PASAChalk project (partially saturated chalk) : constitutive modeling, determination of parameters using specific stress paths and application to the waterflooding.

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1. Introduction

The paper presents the up to now obtained results in the framework of the "Pasachalk" EC "Thermie" Project.

As chalk in oil reservoir is generally saturated by two or more different fluids, the basic idea of this project is to apply some approaches of the unsaturated soil mechanics to the study of chalk, especially during waterflooding (Delage, Cui & Schroeder 1996).

A constitutive law is proposed for the modeling of the mechanical behavior of chalk. The effects of the suction (related to some specific forces, including capillary pressure) are taken into account. They are considered as an independent variable, as in the basic model of Barcelona developed for unsaturated clay (Alonso, Gens & Josa 1990).

In the model, the experimental results have lead to consider internal friction and pore collapse as independent mechanisms.

The experimental work is focused on one hand on tests with different suction levels and on the other hand on the determination of the parameters of the failure mechanisms, including the hardening, for the two extreme saturation conditions (oil and water).

In a further stage, the waterflooding will be studied using the proposed model, and the results will be compared to that obtained using the Piau-Maury approach (Piau & Maury, 1996) which could be included within the framework of Barcelona.

2. Constitutive law

The Pasachalk Cap Model (Figure 1) is a combination of a CamClay family model (for the pore collapse) and an internal friction model (for the shear failure). The effect of suction is accounted by using the Barcelona's model.

2.1. CamClay Model

The classical CamClay model has been modified introducing a dependence on the third deviatoric stress invariant and the Lode's angle, using a parameter, *m*. Therefore, the shape of the surface in the deviatoric plane is not a circle.

$$f = II_{\hat{\sigma}}^2 + m^2\left(I_\sigma - \frac{3c}{\tan\phi_c}\right)(I_\sigma + 3p_0) = 0$$

The coefficient *m* is defined by:

$$m = a(1 + b\sin 3\theta)^n$$

θ being the Lode's angle derived from the equation of the third invariant:

$$\theta = -\frac{1}{3}\sin^{-1}\left(\frac{3\sqrt{3}}{2}\frac{III_{\hat{\sigma}}}{II_{\hat{\sigma}}^{\ 3}}\right) \quad \text{with} \quad III_{\hat{\sigma}} = \frac{1}{3}\hat{\sigma}_{ij}\hat{\sigma}_{jk}\hat{\sigma}_{ki}$$

and *a*, *b* and *n* must verify different conditions (Van Eekelen, 1980)

For the plastic potential, an associated plasticity has first been chosen. Non-associated model will be implemented later, when experimental results will provide more information.

2.2. Internal Friction Model : PLASOL

This model is built from the Drucker Prager's cone by introduction of a dependence on the Lode's angle θ in order to match more closely Mohr Coulomb criterion. It consists of a smoothing of the Mohr Coulomb's plasticity surface. The formulation proposed by (Van Eekelen, 1980) is adopted, and it can be written in a very similar way to the Drucker Prager's criterion:

$$f = II_{\hat{\sigma}} + m\left(I_\sigma - \frac{3c}{\tan\phi_C}\right) = 0$$

where the coefficient *m* is the same as above.

2.3. Traction

A third yield surface is introduced consisting on a limitation of the mean stress in traction, independently of the stress deviator.
In the plane $(I_\sigma, II_{\hat{\sigma}})$, the yield surface is given by the following relation:

$$f = I_\sigma - 3\sigma_t = 0$$

Associated plasticity is used for this surface with no hardening.

2.4. Suction

Suction results in elastic strains but also plastic ones. Moreover the yield surface in the $(I_\sigma, II_{\hat{\sigma}})$ plane is influenced by suction. But the introduction of suction in the yield surface is not enough to reproduce all the experimental behavior of unsaturated soils. New yield surfaces will be necessary. The yield surface has not to be described only in the $(I_\sigma, II_{\hat{\sigma}})$ plane but in the $(I_\sigma, II_{\hat{\sigma}}, s)$ space (Alonso, Gens & Josa 1990), (LI, 1999).

