International Journal of Rock Mechanics & Mining Sciences 48 (2011) 1145–1152

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

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

Stress evolution with time and space during mining of a coal seam

Wei Yang [a,b], Bai-quan Lin [a,b,*], Yong-an Qu [c], Zi-wen Li [a,b], Cheng Zhai [a,b], Li-li Jia [d], Wu-qiang Zhao [c]

[a] *Faculty of Safety Engineering, China University of Mining & Technology, Xuzhou, Jiangsu 221116, China*
[b] *The State Key Laboratory of Coal Resources and Mine safety, China University of Mining & Technology Xuzhou, Jiangsu 221116, China*
[c] *Hancheng Mining Co. Ltd., Shanxi coal, Hancheng, Shanxi 715400, China*
[d] *College of Literature, Law & Politics, China University of Mining & Technology, Xuzhou, Jiangsu 221116, China*

ARTICLE INFO

Article history:
Received 2 August 2010
Received in revised form
18 May 2011
Accepted 20 July 2011
Available online 4 August 2011

Keywords:
Coal mine
Protective coal seam
Gas
Stress evolution

ABSTRACT

Mining of the upper protective coal seam is widely practiced in China for coal mine safety, but relief gas may present a new risk of blasting. To control the relief gas effectively, a strain-soften model was built by FLAC^{3D} software to investigate the stress evolution during the process of mining the upper protective coal seam. The results show that the abutment stress changes rapidly within 10 m in front of the coal face, and the maximum abutment stress is approximately twice the original when the coal seam is mined 20–30 m. The abutment stress should break the rock mass and cause the gas to flow easily. In the stable mining period, the change trends of the *x*-stress and *z*-stress are different, and these should also pre-break the rock mass. The stress distributions of the rock mass at different distances under the protective coal seam are different, especially near the coal face, which should greatly affect the gas flow when the space of the protective and protected coal seams change over a large range. The relief angle also changes over a large range, increasing to a maximum approximately 30 m behind the coal face, and it decreases gradually when it is far away from the protective coal seam. The results are helpful for designing the coal face of protected coal seams and borehole layouts to control the relief gas.

1. Introduction

China is a country rich in coal resources but poor in oil and gas. For many years, coal has supplied more than 70% of China's energy. In 2010, coal production reached approximately 3.2 billion tons, and it currently supports the rapid growth of China's GDP. However, more than 95% of China's coal mines are underground, and 17.6% of key state-owned coal mines are coal and gas outburst mines, which seriously threaten coal mine safety. In 2008, for example, 25 accidents caused 120 deaths. To effectively control coal and gas outburst accidents, the State Administration of Work Safety unveiled the "Provisions for the prevention of coal and gas outburst" in August 2009, which stresses regional gas control mainly by mining protective coal seams and by methane pre-drainage to eliminate the risk of outburst from a large region. Additionally, the mining of protective coal seams should be preferentially selected if possible [1].

After the protective coal seam is mined, the stress of the protected coal seam decreases and the permeability increases, which causes the methane to be released continuously, and the outburst danger is eliminated [2,3]. However, during the process of mining the protective coal seam, the relieved gas from the current and adjacent seams may flow into the coal face, causing the methane to overrun. The relieved gas flow and the protected range are determined by the stress distribution [4]. The stress distribution of mining fields and roadways has been extensively studied for many years, but most of these studies only address some static states [5,6]. Because mining is a dynamic process, the stress field evolves dynamically with time and space, which causes the gas flow and the protected range to change dynamically [7]. Therefore, the stress distribution during the process of mining a protective coal seam must be studied from a dynamic viewpoint while considering the stress evolution with time and space for gas relief control and coal face arrangement. However, this question is not addressed in the current literature, so it is necessary to study the issue thoroughly.

The geological condition of a coal mine is non-uniform and complex, which makes it a challenge to study the stress distribution and evolution with time and space with only field or laboratory experiments. Professional geotechnical numerical analysis software could be a good choice for this situation.

2. Establishment of a numerical model

FLAC^{3D} is one of the most important numerical software tools in current rock mechanics calculations. This tool is particularly

* Corresponding author at: Faculty of Safety Engineering, China University of Mining & Technology. Xuzhou, Jiangsu 221116, China.
Tel./fax: +86 516 83590593.
E-mail address: ywcumt@163.com (B.-q. Lin).

