International Journal of Rock Mechanics and Mining Sciences 111 (2018) 84–93

Contents lists available at ScienceDirect

International Journal of Rock Mechanics and Mining Sciences

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

Field experiments on fracture evolution and correlations between connectivity and abutment pressure under top coal caving conditions

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ARTICLE INFO

Keywords:
Top coal caving
Mining dynamics
Abutment pressure
Mining fractures
Connectivity

1. Introduction

Top coal caving is one of the most effective methods for mining thick coal seams.[1,2] With regard to the coal mining method, researchers in China and other countries have conducted a great deal of in-depth research. Kang et al. have studied the caving characteristics of the fully-mechanized long-wall top coal caving full-seam mining with high bottom cutting by the large-scale physical simulation test.[3] Huang et al. proposed a method to improve the top coal cavability by top coal and roof hydraulic fracturing.[4] Zhang et al. conducted a series of laboratory unloading experiments to understand the mining-induced coal permeability change.[5] Alehossein et al. developed a yield and caveability criterion based on in situ conditions in the top coal in advance of the mining face and behind the supports.[6] Rezaei et al. proposed an analytical model based on the strain energy balance in long-wall coal mining to determine the mining-induced stress over gates and pillars.[7] Xie et al. have discussed a new theory and technology of top coal caving with vibration to understand the top coal caving process and increase the top coal recovery ratio.[8]

The top coal caving process leads to large-scale motion in the coal rock layer. Under the coupled influence of mining dynamics and gas pressure in the coal body, the mining-induced fracture field and primitive fracture field are superposed in the overlying rock layer, and the associated laws of temporal and spatial evolution are extremely complicated. Gas appears as a result of irregular aggregation and upwelling, resulting in serious potential safety hazards, one of the main factors in the restriction of continued high-intensity mining. Therefore, when using high-intensity mining techniques, it is particularly important to correctly describe the characteristics of the dynamic response and the fracturing law of the coal rock during the mining operations.

The dynamics of the mining operations often include the large-scale motion and stress redistribution of the overlying rock layers caused by the mining activities, particularly variations of the bearing stress in the coal rock body in advance of the working plane.[9] In order to describe the mechanical behavior of a mine during the underground mining process, scholars in China and other countries have carried out many in-depth studies using laboratory experiments, field experiments, and numerical simulations. Yavuz et al. studied the redistribution distance of abutment pressure on the working plane of long walls and the law for the appearance of pressure in the goaf areas.[10] Luxbacher et al. and Hosseini et al. studied the characteristics of stress redistribution under the influence of mining dynamics based on monitoring of the seismic wave speed and using digital geological technologies.[11,12] Suchowerska et al. studied the law of variation of the vertical stress under multi-coal-seam mining conditions.[13] Xie et al. combined a large number of on-site abutment pressure data sets and generalized the results to propose a model of mining dynamic behavior under various mining conditions; they then used conventional triaxial compression laboratory loading experiments to simulate the stress path of different mining techniques and interpreted the difference in mining dynamic behavior between the various techniques from a qualitative perspective.[9] Along with the development of computer technology, the introduction of numerical

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https://doi.org/10.1016/j.ijrmms.2018.01.003
Received 24 April 2017; Received in revised form 28 December 2017; Accepted 1 January 2018
Available online 10 October 2018
1365-1609/

calculation methods has provided new opportunities for studies of mining dynamics. For coal seams with igneous intrusions and the characteristics of potential gas diffusion, Islam et al. used a combined numerical simulation approach to analyze the characteristics of the stress field and the displacement field in tunnels.[14,15] Wang et al. used simulations to analyze the dynamic characteristics exhibited by coal pillars in the working plane during the mining process.[16] Yang et al. modelled the distribution characteristics and evolution law of abutment pressure on the working plane under different mining heights and proposed a gas administration scheme according to the characteristics of the de-stressing distribution in the slope.[17] For the top coal caving operations, Xie et al. combined the real-time monitoring of stress in front of the mining face with the stress caused by the mining face brace and studied the response characteristics of basic mining dynamic behavior and local mining dynamic behavior during the actual mining and coal caving process.[18]

