

A coupled elastoplastic damage model for semi-brittle material and uncertainty analysis of the material parameters determination

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ABSTRACT: This paper presented a coupled elastoplastic damage model for the semi-brittle material argillites in unsaturated and saturated conditions. The experimental investigation introduced in the first part, shows an important plastic deformation coupled with damage induced. Influence of stress state and water contents on the mechanical behaviour of material is also presented. Base on these experimental results, a new coupled model is proposed for the poromechanical behaviour of this material. The model is formulated under the framework of poroplasticity and continuum damage mechanics. Then it is also extended to unsaturated condition by introducing the concept of plastic effective stress. The approach of determining the model's parameters based on the undrained compression experimental data is proposed. In additions, a parametric study is performed in order to illustrate the influence of water saturation degree and stress state. Finally, the comparisons between numerical simulations and test data show that the proposed model is capable to reproduce the main mechanical features of semi-brittle material.

1 INTRODUCTION

In some specific applications, like in nuclear waste storage and petroleum drilling, materials are always submitted to various coupled perturbations such as mechanical loading, hydraulic flow, desaturation and resaturation, temperature variation and chemical reactions. A good understanding of the mechanics character of materials under these perturbations is one basic problem for the risk analysis of the whole structure. For this aspect, it is necessary to develop coupled constitutive model taking into account all the phenomena above to describe the mechanical features.

The present work of this paper was carried out in the context of feasibility study of underground storage of radio wastes coordinated by the French Agency National de Gestion des Déchets Radioactifs (Andra). The material studied is a sedimentary rock called argillite, which was chose as a possible barrier used for the nuclear waste storage because of its good geological properties. In this context, the rock material is also submitted to various coupled perturbations as mentioned above. The research of the coupled mechanical behavior of argillite is the main task of this work.

According to the experimental data, significant residual strains and decrease of the elastic stiffness due to the growth of micro-cracks were observed. Therefore, plastic deformation and damage are coupled mechanism for this kind of material. A large number of plastic models have been proposed for various materials and a standard framework has been formed. In recent years, the research work of constitutive modeling of induced damage in brittle materials (rock and concrete) was very active. Lots of damage models have been proposed which could be divided into two classes: phenomenological models and micromechanical approaches. The phenomenological models provide efficient tools for numerical analysis of engineering structure in complex loading conditions. This kind of framework was adopted in this paper. The representative models for rocks include Andrieux et al. (1986), Halm and Dragon (1998), Murakami and Kamiya (1997), Ortiz (1985), Shao and Rudnicki (2000), Swoboda and Yang (1999a,b) and Yazdani and Schreyer (1988). Some coupled elastoplastic models have also been proposed for geomaterials (rock and concrete), for instance, Hayakawa and Murakami (1997) and Ju (1989). However, most of these models were induced from

dry material or essentially dedicated to tensile loading, and damage was considered as the principal failure mechanism. And based on the experiment results, plastic deformation seems to be dominant mechanism for irreversible dissipation process in the argillite under high pressure. However, in this context of work, the rock was mainly subjected to compression pressure in saturated and partially saturated condition. Therefore, coupled hydromechanical behavior should be investigated and generally plastic was considered as the dominant mechanism against damage for this kind of material. So a new coupled model is necessary to be proposed. Lots of research work has been performed in the constitutive model studying. Shao (2006) constructed a framework for semi-brittle material and proposed a coupled elastoplastic damage model for argillite based on the thermodynamic theory. A further study could be found in Jia (2007). All the main plastic features were well simulated by the models, for example, a non-linear failure surface, strain hardening, and the transition from plastic compression to dilatancy.

Based on the experimental data of argillite, the purpose of this paper is to propose a new coupled elastoplastic damage model by doing some further research on the damage evolution law and plastic flow under the same framework of the models mentioned above. The variation of the plastic effective stress in function of water content is another emphasis of this work. The influences of saturated degree and stress state on the effective stress coefficient β , which was widely used in plastic efficient stress, was discussed and an empirical relation was also proposed. A new approach for the determination of model parameters based on the undrained experimental data was also suggested.

2 SUMMARY OF EXPERIMENTAL INVESTIGATION

The material studied is a sedimentary rock called argillite, from the site in the eastern Paris Basin (France), where the underground research laboratory for nuclear waste storage is under construction. Experimental tests have been conducted on the samples cored from three different depths. Mineralogical compositions, initial porosity and natural water content of sampled were first determined. A mineralogical study showed a rather homogeneous composition of quartz (23%), calcite (27%) and clay minerals (45%) together with subordinate feldspars, pyrite and iron oxides (5%).

