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Energy evolution mechanism in process of Sandstone failure and energy strength criterion

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ABSTRACT

To reveal the inherent relation between energy change and confining pressure during the process of sandstone damage, and its characteristics of energy storage and energy dissipation in different deformation stage. Obtaining the mechanical parameters by testing the Sandstone of two$_1$ coal seam roof under uniaxial compression in Zhaogu coalmine, using Particle Flow Code (PFC) and fish program to get the meso-mechanical parameters, studying Sandstone energy evolution mechanism under different confining pressures, and deducing energy strength criterion based on energy principle of rock failure, some main researching results are reached as follows: with the increasing of confining pressure, the Sandstone yield stage and ductility increases, but brittleness decreases; Under higher confining pressure, the elastic strain energy of Sandstone before peak approximately keeps constant in a certain strain range, and rock absorbs all the energy which converts into surface energy required for internal damage development; Under lower confining pressure, Sandstone no longer absorbs energy with increasing strain after peak under lower confining pressure, while it sequentially absorbs energy under higher confining pressure; Under lower confining pressure, the energy Sandstone before peak absorbed mainly converts into elastic strain energy, while under higher confining pressure, dissipation energy significantly increases before peak, which indicates that the degree rock strength loss is higher under higher confining pressure; with the increasing of confining pressure, the limit of elastic strain energy increases and there exists a favourable linear variation relationship; At the peak point, the ratio of elastic strain energy to total energy of Sandstone nonlinearly decreases, while the ratio of dissipation energy to total energy nonlinearly increases with the increasing of confining pressure; According to energy evolution mechanism of rock failure, an energy strength criterion is derived. The criterion equation includes lithology constants and three principal stresses, and its physical meaning is clear. This criterion has an evident advantage than Hoek-Brown and Drucker-Prager criterion in calculation accuracy and can commendably describe rock failure characteristics.

1. Introduction

Rock deforms under action of outer loads even loses stability which accompanying by energy transformation. The energy of rock destroying produces partly as elastic energy and partly as dissipation energy. The dissipation energy causes internal damage and strength losing while elastic energy causes rock overall failure (Xie et al., 2005). The rock damage is because energy drive in nature. Consequently, from the energy view on rock damage mechanism and derive rock damage energy strength criterion is one of the present research hot spots in rock mechanism fields.

The energy evolution and strength criterion of rock have been widely concerned by sholars at home and abroad and achieved fruitful results. Xie et al. (2005) studied the intrinsic relationship between the rock failure and energy dissipation and release, and presented a rock failure criterion based on elastic strain energy. Zhang and Gao (2015) investigated the effect of water content on the energy evolution of red sandstone and analyzed the distribution and evolution of elastic energy and dissipated energy. Huang et al. (2012) and other researchers pointed out that the energy dissipation of rock causes internal damage and loss of strength, and analyzed strain energy conversion during unloading (Huang and Li, 2014). Liu et al. (2013a) calculated the specific energy values of rock at different failure stages by mathematical and physical analysis. Li et al. (2011) studied the energy variation of rock in the process failure. You and Hua (2002) studied the relationship between absorption energy of siltstone and confining pressure. Ayatollahi et al. (2015) proposed a modified mixed mode fracture model called the generalized strain energy density criterion. Based on energy dissipation, a new damage constitutive model was developed to describe the behaviour of rocks under cyclic loading (Liu et al., 2016). Zhang et al. (2013) studied the energy transformation of marble in process of failure under different initial confining pressure, unloading rate and unloading stress levels. Yang et al. (2007) analyzed the deformation and energy property of marble under triaxial compression

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test. Poulsen et al. (2015) established a synthetic rock mass model to estimate the mass scale properties of rock directly from properties of intact rock and observed jointing geometry and strength. To overcome these limitations of Mohr-Coulomb criterion, Mahendra Singh deduced a semi-empirical expression for non-linear criterion (Singh and Singh, 2012). A quantitative comparison of some of the most common criteria for rock failure (Thomas and Radu, 2008; Colmenares and Zoback, 2002). Aubertin et al. (2000) proposed a general multiaxial criterion for describing the short-term failure strength as well as the damage initiation threshold of rocks and rock masses. Fuenkajorn et al. (2012) assessed the influence of loading rate on the compressive strength and deformability of the Maha Sarakham salt. Cornetti et al. (2006) introduced a new failure criterion in the framework of Finite Fracture Mechanics. Tarasov and Potvin (2013) analysized the applicability of various criteria for assessing rock brittleness. Yu et al. (2000) summarized the development of rock strength theory in twentieth Century. As well as, study on energy failure criterion of geotechnical materials (Gao et al., 2007; Liu et al., 2013b).

This text revealed the inherent relation between energy change and confining pressure during the process of sandstone damage, and its characteristics of energy storage and energy dissipation in different deformation stages. From a new point of view i.e. relation of maximum elastic energy limit and confining pressure built up a strength criterion based on energy theories. After contrasting the analyzing results with those of classic Hoek-Brown criterion and Drucker-Prager criterion, this energy strength criterion was regarded practicable and applicable. Related research results are of great importance when used to guide the underground rock analysis of the damage mechanism and stability judging.

