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Research Paper

Constitutive modelling of the time-dependent behaviour of partially saturated rocks

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ABSTRACT

This paper presents a new constitutive model for the time-dependent behaviour of partially saturated rocks. Hydromechanical coupling is formulated in the framework of porous media. Viscoplastic and isotropic damage laws are extended from the original Lemaitre's model using an equivalent pore pressure and an effective stress variable. The model contains a moderate number of parameters which can be identified from the results of typical laboratory experiments. This model can be used for simulating both saturated and unsaturated rocks in a unified manner. It is validated by experimental data obtained from some rocks. Its thermodynamic consistency is also discussed.

1. Introduction

Rocks generally exhibit significant irreversible time-dependent responses [1–3]. Quantifying time-dependent rock deformation is very important for many engineering applications, such as mining industry and petroleum engineering [4]; geohazard prediction [5]; and safety assessment of radioactive waste disposal [4,6]. Regarding the last topic for example, the creep behaviour of the host rock has to be accounted for to see whether it promotes the dissemination of radionuclides and thereby affect the long term safety of the repository [7,8].

In the last decades many constitutive models have been proposed to describe the time-dependent behaviour of rocks. Cristescu [9,10] suggested an efficient approach to model the creep behaviour of rock salt. Using this procedure, Maranini and Yamaguchi [11] proposed a non-associated creep model for the behaviour of Inada granite. Hou and Lux [6] also provided a complete model which investigates a variety aspects of the creep behaviour of rock salt such as strain hardening, recovery, damage and healing. A relatively simple model that allows to describe both instantaneous plastic and time-dependent viscoplastic strain of weak rocks was proposed by [12]. Similarly, Grgic [13] proposed a unified model for both the plastic and viscoplastic behaviour of rocks. Moreover, this model also accounted for (isotropic) damage and failure of rocks, as well as thermodynamic restrictions. Pellet et al. [14] extended the original Lemaitre's model by inserting an anisotropic damage variable. Different from the above models in which purely phenomenological approach is used, Shao et al. [15,16] modelled the time-dependent behaviour of rocks by relating it to the microstructure evolution under loading such as crack propagation.

It is worth noting that all the above models are formulated for dry rocks. Yet, rocks in many applications are saturated by one or several fluids [4,17]. Moreover, pore pressure has an important impact on the time-dependent behaviour of rocks due to pressure-induced mechanical and chemical effects. Mechanically, a (positively) pressurized pore fluid acts to reduce all the applied normal stresses and thereby promotes plastic shearing and dislocation creep [18]. On the same physical grounds, a negative pore pressure (also called "suction" in many situations) tends to confine the solid matrix and limit long-term deformation. In parallel, the absorption of pore fluid onto the internal pore surface and especially the chemical reactions between fluid and solid skeleton might lead to the weakening of rocks [18]. The latter favours subcritical crack growth and refers to stress corrosion phenomenon which is considered as one of the most important mechanisms of creep deformation in brittle rocks [1]. Hence, both mechanical and chemical phenomena induced by pore pressure could lead to

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the weakening effect on the time-dependent behaviour of rocks, which has been experimentally confirmed on many types of rock [5,19–23].

However, in the literature, few constitutive models have examined the effect of pore pressure (or suction) on the long-term behaviour of rocks. Zhou et al. [24] proposed a unified framework to model both the short and long-term deformation of saturated rocks. This model has been extended to unsaturated condition [25], in which the effects of suction on both elastic, plastic, viscoplastic and damage evolutions are considered. The model is sophisticated but it encompasses a large number of parameters. De Gennaro and Pereira [26] combined the so-called isotach approach and the Barcelona Basic Model [27] to describe the time effect on unsaturated soils and soft rocks. Hoxha et al. [28] took into account empirically the influence of relative humidity on creep activation energy to model the creep deformation of the Grozon gypsum rock. This approach is relevant to the available experimental results on that gypsum rock but would not be appropriate to describe the effects of pore pressure in the general case. Recently, Bui et al. [29] proposed a thermodynamically modelling framework for the poroviscoplastic damageable behaviour of rocks but only limited to fully saturated state.

This paper presents a new Unsaturated ViscoPlastic creep with Isotropic Damage (UVPID) model for the time-dependent behaviour of rocks. Formulated within the framework of poromechanics [30,31], the model aims to take into account, in a phenomenological manner, the effects of pore pressure effects as well as hydromechanical couplings. The viscoplastic and damage laws are extended from Lemaitre's model [32] to porous media by means of an equivalent pore pressure and an effective stress variable. The latter allows us to describe the effect of pore pressure in both fully and partially saturated states in a unified and continuous way. A non-associated flow rule is used to reproduce more correctly the creep dilatancy of rocks. Despite the presence of complex couplings, the model is simple enough for applications while its thermodynamic consistency is still satisfied under a realistic constraint discussed in Section 3.