1365-1609/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijrmms.2011.07.006

Table 1
Values of model parameters.

parameters	Density (kg/m^3)	Bulk modulus (GPa)	Shear modulus (GPa)	Friction angle (deg.)	Cohesion (MPa)	Dilation angle (°)	Tensile strength (MPa)
Coal	1450	1	0.8	16	0.5	10	0.5
Mudstone	2000	2	1.5	22	0.8	10	0.8
Coarse-grained sandstone	2200	2.5	2	25	1.5	10	1.5
Fine-grained sandstone	2500	4	3	28	2.5	10	2.5
Siltstone	2700	3	2.5	30	3	10	3

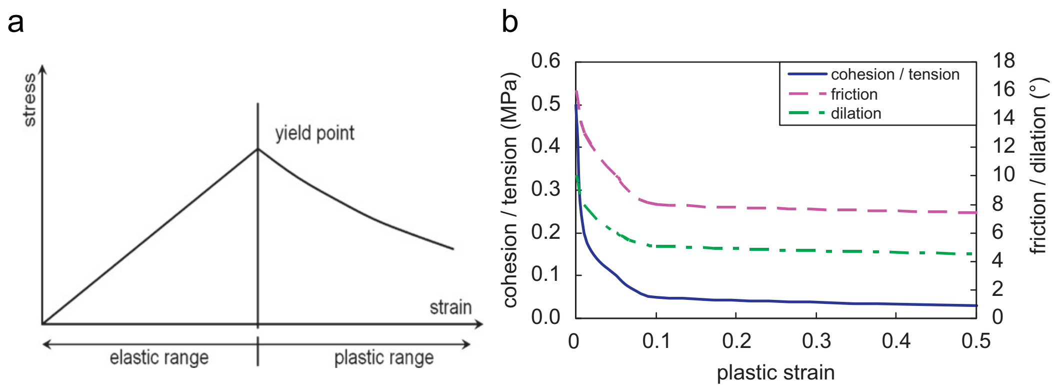

Fig. 1. Evolution of material strength with strain: (a) sketch of stress-strain curve of plastic material and (b) relationship between plastic strain and strength of coal.

suitable for solving nonlinear large deformation problems in geotechnical mechanical engineering and is widely used in the field of mining engineering, among other fields [8,9]. The software contains eleven kinds of material constitutive models, as follows: one empty element model, three elastic material models and seven plastic models. Mining a coal seam will cause rock mass deformation and will decrease the rock strength; thus, the rock mass is assumed to be an elastic-plastic material, and it presents strain-softening characteristics after it is damaged. Therefore, the strain-softening model was chosen. The coal strength parameters are shown in Table 1 according to the typical values of the Hancheng Mining Co. Ltd.

The strain is both elastic and plastic. The stress initially changes linearly with the elastic strain, but a strain-softened character will appear after the rock mass is damaged beyond the yield point [8]. Thus, the friction angle, cohesion, dilation angle and tensile strength soften as the plastic strain increases. Many researchers use a linear softening model [10–12], but a different relationship was proposed because the strength decreases much faster in the beginning, as shown in Fig. 1 [13].

The model was built according to the geological conditions of the Xia Yukou coal mine of the Hancheng Mining Co. Ltd., where the long wall mining method is widely used. The length, width and height of the model are 320, 260 and 120 m, respectively, with 520,800 zones and 582,144 grids. The #3 coal seam has the highest outburst danger, so the #2 coal seam was mined first as the protective coal seam to eliminate the outburst risk of the #3 coal seam. In Hancheng, the ground stress gradient is approximately 0.025 MPa/m. Considering that the model top is approximately 400 m below the ground surface, a compressive stress of 10 MPa was loaded on the top of the model as the in-situ stress. The protective coal seam is approximately 470 m below the ground surface, and the in-situ stress was approximately 12 MPa in the protective coal seam. At the same time, the rolling boundaries were loaded on the other sides. Fig. 2 shows the integrated histogram and grid method of the model [14].

The model was built according to the 21,206-long wall working face in the protective coal seam. The mined length of the protective coal seam is 160 m, extending from –80 to 80 m in the *x*-direction; the width is 96 m, extending from –48 to 48 m in the *y*-direction; and the mining height is 1 m. The software iterated 250 steps for each 2-m length mined.

3. Results and discussion

3.1. Evolution of abutment stress in front of the coal face

During the mining process, stress will increase in front of the coal face (Fig. 3). This stress is called the abutment stress, and it can compress and break the coal and rock mass ahead of the coal face, generating cracks and affecting the gas flow in the coal seam [15]. Therefore, it is necessary to study the dynamic evolution regularity of abutment stress during the mining process for gas control.

The abutment stress evolution regularity can be studied by the stress distribution at different mining lengths. Fig. 4 shows 16 abutment stress distribution curves ahead the coal face when the protective coal seam is mined 10, 20, 30, …, and 160 m, respectively. Note that vertical coordinates presents the vertical abutment stress in front of the coal face (*z*-stress), negative values indicate compression. For example, a curve of 10 m presents the abutment stress distribution in front of the coal face when the coal seam is mined 10 m, and it intersects the horizontal ordinate at 70 m, which means the coal face is at 70 m.

Fig. 4 shows that the stress changes complexly and rapidly within 10 m in front of the coal face. The stress at the coal face is approximately 0 MPa, and it rapidly increases to a maximum value of approximately 20–24 MPa (1.67–2 times the original) approximately 5 m in front of the coal face. The stress then decreases rapidly to the original stress approximately 10 m in front of the coal face. The severe stress change will break the coal