Mechanical behaviour modeling of an unsaturated sandy silt
Modélisation du comportement mécanique d'un limon sableux non saturé

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ABSTRACT : A sandy silt has been tested under saturated and unsaturated (suction controlled) conditions. The constitutive law proposed by Alonso and Gens for unsaturated materials is used to model the mechanical behaviour of this material. First the model equations are highlighted. Then the parameters are determined. Finally different tests (oedometer tests, isotropic and triaxial tests) are simulated and the numerical and experimental results are compared.

RESUME : Diverses expériences ont été réalisées sur un limon sableux dans un état saturé et non saturé (la succion étant contrôlée). Alonso et Gens ont proposé une loi constitutive adaptée aux sols non saturés. Cette loi est utilisée pour modéliser ce limon sableux. Ses équations sont rappelées brièvement. Les paramètres sont ensuite déterminés à partir des résultats expérimentaux. Enfin plusieurs expériences (oedomètre, compression isotrope, compression triaxiale) sont simulées. Les résultats experimentaux et numériques sont comparés.

1 INTRODUCTION

Many geotechnical problems are related to the coupling between the solid matrix deformation and the pore fluid flow. This is mostly observed in unsaturated soils, e.g. in dam building, tunnel stability, loading of road foundations, stability of engineered clay barrier in waste disposal,.... The unsaturated state can be a natural phenomenon, related to infiltration and evaporation, or it can result from a compaction forces.

This paper is concerned with the modelling of the unsaturated mechanical behaviour of silts. First after a review of some existing models, the model proposed by Alonso, Gens and Josa (1990) is presented. It is implemented in the finite element code LAGAMINE. The second part of the paper deals with the model validation. A large experimental investigation has been done about the mechanical behaviour of an artificial sandy silt from Sion (Switzerland) . The obtained results are summarised. Some of the different tests are then modelled. The numerical results are compared to the experimental ones.

2. CONSTITUTIVE MODELLING

The mechanical behaviour of unsaturated soils has been studied for some decades. Richard's and Bishops works are well known. It is presently clear that the partial saturation within two fluids implies the presence of menisci between the soils grains, and the associated surface tension is increasing the inter-granular stresses. The first attempt to model the partial saturation effect was a trial to define a alternative *effective stress* concept:

$$\underline{\sigma}' = \underline{\sigma} - \chi(s)\, s\, \underline{I} \qquad (1.)$$

where $\underline{\sigma}'$ is the " effective stress tensor ", $\underline{\sigma}$ is the total stress tensor, $\chi(s)$ represents the coefficient of Bishop which depends on the suction , and s is the suction.

This concept is appealing. Schrefler (1990) has proved that it is related to some micro-mechanical concepts through a simple homogenisation technique. Moreover it is easy to implement in a finite element code (Schrefler et al. (1996), Charlier et al. (1997)).This model has shown qualitatively good predictions for problems involving mainly shear stresses.

2.1. Alonso-Gens mechanical model

However Alonso, Gens and Josa (1990) have shown that the volumetric behaviour is not well modelled. Especially swelling or collapse can occur in an oedometer, when wetting a clay sample which has experienced high suctions in the past. The model proposed by Alonso et al. is based on the well known CamClay model, which is a very good one for the modelling of normally consolidated clays. The basic idea is that the suction has to be considered as a state variable in the same sense as the stress tensor. Therefore the plastic yield surface is also a function of this new variable. In the suction - net mean stress plane (s - p^* with $p^*=p-u_a$), a Loading Collapse LC curve is defined (fig. 1), which is a part of the yield surface. The model equations proposed in Alonso et al. (1990) have been implemented in the finite element code LAGAMINE (developed in the MSM Department). Some basic equations are recalled here.

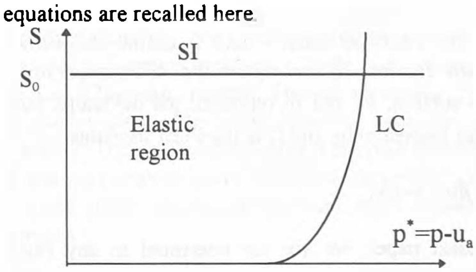

Figure 1. Yield surface in the suction -net mean stress space

The response to an isotropic path is :

$$dv = -\kappa \frac{dp}{p} \quad (elasticity)$$
$$dv = -\lambda(s)\frac{dp}{p} \quad (plasticity) \qquad (2.)$$

with:

