VIII International Conference on Computational Plasticity
COMPLAS VIII
E. Oñate and D. R. J. Owen (Eds)

ELASTOPLASTIC MODELLING OF HARD SOILS AND SOFT ROCKS: FORMULATION AND APPLICATION

Antonio Gens*, Jean Vaunat* and Benoît Garitte*

* Departamento de Ingeniería del Terreno
Universidad Politécnica de Cataluña
Campus Nord UPC, 08034 Barcelona, Spain
e-mail: antonio.gens@upc.edu

Key words: Computational Plasticity, Geomechanics, Constitutive model, Damage, Bonding.

Summary. *An elastoplastic constitutive law is presented that is able to reproduce a number of transitional behaviour features of hard soils and soft rocks. It models the material as a bonded matrix and distinguishes two different behaviours. The response of the matrix is described by the constitutive law of a soil, but can include, in the most general case, any constitutive law commonly used to represent the response of ductile materials. The response of the bonds is modelled through a semi-logarithmic damage elastic law. A method is finally proposed to combine these two behaviours on the basis of energy considerations. An interesting feature of the model is its ability to represent distinct rock response depending on the state of stresses at which bonding is assumed to have taken place during rock diagenesis. A numerical model incorporating this constitutive law is applied to the study of a circular excavation into the Callovo-Oxfordian mudstone, selected by the French nuclear agency to host the underground research laboratory for deep radioactive waste disposal.*

1 INTRODUCTION

Hard soils and soft rocks (HSSR) are geological materials that exhibit a response intermediate between that of a rock and a soil. They include hard clays and clay-shales, soft sedimentary rocks (mudstones, claystones, marls, shales, calcarenites and weak limestones), weak pyroclastic rocks like tuffs, cemented coarse-grained materials like weak sandstones, residuals soils, and very weathered hard rocks. In their intact state, they may have strength close to that of hard rocks and the modelling of their behaviour must consider features typical of quasi-brittle materials. When exposed to mechanical or environmental actions, they are prone to lose their induration and, thereby, to transform themselves into a soil-like material. A complete modelling of these materials requires therefore the definition of a framework allowing for the transition from quasi-brittle to ductile response. In this contribution, a model is proposed that combines a framework used for soils with another one intended for quasi-brittle materials. The model allows for a representation of structuration and bonding in these materials and their degradation due to mechanical strains or other causes.

2 CONSTITUTIVE MODEL

3.1 Soil matrix

During the formation of a natural soil deposit, material will suffer a consolidation process followed by ageing and possibly creep. Such phenomena can be adequately represented by elastoplastic models developed for soils. A large variety of models exist to describe the behaviour of clays, with different levels of sophistication depending on the features they want to represent. For the sake of model presentation one the simplest models, the modified Cam clay model (MCCM), will be used in this paper. The relevant equations are:

$$dp_M = \frac{(1+e)\,p_M}{\kappa_M}\left(d\varepsilon_{vM} - d\varepsilon_{vM}^p\right)\ ;\ dq_M = G_M\left(d\varepsilon_{qM} - d\varepsilon_{qM}^p\right) \tag{1}$$

$$F_M = {q_M}^2 - {M_M}^2 p_M\left(p_M - p_{0M}^*\right)\ ;\ G_M = \alpha_M q_M^2 - {M_M}^2 p_M\left(p_M - p_{0M}^*\right)\ ;\ dp_{0M}^* = \frac{(1+e)\,p_{0M}^*}{\lambda_M - \kappa_M} d\varepsilon_{vM}^p$$

where e is the void ratio, p_M and q_M the mean and deviatoric stress, $d\varepsilon_{vM}$ and $d\varepsilon_{qM}$ the volumetric and shear strain increment, p_0* the isotropic yield locus, M_M the slope of the critical state line in the p_M-q_M plane, κ_M and λ_M, the slopes of the unloading/reloading and virgin loading lines in the $e\text{-}ln(p_M)$ diagram and α_M an parameter expressing the non associativity of the flow rule. F_M stands for the yield function and G_M for the plastic potential. Effective stresses are considered and subscript M is added to indicate that the quantities refer to the clay matrix.

Ageing results in further stiffening of the material that increases the size of the yield surface because of development of weakly-bonded fabric. This effect can be tackled within the extension of the elastoplastic framework proposed in[1] to incorporate the effect of structuration. They introduce a parameter b that degrades as plastic strains develop following the law:

$$db = -b_0 e^{(h-h_0)} dh \quad \text{with} \quad dh = h_1 d\left|\varepsilon_{vM}^p\right| + h_2 d\left|\varepsilon_{qM}^p\right| \tag{2}$$

b_0 gives the structuration of the material due to ageing and h_0 the amount of plastic strain at which degradation starts. h_1 and h_2 control the rate of degradation due to dilation and shear. Considering a linear increase of the isotropic yield locus with b and the development of a tensile strength due to ageing (taken as proportional to b through coefficient α_t), equation of the yield surface for the aged clay takes finally the form:

$$F_M = {q_M}^2 - M^2\left(p_M + \alpha_t b\right)\left(p_M - (1+b)\,p_0^*\right) \tag{3}$$

3.2 Bonding and cementation

The additional structuration caused by cement deposition is accounted for in the model through the introduction of a second material component, called bond, endowed with behaviour typical of quasi-brittle materials.

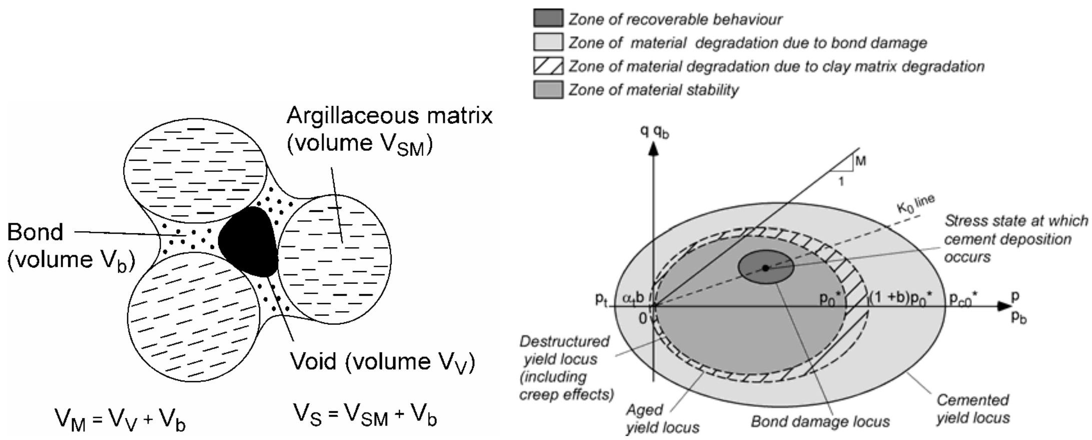

Figure 1. Schematic arrangement considered for a bonded material (left). Location of the different zones of material behaviour (right)

Any load applied to an element of cemented material after the time of bond deposition will distribute itself between the soil matrix and the bonding according to a ratio that depends on the geometric arrangement of both components. Here, stress partitioning is based on the use the energy equivalence principle that sets the equality between the energy of the composite material and the sum of energies for all components.

$$\begin{aligned}&(p-p_{b0})(\varepsilon_v-\varepsilon_{v0})+(q-q_{b0})(\varepsilon_q-\varepsilon_{q0})=(p_M-p_{b0})(\varepsilon_{vM}-\varepsilon_{v0})+\\&+(q_M-q_{b0})(\varepsilon_{qM}-\varepsilon_{q0})+p_b\varepsilon_{vb}+q_b\varepsilon_{qb}\quad\forall\varepsilon_v=\varepsilon_{vM}-\varepsilon_{vb},\quad\forall\varepsilon_q=\varepsilon_{qM}-\varepsilon_{qb}\end{aligned} \tag{4}$$

Defining $\chi_v = \varepsilon_{vb} / (\varepsilon_v - \varepsilon_{v0})$ and $\chi_q = \varepsilon_{qb} / (\varepsilon_q - \varepsilon_{q0})$ equation (4) becomes:

$$p = p_M(1+\chi_v)+\chi_v(p_b-p_{b0})\ ;\ q=q_M(1+\chi_q)+\chi_q(q_b-q_{b0}) \tag{5}$$

Relationship between $(p_b,\ q_b)$ and $(\varepsilon_{vb},\ \varepsilon_{qb})$ is provided by the constitutive law of the bonding based on the scalar semi-logarithmic damage model established in[2]:

$$p_b=(1-D)K_{b0}\varepsilon_{vb}\ ;\ q_b=(1-D)G_{b0}\varepsilon_{qb} \tag{6}$$

Establishing a evolution law for D, the effects of destructuration are incorporated into the model. Finally:

$$\chi_v=\chi_q=\chi=\sqrt{1-D}\,\chi_0 \tag{7}$$

where χ_0 is a coefficient related to cement concentration. According to Equation (7), χ_v and χ_q evolve from χ_0 to 0 during the process of bond damage. This mechanism is accompanied by a destructuration of the material and a progressive transfer of load from bonds to clay matrix.