The main influences of suction are:

- Preconsolidation pressure p_0 varies with suction following the expression of LC curve considered in the model of Barcelona:

$$p_0 = p_c \left(\frac{p_0^*}{p_c} \right)^{\frac{\lambda(0)-\kappa}{\lambda(s)-\kappa}}$$

with $\lambda(s) = \lambda(0)\left[(1-r)\exp(-\beta s)\right]$

where p_0^* is the preconsolidation pressure for $s = 0$, p_c is a reference pressure, κ and λ the elastic and the plastic slope in the oedometric plane.

- Cohesion increases with suction following the relation :

$$c(s) = c(0) + k\, s$$

It is assumed that friction angle is not affected by suction and that suction has no influence on traction resistance.

The three yield surfaces have then the following formulations affected by suction:

CamClay model: $f = II_{\hat{\sigma}}^2 + m^2 \left(I_\sigma - \frac{3c(s)}{\tan \phi_C} \right) \left(I_\sigma + 3 p_0(s) \right) = 0$

PLASOL model: $f = II_{\hat{\sigma}} + m \left(I_\sigma - \frac{3c(s)}{\tan \phi_C} \right) = 0$

Traction model: $f = I_\sigma - 3\sigma_t = 0$

With these surfaces, no irreversible strains will be produced for an increase of suction. A fourth yield criterion is needed, the SI curve:

$$s - s_0 = 0$$

2.5. Parameters

The parameters of the model can be divided into three types:

Elastic parameters:
E Young modulus, ν Poisson's ratio (linear elasticity for "triaxial": stress paths), κ elastic stiffness parameter, ν Poisson's ratio (non-linear elasticity for "oedometric" stress paths).

Yield parameters:
p_0 preconsolidation pressure, c cohesion, ϕ frictional angle, ψ dilatancy angle, λ plastic stiffness parameter.

Suction parameters (Barcelona model):
p_c reference pressure, r parameter defining the maximum soil stiffness, β parameter controlling the rate of stiffness increase.

They values are derived from the experimental works.

3. Experimental work

3.1. Tests at different suction levels

Tests at several suction values were carried out in order to determine the parameters related to the volume change behavior during oedometric compression.

Osmotic oedometer (Figure 2) was used for these tests. The principle is based on the use of the polyethylene glycol (PEG) solution and a semi-permeable membrane. The semi-permeable membrane allows the water to go through, but not the large PEG molecules. The deficient of the chemical potential of water in two sides leads to a water flow to the PEG solution.

Finally, the osmotic force will be at equilibrium with the gravitational one. Therefore, for the suction control, one just needs to control the PEG concentration, which is previously calibrated to give the suction values.

The results of twelve tests (Figure 3) with different suction values (0 to 5MPa) indicates that the elastic coefficient κ and the plastic coefficient λ seem to be little dependent of the suction. The apparent preconsolidation pressure (yielding point) seems to increase with suction. The void ratio decreases when suction is reduced at constant stress. The s : σ_{v0} plot (increase of the apparent preconsolidation pressure with suction) shows a relationship like the LC curve (Figure 4).

The results of recent tests performed at several loading rates suggest that the increase of preconsolidation pressure is related to the loading rate and that the suction effects influence strongly the creep behaviour.

3.2. Determination of the failure and hardening parameters

For the accurate determination of the parameters and especially those concerning the hardening, several kinds of tests have been performed on oil or water saturated outcrop chalk.

The main conclusions of the 45 tests (20 water and 25 Soltrol saturated samples, Figure 5 and 6) are:

- there is no influence of the stress paths on the yield values.

- the plastic hardening is clearly shown for the volumic behavior.

- the shapes of the plastic volumetric yield lines are different for the oil and water saturated samples, so the hardening rules must take into account the fluid changes.

- there is no change in the shear (brittle) failure line after hardening.

- after hardening, during the reloading, some samples show first a plastic yield and, if the loading is continued, the shear failure can be obtained for the same sample.

Another set of 16 hydrostatic tests (Figure 7) has been performed on chalks with various Sr_w (initial water saturation degrees, ranging from 0 to 98.6%) and then saturated with Soltrol. The results are in good accordance with the previous results (Schroeder, Bois, Hallé, Maury, 1998) and give an accurate value of the "critical" initial water saturation degree i.e. the threshold between the "water-like" and the "oil-like" behavior.