The experimental results from hydrostatic compression tests (Chiarelli, 2000) have shown that a difference of strain exists between the directions parallel and perpendicular to the natural bedding plan (Fig 1). This indicates an initial anisotropy of the argillite, which seems to be very small.

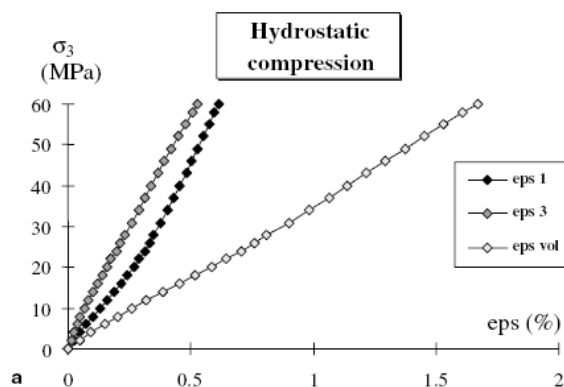


Fig.1 Example of stress-strain curves in a hydrostatic compression test (Chiarelli, 2000)

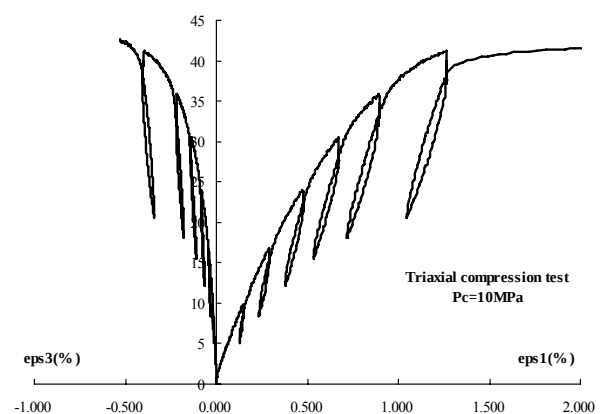


Fig.2 Examples of stress-strain curves from a triaxial compression test with unloading-reloading cycles. (Andra C RP 0 ENG 03.0380/D)

Typical stress-strain curves from triaxial compression tests have shown two basic phenomena on the overall mechanical response of the argillite (see Fig.2). First, large residual strains were observed both in axial and lateral directions after unloading of deviatoric stress. This is observed in all the tests including uniaxial compression test. According to the microscopic analyses of the argillite by

using SEM on thin sections (Chiarelli, 2000), such irreversible strains are essential related to plastic deformation by clay sheet sliding. Secondly, by determination of elastic stiffness during the unloading-reloading cycles, a progressive decrease of the elastic stiffness is obtained as a function of applied stress level. Based on SEM on thin sections, carried out on the tested samples, this degradation of elastic properties can be considered as a consequence of induced damage by microcracks (Chiarelli, 2000). Therefore, coupled plastic deformation and induced damage represent two principal mechanisms for irreversible dissipation process in the argillite. It must be emphasized that, under high confining pressure, plastic deformation seems to be dominant mechanism for irreversible dissipation process in argillite. Furthermore, in brittle material, the induced damage is generally anisotropic due to an oriented distribution of microcrack. However, for the sake of simplicity, we assume an isotropic damage in this work.

3 FORMULATION OF THE MODEL

The proposed model was formulated in the framework of poroplasticity and continuum damage mechanics.

The emphasis of this work is to study the plastic deformation and damage induced in saturated and unsaturated conditions. As discussed above, based on the experimental features, the mechanical behavior of argillite should be described by elastoplastic coupled damage model. In this work, the assumption of small strains is adopted, so in the isothermal condition, the state variables are constituted of total strain tensor ε , scalar damage variable ω , plastic strain ε^p and internal variable for plastic hardening γ_p . As classically, the total strain could be decomposed into an elastic part ε^e and a plastic part ε^p , expressed as following:

$$\varepsilon = \varepsilon^e + \varepsilon^p, d\varepsilon = d\varepsilon^e + d\varepsilon^p \quad (1)$$

It is worthy to be mentioned here that, according to the experimental data of the variations of elastic parameters on unloading paths during triaxial compression test, the elastic modulus decreases with the growth of the induced damage. In this work, the following form was adapted for considering the degradation of elastic properties caused by damage (Nemat-Nasser and Hori, 1993; Krajcinovic, 1996; Pensee et al., 2002):

$$k(\omega) = k(1 - \alpha\omega), \mu(\omega) = \mu(1 - \beta\omega) \quad (2)$$

