

## Research Article

# Seepage Law of Injected Water in the Coal Seam to Prevent Rock Burst Based on Coal and Rock System Energy

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Received 5 July 2018; Accepted 30 August 2018; Published 21 November 2018

Academic Editor: Yan Peng

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Rock burst is one of the typical dynamic disasters in coal mining. In order to reveal the mechanism of rock burst from the energy view point, the relationships between the maximum, minimum, and intermediate principal stresses and the concentration coefficients of the gravity stress  $k_1$ ,  $k_2$ , and  $k_3$  are determined through the geostress measurement combined with engineering practice of coal mining. The coal and rock system model based on the tectonic stress is established. The relationship between energy and scale radius of the coal and rock system is determined to reveal the law of energy accumulation, release, and transfer in the coal and rock system. In view of the characteristics of the porous medium in the coal seam, the measures of water injection are put forward to relieve pressure in the coal seam, and the law of water seepage in the process of water injection in the coal seam is studied based on the seepage mechanics. The result shows that the trend of released energy of damaged coal has good consistency with the variation of permeability, and water injection can reduce the stress concentration and energy concentration of the rock burst system. The engineering practice of the rock burst prevention was taken in Yuejin Coal Mine. The energy characteristics of the coal and rock system in the working face are analyzed, and the measures of water injection and the corresponding parameters are determined.

## 1. Introduction

Coal is the main energy resource and important chemical raw material in China. According to the sustainable development strategy report of China, it is estimated that coal consumption will still account for more than 50% of the total energy consumption in 2050 [1]. In 2017, the production of raw coal in China is 3.52 billion tons with the data released by the National Bureau of Statistics. However, underground mining is a main means of coal resource mining in China, which is often associated with dynamic disaster phenomena [2–4]. Rock burst is a typical dynamic disaster in the process of coal mining. During rock burst, coal and rock will suddenly be crushed and ejected into the working space

[5, 6] when the coal and rock mechanic system reaches its ultimate strength, accompanied by sharp and violent shock and bomb, which will cause equipment damage and casualties [7, 8]. With the increasing mining depth, dynamic disasters, such as rock burst, will be more serious and become a great threat to coal mine safety production (Figure 1). By now, there are approximately 210 coal mines where rock burst has occurred in China, as the numbers, intensity, and frequency of this disaster are still increasing.

The mechanism of rock burst has been a long-standing and unsolved scientific problem in the field of mining engineering and rock mechanics. Some theories have been proposed, such as the instability theory, the strength theory, the stiffness theory, the impact orientation theory, and the



FIGURE 1: Scene picture after rock burst disaster occurred.

energy theory [9–13]. Recently, with the application of interdisciplinary and nonlinear science, as well as the computer simulation technology in the research of rock burst, the research methods of CT scanning, 3D printing, and 3D numerical simulation were used to study the conditions of the inoculation and occurrence of rock outburst under the dynamic and static combined stress in the mesoscale, experimental scale, and engineering scale [14–17]. It has become a research hotspot to reveal the unstable evolution process of the rock and coal structure under rock outburst and to explore effective prevention and control measures for rock burst [18–20]. Because of the complexity of the rock burst, most of the above studies are the mechanism and experimental analysis, which is hard to effectively verify in-site. A unified understanding of rock outburst has not yet formed when this great limitation is confronted.

The inoculation of rock burst is affected by the stress concentration and strain energy in the regional coal and rock system, which should have a certain scale range. In terms of the energy characteristics of rock burst, a coal and rock system model was established based on the tectonic stress field, and the energy concentration, release, and transfer law of the coal and rock system were analyzed. The water injection measure for stress relief was put forward to determine the relationship between the trend of released energy and the permeability variation of damaged rock mass so as to reveal the law of water migration in the coal and rock system.