$$\lambda(s) = \lambda_0\left((1-r)e^{-\beta s} + r\right) \qquad (3.)$$

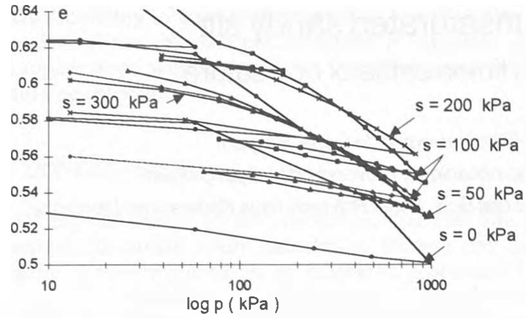

Figure 2. Results of the oedometer tests

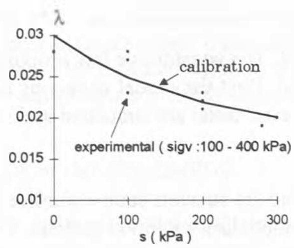

Figure 3. Evolution of plastic slope with suction

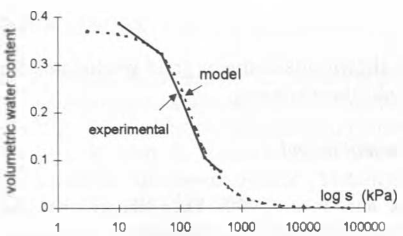

Figure 4. Calibration of the retention curve

The elastic strains under a deviatoric stress path is given by:

$$d\hat{\varepsilon}_{ij} = d\hat{\sigma}_{ij} / 2G \tag{4.}$$

Under a suction path (so-called hydric path), one assumes:

$$dv = -\kappa_s \frac{ds}{s + p_{at}} \quad (elasticity)$$
$$dv = -\lambda_s \frac{ds}{s + p_{at}} \quad (plasticity) \tag{5.}$$

Where v is the specific volume, $\lambda(s)$ and κ are the stiffness parameters for changes in net mean stress, $\lambda(0)$ represents the parameter on saturated state, r and β define the variation of stiffness with suction, λ_s and κ_s are the stiffness parameters for changes in suction, $\hat{\varepsilon}_{ij}$ and $\hat{\sigma}_{ij}$ represent the deviatoric strain and stress tensor respectively, and G is the shear modulus.

2.2. Fluid flow model

In the present paper, we are not interested in any fluid flow. However undrained behaviour will be considered. Therefore a storage law has to be postulated, which is similar to a retention curve :

$$S_r = arctg\left[\frac{s}{\alpha_r} + \beta_r\right] \tag{6.}$$

where S_r is the water saturation, α_r and β_r are parameters for retention curve.

3. LABORATORY CHARACTERISATION OF THE SION SANDY SILT

The Sion silt is an artificial sandy silt coming from Switzerland.

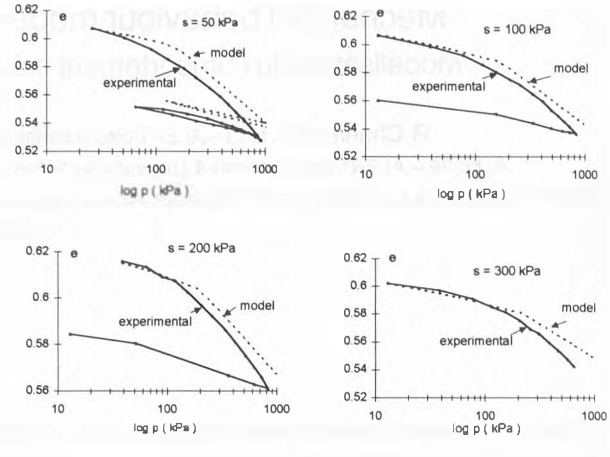

Figure 5 Simulation of the suction controlled oedometer tests

The dry powder is first mixed with water in order to prepare a slurry which is then partly consolidated under K_0 or isotropic stress conditions.

3.1 Realised experiments

An experimental characterisation has been realised in two collaborating laboratories, the Laboratoire de Mécanique des Sols, Ecole Polytechnique Fédérale de Lausanne, Switzerland, and the
Laboratoire d'Infrastructures et de Géomécanique, Université de Liège, Belgium. Triaxial and oedometer tests have been done in saturated and unsaturated state. Suction has been controlled by the translation axis technique in Lausanne lab (high air pressure)(Fredlund et al. 1993) and by the osmotic technique (Delage(1987)) in Liege lab. The experimental results and the technical procedure is more extensively described in the parent paper by Laloui et al. (1997).

3.2. Experimental data and parameters calibration

3.2.1 Oedometer and isotropic tests

A series of oedometer tests have been performed using the osmotic technique. Some are presented on the figure 2. The loading path in the *e-log p* of the remoulded material is not really bilinear but seems more to be parabolic. The unloading curve exhibits an elastic behaviour linear in this space *e-log p*. As a first approximation it is supposed that the volumetric parameters involved in the equations (2) can be obtained on theses curves. The slopes κ and $\lambda(s)$ are measured on these curves for various suctions. The plastic slope $\lambda(s)$ is dependent on the suction (eq. (3) and figure 3). The parameters used in equation (3) are listed in table 1. They govern the plastic hardening rule.