Lots of experimental results have shown that, for unsaturated materials, both elastic and plastic deformations were influenced by water saturation degree. In order to take account into the influence of water content, two methods are largely used for the non saturated material. The first method consists to find an effective stress as a function of pore pressure and saturation degree to replace the total stress. In this way, the model proposed can be extended to partially saturated conditions. The framework of this approach was constructed by Coussy based on thermodynamic theory. The further studies of partial validation could be found in Chateau and Dormieux (2002) and Lydzda and Shao (2002). Although lack of full validation, this approach is popular used in cohesive materials. The second approach was proposed by Alonso et al.(1990). In this method, the capillary pressure (suction) was used as an independent variable. However, this method is based on extensive data from unsaturated soils and clays, and mainly suitable to this kind of material. In this work, considering the coupling elastoplasticity and damage in the partially saturated materials, the first approach is preferred. The concept of plastic effective stress was introduced which is defined in the expression of $\sigma_{ij}^{pl} = \sigma_{ij} + \beta p \delta_{ij}$. The parameter β is called effective stress coefficient for plastic flow. The physical meaning of β could be considered as the percentage of the porosity plastic dilation of the volume plastic dilation ε_v^p , which could be expressed by the following expression $\phi^p = \beta \varepsilon_v^p$. The

volume plastic dilation undergone by the skeleton is due to both the plastic change in porosity and the volume plastic dilation ϵ_s^p undergone by the solid matrix. We write:

$$\epsilon_v^p = (1 - \phi_0) \epsilon_{vs}^p + \phi^p \quad (3)$$

However, the validity has only been proven in some specific cases by using homogenization techniques (Buhan and Dormieux, 1996; Lydzda and Shao, 2002). The concept also could be extended to partially saturated material. It is proposed to substitute interstitial pressure with an equivalent interstitial pressure π in order to take into account to capillary effects. Various forms could be adopted for the equivalent interstitial pressure (Bishop and Blight, 1963; Lewis and Schrefler, 1998; Coussy, 2004). In this work, a simply form was adopted as equivalent interstitial pressure which was proposed by Coussy:

$$\sigma_{ij}^{pl} = \sigma_{ij} + \beta \pi \delta_{ij} \quad (4)$$

In this expression, the equivalent interstitial pressure π is a function of water saturation degree and water retention curve of material. It is defined as following:

$$d\pi = dp_{gz} - S_{iq}(p_{cp}) dp_{cp} \quad (5)$$

The parameter β defines the influence of capillary pressure and gas pressure on plastic deformation. Generally speaking, it is mainly influenced by saturation degree and confining pressure. A further discussion could be seen in the following section. In this way, the constitutive equations for elastic plastic damage behaviour are extended to the unsaturated conditions:

$$\dot{\sigma} = C(\omega) : \dot{\epsilon}^e + (C' : \epsilon^e) \dot{\omega} - \beta (\dot{p}_g - S_w \dot{p}_c) \delta \quad (6)$$

Based on thermodynamic theory, the plastic potential energy ψ could be expressed as following:

$$\psi = \frac{1}{2} (\epsilon - \epsilon^p) : C(\omega) : (\epsilon - \epsilon^p) + \psi_p(\gamma_p, \omega) \quad (7)$$

$C(\omega)$ is the fourth order elastic stiffness tensor of damaged material, and the function ψ_p is the locked plastic energy for plastic hardening of damaged material. The standard derivation of the thermodynamic potential yields the state equation:

$$\sigma = \frac{\partial \psi}{\partial \epsilon^e} = C(\omega) : (\epsilon - \epsilon^p) \quad (8)$$

3.1 Plastic characterization

Based on the experimental data, argillite is a pressure sensitive material. Extensive experimental data (for instance, Chiarelli, 2000; Andra C RP 0 ENG 03.0380/D) suggests that a curved failure surface is necessary. Here a quadratic function is adapted to describe the plastic yield function and failure criterion.

