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Mechanical analysis of effective pressure relief protection range of upper protective seam mining

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ABSTRACT

This paper analyzes the control mechanism of coal and gas outbursts and proposes the concept of an effective pressure relief protection range, based on the stress relief of the underlying coal-rock mass and the development of a plastic zone. Also this study developed a stress change and fracture development model of the underlying coal-rock mass. In addition, the stress and depth of fracture of any point in the floor were deduced with the application of Maple Calculation Software. The specific engineering parameters of the Pingdingshan No. 12 colliery were applied to determine the relationship between the depth of fracture in the floor and the mining height. The pressure-relief principle of the underlying coal-rock mass was analyzed while varying the mining height of the upper protective seam. The findings indicate that as the depth of fracture in the floor increases, the underlying coal-rock mass experiences a limited amount of pressure relief, and the pressure relief protection range becomes narrower. Additionally, the stress distribution evolves from a "U" shape into a "V" shape. A 2.0 m mining height of protective seam situates the outburst-prone seam, Ji_{15}, within the effective pressure relief protection range. The fracture development and stress-relief ratio rises to 88%, ensuring the pressure-relief effect as well as economic benefits. The measurement data show that: after mining the upper protective seam, the gas pressure of Ji_{15} dropped from 1.78 to 0.35 MPa, demonstrating agreement between the engineering application and the theoretical calculation.

1. Introduction

As coal exploitation and mining activity have intensified, an increasing proportion of the coal seams being mined are outburst-prone, with high gas contents and low permeability. A technique combining protective seam mining and gas drainage to relieve pressure from the protected seam has been developed to prevent regional coal and gas outbursts, and long-term theoretical research and actual mining operations have demonstrated that it is the most effective and economical measure [1–4]. In the engineering design of protective seams, the most crucial task is to determine the range of protection in which outburst prevention is effective.

After the upper protective seam (UPS) has been mined, the coal and rock mass in the floor of the goaf tends to undergo stress relaxation, dilation towards the goaf, and fracture development. These conditions allow the release and flow of the gas contained in the underlying outburst-prone coal within the range of protection offered by the UPS [5]. The existence of a stress-relaxed zone within the fractured rock occupying the lower part of the goaf has been recognized as the theoretical basis for the technique of mining the UPS to relieve gas pressure and increase coal permeability [5,6]. Therefore, the key to determining the range of protection is accurate prediction of the depth of the fracture zone in the floor, the rate of stress relief, and their spatial relationship.

The ranges of protection and effectiveness of protective seams have been studied extensively. Hu and Wang constructed a solid-fluid dynamic coupling model to simulate coalbed methane flow during UPS mining and delineated the boundary of the protected region using the criterion of ultimate gas pressure [7–9]. In one case study, the range of protection provided by a protective seam was determined by field observation and analysis of gas flow and gas content contrast, as well as a numerical simulation based on practical engineering considerations [10].

When conducting experiments in the field, due to the complexity of underground rock mass, there are always lots of limitations and errors. Therefore, most previous studies of the stress-relieving effect of UPS mining have used numerical simulations and field measurements [11,12]. They tend to focus on the

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parameters of gas contained in outburst-prone seams, such as gas pressure, concentration, and movement pattern. However, few theoretical studies have examined the internal factors causing variation in these parameters, including the pattern of stress relief and characteristics of fracture development experienced by the underlying strata after protective seam mining. The growing mining industry now needs research to establish the theoretical calculation of the distribution of fractures and the stress relief pattern, as well as accurate prediction of the range of protection provided by the UPS.

The present study was modelled on the engineering practice of the Pingdingshan No. 12 Coal Mine. A mechanical model was constructed for the floor strata underlying the protective seam based on the theory of elasticity. The pattern of stress relief and characteristics of fracture development in the underlying coal and rock were theoretically analyzed. The region in the floor strata that was effectively protected by the UPS was then delineated to provide a theoretical basis for the engineering design of upper protective seams.

2. Outburst prevention mechanism of the UPS and effective protection range of stress relief

2.1. Analysis of the outburst prevention mechanism of the UPS

After the UPS has been mined, the disturbance of the balance of stress around the working face can cause the floor of the goaf to deform, break and move, resulting in the redistribution of the stress field and fracture field in the floor. Along the strike of the working face, the floor strata can be divided into three zones depending on the stress level, namely, the original stress zone (A), bearing stress zone (B), and stress-relieved zone (C), as shown in Fig. 1. The stress-relieved zone is adjacent to the stress recovery zone where the stress tends to gradually recover to the level of in-situ stress [13].

