International Journal of Rock Mechanics and Mining Sciences 110 (2018) 151–160

Contents lists available at ScienceDirect

International Journal of Rock Mechanics and Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

A plastic strain-based damage model for heterogeneous coal using cohesion and dilation angle

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ARTICLE INFO

Keywords:
Plastic strain
Damage model
Heterogeneity
Cohesion
Dilation angle
Numerical modelling

ABSTRACT

Coal as the fundamental element in underground coal mining is well-known as a heterogeneous geomaterial, and the knowledge of its deformation processes and failure mechanisms is important for the prediction and prevention of dynamic disasters and the design of stable underground structures. In this paper, after analysing the pre-peak strain hardening, the post-peak strain softening, and the associated dilation behaviours of heterogeneous coal under loading, a plastic strain-based damage model that consists of the heterogeneity function, the damage stress-strain function, the cohesion function and the dilation angle function, was developed. In this model, the heterogeneity was characterised by considering the micro-unit strength as referring to the Weibull function. The damage stress-strain function was defined by the Weibull function and the plastic strain based on the continuous damage mechanics theory. The cohesion and the dilation angle were expressed by a modified damage function while the friction angle is constant, which were simultaneously implemented in a geotechnical simulator together with the heterogeneity function and the Mohr-Coulomb yield criterion with an embedded tension cut-off. The numerical results are consistent with the experimental and theoretical results. It can be concluded that a large variety of stress-strain relation curves, characterised by the pre-peak elastic and strain-hardening and the post-peak strain-softening, as well as their dilation behaviour, can be accurately reproduced by a group of fitted parameters.

1. Introduction

In underground coal mining, the structural elements are the coal and rock strata surrounding the excavated areas. During longwall mining, coal extraction results in abutment stress immediately in front of the face and ribs of longwall panels.[1] Failures of underground coal mine structures, such as pillars and entries, are caused by the combined effects of the mining-induced stresses and coal strength. The failures often result in catastrophic dynamic disasters, such as the collapse of roofs, ribs, or working faces, and the occurrence of rock bursts.[2] Many researchers have reported that slabbing and spalling are the dominant failure mode around underground excavation in coal subjected to high hydrostatic stress.[3,4] Coal fracturing usually starts at the excavation boundary, where the vertical stress is the post-peak residual stress and transfers gradually to deeper solid coal along with the coal excavation. This means that, from deeper solid coal to the excavation boundary, coal gradually experiences the elastic deformation, pre-peak plastic deformation and strain hardening and the post-peak strain softening and the associated dilation. There are two fundamental factors, namely stress and strength, controlling these failures. These two factors and the associated failure process of coal have been extensively investigated,[5–9] and it has been recognised that coal exhibits significant non-linear elasticity behaviour, such as strain hardening/softening and dilation. Therefore, it is important to understand complete stress-strain relations before and after the peak stress, and subsequently test the behaviour under various loading conditions in numerical modelling with a constitutive model for a better understanding of coal failure process. However, it is a very challenging task to develop a constitutive model that can adequately represent the complete stress-strain behaviour of coal, especially for the nonlinear response such as dilation and strain

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https://doi.org/10.1016/j.ijrmms.2018.08.001
Received 6 March 2017; Received in revised form 4 August 2018; Accepted 7 August 2018

hardening/softening.

The most well-known failure criterion for coal and rocks is the Mohr-Coulomb criterion, whose parameters have physical interpretations. When the dilation angle and cohesion are considered in engineering analysis, especially for numerical modelling studies, the common approach is to simplify dilation angle and cohesion by assuming they remain constant while coal is deforming. This is an over-simplified assumption since numerous experiments and field observations suggested the dilation angle and cohesion is a function of plastic parameters and confining stress.[10–12] In numerical simulation using $FLAC^{3D}$, the impact of the dilation angle and cohesion can be addressed by using the strain hardening/softening Mohr-Coulomb model with non-associated shear flow rules.[13] The dilation angle/cohesion/friction angle can be defined as a piecewise linear function of plastic strain, in order to simulate strain hardening/softening behaviours. However, there are only limited suggestions on how to determine those plastic strain dependent parameters, and most of their applications were achieved by using a monotonic function for cohesion and friction angle.[5,14–16]

To address issues above, there are a few pioneering works[5,6,11,12,17] regarding to use empirical functions to represent the cohesion and the dilation angle changes simultaneously with the plastic strain for coal and rocks. In the function of the dilation angle, however, the negative dilation angles before the transition of the dilation state from the relative to the absolute were not considered for simplicity,[5] and sometimes even neglected all the pre-peak dilation angles.[6,12] These simplicities might not be a true reflection of coal/rock failure process.

Another issue to be addressed is the heterogeneity nature of coal/rock[6,18–20] as a geomaterial. This heterogeneity at micro- or meso-scale is attributed to the presence of pores, micro-scale damage, grains, and mineralogy variation. Heterogeneity is found to strongly impact the macroscopic failure characteristics and is one of the fundamental reasons for the complex mechanical behaviour of coal. This also explains why the inherent properties of coal vary considerably from sample to sample even for those of the same coal rank or being collected from the same site. A better approach to relate the micro-damage processes and the macro-failure characteristics is to adopt a statistical damage concept.[8,21–23] Therefore, it is important to investigate the constitutive behaviour of coal by considering the heterogeneity and the damage description, especially in numerical simulations.

In summary, correctly estimating these nonlinear behaviours is of considerable importance to understand the mechanism of rock unstable failure[24] and burst liability[25] and resolve many rock mechanics challenges, such as rock burst prediction[26,27] and prevention,[28] rock-support interaction design and optimisation,[29] mining-induced micro-seismicity analysis,[30] and estimation of excavation damaged zone size. However, further developments in addressing these issues and fully appreciating the nonlinear stress-strain mechanism in coal need an improved dilation and strain hardening/softening model which can capture the failure behaviour of coal/rock.

In this paper, after analysing the strain hardening/softening, the dilation process, and the associated coal failure during uniaxial or triaxial compression tests, a plastic strain-based damage model that consists of the heterogeneity function, the damage stress-strain function, the cohesion function and the dilation angle function, was developed. Subsequently, the influences of the model parameters were discussed, and both were validated by comparisons between numerical, theoretical and experimental results.

2. Failures of coal under loading

The failure behaviours of coal under loading have been widely examined by uniaxial and triaxial compressive tests utilising stiff servo-controlled test machines. Both the pre- and post-peak elasto-plastic behaviours of coal have been extensively plotted and interpreted (Fig. 1(a)). It can be divided into five stages: (1) 0A stage: crack closure; (2) AB stage: elastic deformation; (3) BC stage: stable crack growth; (4) CD stage: unstable crack growth; and (5) DE stage: post-peak softening and residual strength. These stages are also accompanying with damage accumulation, strain hardening/softening and dilation behaviours.

2.1. Damage process in experimental observations

According to the plastic strain-based damage accumulation function (to be clearly defined in Section 3.1), the damage process of coal under loading is closely related to the plastic strain accumulated. In general, the plastic strain is calculated by subtracting the elastic strain from the total strain according to the plasticity theory[5]:

$$\varepsilon_e = \frac{\sigma_1 - 2\nu\sigma_3}{E} \text{ and } \varepsilon_p = \varepsilon - \varepsilon_e \tag{1}$$

$$\varepsilon_{ev} = \frac{(1 - 2\nu)(\sigma_1 + 2\sigma_3)}{E} \text{ and } \varepsilon_{pv} = \varepsilon_v - \varepsilon_{ev} \tag{2}$$

$$\varepsilon_v = \varepsilon + 2\varepsilon_r \tag{3}$$

where ε is total axial strain, ε_e is axial elastic strain, ε_p is axial plastic strain, ε_v is total volumetric strain and ε_{ev} is elastic volumetric strain, ε_{pv} is plastic volumetric strain, ε_r is radial strain; E and ν are Young's modulus and Poisson's ratio, respectively.

Under compressive loading, the axial plastic strain versus the total axial strain is depicted in Fig. 1(a). It shows that the plastic strain first increases and then decreases to a small constant value (always approaching zero) as the increase of the total strain at the stage 0A where pore and fissure closure occurs. At the elastic deformation stage, the plastic strain remains at a constant value until the point B. This point is the strength yielding point, where the pre-existing fissures and pores have been compressed and new cracks are not initiated yet. After this stage, the cracks are initiated and the coal specimen enters the stages of stable crack growth, unstable crack growth, post-peak softening and residual strength. Over this period, the plastic strain increases nonlinearly and eventually reaches the maximum. All these evolution trends can also be described by the damage variable D, which will be discussed in Section 3.1. It should be noted that the initial damage $D > 0$ is due to pre-existing micro fissures and pores. For some dense rock material, the damage variable here can be approximated to zero ($D = 0$). Since this paper focuses on understanding the pre-peak hardening and post-peak softening failure behaviour of coal and the pre-existing fissures/pores are very difficult to be quantified, the initial stage 0A was not considered in the model.

2.2. Dilation and strain hardening/softening behaviours

Dilation is the volume change observed in granular materials when they are subjected to shear deformations. This phenomenon was extensively observed in compressive loading tests of various geomaterials and has become a part of the broader topic of soil mechanics. In the laboratory, dilation is usually described by volumetric strain, as shown in Fig. 1(a). There are three phases to express the dilation evolution: compression in the initial stage of crack closure, relative dilation at stages of elastic deformation and stable crack growth, and absolute dilation afterwards. To be specific, after the elastic stage (point B), dilation is initiated with the volume increase induced by failure or micro-crack propagation. Following this, the rate of volume decrement under the compressive stress decreases because the tensile cracks induce voids within the coal. The minimum value of the dilation is obtained at the point C. From this point, the volume of the coal sample increases with increasing axial stress until the peak strength, where the volumetric strain is almost zero and increases afterwards.

The parameter most widely used to define dilation is the dilation angle ψ, which can be obtained from triaxial compression tests by calculating plastic axial and volumetric strain increments[31]: