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Analysis of Mechanical Behavior of the Callovo-Oxfordian Argillite

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Abstract. This paper presents an overview of analysis the mechanical behavior of argillite; FE simulation uses an elastoplastic model that has been developed based on a competition between an anisotropic ductile behavior (direction of the subsidence's strain) and an anisotropic semi-fragile behavior (direction of the extension's strain), a nonlinear damage cumulative is considered to evaluate the creation of discontinuities due to material degradation. FE results matches well with the experimental results on the core samples. Consequently, the model shows that it can be applied to evaluate the retaining walls of future storage structures of nuclear waste.

1. Introduction

The ANDRA, French National Radioactive Waste Management Agency, has the role of designing, carrying out and exploiting centers of storage dedicating to the radioactive waste. This radioactive waste is very dangerous because of its high-level and long-lived property [1]. The research aims to prevent the dispersion of the radioelement in the environment and isolate them from any contact with the man for very long time (thousands of years). Therefore, the underground research laboratory (URL) Meuse and Haute Marne is built in Bure, France to evaluate the behavior of the argillite of Bure (Callovo-Oxfordian) that refers to as a geological barrier of the radionuclides containment [1, 2, 3]. The evaluation of the storage safety on the Meuse/haute Marne argillite requires mechanical behavior models of the rock, to calculate the distribution of the mechanical perturbations in terms of extension of damaged and fractured zones. This zone of damage rock, often known as the Excavation Damaged Zone (EDZ) is of importance for storage structure where the host rock plays a confining role.

In this context, the objective of this paper is limited to a model constitutive of the elastoplastic type associated an anisotropic damage to describe the mechanical behavior of argillite of Callovo-Oxfordian under mechanical loadings.

2. Method

2.1. Model formulation

According to previous results, conceptual model of Cox claystone is based on:

- Continuity of the stress-strain relation [1].
- Interaction between solid phase and interstitial fluid with an adaptation of Biot theory [2, 3].
- Internal reinforcement of the argillaceous phase [1].
- Elastoplastic behavior with an anisotropic damage [4, 5, 6].

In its initial state, the argillite is considered as undisturbed, with insignificant anisotropy and without damage. Under solicitation, the resulting behavior is a competition between the ductile behavior in the direction of the settlement deformations and the semi-fragile behavior in the directions where shear and extension take place [4]. The overall strain tensor is separated into the elastic strain and the plastic strain:

$$\underline{\underline{\varepsilon}} = \underline{\underline{\varepsilon}}^{e} + \underline{\underline{\varepsilon}}^{p} \quad (1)$$

Elastoplastic ductile behavior is characterized by a large elastic domain with a diagenesis yield surface F_D and a collective surface F_P. The argillite behaves elastically when P-Q relation is within the collective surface FP and elastoplastically when P-Q relation is beyond FP.

$$\begin{aligned} \tilde{F}_D = \tilde{G}_D = (p',q,\theta) = q^2 - 0.5L^2(p' + \tilde{p}'_{cohe})^2 a(1 - \frac{p'}{\tilde{p}'_{cf}}) = 0 \\ \tilde{F}_p(p',q,\theta) = q^2 - L^2 \times (p' + \tilde{p}'_{cohe})^2 a \times (1 - \frac{p'}{\tilde{p}'_{cf}}) = 0 \\ \tilde{G}_P(p',q,\theta) = q^2 - (p')^2 \times \left(\left(\frac{p'_g}{p'} \right)^{1/2r} - 1 \right)^{2r} = 0 \end{aligned} \quad (2)$$

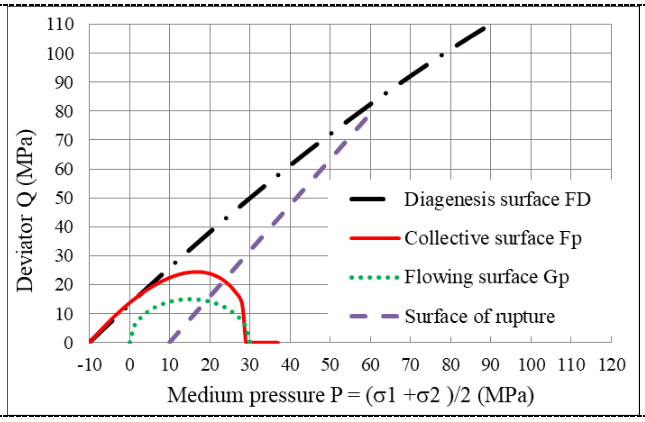

Figure 1. Surface of charges.

Semi fragile damageable elastic behavior is related to anisotropic damage. The damage is induced by solicitation concerning the carbonate phase, and by hypo-elasticity describing the behavior of the argillaceous phase [6]:

$$\varepsilon_{ij}^{e} = \left(S_{ijkl}\left(\underline{\underline{D}}\right) + S_{ijkl}\left(P'\right) \right) \times \sigma'_{kl} \quad (3)$$

The plasticity deformation derives from the surface of flowing GP with:

$$d\varepsilon_{ij}^{p} = dh \frac{\partial G}{\partial P} \quad (4)$$

2.2. Damage variables

The damage in the material is represented by a variable corresponding to an average material degradation affecting stiffness, strength, anisotropy. The anisotropic damage is described by a tensor $\underline{\underline{D}}$

$$\underline{\underline{D}} = \sum_{i=1}^{3} D_i n_i \otimes n_i \quad (5)$$

Where D_i and n_i are the principal value and the unit vector of principal direction of the tensor $\underline{\underline{D}}$, respectively.

2.3. New formulation of elastoplastic model with anisotropic damage

According to the microscopic observations on argillite samples before and after mechanical test [9], the argillite of Bure has an anisotropic damage induced by the existence of the strain in extension.

The damage is related to the existence of the strain in extension that is obtained from the spectral decomposition of the elastic strain tensor [7,8] such as:

$$\underline{\underline{\varepsilon}} = H(-n_i.\underline{\underline{\varepsilon}}.n_i)(n_i.\underline{\underline{\varepsilon}}\ .n_i)n_i \otimes n_i = \underline{\underline{P^{+}(\varepsilon\ )}} : \underline{\underline{\varepsilon}} \tag{6}$$

The quantity $\underline{\underline{P}}$ is a fourth–order tensor corresponding to a negative projection operator.

$$\underline{\underline{P}} = H(-n_i \underline{\underline{\varepsilon}}\, n_i)(n_i \otimes n_i \otimes n_i \otimes n_i) \tag{7}$$

Where n_i is the principal directions of the damage and H is the Heaviside function defined by

$$H(x) = \begin{cases} 1 & if \quad x < 0 \\ 0 & if : x > 0 \end{cases} \tag{8}$$

Elsewhere, one of the bases of the model is the coupling between the strain tensor $\underline{\underline{\varepsilon}}^{+}$ and the damage tensor $\underline{\underline{D}}$ by the energy of Helmholtz.

The free energy Ψ is the contribution of the decreased elastic energy of the dissipation energy due to the damage. Namely, we will postulate the following expression for the Helmholtz free energy [8,9]:

$$\rho\Psi = \frac{1}{2}\underline{\underline{\varepsilon^{e}}} : \underline{\underline{\tilde{C}(D)}} : \underline{\underline{\varepsilon^{e}}} + \Psi_p(\gamma_p, \underline{\underline{D}}) = \frac{1}{2}(\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon^{p}}}) : \underline{\underline{\tilde{C}(D)}} : (\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon^{p}}}) + \Psi_p(\gamma_p, \underline{\underline{D}}) \tag{9}$$

In the model, the Helmholtz specific free energy was used as potential, Ψ_p is a function translating the energy blocked by plastic hardening, $\underline{\underline{\tilde{C}(D)}}$ is the fourth order tensor or the tensor of damage material rigidity.

$$\underline{\underline{\sigma}} : \underline{\underline{\varepsilon}}^{*} - \rho\Psi^{*} \geq 0 \tag{10}$$

An elastic law of behavior is characterized by a relation between the stress vector and the strain vector. By definition, the stress is derived from potential

$$\underline{\underline{\sigma}} = \rho\frac{\partial\Psi}{\partial\underline{\underline{\varepsilon^{e}}}} = \underline{\underline{\tilde{C}(D)}} : \underline{\underline{\varepsilon^{e}}} = \underline{\underline{\tilde{C}}} : (\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon^{p}}}) \tag{11}$$