The response of mining dynamics is often accompanied by discernable fractures in the coal rock; the evolution of a mining-induced fracture network is the most direct response of this process. For many years, the law of evolution for a network of mining fractures has been a subject of significant interest in the studies by domestic and foreign mining scholars. Qian and Xu applied laboratory experiments, image analysis, and discrete element simulations to study the distribution of mining-induced fractures in the overlying rock layer, in order to construct a model of a coal face and rock masonry beam. The researchers also proposed the critical layer distribution theory of fractures, revealing that the fractures appear as distributed "O"-shaped circles under the influence of mining operations.[19,20] Starting with how the properties of the overlying rock body influences the fracture zone, Kang et al., Li et al., Cheng et al., and Xu et al. investigated the mechanism underlying the occurrence of a mining-induced fracture zone in the coal rock body and analyzed the morphological characteristics of the fracture zone.[21–24] Xie et al. conducted experiments with a model of a similar material, and simulated the morphology of fracture distribution in the mining-induced rock body and revealed that the distribution of fractures in the mining-induced rock body has fractal characteristics. By using fractal dimensionality, the degree of mining-induced fracturing in the rock body can be comprehensively described.[25,26] Zhou et al. also invoked the fractal geometric theory to study the characteristics of the spatial distribution of mining-induced fractures in the overlying rock based on a similar material model. They concluded that a relationship exists between the length of mining-induced fractures in the overlying rock and their fractal dimension as the mining face moves forward.[27] Gao et al. used an improved rock drilling detector for the real-time observation of mining-induced fractures in coal rock bodies and combined these studies with fractal theory to analyze the distribution characteristics and connectivity properties of mining-induced fractures.[28,29] However, although we now have a relatively complete understanding of the evolution of fracture networks and the evolutionary law of mining-induced stress, it is difficult to develop possible prevention mechanisms and the associated spatio-temporal effects throughout the entire evolutionary process from a quantitative perspective or even a semi-quantitative perspective.

To determine the condition of a coal seam mined in accordance with high-strength fully mechanized caving mining conditions in the Datong Coal Field mining region, we carried out on-site abutment pressure monitoring and fracture recording using borehole video instruments. We then combined our results with the critical quantitative index to investigate the abutment pressure, degree of complexity of the mining-induced fracture network, and the evolutionary trend of connectivity under the high discharge condition. Based on the evolutionary velocity of the mining-induced fractures and the abutment pressure within the mining face, we made a preliminary study of the law of fracture evolution and the correlation between connectivity and abutment pressure under the top coal caving conditions. The results were then used to establish a relatively complete and qualitative (semi-quantitative) analytical framework for interpreting the response characteristics and evolutionary trends regarding the dynamics of mining, providing a theoretical and scientific basis for conducting mining activities under thick coal seams.

2. Field experiment

2.1. Rationale for the field experiments

We selected the Datong Coal Mining Group of Shanxi Province, China, as the basis of the experiment. The Datong Coal Mining Group is one of thirteen major energy source bases in China and is an important constituent of China's coal industry. The Datong Coal Field is a dual-system coal seam (i.e., Jurassic and Carboniferous Permian), with abundant coal reserves and a relatively simple geological structure. Most of the coal seams are nearly horizontal with a shallow burial depth and are highly suitable for large-scale high-strength mining. Consequently, the top coal caving technique is the main mining approach used in the Datong Coal Field. It is worth pointing out that the coal seam involved in the experiment features characterized two “hardnesses", namely, the coal seam is hard (hard coal with a firmness coefficient of $f = 3–4.5$), and the rock layers on the top and bottom plates are also hard (mostly thick sandstone with strong integrity and undeveloped joints of conglomerate bedding, with hard properties and a firmness coefficient of $f > 8$). Under the impact of mining, the abutment pressure exhibits irregular behavior, leading to significant challenges for the mining operations and the supporting structures in the vicinity of the mining face.

After careful consideration of the on-site conditions, we selected the 8212 working plane in the Tashan Mine of the Datong Coal Mining Group as the experimental site. This working plane adopts the comprehensive mechanical sub-level mining approach in a sequential coal unloading manner of one cutting and one caving, with a working cycle advance of 0.8 m. The coal seam on the working plane has a complicated structure, and the trending direction of the formation is roughly east of north by 30–45°, with an average dip angle of 4°, which can be viewed as an approximately horizontal structure. The burial depth is about 500 m, and the thickness is 7.25–20.19 m, with an average of 11.17 m; the thickness of the mechanical mining operation is 3.5 m, with an average coal caving height of 7.67 m, meaning that it is classified as high-strength comprehensive top coal caving.

2.2. Design of the on-site experiment and monitoring plan

Under the high-strength mining condition, as the mining face moves forward the disturbance induced by the mining process alters the stress equilibrium state of the original rock in the deep coal seam; both the stress magnitude and stress state of the coal body change continuously. The evolution and development of the mining-induced stress field causes the coal rock body in front of the coal wall and above the brace to generate new mining-induced fractures determined by the existing fractures. The fracture network undergoes constant evolution; hence thus it possesses the characteristics of both temporal and spatial evolution. The fracture field of coal rock bodies, made up of precursory fractures and mining-induced fractures, not only serves as the main path for the percolation, migration, and extraction of gas, but also affects the recovery rate of top coal during the top coal caving, while the fractures at the top of the gallery to some extent affect the cycle and magnitude of the incoming pressure. Therefore, there is an apparent correlation between the evolution of the abutment pressure and the evolution of the mining-induced fracture network. To study this correlation, we monitored both the abutment pressure in front of the mining face and the mining-induced fracture network.

Fig. 1 shows a schematic of the experimental placement of the pressure sensors at the site to measure the abutment pressure. To study how the gradual progression of the mining face affects the dynamic