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Compression–shear strength criterion of coal–rock combination model considering interface effect

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ABSTRACT

Surrounding rocks around coal tunnel in western mining area of China are typical composite structures composed of weakly cemented soft rock and hard coal, and the tunnel stability is closely related to the overall mechanical behavior of the combination body. The equivalent homogeneous model of coal–rock combination body and its stress state expressions were firstly established based on the strain energy equivalency principle. Then, the general compression–shear failure criterion of the equivalent model which takes into account the cohesive strength of the interface between coal and soft rock was derived by assuming that the yielded mediums all met Mohr–Coulomb criterion. Furthermore, accuracy of the proposed analytical model was verified by carrying out laboratory test for coal-mudstone specimen, and it found that the theoretical results were in good agreement with the test values. Strength of the combination body lies between the strong body and weak body. Finally, the effects of interface cohesion strength, rock thickness and stress level on the failure behavior of combination model were analyzed based on the analytical model. Results show that the proposed model not only contains the classical sliding failure theory for two-dimensional weak plane presented by Jaeger, but also reflect strength behavior of a more complex composite model composed of different rock mediums and structural plane. Thus, the analytical model provides theoretical basis for further studying the mechanical behavior of coal–rock combination model.

1. Introduction

Underground engineering is mostly located in layered rock masses with different lithology and stress states, so it is more approximate to regard the surrounding rocks as composite model composed of various rock mediums with different cohesive styles and thicknesses. In western mining area of China, due to the poor characteristics of weakly cemented soft rock, roadway is mainly arranged in coal seam which is relatively stable. Therefore, a distinctive composite model of surrounding rocks composed of soft rock and relatively hard coal is formed. However, a variety of mine disasters such as coal outburst, roof collapse and closure of working face frequently occur. Actually, theses disasters are closely related with the overall structural mechanical behavior of the combination body. Therefore, it has important engineering significance to make clearly the macro strength of surrounding rock from a perspective of composite model.

2. State of the art

Currently, some research achievements have been obtained in light of the mechanical behavior of coal–rock combination model. In terms of experimental studies, Petukhov and Linkov (1979) were the first to have discussed the stability of two-body system composed of roof, floor and coal. Current status show that the impact tendency of coal–rock combination body has become the focal point of study, such as the correlation between the strength of single body and the impact tendency of combination body (Liu et al., 1999), the effect of rock height on the impact tendency of two-body model and three-body model composed of hard rock and coal (Li et al., 2005; Liu et al., 2004a,b), and the influence of coal content on the elastic modulus, strength and outburst indexes of combination model (Dou et al., 2006). Besides, many researchers

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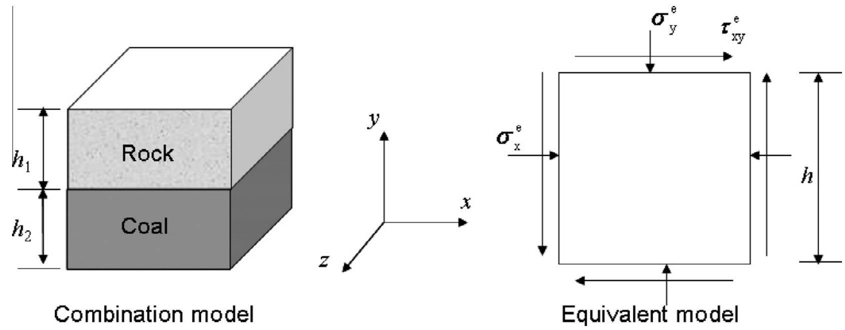

Fig. 1. Equivalent model of coal–rock combined model.

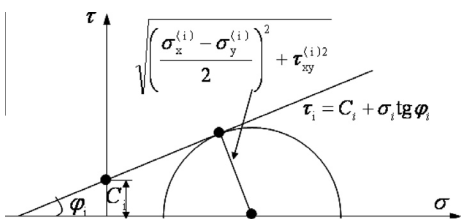

Fig. 2. M–C strength criterion for each medium.