$$f_p(\sigma, \gamma_p) = \hat{q} - \alpha_p g(\hat{\theta}) P_0 \sqrt{A(C_s + \frac{\hat{p}}{P_0})} = 0 \quad (9)$$

$$\begin{aligned}
p &= -\frac{\sigma_{kk}}{3}, q = \sqrt{3J_2}, J_2 = \frac{1}{2}s_{ij}s_{ij}, s_{ij} = \sigma_{ij} - \frac{\sigma_{kk}}{3}\delta_{ij}, \\
g(\hat{\theta}) &= \frac{2(1-R^2)\cos(\theta + \frac{\pi}{6}) + (2R-1)\left[4(1-R)^2\cos(\theta + \frac{\pi}{6}) + 5R^2 - 4R\right]^{\frac{1}{2}}}{4(1-R^2)\cos(\theta + \frac{\pi}{6}) + (2R-1)^2}, \\
\theta &= \frac{1}{3}\sin^{-1}\left[-\frac{3\sqrt{3}}{2}\frac{J_3}{(J_2)^{3/2}}\right], J_3 = \det s_{ij}
\end{aligned} \tag{10}$$

P_0 is defined as 1MPa, and $\hat{p}$ is the mean effective stress, $\hat{q}$ the deviatoric stress and $\hat{\theta}$ the Lode angle associated with the effective stress tensor of the damaged material. The function of $g(\hat{\theta})$ defines the dependency of yield function on the lode angle. An expression of $g(\hat{\theta})$ obtained based on the experimental yield stresses on the deviatoric plane. However, for the reason of simplicity, we considered it as a constant, $g(\hat{\theta})=1$.

The parameter A defines the curvature of failure surface. The plastic strain hardening is presented by parameter α_p which increases with the generalized plastic distortion γ_p . According to thermodynamic theory, α_p could be deduced by standard derivative of the thermodynamic potential:

$$\alpha_p = \frac{\partial \psi(\varepsilon, \omega, \gamma_p)}{\partial \gamma_p} \tag{11}$$

On the basis of the experimental data of argillite, the function of locked plastic energy was proposed as following (Shao and al, 2006):

$$\begin{aligned}
\psi_p(\gamma_p, \omega) &= (1 - \chi\omega)\psi_p^0(\gamma_p) \\
\text{Where } \psi_p^0 &= \left[\alpha_p^0 + (\alpha_p^m - \alpha_p^0)\right]\gamma_p - B(\alpha_p^m - \alpha_p^0)\ln\frac{B + \gamma_p}{B}
\end{aligned} \tag{12}$$

$\psi_p^0(\gamma_p)$ is the plastic hardening energy for undamaged material. As mentioned before, as the damage reduces stress the efficient areas and leads to a redistribution of stress in the efficient area, the damage has influences on the plastic deformation. The model's parameter $\chi \in [0,1]$ is introduced for the coupling between damage evolution and plastic flow. If $\chi=0$, it means there is no coupling between damage evolution and plastic flow. α_p could be obtained as following:

$$\alpha_p = \frac{\partial \psi_p}{\partial \gamma_p} = (1 - \chi\omega) \left[\alpha_p^0 + (\alpha_p^m - \alpha_p^0) \frac{\gamma_p}{B + \gamma_p} \right] \tag{13}$$

Where α_p^0 is the initial plastic yielding threshold, α_p^m is the ultimate value of hardening function. In this work, we chose $\alpha_p^0 = 0, \alpha_p^m = 1$ for simplicity.

As most geotechnical materials, Argillite also has a transition from plastic compression to dilatancy based on experimental data (Chiarelli, 2000; Andra C RP 0 ENG 03.0380/D). In order to account for this, a non-associated plastic flow rule is necessary. Based on the experimental data, a linear function was used:

$$Q_p = \hat{q} + g(\hat{\theta})(1 - \chi\omega)(\hat{\alpha}_p - \beta_p)(\hat{p} + C_s P_0) \quad (14)$$

The parameter β_p controls the transition of the compression ($\hat{\alpha}_p < \beta_p$) to the dilatancy ($\hat{\alpha}_p > \beta_p$). The plastic flow rule is then given by:

$$d\varepsilon_{ij}^p = d\lambda_p \frac{\partial Q}{\partial \hat{\sigma}_{ij}} \quad (15)$$

The loading-unloading condition is defined by

$$f(\sigma, \gamma^p) = 0, d\gamma^p \geq 0, f \bullet d\gamma^p = 0 \quad (16)$$

3.2 Damage characterization

In thermodynamic theory, the variation of damage is always assumed to be related to the variation of elastic and plastic strains. The thermodynamic force associated with the damage variable is defined as following:

$$Y_\omega = -\frac{\partial \psi}{\partial \omega} = -\frac{1}{2}(\varepsilon - \varepsilon^p) : C'(\omega) : (\varepsilon - \varepsilon^p) - \frac{\partial \psi_p(\gamma_p, \omega)}{\partial \omega} \quad (17)$$

