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Numerical modeling of permeability evolution based on degradation approach during progressive failure of brittle rocks

Zhang Chunhui [a,*], Yue Hongliang [a], Zhao Quansheng [a], Wang Laigui [b]

[a] School of Civil Engineering, Hebei University of Science and Technology, Shijiazhuang 050018, China
[b] School of Mechanics and Engineering, Liaoning Technical University, Fuxin 123000, China

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A B S T R A C T

The permeability evolution of rock during the progressive failure process is described. In combination with the strength degradation index, the degradation formulas of *s* and *a*, which are dependent on the plastic confining strain component, the material constants of Hoek–Brown failure criterion are presented, and a modified elemental scale elastic–brittle–plastic constitutive model of rock is established. The relationship between volumetric strain and permeability through tri-axial compression is investigated. Based on the above, a permeability evolution model is established. The model incorporates confining pressure-dependent degradation of strength, dilatancy and corresponding permeability evolution. The model is implemented in FLAC by the FISH function method. The permeability evolution behavior of rock is investigated during the progressive failure process in a numerical case. The results show that the model is capable of reproducing, and allowing visualization of a range of hydro-mechanical responses of rock. The effects of confining pressure on degradation of strength, dilatancy and permeability evolution are also reflected.

1. Introduction

Excavation damage zones occur in all types of excavation, and stress redistribution and changes in permeability due to the excavation within the zones. The interaction between these changes, known as hydro-mechanical coupling, significantly affects the sealability of these zones and both the short- and long-term stability of the excavation. The range of application includes tunneling, coal mining, coal methane extraction, oil and gas extraction, hydrogeological and well test analyses, geothermal energy, deep well injection of liquid and solid wastes, geologic storage of natural gas, and geologic sequestration of CO_2, as well as a variety of geologic processes [1–5]. Triaxial compression testing is often the main approach to the study of micro-structure damage and permeability evolution of rock and is often used to predict damage zones and permeability evolution in rock engineering. In triaxial compression tests, with increasing load and deformation, initial defects will grow and new ones will be initiated; later, they will be connected to each other and consequently permeability increases. Many studies have been conducted to understand the behavior of permeability under compression; for example, Wang and Park [6] found that permeability increases appreciably during the dilation phase. A flow-stress-damage (FSD) coupling model for heterogeneous rocks that takes into account the growth of existing fractures and the formation of new fractures is proposed by Tang et al. [7] to investigate the behavior of fluid flow and damage evolution. Yuan and Harrison [8,9] developed a hydro-mechanical local degradation approach, which was used to investigate progressive damage and associated flow behavior in heterogeneous rock. Jiang et al. [10] found that the permeability significantly increases with the growth and coalescence of micro-cracks. Perera et al. [11] investigated the effects of temperature on the permeability of fractured coal. Xie et al. [12] defined the mining-enhanced permeability as the change in permeability by volumetric change of coal and derived four theoretical models. The Complex Piecewise function is employed to describe the relationship between permeability and volumetric strain by Xue et al. [13]. Yu et al. [14] investigated the permeability evolution of briquette specimens subjected to stress disturbance and variable temperature. When the specimen fails the permeability also increases. Triaxial tests were conducted on three different rocks, and the confining pressure dependence of the permeability of three types of rock was investigated by Badrul et al. [5]. Cai et al. [15] explored the impact of cyclic loading on coal permeability due to reversible deformation and irreversible damage and extension using imaging with X-ray computed tomogra-

* Corresponding author. Tel.: +86 13011592917.
E-mail address: zhangchunhui789@126.com (C. Zhang).

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phy and acoustic emission (AE). Chen et al. [16] proposed an empirical relation to describe the influence of damage evolution and confining pressure on permeability variation. Chen et al. [17] experimentally studied the cracking process of granite under compressive stress and its effect on permeability. Corresponding to the distinct features in stress–strain behavior, the permeability of the Beishan granite was found to evolve with a clear permeability decrease in the initial microcrack closure region, a constant permeability value in the elastic region and a dramatic permeability increase in the crack growth region. Yu et al. [18] proposed a permeability evolution model for rock subjected to loading but found that permeability is influenced by element size. Chen et al. [19] established the correlation between fracture permeability and effective stress for gas shales through theoretical derivation.

In this paper, the degradation formulas of s and a, the material constants of the Hoek–Brown failure criterion are combined with the strength degradation index and a modified elemental scale elastic–brittle–plastic to establish a constitutive model of rock. The relationship between volumetric strain and permeability through tri-axial compression is investigated and a permeability evolution model is established. The permeability evolution behavior of rock is investigated during the progressive failure process in a numerical case.

