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A coupled macro- and meso-mechanical model for heterogeneous coal

Jiachen Wang, Zhaohui Wang*, Shengli Yang

College of Resources and Safety Engineering, China University of Mining and Technology, Beijing 100083, China

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ABSTRACT

A thorough understanding of the deformation behavior, damage accumulation, and progressive failure of heterogeneous coal is a prerequisite for effective control of the surrounding rock and efficient exploitation of resources in underground coal mines. Such understanding can be obtained by analyzing both the macro- and meso-responses of coal to loading. Accordingly, a coupled macro- and meso-mechanical model for heterogeneous coal is developed and implemented in FLAC3D in the present study. The model is based on elasto-plastic mechanics and the energy dissipation and release principle, and heterogeneity is incorporated by the combination of a statistical approach and the discrete fracture network method. The model is calibrated by experimental data and is used to simulate stress-strain responses, the evolution of acoustic emission (AE) events, and energy conversion in compressed coal. The results reveal that: (1) the model can efficiently capture the dependency of the deformability, compressive strength and AE characteristics on the confining pressure; (2) the anisotropic behavior of heterogeneous coal is realistically realized, and the initiation, propagation and coalescence of micro-cracks can be located and tracked; and (3) stress paths, the degree of heterogeneity, and the unloading rate of confining pressure significantly influence the axial stress-strain response and AE event evolution in the stressed coal. The proposed model produces reasonable values for the roof weighting interval and expansion of the excavation-damaged zone around the gate when compared to the field data measured at the Dongzhouyao mine of China.

1. Introduction

In an underground coalmine, a comprehensive understanding of the coal's macroscopic and mesoscopic failure mechanisms is essential to the safety and efficiency of mine operational procedures, such as the control of the surrounding rock and the assessment of top-coal cavability in longwall top-coal caving faces. To achieve the two major goals of underground coal mining, i.e., to avoid uncontrollable failure in surrounding rock and to accelerate the breakage of intact coal [1–3], mining engineering researchers give first priority to the study of coal failure mechanisms, and numerous efforts have been made to provide increasingly deep insight into the field.

The deformation behavior, damage accumulation, and macro-failure patterns of stressed coal are commonly examined by uniaxial and triaxial compression tests [4–6]. The stiff servo-controlled test machine enables researchers to observe realistic rock behavior and extends the analysis to the post-peak range indicated in stress-strain diagrams [7]. Both the pre-failure elastic properties and post-failure plastic parameters of coal have been extensively plotted and interpreted [8–11]. Based on the slope-change trend, the stress-strain curve of coal can be divided into pre- and post-failure stages. The coal exhibits linear elastic mechanical behavior in the pre-failure region and nonlinear deformation behavior (characterized by strain hardening/softening and volumetric dilation) after the initial yield stress is reached [12–15]. In the softening stage, instability occurs as the damage accumulation of coal reaches a critical value [16]. After collapse, compressed coal (or weak rock) exhibits two typical failure modes: axial splitting and shear faulting [17,18]. The mechanisms underlying these two failure patterns can be found in the work by Nemat and Horii[19,20].

Stress-strain curves are typically categorized into two types, namely, class I and class II, based on strike differences in the post-peak region [17,18]. The ductile (class I) or dynamic (class II) failure of coal can be explained by the strain energy dissipation and release principle proposed by Xie [21]. Since the introduction of strain energy theory, analysis into the conversion of strain energy in stressed coal has been extensively performed by various researchers, demonstrating that the load-bearing capacity of coal is positively correlated with its potential strain energy storage capacity [22–24]. Strain energy criteria for predicting the catastrophic failure of surrounding rock and the intensity of potential disasters have also been established [25,26].

Despite extensive studies on the nonlinear macro-mechanical behavior of coal, researchers continue to experience difficulty in

* Corresponding author.
E-mail address: zwang234@uottawa.ca (Z. Wang).

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determining the threshold of accumulated damage to cause a catastrophic collapse; ascertaining this threshold is critical to dynamic disaster prediction. Furthermore, stress-strain curves alone cannot reflect the damage accumulation, deformation localization, and micro-crack propagation within stressed coal. These limitations can be effectively resolved by observing the meso-responses to loading. Advanced testing systems, such as high-speed cameras, scanning electron microscopes, acoustic emission (AE) data acquisition systems, and X-ray computed tomography (CT) scanners, have allowed researchers to monitor the meso-behaviors of coal and to further identify the progressive processes that underlie coal failure [27–31]. Of those, easily detectable AE signals can be used to characterize micro-crack development in the failure process of coal in the lab and serve as an effective precursor for failure, based on which a micro-seismic (MS) monitoring technique has been developed and used to predict dynamic disasters in deep coal mines [32–34]. The X-ray CT technique has been used to reconstruct a 3D model that confirms that coal belongs to the category of heterogeneous materials [27], and the heterogeneity determines the anisotropic mechanical behaviors of coal commonly observed in lab tests [35–40].

Rigorous laboratory studies have been developed to investigate macro- and meso-mechanical behaviors of coal under relatively simple stress paths. However, the failure of underground surrounding rock in complex stress systems remains a major ground control problem. Theoretical methods for coalmine design are based on lab tests and simplified hypotheses and thus may lead to unsafe designs. Numerical modeling, however, may provide an alternative to accurately simulate both macro- and meso-mechanical behaviors of coal undergoing various stress paths. Researchers have built constitutive models using elasto-plastic mechanics to numerically simulate stress-strain responses of coal to loading [41–48]. Based on the strain energy principle, theoretical models have also been developed to simulate AE events and electromagnetic radiation (EMR) pulses during the failure process of coal [49–51]. However, to simultaneously and accurately capture both nonlinear macro- and meso-mechanical behaviors of coal still remains a technical challenge, and current numerical models can accommodate only homogeneous and isotropic characteristics of coal.