It means damage was induced from the phrase of elastic deformation. However, it isn't consistent with the experiment results of most rocks. In regard to argillite, during the hydrostatic test, no obvious microcrack was detected. Therefore, we assumed that the growth damage is only related with the plastic deformation. The following damage criterion was adopted here:

$$f_\omega = \omega - \omega_c \left[1 - \frac{1}{\exp(B_1 Y_\omega^p)} \right] = 0 \quad (18)$$

with

$$Y_\omega^p = -\frac{\partial \psi_p}{\partial \omega} = \chi \left[\gamma_p - B \ln \frac{B + \gamma_p}{B} \right] \quad (19)$$

$$d\gamma_p = \frac{\sqrt{\frac{2}{3}} de_{ij}^p de_{ij}^p}{\chi_p}, de_{ij}^p = d\varepsilon_{ij}^p - \frac{d\varepsilon_{kk}^p}{3} \delta_{ij} \quad (20)$$

ω_c is the critical value of damage and the parameter $B1$ control the kinetic of damage evolution.

The evolution of damage should be satisfactory to the following condition:

$$f_\omega(\gamma_p, \omega) = 0, d\lambda_\omega \geq 0, f_\omega(\gamma_p, \omega) d\lambda_\omega = 0 \quad (21)$$

3.3 Coupled elastoplastic damage behaviour

Considering the damage and plastic deformation are coupled mechanism for argillite, the evolution of the damage and the plastic deformation should be determined at the same time. We can obtain the following equation by applying the plastic and damage consistency conditions in a coupled system.

$$\begin{cases} df_{\omega} = d\omega + \frac{\partial f_{\omega}}{\partial Y_{\omega}^p} dY_{\omega}^p = 0 \\ df_p = \frac{\partial f_p}{\partial \sigma} d\sigma + \frac{\partial f_p}{\partial \alpha_p} d\alpha_p = 0 \end{cases} \quad (22)$$

By introducing the constitutive equations, plastic hardening law and damage criterion, we obtain the system to be solved to determine the plastic and damage multiplier:

$$\begin{cases} d\lambda_{\omega} + \frac{\partial f_{\omega}}{\partial Y_{\omega}^p} \frac{\partial Y_{\omega}^p}{\partial \gamma_p} H(\gamma_p, \omega) d\lambda_p = 0 \\ \frac{\partial f_p}{\partial \sigma} : (C(\omega) : d\varepsilon) = \\ \left[\frac{\partial f_p}{\partial \sigma} : (C(\omega) : \frac{\partial Q_p}{\partial \sigma}) - \frac{\partial f_p}{\partial \alpha_p} \frac{\partial \alpha_p}{\partial \gamma_p} H(\gamma_p, \omega) \right] d\lambda_p - \left[\frac{\partial f_p}{\partial \sigma} : C'(\omega) : \varepsilon^e + \frac{\partial f_p}{\partial \alpha_p} \frac{\partial \alpha_p}{\partial \omega} \right] d\lambda_{\omega} \end{cases} \quad (23)$$

4 DETERMINATION OF PARAMETERS AND NUMERICAL SIMULATION

4.1 The determination of parameters based on the data of undrained triaxial test

In this section, the general methodology for the determination of parameters of the proposed model is outlined. All the experimental data is derived from the report of Andra (C RP 0 ENG 03.0380/D).

Generally, the parameters should be determined by drained triaxial test in order to avoid the influence of the water pressure. The stress paths in drained (OB) and undrained (OC) conditions are respectively presented in Fig.3. The points A and C correspond respectively to the failure state in $p-q$ space and $\hat{p}-\hat{q}$ spaces. The point B presents the failure point under drained condition.

However, as mentioned in proceeding part, the argillite is poor permeable (10^{-19} - 10^{-21}). As result, it is very difficult to carry out the totally drained triaxial experiment which can be lasted more than one year. In the report mentioned above, the deformation rate of triaxial tests was controlled at $3.0 \times 10^{-6} / s$ which means most of them were finished in two hours. In this case, most internal water can't be drained out, so it only can be considered as undrained test. However, the referenced data of internal water pressure is lacked, so the effective stress could not be determined. It makes the problem much more complicated.