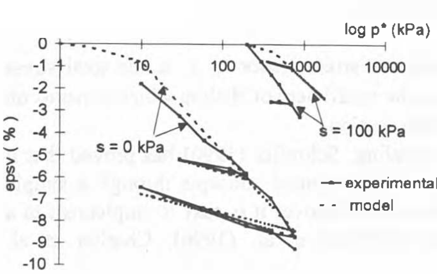

Figure 6 Simulation of saturated and unsaturated isotropic tests

At the initial state the void ratio vary largely from test to test and between the labs, indicating variations in the prepared soil samples, which do not affect the slopes κ and λ.

3.2.2 Shear and deviatoric behaviour

Triaxial compression tests have been performed under various conditions: saturated drained, saturated undrained, unsaturated drained and unsaturated undrained. The normally consolidated saturated tests allow the determination of the internal friction angle at the deviatoric stress peak. Measured angles lie between 31° and 35°, with a mean value ϕ=33°. Unloading paths were used to give the shear modulus value G. No cohesion seems to exist for saturated samples. However unsaturated tests exhibit a progressive cohesion and a quite constant friction angle.

3.2.3 Fluid flow

The retention curve is modelled by the equation (6) whose coefficients are given in the table 1. The experimental points and the model are showed on the figure 4.

Table 1. Material parameters

parameter	symbol	value
Poisson's ratio	ν	0.4
friction angle	ϕ	33°
saturated virgin compression index	λ_0	0.028
elastic compression index	κ	0.007
reference stress	p_c	20 kPa
high suction parameter	r	0.65
suction stiffness parameter	β	0.005 kPa^{-1}
plastic suction index	λ_s	0.25
elastic suction index	κ_s	0.025
increase in cohesion	k	0.8
retention curve parameter	α_r	135 kPa
retention curve parameter	β_r	-85.

4. MODEL PREDICTION AND EXPERIMENTAL COMPARISON

All realised experiments are supposed to be homogeneous. Therefore only one finite element is used for each simulation. In the following, we present and compare numerical and experimental results.

4.1. Unsaturated oedometer tests

Four oedometer tests at different suction values were performed (fig. 5.) During these tests the suction is first imposed under a very small load. It is then maintained at a constant value and the axial load is increased first and then decreased. The numerical response compares well with the experimental observations.

4.2. Saturated and unsaturated isotropic tests

Two isotropic compression tests were simulated.(fig. 6). In the first case the material is fully saturated. In the second case a constant suction (s=100 kPa) is first applied and then the axial load is increased. An unloading - reloading cycle is realised. The numerical response is good. However it appears that the loading slope under the imposed suction is slightly to stiff.

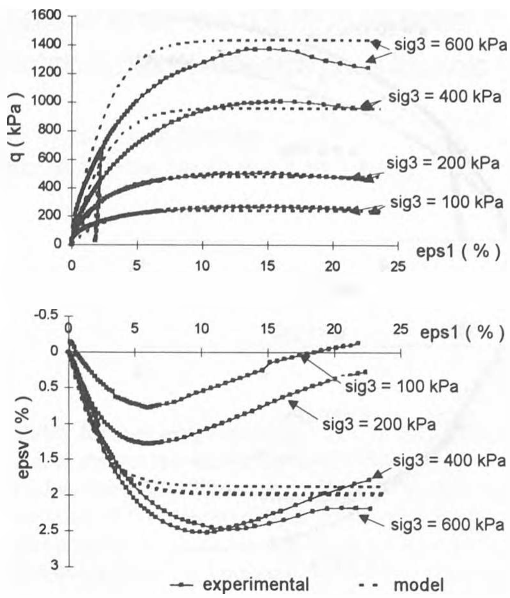

Figure 7 . Simulation of saturated triaxial drained tests (normally consolidated)

4.3 Triaxial tests, saturated and unsaturated, drained and undrained

A series of drained triaxial compression tests at different stress levels and at different suction levels have been modelled (fig. 7 and fig. 8). On figure 8, the influence of the suction on the mechanical responses of material is shown. For unsaturated tests, the material is normally consolidated before the suction increases. Then the sample is sheared. The deviatoric stress- axial deformation (q - ε_1) curves are relatively well modelled. However the volumetric strain is not very well represented.