This threshold seems to be around 5% but in fact the evolution is continue and the change occurs within a small range of Sr_w values, from 2 to 10%.

4. Simulations

From the experimental results, the parameters of the Pasachalk model were determined. The model is implemented in the LAGAMINE finite element code.

For the oedometric tests simulation (Figure 8), the function $\lambda(s)$ and the reference pressure p_c have been chosen in a manner that the LC curve fits well with the experimental results. A qualitative good agreement between experiment and numerical results is obtained.

The triaxial tests were performed on water or Soltrol saturated samples (Figure 9).
For these stress path too, a good agreement is obtained between the numerical results and the experimental results.

5. Conclusions

The work performed up to now allowed to build a model taking into account the actual mechanical behavior of the partially saturated chalks. The introduction of the suction as independent variable allows to reproduce the waterflooding effects

The model proposed earlier by Piau and Maury can be considered as a special case of the model presented in this paper. The Piau - Maury approach is based on the CamClay model (similar to the cap of the present model). It considers two different states and two sizes of the yield surface. The first one is related to a so-called *fully oil saturated chalk*, while the other one is related to a *fully water saturated chalk*. The present model is proposing a transition between these two extreme states, allowing to model actual saturation states and not only extreme ones. But, as it is clearly shown by the retention curve shape, the transition is in fact very sharp.

6. Acknowledgements

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7. References

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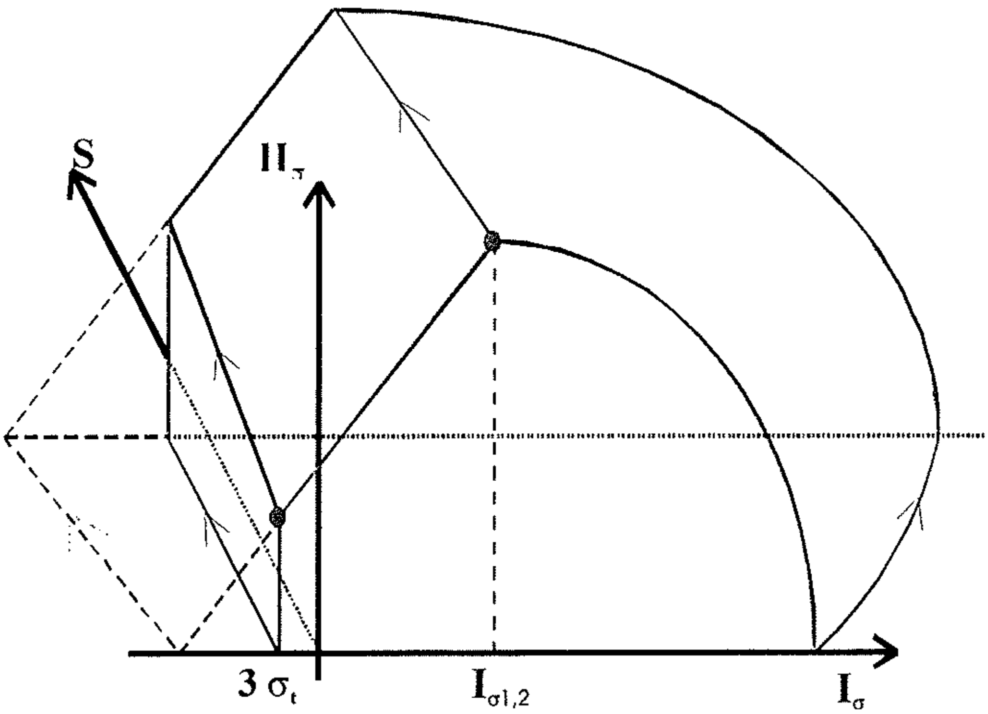

Figure 1: Cap model in the $(I_\sigma, II_{\hat{\sigma}}, s)$ space, soil and rock mechanics sign convention