## 2. Distribution Characteristics of Geostress Field in Coal Mines with Rock Burst Risk

**2.1. Measurement of Geostress in Coal Mines with Rock Burst Risk.** The International Union of Geological Sciences and International Union of Geodesy and Geophysics listed ground stress research as a key content for the international solid geoscience research program and pointed out that “the research on ground stress has distinctive importance on learning composition activity process and the direction and grade of ground stress is a requisite to learn all the problems on geological structure.” The research showed that disasters like earthquake in the world happened in the tectonic mobile zone where horizontal or nearly horizontal stress activities

were advantageous, while strong earthquakes do not happen in areas where horizontal stress equaled vertical stress or vertical stress was greater than horizontal stress [21]. Based on the above opinion on the ground stress field and in terms of engineering practice on mine rock burst in China, the widely applied hollow inclusion stress method is adopted to measure the mine ground stress of the Pingdingshan No. 12 Mine, Buxin Wulong Mine, Daitajing. The maximum principal stress, intermediate principal stress, and minimum principle stress are shown by  $\sigma_1$ ,  $\sigma_2$ , and  $\sigma_3$ . Table 1 lists the measurement results of the ground stress and stress at measuring points in the mine zones (mines).

### 2.2. Measured Results of Geostress Field

**2.2.1. Distribution Laws of the Maximum Principal Stress  $\sigma_1$ .** According to the practically measured material, the variation curve of the maximum principal stress changing with depth can be obtained (Figure 2), and regression coefficient  $k_1 = 1.9656 \approx 1$ :

$$\sigma_1 = 1.9656\gamma h \approx 2.0\gamma h, \quad (1)$$

where  $\gamma$  is the volume-weight ( $N/m^3$ ) and  $h$  is the buried depth (m).

**2.2.2. Distribution Laws of the Vertical Stress  $\sigma_2$ .** According to the practically measured material, the relationship of vertical stress and depth can be obtained (Figure 3), and regression coefficient  $k_2 = 1.1392 \approx 1.0$ :

$$\sigma_2 = 1.1392\gamma h \approx 1.0\gamma h. \quad (2)$$

**2.2.3. Distribution Laws of the Minimum Horizontal Stress  $\sigma_3$ .** According to the practically measured material, the relationship of vertical stress and depth can be obtained (Figure 4), and regression coefficient  $k_3 = 0.7149 \approx 0.7$ :

$$\sigma_3 = 0.7149\gamma h \approx 0.7\gamma h. \quad (3)$$

From formulas (1)–(3),  $\sigma_1$ ,  $\sigma_2$ ,  $\sigma_3$ , and  $\gamma h$  show the linear distribution characteristic and  $k_1 = 2$ ,  $k_2 = 1.0$ , and  $k_3 = 0.7$ .

The tectonic stress field of China is affected by the collision and extrusion of the surrounding plates, and the

TABLE 1: Geostress distribution characteristics of some rock bursts in China.

Number	Location	Buried depth (m)	Maximum principal stress			Intermediate principal stress			Minimum principal stress		
			Magnitude (MPa)	Azimuth (°)	Inclination (°)	Magnitude (MPa)	Azimuth (°)	Inclination (°)	Magnitude (MPa)	Azimuth (°)	Inclination (°)
1	Pingdingshan 12th Mine	770	41.34	255.04	-2.63	19.28	-25.00	75.25	17.32	165.72	14.49
		830	48.25	122.89	-4.10	20.98	44.34	70.13	18.84	211.45	19.41
		620	33.46	110.24	-5.39	16.94	-21.50	-81.93	11.81	200.80	-5.98
2	Pingdingshan 8th Mine	495.4	28.10	119.23	-0.43	12.46	28.49	-59.68	5.97	209.50	-30.31
		807.3	34.15	224.25	3.02	22.38	-16.13	72.47	14.69	153.31	17.25
		602.9	29.06	251.71	6.54	17.90	5.03	73.84	10.22	159.98	14.71
3	Fuxin Wulong Mine	773	29.45	102.3	-15.3	18.03	-19	-62.2	11.69	198.9	-22.6
		774	31.89	100.3	-21	20.57	-42.7	-64.3	17.79	195.9	-14.1
4	Dataijing Mine	884	42.56	264.49	-26.92	23.84	59.45	-60.73	8.85	169.02	-10.63
		816	35.82	118	13	29.65	58	-64	9.4	203	-21
5	Muchengjian Mine	600	28.7	267.94	-0.43	18.9	-1.57	-48.7	11.4	177.57	-41.3
		600	43.3	38.9	-9.2	24.83	308	-9.5	16.7	352	76.7

