

Research Article

Mesomechanism of Effects of Water on Strain Rockburst Prevention

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In deep mining engineering, rockburst is an instantaneous release of a large amount of strain energy stored in rock mass, in which occurrence is closely related to initial high stress state and excavation unloading effect. Water can permeate the pores and cracks of rocks and often have a significant effect on the failure mode under stress. The effect of water on rockburst prevention and control has been observed by many researchers in rock engineering. However, the mechanism of rockburst prevention by means of water is seldom researched. In this study, the forming process of strain rockburst is introduced, and the key point to the mechanism of water spraying or water injection to prevent strain rockburst is that the presence of water could cause a transformation of failure mode of rocks during the strain rockburst incubation stage, thereby destroying its formation. In order to explore the specific influence of water on the change of rock failure mode, a crack propagation model with a single inherent main crack and two wing cracks was established, and the most-easily cracking angle ξ was proposed to analyze the mechanism of the failure mode influenced by different water contents. According to the calculated results of ξ , it was found that when rock is completely dry, the wing crack wing extends towards the loading direction, and ξ is around 90° which mainly induces its splitting failure; conversely, as the water content increases, the wing crack deviates from the loading direction; ξ is around 100° which mainly causes its shear failure. The proposed model in this study can reveal the mechanism of the effects of water on strain rockburst prevention in the view of mesoscale.

1. Introduction

As a typical geological disaster in deep engineering, rockburst occurs in highly stressed underground excavation such as mining and tunnel engineering, which severely threatens the safety of underground structures, human life, and equipment. Rockburst can be defined as a dynamic instability phenomenon of surrounding rock mass of an underground opening in the highly stressed zone that is accompanied by a violent release of strain energy stored in the rock mass [1, 2]. Many researchers have classified rockburst based on a large number of engineering practices. Ortlepp and Stacey [3] put forward the concept of strain rockburst earlier. Strain rockburst usually occurs during the excavation of a complete rock mass. Its failure characteristics are mainly partial expansion of rock mass or small pieces of

rock ejection. Earlier scholars tended to hold that strain rockburst is shear failure. With the deepening of research, scholars gradually found that strain rockburst is essentially a kind of tensile failure caused by stress concentration and excavation unloading, similar to the rock specimen in unconfined uniaxial compression [4]. According to Feng and Pan [5], the occurrence of rockburst is a process from microscopic fracture to macroscopic fracture. He et al. [6] emphasized that the evolving process of strain rockburst near the sidewall of a drift can be divided into four stages, including tensile crack propagation, spalling into plates, shearing into blocks, and ejection of blocks, as shown in Figure 1.

It can be seen from Figure 1 that, after the excavation of a drift, the internal cracks of rock mass gradually extended and penetrated under the concentrated tangential stress. Then, a