2. Elemental constitutive law of rock

Ignoring the compaction stage inside the rock sample before peak strength is reached, rock may be viewed as an elastic–brittle–plastic material [18], and the relationship of the whole stress–strain curve is simplified into three stages including a linear elastic stage (OA), a brittle degradation stage (AB) and an ideal plastic stage (BC) under the compression states (Fig. 1).

2.1. Elastic stage

In the linear elastic stage, the components of stress are linear functions of the components of strain according to Eq. (1):

$$\Delta\sigma_{ij} = 2G\Delta\varepsilon_{ij} + (K - 2/3)G\Delta\varepsilon_{kk}\delta_{ij} \tag{1}$$

where K is the bulk modulus and G is the shear modulus. δ_{ij} is the Kronecker delta, $\Delta\sigma_{ij}$ and $\Delta\varepsilon_{ij}$ are increments of effective stresses and strains, respectively.

2.2. Failure criterion

When the peak stress is reached, i.e. shear failure begins, brittle degradation occurs. In this case, the non-linear Hoek–Brown failure criterion is appropriate to describe the non-linear behavior considering the confining pressure:

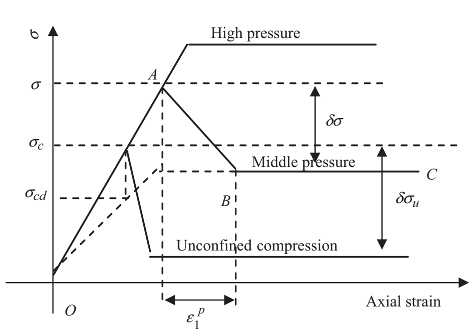

Fig. 1. Simplified deformation process for rock element.

$$F = (\sigma_1 - \sigma_3) - \sigma_c\left(m_i\frac{\sigma_3}{\sigma_c} + s_i\right)^{0.5} = 0 \tag{2}$$

where σ_1 and σ_3 are the major and minor effective principal stresses at failure, σ_c is the unconfined compressive strength of the intact rock material, m_i and s_i are material constants of rock.

2.3. Residual strength dependent of confining pressure

The extension of inner micro fissures degrades the mechanical properties of the rock, and the brittle degradation stage begins. When the residual strength is reached the degradation ceases and ideal plastic flow is maintained. The dependence of residual strength on confining pressure has been proved to be correct from experimental results, and may be described by a degradation index proposed by Fang and Harrison [20,21]:

$$\sigma_r = \sigma\left(1 - \frac{r_d\delta\sigma_u}{\sigma_c}\right) \tag{3}$$

where $\delta\sigma_u$ is the strength degradation in the unconfined case, σ is the peak strength at a confining pressure of σ_3, r_d is the strength degradation index, and is expressed as [20]:

$$r_d = \exp(-n_d\sigma_3) \tag{4}$$

where n_d is a fitting coefficient.

The residual strength of a rock element also follows the Hoek–Brown failure criterion with the material parameters of s_d and m_d degradated from s_i and m_i, which are written as [18,20]:

$$s_d = \left(\frac{\sigma_{cd}}{\sigma_c}\right)^2 \tag{5}$$

$$m_d = m_i\left(\frac{\sigma_{cd}}{\sigma_c}\right)^{9/14} \tag{6}$$

$$\sigma_{cd} = \sigma_c - r_d\delta\sigma_u \tag{7}$$

where s_d and m_d are the Hoek–Brown material parameters of the residual strength.

Replacing m_i and s_i in Eq. (2) with s_d *and* m_d defined by Eqs. (4) and (6) respectively, we obtain

$$F = (\sigma_1 - \sigma_3) - \sigma_c\left(m_d\frac{\sigma_3}{\sigma_c} + s_d\right)^{0.5} = 0 \tag{8}$$

Eq. (8) defines the degraded strength surface for a failed element.

2.4. Brittle degradation

Brittle degradation is dependent on confining pressure. The degradation and dependence behavior is provided by specifying tables in FLAC that relate each of the properties s_i, m_i to a softening parameter. The softening parameter selected in this paper is the plastic confining strain component, e_3^p. The choice of e_3^p is based on physical grounds. For yield near the unconfined state, the damage in brittle rock is mainly by splitting (not by shearing) with cracks normally oriented in the σ_3 direction. The parameter e_3^p is expected to correlate with the micro crack damage in the σ_3 direction. Therefore, it is assumed that the strength parameters decrease linearly with ongoing plastic strain e_3^p, as shown in Fig. 2.

The plastic confining strain component e_3^p, is confining pressure-dependent. According to investigation of typical lab results, a function is used to describe the relation between e_3^p and confining pressure σ_3:

$$\Delta e_3^p = D\exp(K\sigma_3) \tag{9}$$

where D and K are fitting parameters.