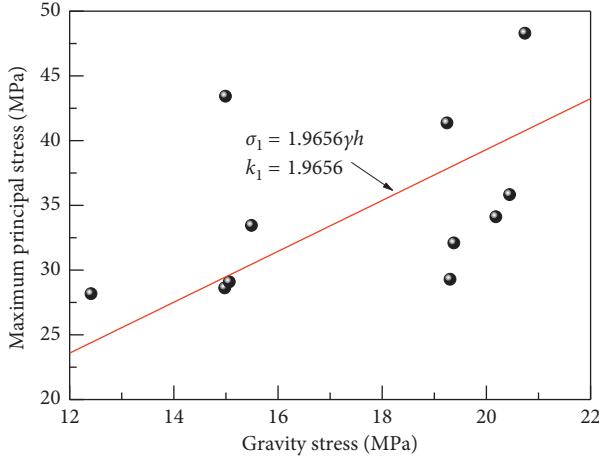


FIGURE 2: Relationship between maximum horizontal principal stress and gravity stress.

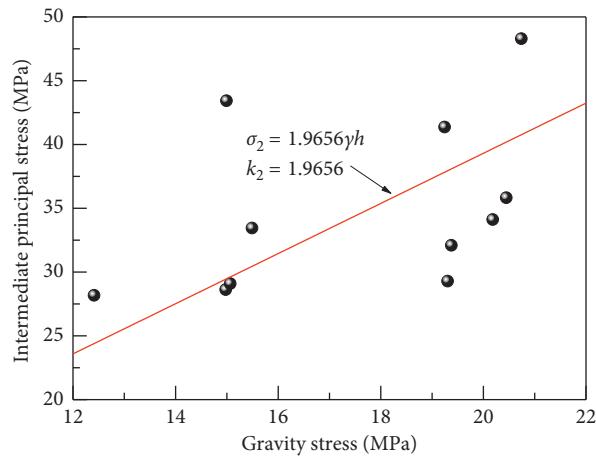


FIGURE 3: Relationship between intermediate horizontal principal stress and gravity stress.

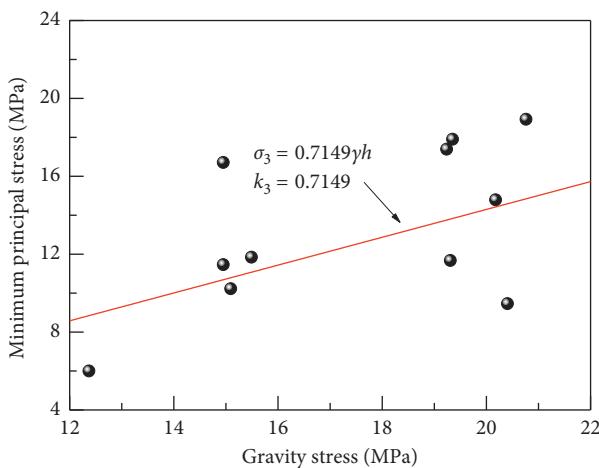


FIGURE 4: Relationship between minimum horizontal principal stress and gravity stress.

stress field in the spatial distribution is characterized by the homogeneity of the large region and the inhomogeneity of the local area, and it is relatively stable in

temporal distribution. According to the measured results of the geostress of many coal mines with rock burst risk in China, the rock bursts mostly happened under the condition of the tectonic stress field and mainly with the horizontal extrusion type of the maximum principal stress and with the same direction of the regional tectonic stress field.

### 3. Energy Distribution Characteristics of Coal and Rock System

**3.1. Analysis of Elastic Energy of Mine Volume Accumulation.** The rock burst dynamic system on the original rock stress field is mainly affected by the coefficient of the self-weight stress field and tectonic stress field. The energy-bursting ground stress dynamic system is mainly produced by the self-weight stress field and tectonic stress field. When the effect of engineering activity bothers the original rock balance, energy will be released and transferred. In other words, the elastic energy of high volume accumulation of mines is a prerequisite for rock burst. Elastic mechanics held that any of the unit of earth crust's rock was affected by stresses at three directions, and the units were under elastic formation condition. The unit volume accumulation elasticity deformability is shown in Figure 5, and the elasticity deformability energy under the original rock stress field can be expressed as

$$U_0 = \frac{1}{2E} [\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\mu(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_1\sigma_3)], \quad (4)$$

where  $U_0$  is the elastic energy accumulated in unit volume ( $J/m^3$ ),  $\sigma_i$  is the principal stress in three directions (MPa),  $E$  is the elasticity module (GPa), and  $\mu$  is the Poisson ratio.