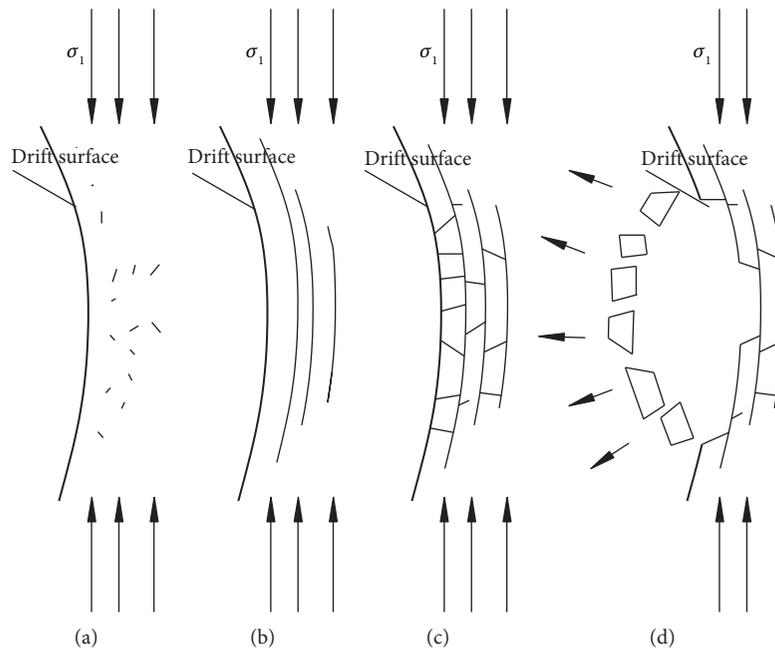


FIGURE 1: The evolving process of strain rockburst in a drift. (a) Tensile crack propagation. (b) Spalling into plates. (c) Shearing into blocks. (d) Ejection of blocks.

macroscopic tensile fracture surface is formed which caused the shallow rock spalling into plates roughly parallel to the drift surface rock slab. As the tangential stress increases, rock plates continue to accumulate elastic strain energy. When the fracture surface expands to the drift surface or it is disturbed by external forces, the elastic energy is instantly released and broken rock blocks are ejected. It should be noted that splitting into plates is the incubation stage of strain rockburst. Obviously, restraining the formation of strain rockburst at the spalling into the plate stage is the key to prevent strain rockburst.

As the depth of underground mining increases, rockburst control becomes an important aspect to ensure the safety of mining operations [7–9]. In terms of rockburst control, several techniques such as the application of energy-absorbing bolts, ground preconditioning (e.g., destress drilling, destress blasting, and water injection), and alternative mining methods (e.g., pillarless mining and mining with sacrifice galleries) have been suggested as the potential solutions for rockburst mitigation [10]. From the viewpoint of rockburst prevention and control, water spraying or water injection is a simple and effective measure. Based on a large number of research studies on rockburst in hard rock mines, it is found by Cook [11] that rocks with high water content is less likely to experience rock bursts. Frid [12] also pointed out that water spraying or water injection on the surrounding rock of the tunnel can effectively prevent rockburst. Many rocks show a significant strength decrease with the effect of water, the reason of which is discussed in detail in a number of papers. It is well known that water could significantly degrade strength and stiffness of rock materials, as well as increase their deformability [13]. In the biaxial compression test, Li et al. [14] simulated the rockburst

process of the roadway by bidirectionally loading the marble and granite samples with circular holes and analyzed the rockburst failure phenomenon and acoustic emission characteristics in the water-saturated, dry, and natural state of rocks. In terms of triaxial tests, Sun et al. [15] carried out true triaxial rockburst tests on three types of water content sandstones and pointed out that the increase of rock water content will weaken the strength of the rock and reduce the acoustic emission count and energy during the rockburst. On the basis of experiments on saturated sandstone, based on the static and dynamic failure characteristics of saturated rocks, Wang et al. [16] discussed the mechanism of water prevention and control of strain rockburst. In their study, static destructions of water-saturated sandstone are shown as extension-shear failure and tensile failure, which can inhibit surrounding rock splitting into plates, so preparation process of strain rockburst is prevented. However, its mechanism by means of water is rarely studied. Water can permeate the pores and cracks of rock and often have a significant effect on its strength and failure mode. It was found by Hawkins and McConnell [17] that the deformations or failure mode of rock vary with water content. A transformation of failure pattern from axial splitting to shear failure is also found with the increase of water content by Zhang et al. [18]. However, the mesomechanism of this transformation of the failure mode cannot be explained well. Currently, many research studies on the failure mechanism of rock bodies mainly focused on the development states of microcracks and transfixion patterns of cracks. It was put forward by Zhang et al. [19] that the failure of crack bodies was caused by the failure evolution on a local region of the specimen and a model which is developed for the growth and interaction of cracks in brittle solids under compressive

stress states was proposed. Pu and Cao [20] found that fissure inclination angle was the major influencing factor on the failure characteristics of fissure bodies. The process of rock failure could be regarded as a process of the damage evolution and macrocracks' expansion. It is generally recognized that the expansion, initiation, and penetration of microcracks in rocks under external force determine the final macroscopic deformation characteristics [21]. Nevertheless, few scholars consider the expansion of cracks in rocks due to the presence of water. In addition, existing macromechanical analysis methods are inadequate for explaining the relation between water and failure mode.