The characters A and C_s , characterize the failure surface of saturated materials ($P_{cp} = 0$). Because the initial water pressure of sample was kept on hydraulic state, the initial capillary pressure could be considered as zero. From the equation of plastic effective stress $\sigma_{ij}^{pl} = \sigma_{ij} + \beta p \delta_{ij}$, we can conclude that the intersection of the failure curve with p axis in the space of $p-q$ is the same as it in the effective stress space of $\hat{p}-\hat{q}$. In this way, the value of $C_s P_0$ can be determined by drawing the failure line in $p-q$ plane, seen in the Fig.4.

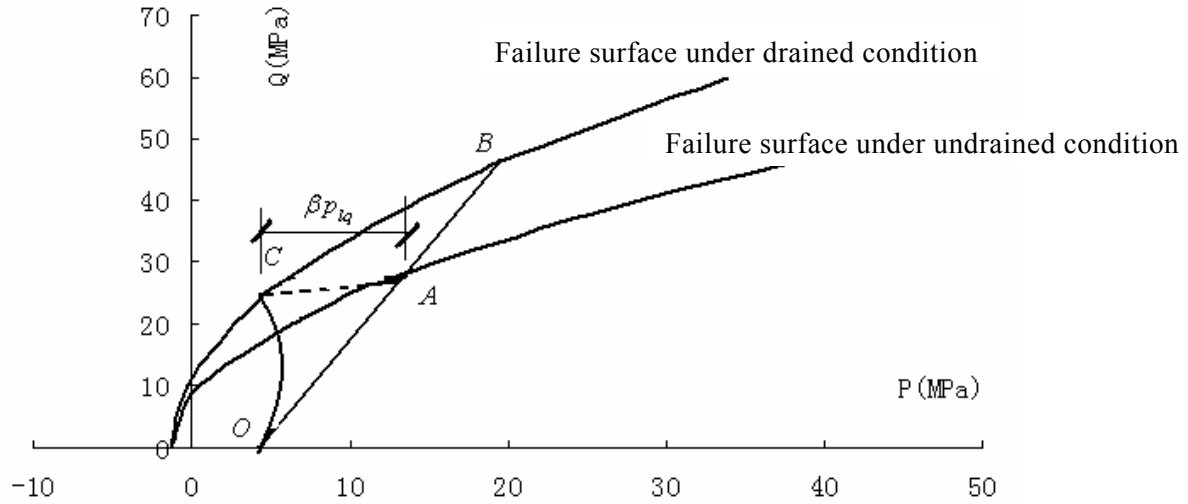


Fig.3 The stress path of drained and undrained conditions

As mentioned before, P_0 is defined as 1MPa, so the value of C_s was determined at 1.3. The value of parameter β_p defining the compressibility-dilatancy boundary is obtained by identifying stress points corresponding to $\dot{\varepsilon}_v^p = 0$ from triaxial tests on saturated samples. The plastic hardening parameter B controls the evolution of hardening. The values of A and B could be determined by the comparisons between a large number of simulations and the experimental data. By comparing the plastic hardening curves under different confining pressures, the parameter β can be determined.

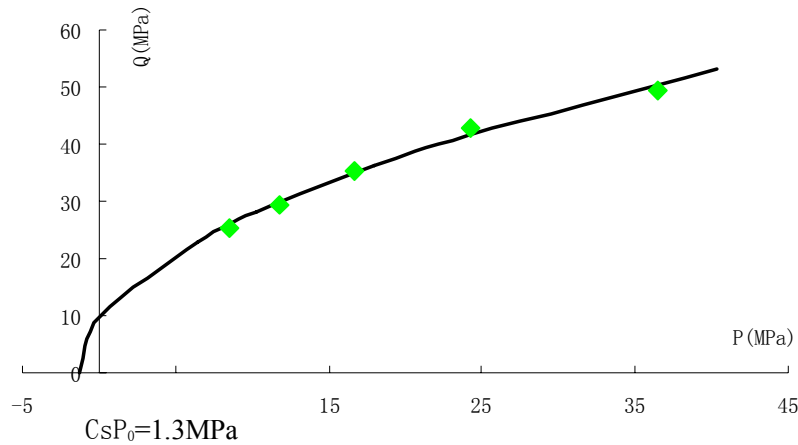


Fig.4 Illustration of the failure surface under undrained condition

Table 1 Representative values of parameters used in saturated simulations

Initial elastic parametres	Plastic parameters	Damage parameters
$E_0 = 5500 \text{ MPa}$	$A = 150$	$\omega_c = 1.0$
$\nu_0 = 0.17$	$C_s = 1.3$	$B1 = 130.0$
	$B = 1.0E - 4$	
	$\beta^1 = 1.0$	
	$\beta_p = 0.8$	

ω_c is the critical value of damage, so it is reasonable to take the value as 1 at failure state. In addition, the value of $B1$ can be determined by evaluating the evolution of elastic modulus with the damage force Y_d^p is evaluated. In Table 1, the parameters determined based on the experimental data are presented.