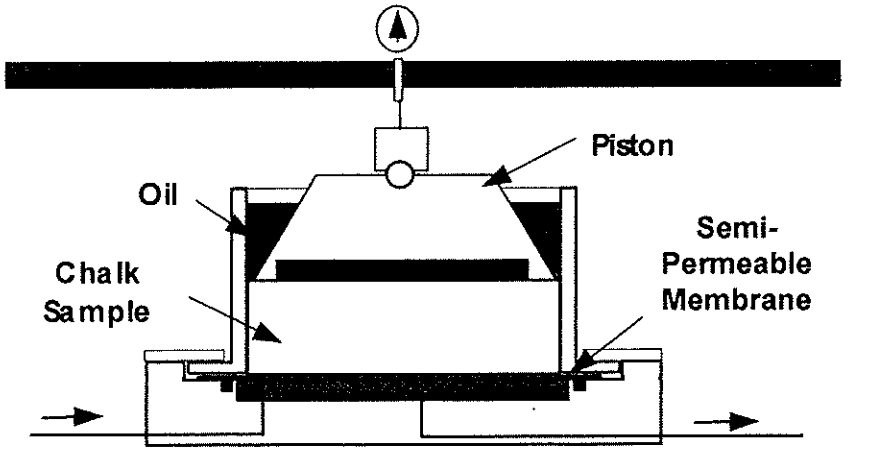

Figure 2: Osmotic oedometer

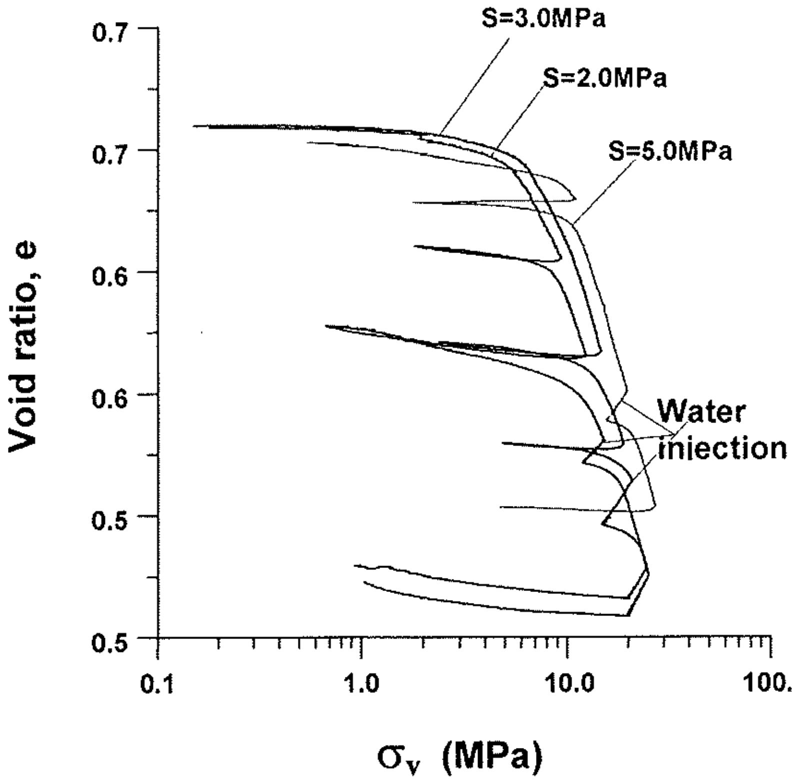

Figure 3: Oedometer tests at different suctions in e-log σ_v plan.