In this study, in order to gain a comprehensive understanding of the effect of water on the failure mode of rocks, a crack propagation model with a single main inherent crack and two wing cracks based on the sliding crack model is established. Furthermore, the most-easily cracking angle ξ is proposed to determine the final failure mode, and the relationship between water content and wing crack propagation was also obtained.

2. Sliding Crack Model

Numerous researchers have used mesomechanical methods to analyze the process of the evolution and failure mode of rock cracks [22]. The sliding crack model [23] has been widely applied in the damage and fracture analysis of rock mass, and the model consists of one main crack whose length is $2c$ with two wing cracks. According to Ashby and Hallam, a critical stress is required to initiate crack growth which depends on the initial crack length and orientation, the coefficient of friction, and the stress state. The crack would grow in a stable way until they start to interact. This interaction increases the stress intensity driving crack growth and leads to the final failure of the rock mass. Although researchers used different calculation methods in studying this model, the stress intensity factor plays a key role in the extension of cracks. The sliding crack model assumed that there is a friction between the crack surfaces of the internal compression-shear cracks of the rock mass during compression, and the pressure and friction both satisfy the Mohr–Coulomb criterion. When the shear stress on the crack surface is greater than the friction, the stress concentration occurred at the crack tips would cause the wing crack to initiate and develop. According to Li et al. [24], due to the excavation unloading, the stress concentration in the surrounding rock is caused; for the surrounding rock of the drift surface, the radial stress is immediately unloaded to 0; in contrast, the tangential stress increased several times. In this case, the surrounding rock stress is similar to the rock specimen in unconfined uniaxial compression. Based on the above discussion, a crack propagation model with pore water is established, as shown in Figure 2.

According to Horri and Nemat-Nasser [25], the value of stress intensity factor K_1 can be calculated using the following equation:

$$K_1 = \frac{2c\tau_{\text{eff}} \sin \theta}{\sqrt{\pi(l+l^*)}} - \sigma'_n \sqrt{\pi l}. \quad (1)$$

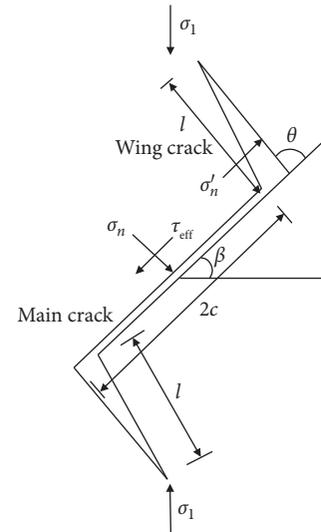


FIGURE 2: Sliding crack model.

This calculation model is denoted as the HN mode in this study. Steif [26] simplified the wing crack in the sliding crack model, proposed another similar calculation model in which the wing crack is straight, and obtained the expression of the stress intensity factor at the main crack tip:

$$K_1 = \frac{3}{4} \sqrt{\frac{\pi}{2}} \tau_{\text{eff}} \left(\sin \frac{\theta}{2} + \sin \frac{3\theta}{2} \right) \cdot (\sqrt{2c+l} - \sqrt{l}) - \sigma'_n \sqrt{\frac{\pi \cdot l}{2}}. \quad (2)$$