According to the plasticity failure theory of floor strata, when the advanced bearing stress in the floor reaches or exceeds the elastic limit of the rock, the rock mass deforms plastically, forming three plastic zones, that is, the active limit zone (I), transition zone (II), and passive limit zone (III) [14]. The rock in zone I compresses and transfers the stress. When the bearing stress reaches its ultimate load, causing complete failure of the rock mass, the plastic zones around the bearing stress zone consolidate into a single zone. Meanwhile, the rock in zone II slides to zone III, and stress is transferred, leading to floor heave in the goaf area. The plastically deformed rock moves to the goaf, producing a continuous sliding surface that forms the boundary of the whole plastic zone.

The passive limit zone (III) where the fracture is fully developed exhibits the most severe swelling deformation. The plastic zone of the floor continues to move as the working face advances. The passive limit zone (III) gradually transitions to the stress-relieved zone, where the protected seams tend to dilate due to stress relief, inducing secondary fractures in addition to primary fractures. As a result, the coal permeability increases exponentially, providing favourable conditions for pressure-relief gas drainage from the protected seams [5]. Fig. 1 illustrates the stress zones and plastic deformation in the floor.

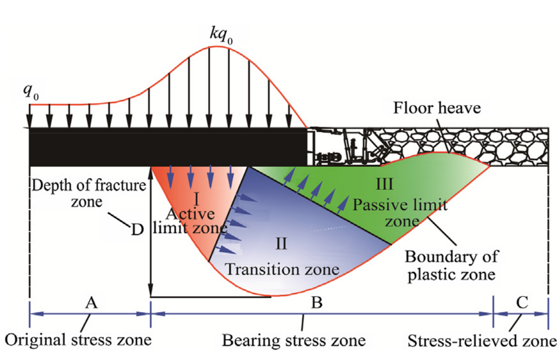

Fig. 1. Stress zones and plastic zones in the floor.

2.2. Delimition of the effective protection range of stress relief provided by the UPS

After the UPS has been mined, the mine roof tends to either remain suspended or partly collapse; the geostatic stress is transferred from the roof above the goaf to the lateral bearing stress zone in the coal wall. Additionally, a stress-relieved zone develops within the goaf floor. According to statistics of actual measurements, the stress-relieved zone in the goaf floor is normally deeper than 50–60 m, and can even exceed 100 m [15,16]. As the floor depth increases, the rate of stress relief gradually decreases. The depth of the fractures in the goaf floor is normally in the range of 15–25 m and can reach 30 m in rare cases. Therefore, the depth of the fracture zone is much shallower than that of the stress-relieved zone. One study found that the effective protection range of stress relief in which the risk of outbursts is eliminated is smaller than the stress-relieved zone, because fracture does not occur in all seams within the stress-relieved zone [17]. If an underlying seam undergoes stress relief without being fractured, the risk of coal and gas outbursts is likely to remain. For this reason, this paper proposes the concept of an "effective protection range of stress relief," which refers to the fracture development zone within the stress-relieved zone. Gas pressure relief and fractures will develop in the outburst-prone seams within this zone, providing a low-stress environment and passages for gas drainage. Fig. 2 illustrates the effective protection range of stress relief.

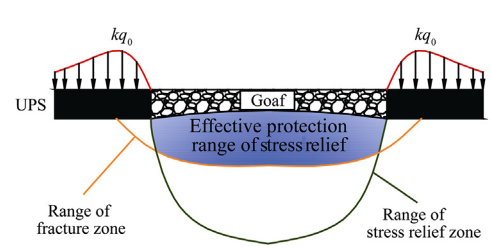

Fig. 2. Effective protection range of stress relief.

3. Stress distribution law of underlying strata

3.1. Establishment of mechanical modeling

A mechanical model of a working face along the dip direction was constructed using elastic theory, in order to research the state and evolution of stress in the floor of a goaf left by UPS mining and to analyze the rate of stress relief in the protected seams [18]. The underlying strata were treated as a continuous elastic material. As the gravitational stress in the overlying strata is transferred to both sides of the working face after UPS mining, a relatively large stress concentration occurs in the lateral bearing stress zone in the wall, which is designated zone S and consists of a plastic zone S_1 and an elastic zone S_2. A mechanical model for calculating the distribution of bearing stress is shown in Fig. 3.

During modeling, the following simplifications were made to facilitate analysis: (1) Since the floor strata can extend infinitely, the problem was viewed as a semi-infinite body problem; (2) Stress in the floor of the goaf left by UPS mining was determined