**3.2. Analysis of Energies of Coal and Rock System.** Rock burst is produced by the coefficient of the self-weight stress field and tectonic stress field. By analysis, the rock burst condition to the burst ground pressure mine in China happened commonly in the tectonic stress field. It can be taken that the tectonic stress field is the main factor to cause rock burst. On the tectonic stress field, when the storage energy of the rock burst dynamic system reaches the critical value to cause rock burst, rock burst will happen if evoked by external mining project activity. In order to better understand the relationship between the energy of the rock burst dynamic system and rock burst, this paper establishes a model for the “spherical” rock burst dynamic system (Figure 6), and the energy of the rock burst dynamic system under tectonic stress field condition can be obtained:

$$V = \frac{4}{3}\pi R^3, \quad (5)$$

where  $V$  is the volume of the rock burst dynamic system ( $m^3$ ) and  $R$  is the dimensional radius of the rock burst dynamic system (m).

Formulas (1)–(5) were used to obtain the energy of the rock burst dynamic system under tectonic stress field condition:

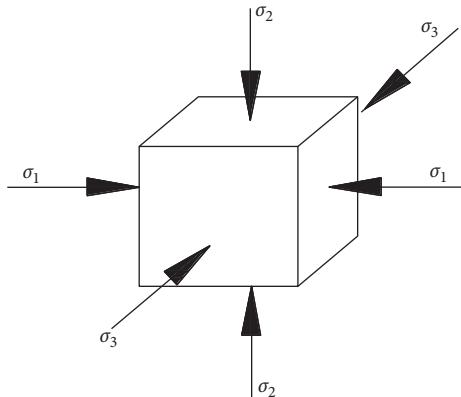


FIGURE 5: Mine rock unit compressed from three directions.

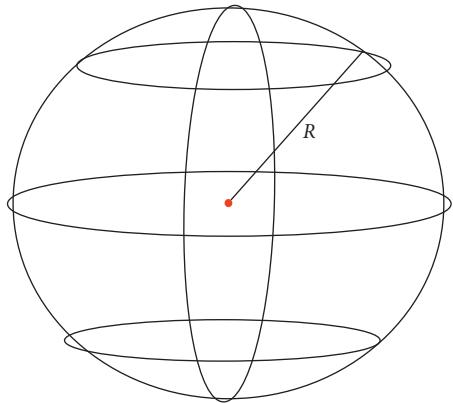


FIGURE 6: Spheroid burst ground stress dynamic system.

$$U_G = \frac{2\pi R^3}{3E} \left[ 4\gamma^2 H^2 + \gamma^2 H^2 + 0.49\gamma^2 H^2 - 2\mu(2\gamma^2 H^2 + 0.7\gamma^2 H^2 + 1.4\gamma^2 H^2) \right], \quad (6)$$

$$U_G = \frac{2\pi}{3E} (5.49 - 8.2\mu)\gamma^2 H^2 R^3. \quad (7)$$

**3.3. Relationship between the Energy and the Size Scale of Coal and Rock System.** The stored energy in the coal and rock system is in a relatively stable state when it is not affected by excavation. Under the influence of excavation engineering disturbance, the coal and rock system may enter the sub-stable state, and the energy of the whole system will reach its critical state followed by the instantaneous release of energy to form a rock burst disaster. Then, the coal and rock system will form a new equilibrium state, and the energy begins to transfer-aggregate-get stored again. When the storage energy reaches the critical value, the next rock burst will occur again under the mining disturbance. It can be seen that the inoculation and occurrence of rock burst is a nonlinear dynamic process of energy accumulation in a stable state and

energy release in the unstable state in the coal and rock system [22].

