the subsequent constant volumetric strain indicated in Figure 5. The projection of this line to the $\varepsilon_v - log(\Psi / \Psi_0)$ plane is a potential, corresponding to the equation:

$$\varepsilon_v = 24.5 \cdot (\Psi/\Psi_0)^{0..2} \tag{4}$$

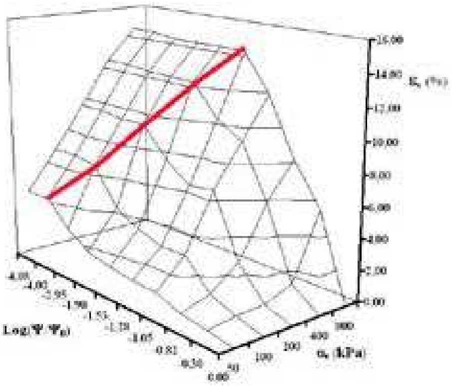

Figure 7. 3D picture of model.

Eq. 3 depends upon two fundamental parameters: the initial suction, Ψ_0, and the constant C.

The initial suction may be obtained by any of the techniques for measuring suction in soils compatible with the range of suctions of the sample: tensiometer, filter paper, psicrometer, etc. To obtain the constant C, suction controlled oedometer test must be performed subjecting the sample at least to two different vertical pressures.

This way, with the determination of Ψ_0 and the C coefficient, it is possible to establish a simple method that will represent with sufficient approximation the collapsing behavior of a collapsing soil from the initial suction until saturation.

5 CONCLUSIONS

Recent models to predict the collapsing behaviour in low density, partially saturated soils, obey to very complex formulations with a high number of parameters. These parameters can only be carried out using advanced laboratory tests, not commonly available even in advanced laboratories.

For many problems of foundations on collapsing soils it may be assumed that displacement are one dimensional and also that wetting of the soil and collapse occurs after the soil is loaded. For this cases, a simple model has been presented in this paper that describes, with sufficient precision, the behaviour of a collapsing soil (a mixture of sand, silt and clay) when subject, under oedometric conditions, to a wetting stress-path under constant vertical stress.

The model proposed is based on a linear relationship between volumetric deformation, the log of relative suction and the log of the vertical pressure. The equation depends upon a coefficient called the Instability Index, which in turn is proportional to the log vertical pressure.

The model is valid until the samples have reached the field capacity; then the volumetric strain becomes constant.

This model needs only two parameters to be defined: the initial suction and the coefficient C that relates the Instability Index with the log of the vertical pressure. This parameter is obtained in suction controlled oedometer tests, for two different constant vertical pressures.

The simplicity of the proposed model makes it interesting for a quick estimate of the collapse vertical strains in partially saturated soils.

6 ACKNOWLEDGEMENTS

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