In the following, Section 2 presents the general poromechanical framework. The specific formulation of the model is then presented in Section 3. Section 4 suggests a procedure for determining model parameters and is followed by some numerical validations against experimental results obtained from brittle and quasi-brittle rocks (Section 5). In this work the sign convention of continuum mechanics is adopted (expansive strain and tensile stress counted positively), except in Section 5 where numerical results are represented according to the sign convention of soil mechanics (expansive strain and tensile stress counted negatively) so as to be consistent with traditional interpretation of experimental results. Scalars are denoted in normal character while vectors and tensors are denoted in bold.

2. Poromechanical framework

2.1. Preliminary remarks

An unsaturated rock can be described as a porous medium composed of a solid matrix and a porous space filled by two immiscible fluids noted by subscripts $\alpha \in \{w, g\}$, where w and g stand for the wetting (liquid water) and non-wetting fluid (gas), respectively. The porous network is composed of connected pores, and characterized by the porosity ϕ. Each saturating fluid has its own pore pressure, noted p_w and p_g, and occupies a different porous space respectively represented by the porosities ϕ_w and ϕ_g. The degree of saturation for each fluid is then defined as: $S_w = \phi_w/\phi,\ S_g = \phi_g/\phi$. Apart from the three bulk phases, the interfaces between them can be considered as a fourth phase which has no volume, but possesses its own energy, due to surface tension effect. This interfacial phase and energy have been mentioned in previous works using both phenomenological [31,33] and micromechanical [34] approaches.

The total strain tensor $\boldsymbol{\varepsilon}$, total porosity ϕ, and degree of water saturation S_w are used as observable (external) state variables; while the viscoplastic strain tensor $\boldsymbol{\varepsilon^{vp}}$, viscoplastic porosity ϕ^{vp}, isotropic hardening variable γ_{vp} and isotropic damage variable D are considered as internal variables describing dissipative mechanisms. For the sake of simplicity, only isotropic damage is considered in this paper and damage-induced anisotropy, which is one of the main features of brittle rocks, will be addressed in a future publication.

We also assume that the rock behaves isotropically at their intact state prior to damage; and that strains, porosity and displacement are infinitesimal. Also for simplicity reasons, the following phenomena are *not* considered: the effect of temperature (isothermal condition is adopted), creep recovery, capillary hysteresis, and the dependency of elastic modulus on water pressure.

2.2. Thermodynamic framework

The total strain tensor $\boldsymbol{\varepsilon}$ and total porosity variation $\Delta\phi$ are classically supposed to be decomposable into an elastic $\boldsymbol{\varepsilon^e}$ and a viscoplastic part $\boldsymbol{\varepsilon^{vp}}$:

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon^e} + \boldsymbol{\varepsilon^{vp}}; \quad \Delta\phi = \phi - \phi_0 = \phi^e + \phi^{vp} \tag{1}$$

where ϕ and ϕ_0 stands for the current and initial total porosity, respectively. From the Clausius–Duhem inequality which exhibits the non-negativity of total dissipation, and limiting our attention to the intrinsic dissipation of the skeleton [31], we can write:

$$\Phi_s = \boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}} + p_w\dot{\phi}_w + p_g\dot{\phi}_g - \dot{\Psi}_s \geqslant 0 \tag{2}$$

where Ψ_s is the total free energy of skeleton per unit overall volume, $\boldsymbol{\sigma}$ denotes the stress tensor, and the overdot stands for a time derivative. Note that inequality (2) derived by Coussy [31], although classic in poromechanics, is not fully accepted by all researchers (e.g. [35]). It is however adopted in this paper. Introducing the capillary pressure (suction) $p_c = p_g - p_w$, it is more convenient to rewrite (2) as follows:

$$\Phi_s = \boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}} + p^*\dot{\phi} - \phi p_c\dot{S}_w - \dot{\Psi}_s \geqslant 0 \tag{3}$$

where $p^* = p_wS_w + p_gS_g$ is the average fluid pressure, which becomes the pore water pressure when the material is at full saturation ($S_w = 1$).

Inspired by [31], we assume the following energy separation for unsaturated rocks:

$$\Psi_s = \psi_s(\boldsymbol{\varepsilon^e}, \phi^e, D, \gamma_{vp}) + \phi U(\phi, S_w) \tag{4}$$

where ψ_s denotes the free energy of solid matrix and U the free energy of the interfaces per unit volume of porous space. The physical meaning and justification of this decomposition as well as the role of the interfacial energy have been discussed elsewhere [31,36,37] and will not be analysed in detail herein.

Injecting Eq. (4) in the dissipation expression (3), we obtain:

$$\boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}} + \pi_{eq}\dot{\phi} - \phi\left(p_c + \frac{\partial U}{\partial S_w}\right)\dot{S}_w - \dot{\psi}_s \geqslant 0 \tag{5}$$

where the equivalent pore pressure π_{eq} is defined by:

$$\pi_{eq} = p^* - \frac{\partial(\phi U)}{\partial\phi} \tag{6}$$

which acts, from the energetic point of view, similarly as the liquid pressure for saturated media. Using micromechanical analysis, Coussy and Dangla [31] have pointed out that the equivalent pressure should take the following form: