International Journal of Rock Mechanics and Mining Sciences 111 (2018) 1–11

Contents lists available at ScienceDirect

International Journal of Rock Mechanics and Mining Sciences

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

Quantitative determination of mining-induced discontinuous stress drop in coal

Dongjie Xue[a,b,c,*], Jianqiang Wang[a], Yongwei Zhao[a], Hongwei Zhou[a]

[a] School of Mechanics & Civil Engineering, China University of Mining and Technology, Beijing 100083, China
[b] State Key Laboratory of Coal Mine Hazard Dynamics and Control, Chong Qing University, Chongqing 400030, China
[c] Ministry of Education Key Laboratory of Safe and Efficient Mining of Coal, Anhui Science and Technology University, Huainan 232001, China

ARTICLE INFO

Keywords:
Excavation induced stress
Discontinuous redistribution
Stress drop
Statistical yield criterion
Damage
Broken zone

ABSTRACT

Mining induced stress, especially discontinuous redistribution and stress drop, is a major issue of structural stability in deep coal mining. Only considering the yield criterion as the continuous stress equation solution without failure criterion leads to excessive plastic zone and support ability. The discontinuous distribution is illustrated by abutment pressure rather than horizontal stress. First, the weakening of the stress boundary by substituting the Mohr-Coulomb yield equation into the differential equations of stress is discussed. We propose an elastic solution and discontinuous stress boundary for the stress state of coal ahead of working face. Second, it is pointed out that introducing the statistical yield criterion to the stress equilibrium equation can be used for determination of the broken zone. The failure criterion is proposed at the elastoplastic boundary considering the behavior transition for avoiding excessive stress concentration. The equation of stress drop at the transition boundary is proposed for the discontinuous solutions. The influence of the internal friction angle and cohesion on the discontinuous distribution of abutment pressure as well as the peak stress coefficient is discussed. The results show that the discontinuous equations of mining-induced stress distribution effectively represent the stress state in the broken zone. The equitant damage is defined in the broken zone based on the deterioration of rock due to crack generation. The stress drop at the elastoplastic boundary is compared quantitatively by Mohr-Coulomb's solution and the statistical solution equation. When the uniaxial compressive strength is below the original *in situ* stress, the peak stress concentration is mainly a function of the internal friction angle. As the damage increases, the peak stress in the broken zone decreases and the stress drop increases. The experimental results from excavation induced testing by loading multi-stage confining pressures are consistent with theoretical solutions. Finally, the mining-induced unloading ratio is proposed to learn the excavation speed or disturbance intensity. There is a positive linear correlation between the unloading rates and the peak coefficients, and the mining-induced behavior depends on the discontinuous unloading path and rates.

1. Introduction

The excavation-induced stress redistribution and discontinuous deformation is crucial for evaluating the stability of surrounding rocks[1] and for designing the support system[2,3] in coal mining.[4,5] The measurement of the *in situ* stress at enough points is important to determine regional stress, while we often understand the continuous meaning of stress distribution depending on the limited data. The concentrated stress may be beyond the yield surface resulting in the failure.[6] The strong disturbance caused by a large-scale excavation of coal mining may form discontinuous zones, in turn, it will affect the stress discontinuities. As shown in Fig. 1, the discontinuous 3D stress distribution of the tunnel attracts much more attention nowadays.[7,8]

The discontinuous change of abutment pressure near the peak value promote our knowledge of the stability mechanism of surrounding fractured coal. Coal cracking near the free surface experience two processes.[9] The stress concentration causes the continuous-discontinuous behavior by crack generation, and the relieved stress forms smaller block generation. The stress state in surrounding coal is controlled by the dynamic change of the abutment pressure and the horizontal stress distribution.[10–14] Specifically, the stress redistribution manifests as the abutment pressure and the unloading of the horizontal stress increases. With such stress transitions, the hydrostatic triaxial stress in far-field coal gradually changes to the uniaxial stress near the free surface. The triaxial to uniaxial stress transition is established depending on the coal continuously distributed near the free surface,

* Corresponding author at: School of Mechanics & Civil Engineering, China University of Mining and Technology, Beijing 100083, China.
E-mail address: xuedongjie@163.com (D. Xue).

https://doi.org/10.1016/j.ijrmms.2018.08.003
Received 29 May 2017; Received in revised form 23 December 2017; Accepted 7 August 2018

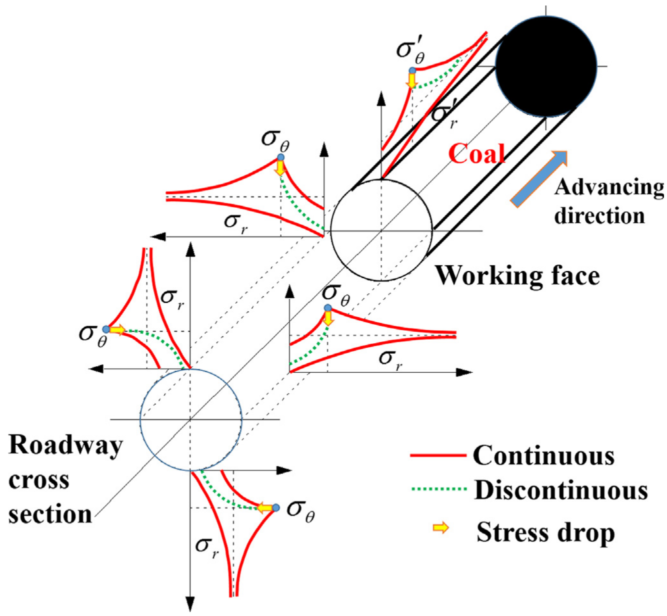

Fig. 1. Discontinuous stress drop and redistribution of the roadway.

which is not exactly matched with the observed coal mass and discontinuous fractured blocks. The discontinuous transition interface is not on the free surface but inside the coal body. Although the continuous support pressure theory proposed the concept of fractured or broken zones,[15,16] it has not been thoroughly solved. The fractured zone and the limit equilibrium zone of plasticity are often determined as the excavation damaged zone (EDZ).[15,17] The larger the excavation damaged zone, the more important the supporting role of plastic deformation. Plastic deformation and fracture generation will consume a large amount of elastic energy weakening the stress concentration of continuous coal. That is, in the process of excavation, elastic energy is gradually and continuously transferred and dissipated by discontinuous or plastic deformation. In most dynamic disasters, the energy released is larger than the elastic energy stored in coal estimated by the continuous theory.[18–20] It is generally believed that the re-distribution of energy due to continuous abutment pressure is insufficient to fully cause dynamic consequences. However, this part of the missing dynamic energy may be not concentrated or dissipated in the excavation damaged zone but transferred into the internal elastic zone.[20] The continuous pressure theory overestimates the energy storage capacity of the fractured zone and weakens the stress concentration of the abutment pressure.

Under abutment pressure loading and horizontal stress unloading, the coal forms a new stress circle with an increasing radius. For coal, the stress circle gradually approaches and breaks through the yield envelope line until failure.[21] This transition means that the brittle failure under confining pressure unloading and the continuous theory believes that the coal is the ultimate stress equilibrium state. The stress state is limited in the yield line without failure, forming a large limit equilibrium zone of plasticity. In fact, the critical stress state is difficult to maintain because the plastic state is in a state of high stress and strain growth, which is an unsustainable mechanical behavior.[22–24] The result of such an understanding is that the energy transfer caused by excavation is consumed by forming the plastic zone, which may be part of the lack of energy of the dynamic disaster and dissipation.

For brittle failure, both indoor experiments and *in-situ* experiments, there is a lot of successful researches.[21,25,26] It is generally believed that the brittle failure is a critical behavior of the sudden drop of stress. At this time, the stress drop does not cause a large strain and is not completely elastically unloading. The elastic energy is not completely released for fracture generation. There is the behavior of a continuous-discontinuous transition near the new fracture crack. The released energy is mainly caused by local stress unloading around the fracture, and the block of coal still retains some elastic energy.

After coal failure, the lateral displacement constraint still exists to maintain the coal group of blocks continuously bearing the overburden pressure. It is a coupling behavior of continuous coal blocks and fracture structures.[27,28] However, such behavior is a discontinuous state under low stress, and part of its elastic energy is finally transferred to internal continuous coal. The stress drop mainly appears in the zone near the abutment pressure peak. Therefore, the evaluation of the quantitative stress drop and re-recognition of the peak stress concentration factors are very important for understanding such continuous-discontinuous transition behavior.

Due to our limited knowledge, there is no perfect technology to measure *in-situ* stress in a continuous zone of surrounding rock by real-time monitoring. To overcome the limited data and horizontal stress recorded at the working face, most of the research focuses on the theoretical continuous stress redistribution[29,30] to better understand experimental results. The distribution of abutment pressure is mainly determined by analytical solutions[31,32] and modified by measured data at limited points. The solution as an empirical equation can be solved based on the continuum medium assumption and the application of the friction theory.[33] However, it is still a challenge to obtain the horizontal stress distribution, especially for the analytical solution of the horizontal stresses ahead of the working face.[34,35] Furthermore, the measured horizontal stress data is limited, and there are only few researches pointing out the discontinuous characteristics of the abutment pressure,[36–38] though many studies on evaluation of the brittleness index of the stress drop have been reported. In this paper, the discontinuous solutions focus on the quantitative determination of the radial and tangential stresses surrounding the roadways,[39] as well as the analytical values of the abutment pressure and the horizontal stress ahead of the working face and their distributions[40].

2. Material and methods

2.1. Coal geology and sample preparation

The coal blocks are obtained from the working face at a depth of about 600 m in China. The length of the mining face measured in the east-west direction is 864 m, the tilt width of the mining face along the north-south direction is 190 m. The thickness of the coal varies from 3.2 to 3.9 m with an average thickness of 3.6 m. The slope angle of the coal is in a range of 17–25° with an average value of 22°. Large and whole blocks of the coal with a length greater than or equal to 300 mm and a width and height greater than 200 mm were selected near the mining face for the coal samples processing. These blocks were made into standard samples for the triaxial tests in the laboratory. According to the ASTM standard D4543-08, the diameter was set to 50 mm, the ratio of height to diameter was set to (2 ± 0.2): 1.

2.2. Experimental setup

MTS815 GT Rock Test System was used for all experiments. This system has large axial rigidity, high precision, and is very stable. The range of axial load for compression and tensile tests are 0–4600 kN and 0–250 kN, respectively. The maximum confining and pore pressures are both 140 MPa. The range of the strain gauges, to measure the vertical and horizontal deformations, are 2.5–5.0 mm and −2.5–8.0 mm, respectively; the room temperature for all experiments remains at ∼ 20 °C. The precision for all the sensors is within 0.5%.

2.3. Experimental design and methodology

The purpose of the rock mechanic tests in the laboratory is to reproduce the damage generation of the excavated coal with stress evolution. It provides knowledge on both the material properties and the