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Coupling between the statistical damage model and permeability variation in reservoir sandstone: Theoretical analysis and verification

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ABSTRACT

Reservoir sandstone contains pre-existing weaknesses, and its fluid flow properties may be altered when subjected to mechanical loading. Simulation of the complete deformation process of reservoir sandstone and its fluid transportation is important in the fields of rock mechanics and gas production. Based on the statistical damage theory with consideration of void volume changes and fluid pressure, a new constitutive model was developed to describe the mechanical characteristics of saturated porous media in geomaterials. On the basis of the Weibull distribution for rock micro-strength, the damage variable was defined and a semi-analytical permeability variation model was established. Experimental results demonstrated that the theoretical model was in good agreement with the test data during rock deformation, and the permeability variation is a function of the stress-induced damage. Furthermore, the applicability of the rock failure criterion based on the Drucker-Prager criterion and the energy release principle is discussed. Visible influences of void volume change and fluid pressure in the damage variable calculation were also detected.

1. Introduction

The deformation behavior of reservoir rock, together with its permeability variations, is significant for understanding the mechanical properties of rock. These properties are relevant in several fields, for example energy exploitation such as Enhanced Geothermal Systems, Carbon Dioxide Capture Utilization and Storage, and exploration of unconventional gas, i.e. shale gas and coal-bed methane. Note that the failure of rock around a wellbore and permeability variation is a potential instance considered in petroleum engineering applications. Thus, this behavior has become a topic of substantial interests to researchers working in geoscience disciplines. The damage induced by micro-cracks in porous media such as sandstones and the initiation and accumulation of damage in rock materials under loading conditions results in great variations in the solute transport properties (Jiang et al., 2010; Oda et al., 2002; Shao et al., 2005; Souley et al., 2001).

A number of proposed damage-induced permeability models have attempted to account for the damage mechanisms mentioned above using phenomenological approaches and micromechanical techniques. Phenomenological models (Chow and Wang, 1987; Dragon et al., 2000; Hayakawa and Murakami, 1997; Ju, 1989; Murakami and Kamiya, 1997; Shao et al., 2005; Xu and Arson, 2014) use internal variables to represent the degraded state of the material and damage-evolution laws are formulated in the framework of the thermodynamics of irreversible processes. Micromechanical models (Bary, 2011; Ju and Lee, 1991; Lee and Ju, 1991; Pens et al., 2002; Shao and Rudnicki, 2000; Tvergaard and Nielsen, 2010; Zhou et al., 2007) adopt various types of the available up-scaling approaches, such as the self-consistent estimate and the interaction direct-derivative estimate, to consider the interaction and spatial correlations of cracks. The crack density is used as a precise parameter for quantitative characterization of the effective permeability. Note that the phenomenological damage variables fail to consider relevant microstructural features, and micromechanical models and damage-induced permeability variation models are not very applicable for solving practical rock-

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engineering issues. Both the damage models and the permeability variations require further investigation.

Statistical physics connects continuum mechanics, damage mechanics and material mechanics and has contributed to the development of rock constitutive laws. For instance, the statistical damage constitutive model for rock (Krajcinovic and Rinaldi, 2005; Krajcinovic and Silva, 1982; Lemaitre, 1985), which describes the progressive failure process of intact heterogeneous rock, has been applied successfully to deal with the constitutive response of rocks, and was subsequently further developed by Tang (Tang, 1997). This model involves an analytical probability distribution to characterize the microscopic strength of rock elements, e.g. the normal distribution (Cao et al., 2007), the maximum entropy distribution (Deng and Gu, 2011; Deng et al., 2004) or the Weibull distribution (Li et al., 2012). However, the statistical damage constitutive model is based on the theory of continuum mechanics, which fails to recognize the effect of void volume changes during deformation. It has also been pointed out that the original cracks and their further propagation during progressive failure all contribute to permeability variation.

Hence, a key point for permeability variation within the statistical damage constitutive model is how to define the damage variable more accurately. Lemaitre (Lemaitre, 1985) proposed that the damaged part in a rock cannot resist any load, but Cao (Cao and Zhang, 2005) put forward the view that the damaged part can still resist external loading until the rock strength is completely lost. There has been little development of models incorporating statistical damage-induced permeability variation. In addition, previous models have mainly been focused on external loading and its damage-induced effects, so the working fluid pressure within the porous media (such as rock materials) has been ignored. However, inclusion of this parameter is essential to establish a potentially promising permeability variation model. On this basis, with the main objective of extending previous work, herein we apply a reasonable constitutive relation to reservoir sandstone, which assumes that the materials consist of three parts: voids, the damaged part and the undamaged part. Furthermore, the damage variable has been used to describe the capacity for real fluid transportation in a porous medium. The model described in this study yields the correlation between the stress condition and the permeability more comprehensively. Problems of the criteria used for microelements and other factors, such as the fluid pressure and void change, were also examined, together with their effect on damage estimation.