Thus, the damaged rigidity matrix is:

$$\underline{\underline{\tilde{C}(D)}} = \underline{\underline{M(D)}} : \underline{\underline{C^{o}}} : \underline{\underline{M(D)}} \tag{12}$$

With : $\underline{\underline{M(D)}} = \delta_{ik}.\delta_{jl}.\sqrt{(1-D_i).(1-.D_j)}n_i \otimes n_j \otimes n_k \otimes n_l$ and $\underline{\underline{C^{0}}}$ the initial tensor of rigidity, $\underline{\underline{C^{0}}}$ depends on the Young modulus E and the Poisson coefficient of the isotropic elastic linear material.

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$$\Rightarrow \underline{\underline{\tilde{C}}} = \begin{bmatrix} C_1.(1-D_1)^2 & C_2(1-D_1)(1-D_2) & C_2(1-D_1)(1-D_3) & 0 & 0 & 0 \\ C_2(1-D_1)(1-D_2 & C_1.(1-D_2)^2 & C_2(1-D_2)(1-D_3) & 0 & 0 & 0 \\ C_2(1-D_1)(1-D_3) & C_2(1-D_2)(1-D_3) & C_1.(1-D_3)^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & C_3(1-D_2)(1-D_3) & 0 & 0 \\ 0 & 0 & 0 & 0 & C_3(1-D_1)(1-D_3) & 0 \\ 0 & 0 & 0 & 0 & 0 & C_3(1-D_1)(1-D_2) \end{bmatrix}$$

$$C_1 = \frac{E.(1-\nu)}{(1+\nu).(1-2.\nu)}; C_2 = \frac{E.\nu}{(1+\nu).(1-2.\nu)}; C_3 = \frac{E.(1-2.\nu)}{2.(1+\nu).(1-2.\nu)}$$

The damage appears when the equivalent strain reached its limit, associated on the actual damage state.

$$\vec{f}(\hat{\varepsilon}, \underline{\underline{D}}) = \begin{cases} f^1(\hat{\varepsilon}, D_1) = \dfrac{D_1}{D_1 - 1} + \sqrt{\alpha(a.\hat{\varepsilon} + b.\hat{\varepsilon}^2)} = 0 \\ f^2(\hat{\varepsilon}, D_2) = \dfrac{\beta(a + 2b\hat{\varepsilon})}{\sqrt{a.\hat{\varepsilon} + b.\hat{\varepsilon}^2}} + \dfrac{1 - D_2}{1 - D_1} = 0 \\ f^3(\hat{\varepsilon}, D_3) = f^2(\hat{\varepsilon}, D_2) \;\; = 0 \end{cases} \tag{13}$$

Where α, β, a, b are four material parameters which depend on the medium pressure p and the elastic characteristics of intact argillite (E, ν).

2.4. Model parameters

Base on the experimental results of a cyclic oedometric path, we observe that the loading and unloading oedometric path does not modify the distribution of the pores and does not produce appearance of the cracks. The initial value of the Young modulus and the Poisson coefficient depend on the effective mean stress. We have:

$$\begin{aligned} E_i &= 2400 + 5,3\frac{P_{conf}}{0,1} \\ \nu &= 0,25 - 0,00195\frac{P_{conf}}{0,1} \end{aligned} \tag{14}$$

The damage coefficients D_i are:

$$\begin{aligned} D_1 &= 1 - \frac{1}{1 + \sqrt{\alpha(a\varepsilon_2^+ + b(\varepsilon_2^+)^2)}} \\ D_2 &= 1 + (1 - D_1)\frac{\beta(a + 2b\varepsilon_2^+)}{\sqrt{a\varepsilon_2^+ + b(\varepsilon_2^+)^2}} \end{aligned} \tag{15}$$

Determination of the material parameters damaged is simulated by the drained triaxial path.

$$\begin{matrix} \alpha = (0.017E)^2 \\ \beta = 0.5\nu \end{matrix} \;\; ; \;\; \begin{matrix} a = 0.0047p + 0.0185 \\ b = -0.242p + 2.21 \end{matrix} \tag{16}$$

3. Results and discussion

Figure 2 shows six curves, three of which describe the relation between the deviator stress and vertical deformation (ε_1 – Q) and the other three describe the relation between the deviator stress and horizontal deformation (ε_2 – Q). Three types of curves are presented: elastic model, elastoplastic model and the experimental data. The last is obtained from drained triaxial compression tests for two confining pressures and a value of null suction.

