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# Use of a damage parameter to model the mechanical behavior of marls

## Utilisation d'un paramètre de dommage pour modeler le comportement mécanique des marnes

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ABSTRACT

Hard soils/ soft rocks (HSSR) are natural materials where the bonds between particles have important contribution to their strength and stiffness. Progressive rupture of these bonds affects irreversibly the hydro-mechanical behavior of these materials. Most of the existing models follow the idea that bond degradation depends on accumulated plastic strains. Such is the case of the model used to describe the mechanical behavior observed in oedometer and isotropic compression tests performed on marls.

RÉSUMÉ

Les roches tendres/sols durs sont des matériaux naturels ou ses particules minérales  ont des liaisons permanentes qui contribuent de façon importante pour sa résistance et rigidité. La rupture progressive de cette structure affecte irréversiblement le comportement hydromécanique de ces matériaux. La majorité des modèles actuels suit l'idée d'une dégradation de liaisons, associé aux déformations plastiques accumulées. Tel est le cas dans le modèle utilisé pour décrire le comportement mécanique observé dans les essais de compressibilité exécutés sur des marnes.

Keywords: marls, constitutive model, debonding, structure loss, evolving rocks

## 1 INTRODUCTION

Hard soils/ soft rocks (HSSR) are often treated as bonded materials in which bonds provide strength and stiffness to soil structure. Progressive rupture of these bonds, caused by stress and suction changes, affects irreversibly the hydro-mechanical behavior of these materials.

Several different constitutive models for HSSR can be found in the literature. Soft rocks, in particular, are often treated as composite materials made of a clay matrix interlocked with a bonding material. As the mechanical properties of this type of materials degrade with bond breakage, the way how the main part of the existing models use to describe the behavior of soft rocks follows the idea of bond degradation.

The definition of damage laws depending on accumulated plastic strain was introduced by Gens & Nova [1]. The authors defined an elasto-plastic constitutive framework for saturated HSSR. This approach is equivalent to say that the stress yield space of the bonded material is larger than the corresponding space of the com-

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pletely destructured material. Size difference reduces for decreasing bonding. Several other authors [2,3,4] reproduced the transition between elastic and elasto-plastic behavior by adopting kinematic hardening models with bounding surface plasticity (bubble models).

Bond loss can also be introduced in constitutive models by considering explicitly the rupture of connections. This micromechanical approach was used by Alonso & Alcoverro [5] adopting a model for double structured materials, in which the microstructure represents the bonded clay minerals of the HSSR, where bonds act restraining their swelling deformations, and the macrostructure is the rock matrix. Progressive bond breakage caused by loading history (both stress and suction changes) allows larger deformations and therefore it results in increasing irreversible deformations of the matrix. Another approach can treat HSSR as composite materials made of a clay matrix interlocked with a bonding material (cement) [6,7]. The clay matrix is described with a constitutive model for unbonded clayey soils such as Cam Clay Model. The behavior of the bonds or cements is described by an elastic damage law typical of quasi-brittle materials. The elastic stiffnesses are therefore reduced with damage, which is considered in the definition of the elastic mechanical properties of the bonds as if it was reducing the bonded area which is resisting to loading.

This paper presents the results of oedometer tests and isotropic compression tests performed in samples dried in laboratory environment. The results of the tests are reproduced using a constitutive model for structured materials incorporating a damage parameter to reproduce structure loss caused by loading. The model adopted in the work presented is accordingly to the proposal by Alonso & Alcoverro [5] and will be described with some detail in the paper. It is shown that the model is able to reproduce the main features of the behavior observed in the tests.

## 2 MARL CHARACTERIZATION

Abadia marls studied (upper Jurassic formation of Abadia, Arruda dos Vinhos, Portugal) have a relatively high plasticity ($w_L$=49% and PI=25%) consistent with the nature of the minerals present (mainly chlorite, kaolinite, bentonite, illite and gypsum, quartz, feldspar, calcium carbonate and mica) [8]. Some other relevant properties are a porosity of 37% for *in situ* water content of 17% (saturation degree of 77%) and unit weight of 27.4kN/m$^3$. The saturated permeability is k=8×10$^{-14}$m/s.

A marked volume dependence on water content was registered [8]. Also, when wetted the material exhibits volume increment and micro-cracking (porosity increment). The water retention curve was measured for three drying-wetting cycles (Fig. 1), in which degradation due to wetting with the increment of the saturated water content was observed. This physical degradation was confirmed in Environmental Scan Electron Microscope photographs.

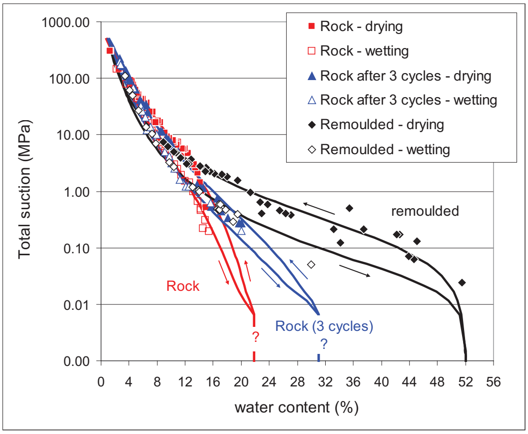

Figure 1. Evolution of the water retention curve [8].

Figure 1 shows the evolution of the curves with increasing cycles, as well as the curve measured for the material prepared with water content w=1.5$w_L$ (destructured material). The convergence of the curves to this boundary case in terms of bonding (complete breakage of bond connections) illustrates well the structure loss suffered by the marls when subjected to suction cycles. The curves were fit using Van Genuchten [9] expression ($S_r$ definition in Eq. 1) (drying: P=0.3MPa, $\lambda$=0.2; wetting: P=0.9MPa, $\lambda$=0.2).

Swelling tests were performed on specimens with different initial suctions and under different vertical stress [8]. The results of these tests allowed the quantification of constant α necessary to calculate effective stresses (Eq. 1) [10]. In Equation 1, $p'$ is the isotropic effective stress, $p$ is isotropic total stress, $s$ is suction and $S_r$ is the saturation degree (Eq. 1) calculated with the water retention curve for the bonded material (first cycle). It was found $\alpha$=4.56 [8].

$$p' = p + sS_r^{\alpha} \text{ with } S_r = \left[1+\left(\frac{\psi}{P}\right)^{\frac{1}{1-\lambda}}\right]^{-\lambda} \qquad (1)$$

## 3 EXPERIMENTAL TESTS

Several oedometric tests were performed in samples (3cm diameter, 1.8cm high, initial void ratio $e$=0.29) where different loading cycles (including stress and suction) were applied. In a first set, three specimens were initially dried (relative humidity $RH$=45%, $s$=124MPa, $w$=3.4%) and then vertical stress was applied in dry (specimen S1) and in fullt saturated conditions (S2), or after partial wetting to $s$=0.5MPa (S3) [8]. A marked swelling deformation was observed when the marl was fully saturated under small vertical stress, which allowed to measure the elastic compressibility index for suction changes $\kappa_s$=0.007 [11]. The horizontal stresses were assumed to be half of the vertical stresses. As observed for unsaturated materials, stiffness increases with suction, as well as the size of the elastic space measured by the yielding stress. BBM constants [11] were determined with the results of these three tests ($\lambda(0)$=0.027, $r$=0.65, $b$=0.05MPa$^{-1}$, $p_0^*$=858kPa, $p^c$=280kPa).

In a second set of tests, the specimens were initially dried to $s$=124MPa and then subjected to different loading paths [8]. Only one test where stress cycles were applied under this constant suction is studied in this paper (S4). The specimen was loaded until 7MPa but three unload-reloading cycles were applied for increasing stresses of 2.2MPa, 4.4MPa and 7.4MPa. The values of κ (0.003, 0.004 and 0.005 for the first, second and third cycles) and λ (λ=0.015) were measured. Then the specimen was reloaded to the vertical stress of 7.4MPa and then fully saturated and unloaded (κ=0.017). This last part of the test was performed to show the high sensitivity of the marls to suction changes. Figure 2 shows the large contrast between the elastic compressibility indexes obtained before and after full saturation.

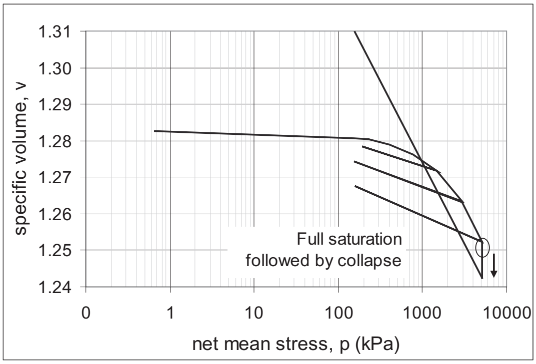

Figure 2. Oedometric test of specimen S4 [8].

The compressibility of the destructured material was also investigated because it corresponds to the situation when the bonding effect restraining the deformations of the clay minerals in the rock matrix is lost. It was found $\lambda$=0.250 and $\kappa$=0.030.

Isotropic compression tests were also performed (see the companion paper [12]). The specimens (approx. 5cm diameter, 10cm high, initial void ratio $e$=0.29) were dried in laboratory environment before testing, which corresponds to $s$=100MPa. Maximum isotropic stress applied was 12MPa and loading cycles were applied at 4MPa, 8MPa and 12MPa (Fig. 3).

The test allowed to obtain $\kappa$ (increasing average values: 0.002, 0.003 and 0.004) and $\lambda$ ($\lambda$=0.017). As observed when loading cycles were applied in oedometric conditions, elastic stiffness reduces with increasing cycles. The values found in this test are very similar to those measured in the oedometric test.

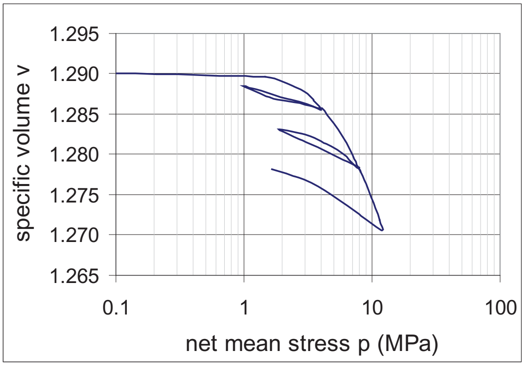

Figure 3. Results of the isotropic compression test.

## 4 MODEL DESCRIPTION

The model adopted is defined for unsaturated materials with double structure previously described. The microstructural volume changes correspond to the swelling deformations of the bonded clayey materials, which increase with bond breakage. Progressive bond breakage allows larger microstructural deformations and results in irreversible deformations with amplitude increasing with bond breakage. Global effect of debonding is introduced in the definition of the interaction between the two structural levels.

The model considers *e* as total void ratio defined by the usual manner for materials with double structure ($e = e_M + e_m$ where $e_M$ and $e_m$ are the macrostructural and microstructural void ratios, respectively). BBM is adopted as constitutive model for the macrostructure and a non linear elastic law is adopted for the microstructure, besides stiffness dependence on current bonding.

Structure loss is simulated through changes in a bonding parameter named *b* (Eq. 3) [1] ($b_0$=0.80, $h_1$=0.02)

$$b = b_0 e^{-h_1 \int \left| d\varepsilon_v^p \right| - h_2 \int \left| d\varepsilon_s^p \right|} \tag{3}$$

which depends on the plastic volumetric strain $d\varepsilon_v^p$ and plastic shear strain $d\varepsilon_s^p$ experienced by the material during loading. $b_0$ is the initial bonding and parameters $h_1$ and $h_2$ provide the rate of debonding as damage accumulates. Shear strains are assumed null although this is only rigorous for isotropic compression. $b$=0 when the bonds are completely broken and no longer restrain the swelling deformations of the clay minerals.

Damage quantified through *b* affects the two structural levels: in the microstructure, to account with the progressive loss of restraints of the clay minerals; in the macrostructure, to simulate softening with increasing degradation. Concerning the macrostructure, this parameter is introduced in the definition of the saturated yielding stress $p_{ob}$* (Eq. 3) until the minimum value $p_o$* is reached, which corresponds to the saturated yielding stress of the fully debonded material (the reference material).

$$p_{ob}{}^* = p_o{}^*(1+b) \tag{3}$$

For bonded saturated materials it can be assumed the existence of a limiting tensile strength named $p_{tb}$. Its evolution with debonding (strength reduction) is defined with an expression similar to Equation 3. It is not presented in this paper because it is not important for the cases studied.

When the material is fully saturated the elastic space for the macrostructure is limited by the values of $p_{ob}$* and $p_{tb}$. The extension to unsaturated cases is identical to the one adopted in BBM [11] but now the definition of the yield surface in *s:p* space depends on parameter *b*.

$$F(s, p, \varepsilon_v^p) = p - p_{ob}{}^* = p - p_o{}^*(1+b) = 0 \tag{4}$$

The hardening law (Eq. 5) is obtained through the consistency equation, where *e* is the total void ratio, $\lambda(0)$ and $\kappa$ are the saturated elastoplastic and elastic compressibility indexes respectively, for defined for the macrostructure. The values for these constants were obtained from the tests performed in undisturbed rock previously described.

$$d\varepsilon_v^p = -\frac{1}{\dfrac{(1+b)(1+e)}{\lambda(0)-\kappa}+b_0h_1}\frac{dp_{ob}*}{p_{ob}*} - \frac{\dfrac{p^c}{p_o*}\dfrac{\lambda(0)r\beta}{\lambda(0)-\kappa}\log\left(\dfrac{p_o*}{p^c}\right)}{\dfrac{(1+b)(1+e)}{\lambda(0)-\kappa}+b_0h_1}ds \quad (5)$$

The definition of the LC yielding curve for current bond *b* is given by Equation 6 (BBM).