(Chen et al., 2010; He et al., 2011; Huang and Liu, 2013; Jin et al., 2013; Lu et al., 2008; Rafael and Cristobal, 2010; Takeuchi et al., 2006) analyzed the deformation and fracture behavior of coal–rock combination body and obtained the precursor information of failure by means of acoustic-electric effect and seismic spectrum analysis respectively. Wang et al. (2014) carried out a double-shear frictional test for sandstone-coal composite sample by biaxial loading system, and discussed the space-time evolution of displacement field as well as the acoustic emission characteristics during sliding. According to the test results, Lu et al. (2007) further put forward a way to reduce the impact tendency of coal–rock combined body by weakening its strength. On the aspect of failure characteristics of the combination model, some scholars analyzed the failure evolution of combination body under uni-axial and tri-axial compression respectively from the microscopic and macroscopic scale based on laboratory experiments, such as the effect of contact angle on the general strength (Guo et al., 2009, 2011), the rupture evolution behavior along with the acoustic emission during failure process under multi-step cycling loading and unloading (Zuo et al., 2011a,b, 2013), and the strength and failure behavior of different combination models such as rock–coal–rock, rock-coal and coal–rock (Zhang et al., 2012). From these studies, it is found that the impact tendency and failure behavior of combined coal–rock body exhibit different characteristics with single rock body.

On the numerical simulation research, some scholars simulated the failure process of coal–rock combination body by Realistic Failure Process Analysis (RFPA) and FLAC3D respectively, and discussed the unstable precursors, resilience, strain localization and size effect (Bao et al., 2013; Chen et al., 1997; Deng et al., 2012; Li et al., 2012; Lin et al., 1999; Liu et al., 2004a,b; Wang et al., 2006; Zhao et al., 2013a, 2013b). Besides, Li et al. (2011), Wang (2006) and Zhang and Dou (2006) discussed respectively the effect of rock height, hardness of coal seams on the outburst tendency of combination body as well as its deformation and failure behavior. Besides, Mu et al. (2009) investigated the influence of roof lithology on the coal seam in the side walls of roadway.

In the aspect of theory research, achievements mainly focus on the nonlinear dynamic behavior during unstable failure of the combination body, such as the proposed cusp catastrophe model for the unstable failure of coal pillar and two-body system (Gao et al., 2005; Pan et al., 2006; Zhang et al., 2009), and unstable failure process of the mechanical system composed of elastic roof and strain-softening coal pillar by employing the cusp catastrophe model (Qin and Wang, 2005).

From the above analysis, the proposed results are mainly concentrated on the impact tendency of coal–rock combination body and failure behavior from experimental aspects, and no relevant theoretical explanations are presented to interpret the strength behavior. Moreover, the conclusions are mainly drawn based on the combination of hard rock and soft coal in order to reveal the engineering catastrophes induced by underground coal mining at great depth. In these models, the rock strength is much higher than that of coal. However, in western mining area of China, roadways are mainly located in soft rock strata which exhibit the characteristic of low strength. Prophase researches have proved that the strength of soft rock was very close to that of coal, sometimes even lower. So the above conclusions do not apply to the features of surrounding rocks in western mining area which is composed of weakly cemented soft rock and relatively hard coal. Besides, the conclusions are lack of generality which are drawn based on specific rock medium.

In view of the above problems, this paper will carry out the theoretical analysis for the strength criterion of soft rock-coal combination model, and eventually establish the theoretical compression–shear strength criterion in order to make up the deficiency in test results, so as to lay the theoretical foundation for further analyzing the general mechanical behavior and roadway stability of soft rock-coal combination model in western mining area.

3. Equivalent model of coal–rock combination body

Coal–rock combination body is actually a kind of multiphase solid which presents step-variation lithology in each layer (Yang and Jiang, 1990). Here, the multiphase model is firstly simplified as homogeneous body by employing the strain energy equivalency principle between the two. For convenience, the following assumptions were firstly made:

(1) Coal and rock are both homogeneous isotropic medium.
(2) The interface thickness is not considered.
(3) The yielding condition of each monomer and the equivalent model as well as the interface all satisfy Mohr–Coulomb strength criterion.
(4) Stresses in each monomer and the equivalent model are all continuous.

A homogeneous rock whose mechanical behavior depends on the mechanical parameters and dimensions of coal and rock as well as the contact state is assumed as the equivalent model of the