The results in simulation and experiment is agreement (34 – 37 MPa), but a little bit Deviator stress–Deformation curve in analysis is smaller than the experiment data because we do not mention about the change of parameters like Young modulus, compressibility factor, preconsolidation pressure … during the triaxial compression path.

When the elastic model is utilized, the Deviator stress– Deformation relation is linear. However, this relation in experimental context is consistent with the elastoplastic model. In addition, the deformation from the elastic model is less than the vertical deformation from the elastoplastic model and data because the plastic deformation and the anisotropic damage are not embedded.

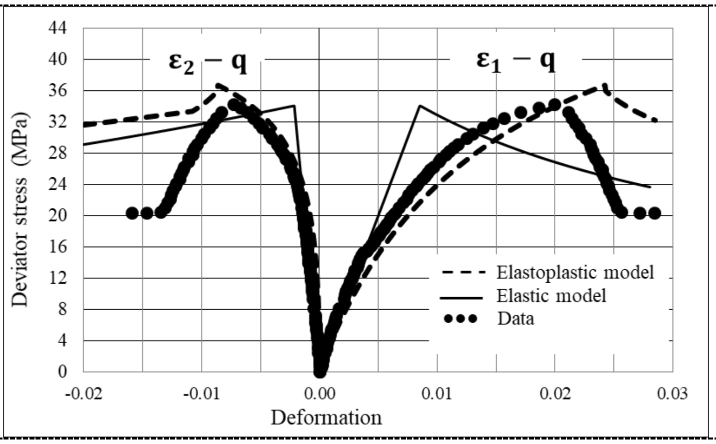

Figure 2. Evolution of deviator stress in the compression test.

To sum up, the suggested model is able to evaluate stress on the retaining walls of future storage structures of nuclear waste as shown in Figure 3.

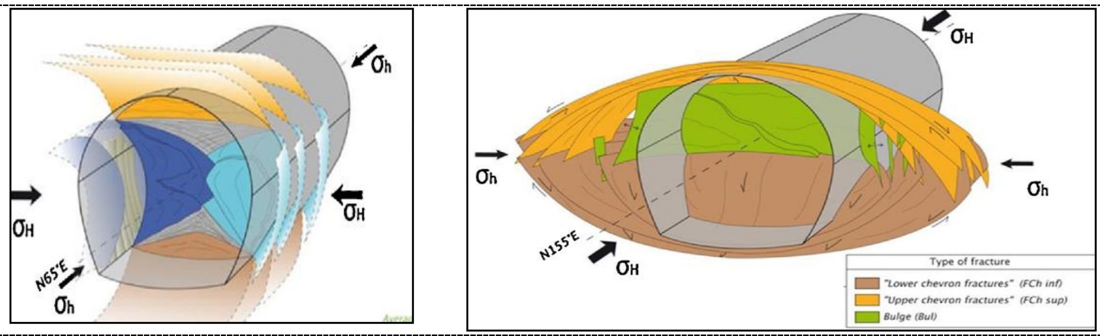

Figure 3. Discontinuity observed in research laboratory [4].

The retaining wall is created after excavation of circular tunnel of 2.6m radius. The process is at 517m of depth of Callovo-Oxfordian argillite [4].The research laboratory is then built up to evaluate the behavior of argillite, especially the long – term one like discontinuity and anisotropic convergence.

4. Conclusion

Argillite's behavior of Callovo-Oxfordian is very contrast: ductile in compression and semi-fragile in extension. A different model is produced to evaluate its mechanical behavior. The model presented is based on experimental results and microscopic observation, it reproduces the effects induced by degradations of the cementation by the extension strain. The model is elastoplastic characterized by two load surfaces, one of diagenesis and the other called collective that is non-associative plastic. The analysis data and experiment are quite similar. The difference between deviator stress of the model and that of the experimental context is only 6%. Therefore, the model is capable to evaluate stress and the discontinuity on the retaining walls of future storage structures of nuclear waste.

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