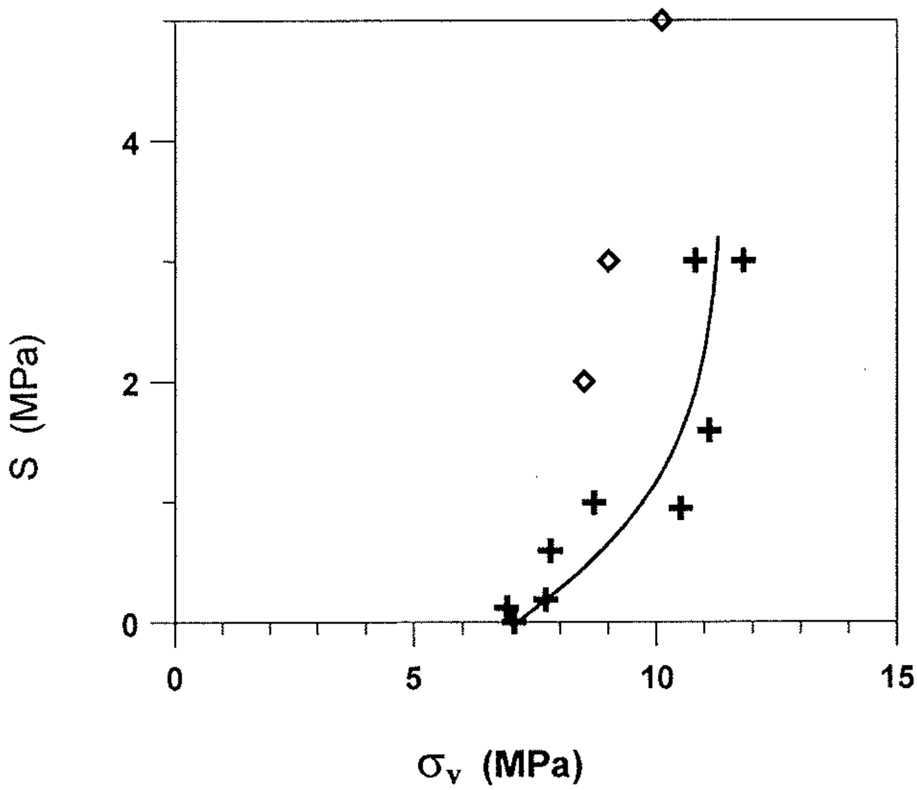

Figure 4: Effect of suction on the preconsolidation pressure – relationship P-σ_{v0}.