4.2 The discussion about the influence of saturation degree and confining pressure on parameter β

Based on the comparison between the experimental data and numerical simulation results in saturated conditions, it was found that the value of β should be changed with the evolution of confining pressure. The dependency becomes more significant with the augmentation of the confining pressure, especially when the confining pressure is superior to the value of 10MPa. In additions, β decrease with the diminution of the water saturation. However, under lower saturation, the influence of confining pressure became more important than that of water content. Consequently, an empirical relation was proposed here:

$$\beta = f(P_c) e^{\frac{1}{P_c+c}(sl-1)}, \text{ where } f(P_c) = \beta_0 + \frac{1-\beta_0}{(a(1-\frac{P_c}{23}))^b} \text{ and if } P_c > 23MPa, f(P_c) = 1.0. \quad (24)$$

Where β_0 denotes the initial value of β when confining pressure is 0MPa in saturated condition, and the value of Biot's coefficient b is suggested here; P_c means the confining pressure, and sl represents the saturation degree. In this work, the parameters were selected as $a=60$, $b=2.6$, $c=0.75$.

4.3 The numerical simulation

Figs 5a-b showed the simulation results of uniaxial and triaxial compression tests under different confining pressures with the parameters given above on saturated samples under undrained conditions. A good agreement between numerical simulations and tests data is obtained. As the data of triaxial tests has been used for the determination of the model's parameters, these comparisons represent only verification of the consistence of the parameters. It should be mentioned here that the experimental value of Young's Modulus was adopted in the simulation in order to take into account the influence of confining pressure.

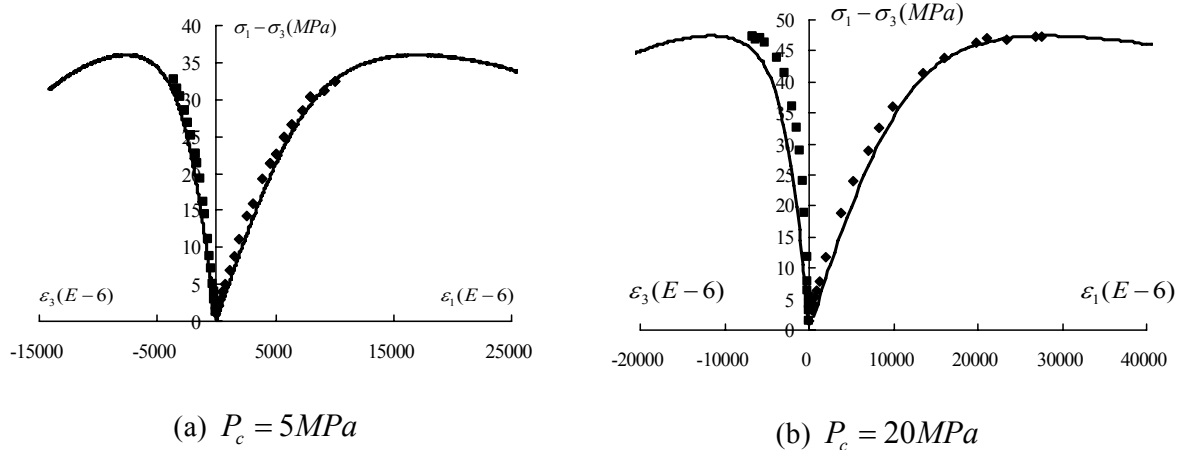


Fig.5 Simulation of triaxial compression tests under different confining pressures(all of the experimental results are obtained from Andra C RP 0 ENG 03.0380/D)

The simulations of uniaxial and triaxial compression test in unsaturated conditions were presented in Fig.6a-b. From the figures, we could notice that a very good agreement was obtained and the capillary effect on mechanical behaviour is correctly described. The experimental value of Young's

Modulus was also adopted in the simulation in order to take into account the influence of confining pressure.