2. The extended statistical damage model

The previous conceptual model for porous media like reservoir sandstone was updated by dividing the materials into three parts: the damaged part, the undamaged part and the voids. All parts are under apparent stress σ_i $(i = 1, 2, 3)$. The definition and derivation of apparent stress is described in (Cao et al., 2010). Then, assuming that the reservoir sandstone is composed of blocks, voids and fractures (which provide fluid migration and storage capacity), the potential void structure can resist a possible loading equal to the hydraulic pore pressure (p).

2.1. Constitutive stress equilibrium

The net stresses σ^u and σ^d are assumed to be supported by the undamaged and damaged parts of the rock, respectively. On the basis of the definitions and assumptions illustrated in Fig. 1, together with the static equilibrium equation, the following relationship applies

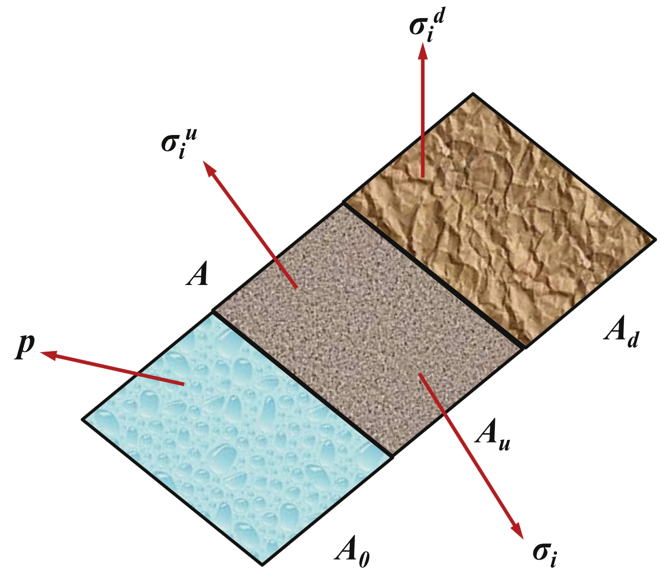

Fig. 1. Schematic diagram of the assumptions about reservoir sandstone (porous media) used in this study.

$$\sigma_i A = \sigma_i^u A_u + \sigma_i^d A_d + pA_0 \tag{1}$$

where A_u, A_d and A_0 denote the areas of the undamaged zones, damaged zones and voids (pores and fractures), respectively, and A represents the cross-sectional area of the rock. In addition, a definition of σ_i^d was developed (Cao and Zhang, 2005).

$$\sigma_1^d = \sigma_3^d \tan^2 \alpha + 2c \tan \alpha \tag{2}$$

$$\sigma_3^d = \frac{(1+\mu)\sigma_c^2 \cot \varphi}{3(1+\tan \alpha)E\varepsilon_1} - \frac{c(\cot \varphi + 2 \sin \alpha)}{\sin \alpha(1+\tan \alpha)} \tag{3}$$

where σ_c is the uniaxial compression strength and μ is the Poisson's ratio for the rock sample, ε_i $(i = 1, 2, 3)$ is the principal strain of the rock specimen under triaxial compression, σ_i^d $(i = 1, 2, 3)$ is the principal stress acting on A_d, φ is the internal friction angle, c is the cohesion and E is the elastic modulus of the rock. Subsequently, α can be determined using the following equation

$$\alpha = \frac{\pi}{4} + \frac{\varphi}{2} \tag{4}$$

where n and the damage variable (D) are defined as

$$n = A_0/A \tag{5}$$

$$D = A_d/(A_u + A_d) \tag{6}$$

By substituting Eqs. (5) and (6) into Eq. (1), the following relationship is obtained

$$\sigma_i = \sigma_i^u(1-D)(1-n) + \sigma_i^d D(1-n) + pn \tag{7}$$

According to the hypothesis of strain equivalence (Lemaitre, 1985), the following basic rules are required

$$\varepsilon_i = \varepsilon_i^u = \varepsilon_i^d \tag{8}$$