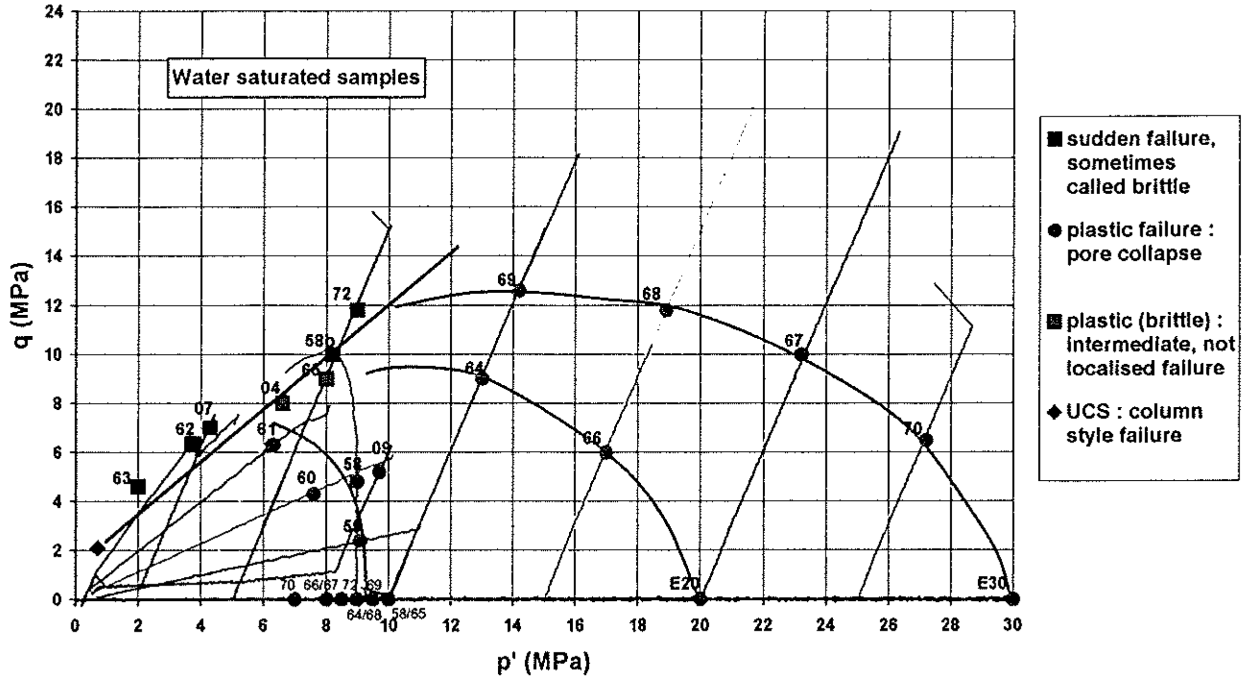

Figure 5: Test on water saturated chalks – Stress paths and failures points

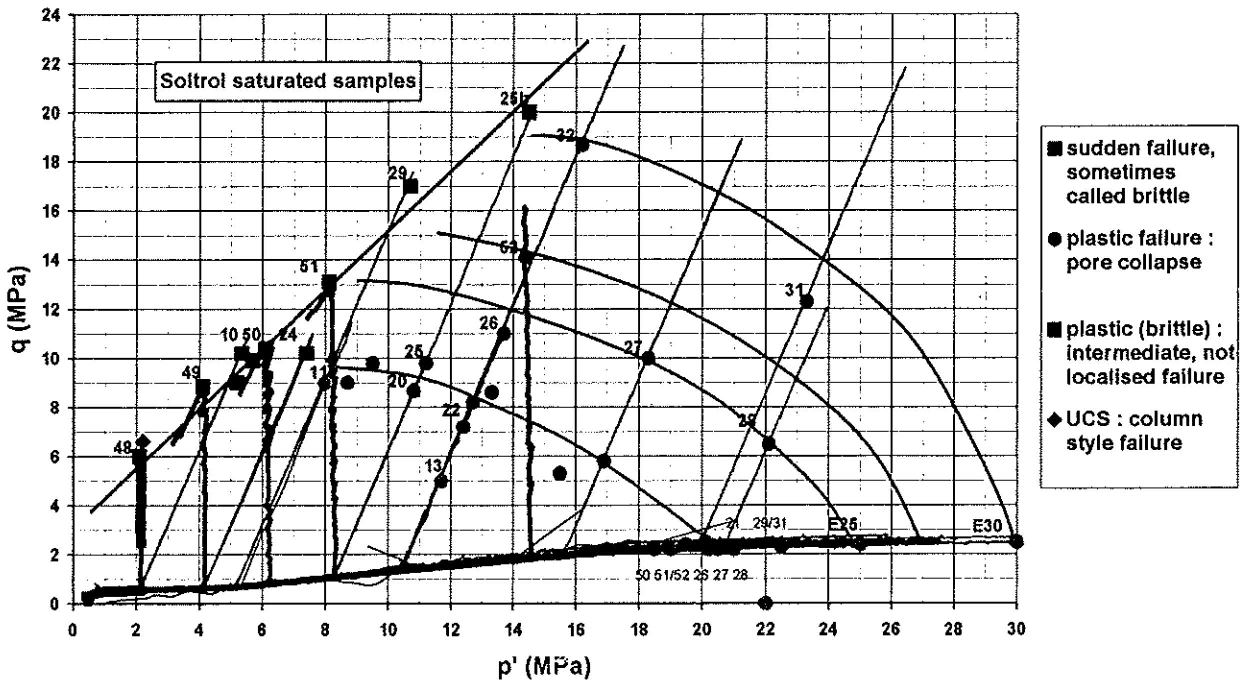

Figure 6: Test on Soltrol saturated chalks – Stress paths and failures points

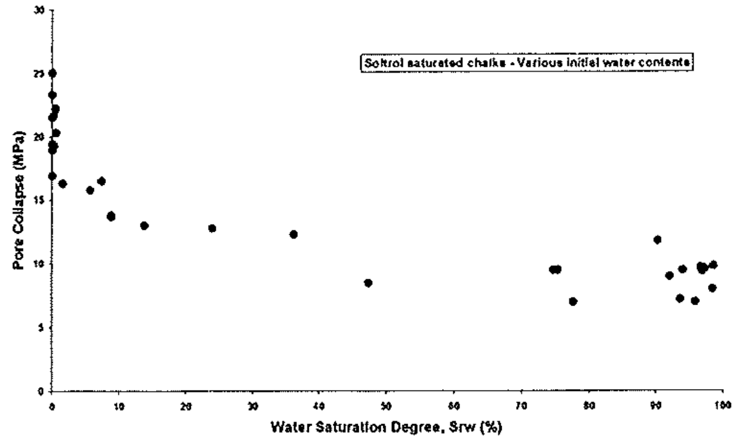

Figure 7: Hydrostatic tests - collapse function of initial water saturation degree