$$p_{ob} = p^c\left(\frac{p_{ob}*}{p^c}\right)^{\frac{\lambda(0)-\kappa}{\lambda(s)-\kappa}} \quad (6)$$

For the microstructure, bonding affects the elastic compressibility of the material given by the elastic compressibility index $\kappa_m$ *(b)* (Eq. 7). A linear variation of $\kappa_m$ *(b)* with *b* is proposed, where $\kappa_{mfd}$ is the microstructural compressibility for the destructured material and $b_i$ is a constant.

$$\kappa_m(b) = \kappa_{mfd}\left(1-\frac{b}{b_i}\right) \quad (7)$$

The microstructural void ratio $e_m$ is given by Equation 8 where $e_{mo}$ is its initial value and $p'$ is the effective stress at this structural level given by Equation 1.

$$e_m = e_{m0} - \kappa_m(b)\times\ln\frac{p'}{p'_{\max}} \quad (8)$$

Equation 8 assumes that $p'_{max}$ acting in the microstructure is always below a maximum value above which no deformations can occur for high confining stress irrespective of the current bonding. The deformations of the microstructure $d\varepsilon_m$ are given by Equation 9.

$$d\varepsilon_m = \frac{de_m}{1+e} = -\frac{\kappa_m(b)}{1+e}\frac{dp'}{p'} - \frac{\kappa_{mfd}}{1+e}\ln\frac{p'}{p'_{\max}}\frac{b}{b_i}h_1\left|d\varepsilon_v^p\right| \quad (9)$$

The first term in Equation 9 gives the strains associated with isotropic unloading. The second term gives the contribution of the induced damage (debonding).

As the stress paths simulated do not include suction changes, the use of the interaction functions defined in double structure constitutive models [5] was not necessary although the influence of the microstructural deformations are considered in global changes in void ratio.

## 5 MODELING THE EXPERIMENTAL TESTS

(7.14)

Only two constants are different for fitting both tests with the model presented. As a matter of fact, the model does not account explicitly with the deviatoric component applied during the oedometric test. Consequently, different saturated yielding stresses were adopted ($p_{0b}$*=858kPa for the oedometric tests and $p_{0b}$*=1440kPa for the isotropic compression tests), which affects the evolution of bonding and hardening. For the same reason, a larger value for the initial bonding parameter $b_i$ was necessary to fit the isotropic compression tests ($b_i$=0.60 for the oedometer tests and $b_i$=0.72 for the isotropic compression tests). A small difference in initial void ratio (0.008) was needed to best fit the results.

Figure 4 presents the results obtained on the oedometric test S5, obviously without including final full saturation.

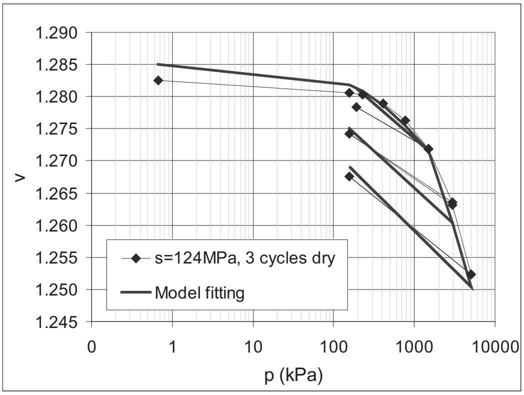

Figure 4. Results of the oedometric test.

Figure 5 presents the results found for the isotropic compression test. A good agreement is found in all cases.

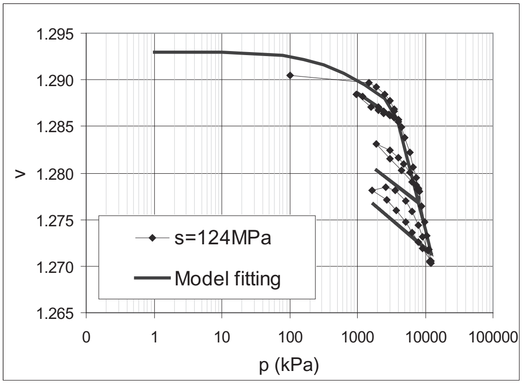

Figure 5. Results of the isotropic compression test.

## 6 CONCLUSIONS

The model used to describe the mechanical behavior of a soft rock is a double structure elastoplastic constitutive one. A damage parameter was introduced to reproduce structure loss caused by loading.

High compressions were attained through stress paths that included multiple unload-reloading phases. The results showed decreasing elastic stiffness for increasing compression stresses as a result of debonding phenomena. Being able to describe this behavior, the model can be considered highly promising.

Its ability to reproduce explicitly deviatoric stresses and suction changes will allow its future application to mimic more complex situations simulating real cases.

## 7 ACKNOWLEDGEMENTS

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