Three undrained triaxial compression tests at three suction levels (100 kPa, 200 kPa and 280 kPa) have also been modelled (fig. 9). The material is again normally consolidated before the suction increases. During the shearing the water phase is not drained, and the water pressure varies. But the air pressure remains constant. Because the suction level is higher than in the previous tests, the *equivalent* pre-consolidation stress is increased.
This means that, for the same isotropic stress, the sample presents a kind of over-consolidated behaviour. The deviatoric stress - axial deformation (q - ε_1) curve exhibits a peak (probably associated with a strain localisation) which is not well modelled by the CamClay like models. This is especially clear for the higher suction case. The water pressure variations modify the suction level. This is modelled using a coupled hydro-mechanical model and the retention curve. However the suction variations are much more lower in the model than those measured in the experiments.

4.4 Suction controlled path test - hydric test

Some drying paths has been performed on sample under isotropic stress (200 kPa and 300 kPa) (fig. 10.). The results in the volumetric strain - suction plane are quasi superimposed. The model predicts the same answer for both samples. It is independent of the stress level. The sudden slope change is not predicted.

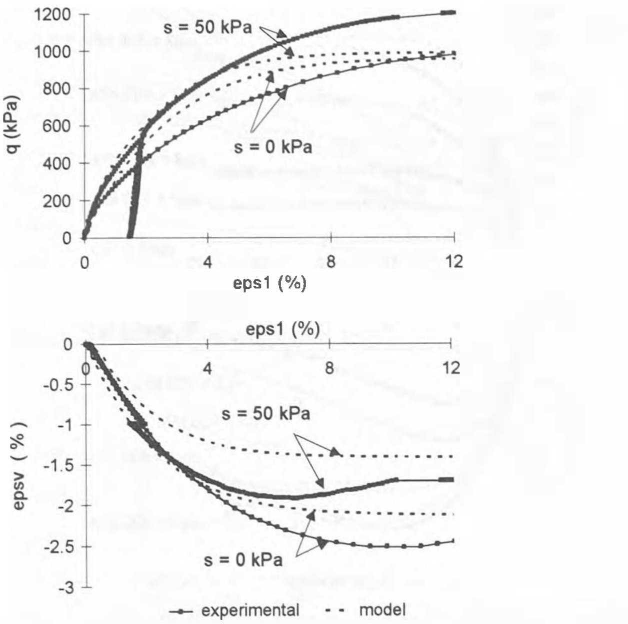

Figure 8. Unsaturated drained triaxial tests. (under a net confined pressure $\sigma_3^* = 400$ kPa)

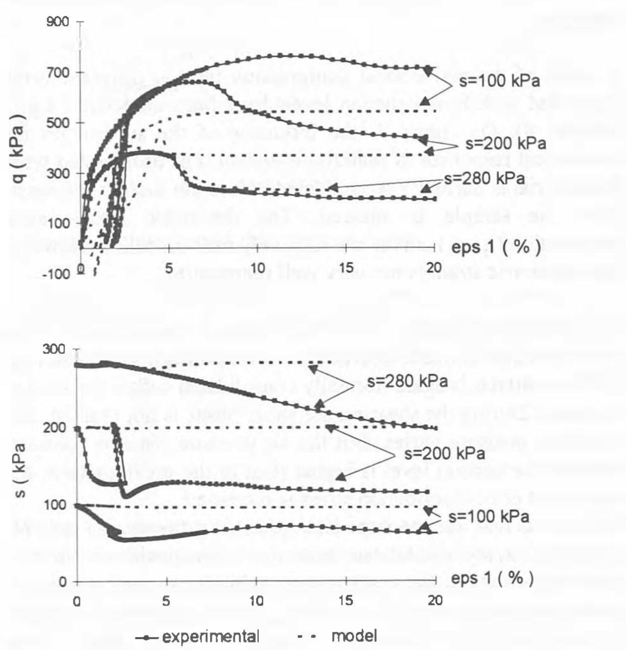

Figure 9. Unsaturated triaxial undrained tests (under a total confined pressure $\sigma_3 = 300$ kPa)

5. CONCLUSION

The Alonso and Gens model for unsaturated soils has been used for the modelling of a sandy silt. Qualitatively good response has been found for most of the considered tests. However the volumetric strains are poorly represented. This means that the dilatancy - contractancy predicted is not well adapted to this sandy material. It would be interesting to compare these results to those obtained with an internal friction model and a Rowe - Taylor dilatancy rule

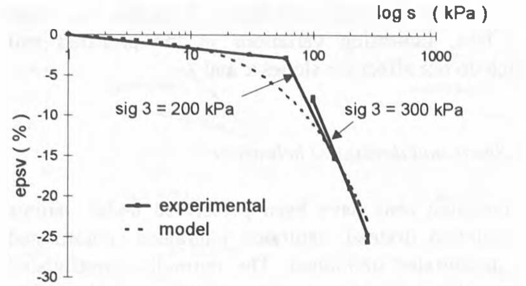

Figure 10 Simulation of triaxial tests with hydric path

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