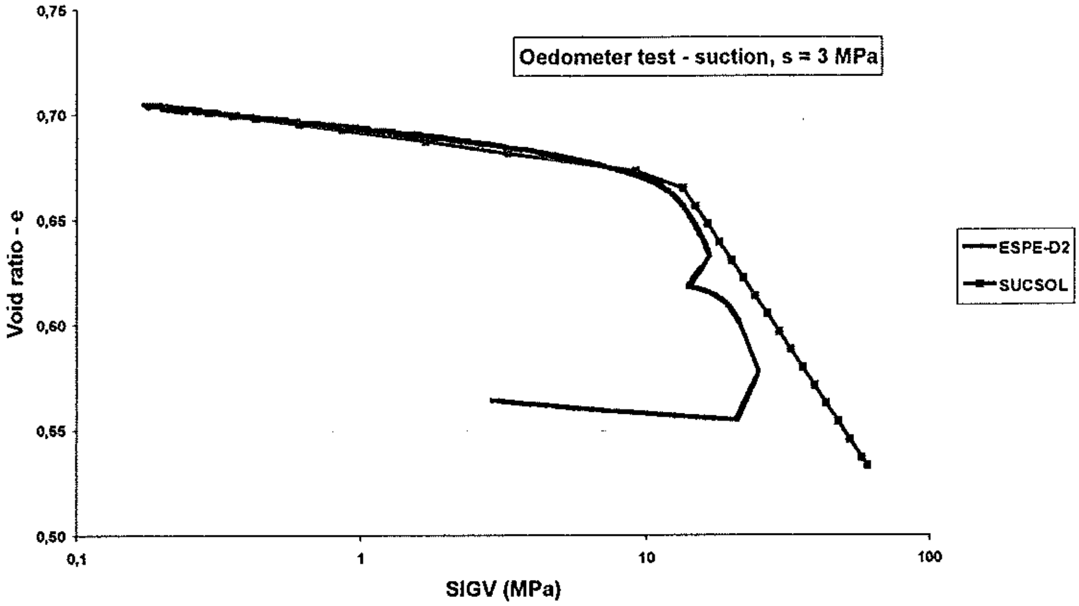

Figure 8: Simulation of an oedometric test

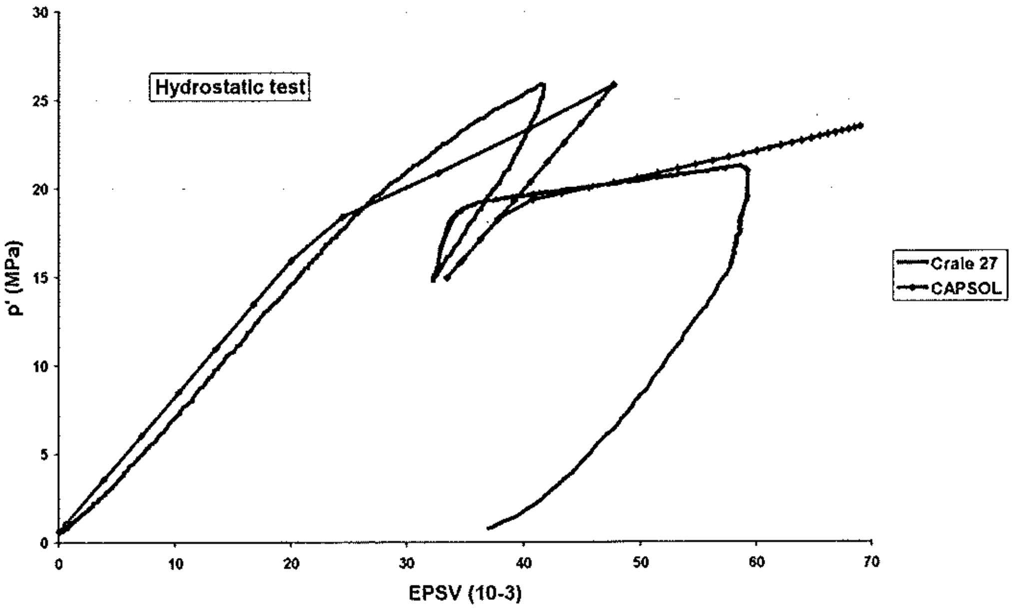

Figure 9: Simulation of an hydrostatic test