The distinct zones of material behaviour are depicted in Figure 1 (right). The zone limited by the yield locus of destructured material is the zone of material stability. During ageing, yield expands, defining a zone that is metastable if the stress state reaches the plastic limit surface. If bond deposition occurs at the current stress state, an additional increase of elastic domain ensues. On the same diagram, the limit of damage locus (expressed in p_b, q_b) is added. Inside the zone delimited by this locus, material has a recoverable behaviour. Outside, loading inside the elastic domain produces degradation of elastic properties and elastic domain due to bond damage. In the present model, therefore, the yield locus of the cemented material is sensitive to loading in the elastic zone.

3 APPLICATION

The model has been implemented in a coupled THM Finite Element code and used to simulate the excavation of the access shaft to ANDRA underground laboratory. The shaft, with a diameter varying between 6.25 and 6.5 m, is currently being drilled in the Callovo-Oxfordian (CO) formation. The zone considered in the simulation is located at a depth of 467 m, because a program of instrumentation is planned at that level to benchmark the numerical predictions with measurements (Fig. 2, left).

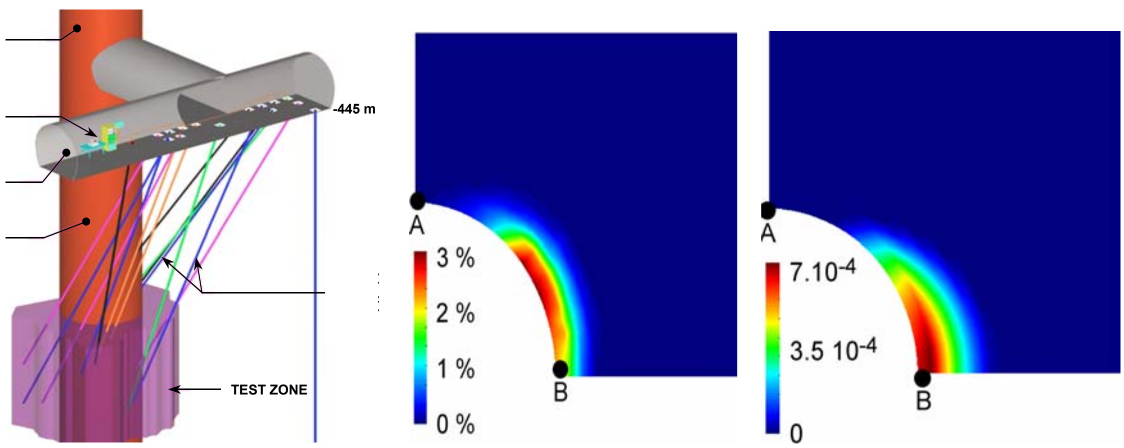

Figure 2. Layout of the instrumentation and drift planned at 467m depth (left). Computed damage zone (centre). Computed plastic zone (right).

Figure 2 (centre, right) presents results of a simulation of the shaft excavation. Installation of a concrete lining after 1 day has been assumed and the shaft is left afterwards open for 100 years with a relative humidity equal to 100%. In this case, numerical results indicate reduced damage. The damage zone extends to approximately 0.75 m inside the rock mass and covers about 2/3 of the shaft periphery. The degree of damage is in fact low (below 3%). The plastic zone is more concentrated along the direction of minor horizontal stress.

REFERENCES

[1] A. Gens and R. Nova. “Conceptual bases for a constitutive model for bonded soils and weak rocks”. *Proc. Symp. on Geotechnical Eng. of Hard Soils – Soft Rocks*, Balkema, 485-494 (1993).

[2] I. Carol., E. Rizzi and K. Willam. “On the formulation of anisotropic elastic degradation. I. Theory based on a pseudo-logarithmic damage tensor rate”. *Int. J. Solids and Struct.*, **38**, 491-518 (2002).