This calculation model is denoted as the S model. Based on the hypothesis of isotropy, uniformity, and continuity of rock under external loading, as one of the most popular strength theories used in rock mechanics, the Mohr–Coulomb criterion judged whether the crack or rock is damaged according to the relationship between Mohr's circle of stress and the crack or rock strength envelope [27]. Considering the Mohr–Coulomb criterion and the sliding crack model in Figure 2,

$$\tau_{\text{eff}} = \tau - \mu \sigma_n, \quad (3)$$

$$\tau = \frac{1}{2} (\sigma_1 - \sigma_2) \sin(2\beta), \quad (4)$$

$$\sigma_n = \frac{1}{2} [(\sigma_1 + \sigma_2) + (\sigma_1 - \sigma_2) \cos(2\beta)], \quad (5)$$

$$\sigma'_n = \frac{1}{2} \{(\sigma_1 + \sigma_2) + (\sigma_1 - \sigma_2) \cos[2(\theta + \beta)]\}. \quad (6)$$

3. The Most-Easily Cracking Angle

The sliding crack model has provided an effective way to explain the mesomechanism of failure modes of rock; as mentioned before, when the stress intensity factor of the crack tip K_1 is greater or equal to the critical value K_0 , wing crack would continue to grow until macroscopic fracture

occurred [28]. Based on the sliding crack model, the most-easily cracking angle ξ was proposed to describe the final macroscopic failure in this study, which can be obtained as

$$\xi = \theta_{\max} + \beta. \quad (7)$$

The most-easily cracking angle indicates that the macroscopic failure mode of rock is mainly determined by two factors: the initial direction of the main crack and the propagation direction of the wing crack caused by external load and the friction of the crack surface. Considering that the values of ξ obtained from different angles of main crack may be different, therefore, it is necessary to compare some different cases by selecting different main crack azimuth angles in order to compare the change of stress intensity

factor with wing crack azimuth angle, where l/c is the ratio of length of wing crack and main crack. Here, β was selected as 36° , 54° , and 72° to represent different calculation modes. By substituting equations (3)–(6) into (1) and (2), K_1/K_0 can be obtained to describe the relation between θ and β , as shown in equations (8) and (9).

The value of K_1/K_0 can be given by the following equation through the HN model discussed above:

$$\frac{K_1}{K_0} = \frac{[\sin 2\beta - \mu(1 + \cos 2\beta)]}{\pi \cdot \sqrt{(l/c) + 0.27}} - \frac{1}{2} \sqrt{\frac{l}{c}} [1 + \cos 2(\theta + \beta)]. \quad (8)$$

Similarly, the value of K_1/K_0 based on the S mode can be given as follows:

$$\begin{aligned} \frac{K_1}{K_0} = & \frac{3\sqrt{2}}{16} [\sin 2\beta - \mu(1 + \cos 2\beta)] \left(\sin \frac{\theta}{2} + \sin \frac{3}{2}\theta \right) \cdot \left(\sqrt{2 + \frac{l}{c}} - \sqrt{\frac{l}{c}} \right) \\ & - \frac{\sqrt{2}}{4} \sqrt{\frac{l}{c}} [1 + \cos 2(\theta + \beta)]. \end{aligned} \quad (9)$$

The presence of water may result in marked variations of parameters such as the fracture toughness, friction coefficient, and initial damage [29]. According to the fracture mechanics, internal crack surfaces of rock mass are not smooth and opening. The microcracks tend to close under compressive stress, forming frictional resistance which could prevent the crack propagation. However, since the pore water penetrated into the internal fissures of the rock, the propagation resistance between microcracks is reduced. When rocks are saturated with water, the crack surface is covered with a layer of pore water film, which has obvious lubricating effect on the crack surfaces in rock, and the friction coefficient μ becomes lower as water saturation increases. The friction coefficients of dry and saturated rocks are quite different. With the decrease of friction coefficient, the stress intensity factor at the crack tip of the crack surface had a tendency to increase, which can be seen from equations (8) and (9).

From the discussion given above, $\mu = 1$ can be assumed in equations (8) and (9) for dry rocks, and choose $\mu = 0.05$ to represent rocks under low water saturation content; in contrast, $\mu = 0.005$ can also be chosen to represent rocks in full water saturation. According to equations (8) and (9), the relation curve between the value of K_1/K_0 and θ can be obtained, as shown in Figure 3.

Figure 3 shows that the most-easily cracking angle ξ has an increasing tendency with the decrease of friction coefficient μ . When the inclination angle of main crack $\beta = 54^\circ$ and $\mu = 0.5$, the value of K_1/K_0 first climbs with the increase of the angle between main crack and wing crack θ in the HN

model, and the stress intensity factor then reached a peak where θ is nearly 36° ; in this case, ξ is nearly 90° . Similarly, ξ was found to be at an angle of 93° in the S model. This situation indicates the wing cracks' formation and propagation for rocks with a low water content; from the figure, the wing crack has been preliminarily formed and then expanded as the inclination angle is 90° ; since the most-easily cracking angle expanded and penetrated, finally, rocks can easily show a splitting failure mode. However, when $\mu = 0.005$, namely, the rocks were in full water saturation and ξ is close to 100° ; therefore, wing crack will expand in the direction of the external load, and it is easy to lead to shear failure. Similar results were obtained in rocks in which the inclination angle of main crack $\beta = 36^\circ$ and $\beta = 72^\circ$. The graphs for the HN model and S model are basically similar; both of them show that water can change the failure mode of rocks from splitting to shear failure.

The most-easily cracking angle based on the sliding crack model reveals the mechanism of the influence of water on rock macroscopic failure from a mesoperspective. The friction coefficient μ became lower due to the effect of pore water; after that, the most-easily cracking angle ξ is close to or exceeds 100° . According to the calculation results of ξ , the wing crack influenced by water deviates from the compression loading direction which correspondingly causes the shear failure. The change of the expansion angle of the microcracks could lead to a macroscopic transformation from axial splitting to shear failure. Since the rock failure mode changes, the initial stage of strain rockburst is also destroyed which can inhibit the process of the strain