To address these issues, this study establishes a theoretical model that can capture both the macro- and meso-mechanical behaviors of heterogeneous coal. The proposed model incorporates anisotropy by combining a statistical approach with the discrete fracture network (DFN) method. The developed model is then embedded in FLAC3D and validated by comparing the numerical results with experimental data. Using the calibrated model, we investigate the mechanical responses of coal under different loading directions, degrees of heterogeneity and unloading rates of the confining pressure. The practical application of the introduced model at the Dongzhouyao mine in China is also described.

2. Mathematical formulation of the mechanical model

2.1. Incremental expression of plastic flow theory

A macro-constitutive model for coal is formulated first. Note that compression and contraction are taken as positive stress and strain tensors. Vectors and tensors are shown in bold, and the three principal stresses are given as $\sigma_1 > \sigma_2 > \sigma_3$ in descending order. Considering the path dependency of coal, all related equations are expressed in incremental form.

2.1.1. Stress-strain relationship

The total strain increment ($d\boldsymbol{\varepsilon}$) of coal can be decomposed into the sum of elastic ($d\boldsymbol{\varepsilon}^{\mathbf{e}}$) and plastic ($d\boldsymbol{\varepsilon}^{\mathbf{p}}$) components:

$$d\boldsymbol{\varepsilon} = d\boldsymbol{\varepsilon}^{\mathbf{e}} + d\boldsymbol{\varepsilon}^{\mathbf{p}} \tag{1}$$

and the linear function below is adopted to correlate the stress increment with the elastic strain increment [52]:

$$d\boldsymbol{\sigma} = Dd\boldsymbol{\varepsilon}^{\mathbf{e}} = \mathbf{D}(d\boldsymbol{\varepsilon} - d\boldsymbol{\varepsilon}^{\mathbf{p}}) \tag{2}$$

where $d\boldsymbol{\sigma}$ is the stress increment tensor and $\mathbf{D}$ represents the elastic modulus matrix defined as [53]

$$D_{ijkl} = \frac{vE}{(1+v)(1-2v)}\delta_{ij}\delta_{kl} + \frac{E}{2(1+v)}(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}) \tag{3}$$

where υ and E are the Poisson ratio and elastic modulus of coal, respectively, and δ denotes the Kronecker delta.

2.1.2. Yield criterion

The Mohr-Coulomb (*M*-C) yield criterion is used to specify the limit stress combination for plastic yield onset [54]:

$$f_i = \sigma_1 - N_\varphi\sigma_3 - 2\sqrt{N_\varphi}C = 0 \tag{4}$$

where f_i is the initial yield criterion, σ_1 and σ_3 are the major and minor principal stresses, respectively, $N_\varphi=(1+\sin\varphi)/(1-\sin\varphi)$, and C and φ represent the initial cohesion and internal friction angle of coal, respectively.

Once the stress state reaches the initial yield limit, plastic flow is initiated, and plastic strain starts to accumulate in coal, causing strength hardening/softening and stress redistribution in the failing coal grains. Because the internal friction angle is resistant to plastic deformation provided that only moderate confining stress is applied [44], cohesion is used to characterize the hardening/softening behavior of coal. By assuming an isotropic hardening/softening rule for coal, the yield function in the subsequent yield stage becomes

$$f_s = \sigma_1 - N_\varphi\sigma_3 - 2\sqrt{N_\varphi}C(\xi) = 0 \tag{5}$$

where C(ξ) is the hardening/softening parameter and ξ is a monotonically increasing parameter (i.e., the state variable) during the irreversible failure process of coal.

In this study, the accumulated plastic strain (APS) is adopted as the state index, which is defined as a function of deviatoric plastic strains [53]:

$$d\xi = \sqrt{\frac{2}{3}d\mathbf{e}^{\mathbf{p}}d\mathbf{e}^{\mathbf{p}}} \tag{6}$$

where $d\mathbf{e}^{\mathbf{p}}$ is the deviatoric section of the plastic strain increment.

The deviatoric plastic strain increment can be calculated by subtracting the volumetric section from the total plastic strain:

$$d\mathbf{e}^{\mathbf{p}} = d\boldsymbol{\varepsilon}^{\mathbf{p}} - \frac{1}{3}\mathbf{I}d\varepsilon_v^p \tag{7}$$

where $\mathbf{I}$ is a second unit tensor and $d\varepsilon_v^p$ represents the volumetric plastic strain increment.

2.1.3. Plastic flow rule and plastic potential

To govern the manner in which plastic strain develops, a non-associated plastic flow rule is used:

$$d\boldsymbol{\varepsilon}^{\mathbf{p}} = d\lambda\frac{\partial g}{\partial\boldsymbol{\sigma}} \tag{8}$$

where dλ is a non-negative proportional scalar (plastic multiplier) that determines the magnitude of the plastic strain increment and *g* is plastic potential function that determines the direction of the plastic strain increment and is given as [52]

$$g = \sigma_1 - N_\psi\sigma_3 \tag{9}$$

where $N_\psi=(1+\sin\psi)/(1-\sin\psi)$ and ψ represents the dilation angle defined as [53]

$$\psi = \arcsin\frac{d\varepsilon_v^p}{d\gamma^p} \tag{10}$$

where $d\varepsilon_v^p$ and $d\gamma^p$ are the incremental volumetric and shear plastic

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