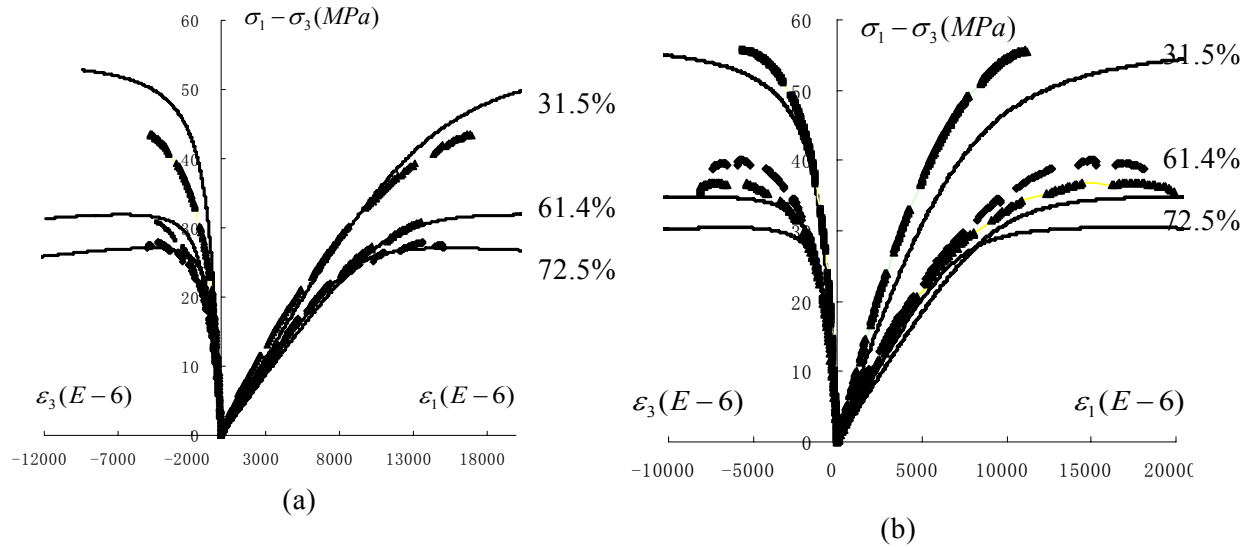


Fig.6 Simulation of triaxial compression test under (a) 5MPa and (b) 10MPa in unsaturated conditions((all of the experimental results are obtained from Andra C RP 0 ENG 03.0380/D))

4.4 uncertainty analysis of material parameters

The parametric uncertainty of the geotechnical material is a critical risk factor in the process of structure design and construction. The uncertainty is mainly caused by the inherent variability of the parameter and the uncertainty of the statistics. So the parameter should be determined based on a large number of experimental results. However, the experimental data is always limited.

For argillite studied, we found the composition of this material was very complicated and a significant variability of the mechanical behaviour was also existed. Taking the Young's Modulus as an example, the average value is 5200MPa, while it is still changeable in the span of $\pm 1900MPa$. From our study, the main physics and mechanical characteristic of argillite are listed in Table 3.

The inherent variability of the physical and mechanical parameter, and also the limitation of experimental results certainly would cause the uncertainty of determined parameters of the model. Therefore, the further study and analysis on the uncertainty of parameters of argillite are still necessary.

Table 2 Representative values of physics and mechanical characters of argillite

Name	Average value	Changeable span
Porosity ϕ	14.9%	$\pm 2.4\%$
compression resistance of uniaxial test R_c	19.1MPa	$\pm 6.1MPa$
Young's Modulus E	5200MPa	$\pm 1900MPa$
Poisson's ratio ν	1.3	± 0.18
modulus of incompressibility K	4400MPa	$\pm 600MPa$
Modulus of Biot M	4900MPa	$\pm 4000MPa$
Coefficient of Biot b	0.6	± 0.2

5 CONCLUSIONS

A new coupled elastoplastic damage model was proposed for the semi-brittle materials. A new approach to determine the model parameters based on the data of undrained triaxial compression test

was suggested. By introducing the concept of plastic effective stress, the model is extended to unsaturated conditions. The influence of confining pressure and saturation degree on the parameter effective stress coefficient β was studied and an empirical relation is proposed. The simulations of laboratory tests have shown a good agreement with the experimental data. As a result, the proposed model is capable to describe the main features of hydromechanical behaviours for this class of material, such as plastic deformation, material damage by microcracks, pressure sensitivity, transition from volumetric compressibility to dilatancy, and strong dependency on water saturation degree.

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