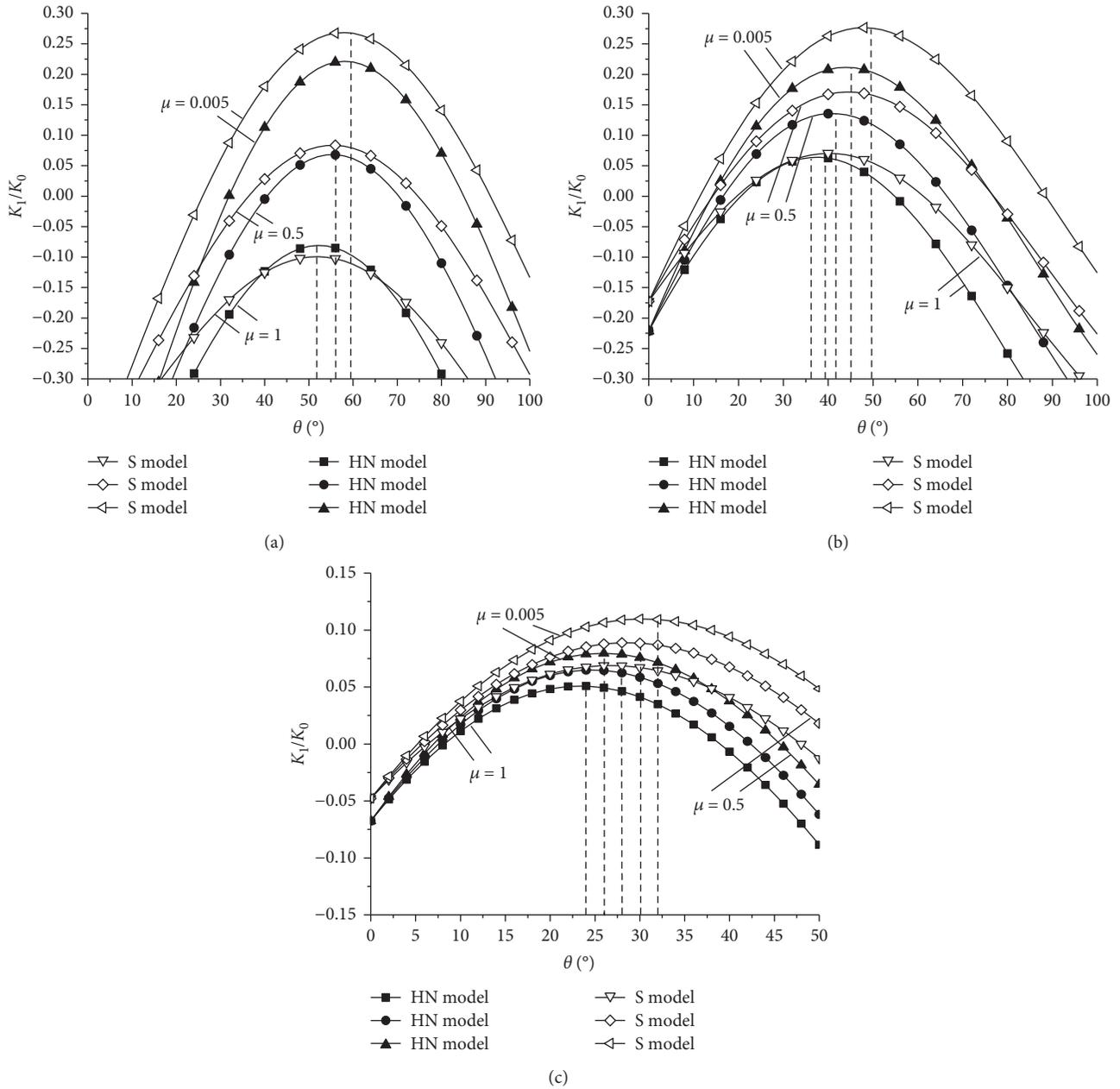


FIGURE 3: Stress intensity factors computed by different models with different β . (a) $\beta = 36^\circ$. (b) $\beta = 54^\circ$. (c) $\beta = 72^\circ$.

rockburst. The mechanism of effect of water on strain rockburst prevention can be revealed preferably in the view of mesoscale.

4. Conclusions

Tensile crack propagation is the initial stage of strain rockburst. From the viewpoint of rockburst prevention in deep underground engineering, water spraying or water injection can effectively prevent strain rockburst. The key is water could destroy the incubation stage of strain rockburst. From a mesomechanism perspective, water can permeate the pores and cracks of rock and often have a significant effect

on its failure mode. The most-easily cracking angle based on the sliding crack model is used to explore the mechanism of failure modes with different contents of water. For dry rocks, the initial crack propagation angle of the wing is close to 90° , which shows the form of axial splitting failure. For water-saturated rocks, as the main crack azimuth angle increases, the wing crack propagation angle finally exceeds 100° , and shear failure characteristic of the final failure mode is more obvious. The presence of water leads to the transition of the rock mass from tensile failure to shear failure, which indicates that water can inhibit the formation of splitting of the rock mass to a certain extent, thereby could destroy the incubation process of strain rockburst.

Abbreviations

ξ :	Most-easily cracking angle
τ :	Tangential stress on main crack
σ_1 :	Vertical stress
β :	Main crack azimuth angle
c :	Main crack length
μ :	Friction coefficient
l^* :	Dimensionless wing crack length
K_1/K_0 :	Stress intensity factor
l :	Wing crack length
σ_n :	Normal stress on main crack
τ_{eff} :	Shear stress on main crack
σ'_n :	Normal stress on wing crack
θ :	Angle between main crack and wing crack.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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