2. Particle flow code and model

Adopting molecular dynamics thoughts P. A. Cundall and O. D. Strack built up particles flow theory based on discrete element analyzing method, from mesoscopic mechanics angle concentrating on explaining material damage and fracture mechanism, analyzing large deformation process from linear elastic stage up to broken damage stage, who mainly was used for rock like material mechanics and engineering characteristics researches. The constitutive relationship of particle model need not be defined beforehand in Particle Flow Code (PFC). Parallel bond model is used in rock like material where the bonding happened within the scope of a radius R circle or a square, which transmitting forces and bending moments simultaneously. Normal stress σ and tangent stress τ acted on parallel bonding model can be computed by formulas (1) and (2), as shown in Fig. 1.

$$\sigma = \frac{-\overline{F}_i^n}{A} + \frac{|\overline{M}_3|}{I}\overline{R} \tag{1}$$

$$\tau = \frac{|\overline{F}_i^s|}{A} \tag{2}$$

In the formula, $\overline{F}_i^n$, $\overline{F}_i^s$ and $\overline{M}_3$ are normal force, tangent force and bending moment separately, A, I are parallel bonding sectional area and rotary inertia separately, $\overline{R}$, $\overline{L}$ are bonding radius and thickness separately.

When loaded stress exceeds bonding strength, parallel bonding breaks. While normal stress and tangent stress exceed the bonding strength which caused tensional and shear cracks (Itasca Consulting Group, 2008).

3. Sandstone characteristic and meso-mechanics parameters

3.1. Sandstone characteristic and mechanics parameters

The Sandstone mined from Zhaogu coalmine 1st division two1 coal seam roof which located in Hui county Henan province. Two1 coal seam belongs to Shanxi Group of Lower Permian System, buried depth is 600 m, the coal seam thickness is 1.21–1.71 m, and average thickness is 6 m, simple structure. The direct roof of two1 coal seam is sandy mudstone, and indirect roof is fine-coarse Sandstone. Sandy mudstone is thin and black and sandstone mudstone locally layer crossing, containing mica fragments and pyrite nucleus. Fine-coarse sandstone presented thin layer and dark grey which made up of quartz, and medium sorting, mud exists between layers and longitudinal fissure joint developed.

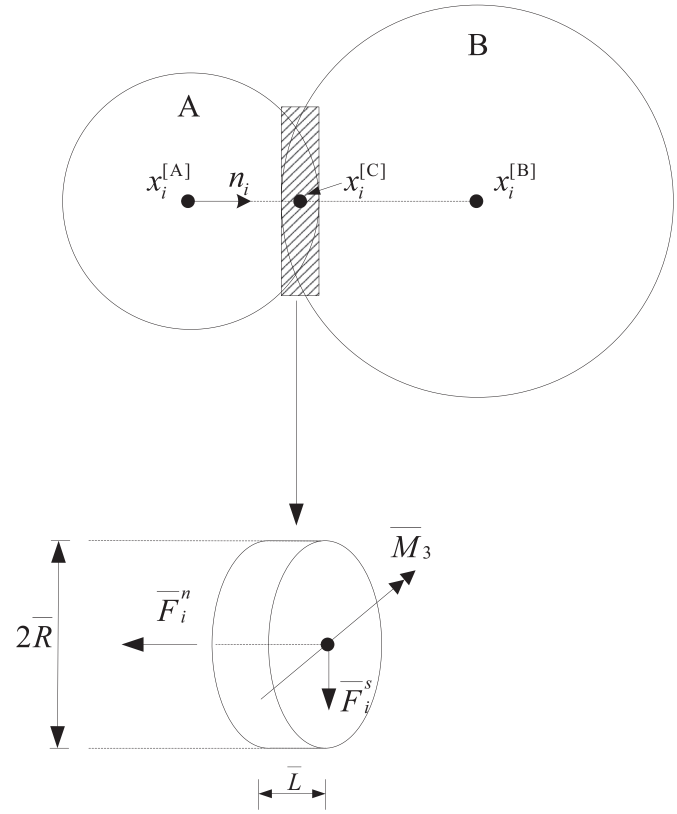

Fig. 1. Parallel bond model.

The transporting tunnel and track tunnel were arranged along the coal seam roof. The mechanic characteristics of the coal seam roof were tested which can be used to analyze the stability of tunnel and assist to choosing rational supporting scheme (as shown in Fig. 2). Processed sample size is 50 mm × 100 mm and the maximum roughness is 0.03 mm satisfying the requirements of testing. The uniaxial compressive strength of sandstone is 122 MPa, elastic modulus is 20 GPa.

3.2. Sandstone meso-mechanics parameters

Uniaxial compressive sample of sandstone size is 50 mm × 100 mm. According to PFC, 29522 different size particle units were established randomly in a certain radius scope which obeying normal distribution. Maximum particle size and minimum particle size ratio is 1.66 and the minimum radius is 0.16 mm. In the parallel bonding model friction factor of particles is 0.5.

The meso-mechanics parameters were given to depict macroscopic mechanics behavior through particle flow code software, which can be anti-analyzed by uniaxial compress experimental results. Final mesoscopic mechanics parameters of sandstone were shown in Table 1.

The mechanic characteristics and energy evolution features during damage process of sandstone under the action of different confining pressure were researched by the sandstone numerical model.