The energy  $\Delta U$  released in rock burst is provided by the energy of the rock burst dynamic system. The energy mainly comes from the energy  $U_G$  that is produced under the tectonic stress field. After the rock burst, there is still some energy left, which is equal to the energy  $U_Z$  that is produced on the self-weight stress field. When the energy accumulated by the coal and rock system is enough to support the occurrence of rock burst, rock burst will happen under the effect of external mining activity. The energy released by rock burst is provided by the rock burst dynamic system. Therefore, it is related to the dimension of the system. The energy released by rock burst and its corresponding system radius  $R$  can be obtained under the presumption that the “spheroid” bursts the ground pressure dynamic system:

$$\Delta U = \frac{2\pi(10.2\mu^2 - 12.69\mu + 4.49)\gamma^2 H^2 R^3}{3E(1-\mu)}, \quad (8)$$

$$R = \sqrt[3]{\frac{3E(1-\mu)\Delta U}{2\pi(10.2\mu^2 - 12.69\mu + 4.49)\gamma^2 H^2}}. \quad (9)$$

#### 4. Analysis of Water Injection into Coal Seam to Prevent Rock Burst in Coal and Rock System

**4.1. Mechanism of Water Injection into Coal Seam to Prevent Rock Burst.** The occurrence of rock burst is not only related to the mining disturbance but also related to the characteristics of the coal and rock system. The physical and mechanical properties of coal and rock can be changed to prevent the occurrence of rock burst. Because of the structural surface and internal cracks in the coal and rock mass in the coal and rock system, the place of rock burst is often located at the junction of the weak surface or the crack extension. The accumulated elastic energy is released to form rock burst when the stress state becomes unstable. The internal cracks converge, nucleate, and expand during the system instability. Therefore, the stress state in the coal seam can be changed by increasing fractures and pore water saturation [23] by water injection. So, the stress and energy concentration of the coal and rock system will be reduced, and this can avoid the occurrence of rock burst. The water injection preventing rock burst in the coal seam is actually a process of water driving gas [24, 25]. The water migration in the coal seam during injection can be regarded as the seepage mechanics problem with the moving interface [26].

**4.2. Analysis of Water Migration in Coal Seam during Injection.** Water injection boreholes in the coal seam are generally parallel drilled. The mechanics model of water injection into the coal seam is shown in Figure 7. Assuming  $R$  is the wetting radius of water injection in the coal seam,  $R_W$  is the radius of water injection boreholes, and  $r_c$  is the radius of the water front surface, which is the water interface when

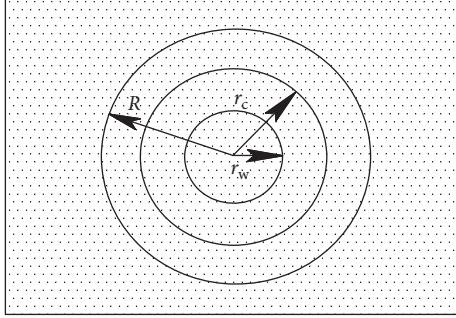


FIGURE 7: Mechanics model of water injection into the coal seam.

it seepages into the coal seam from the borehole changing with time in the process of water injection. The displacement of the water front surface  $F(R, t)$  is a function of time  $t$ , which can be expressed as

$$F(R, t) = R + r_c(t). \quad (10)$$

The velocity of the moving interface is the change rate of displacement with time:

$$\frac{dF}{dt} = \frac{\partial F}{\partial t} + u \frac{\partial F}{\partial r} = 0, \quad (11)$$

where  $u$  is the velocity of fluid particles. From Equation (10), we can derive the following:

$$\begin{cases} \frac{dF}{dt} = \frac{\partial r_c}{\partial t}, \\ \frac{\partial F}{\partial r} = 1. \end{cases} \quad (12)$$

Equation (12) is substituted into equation (11), and the water front interface is obtained, that is, the velocity of the water moving forward from the borehole (the radial velocity of the fluid particle):

$$u = -\frac{\partial r_c}{\partial t}. \quad (13)$$

In order to obtain the radial velocity of fluid particles and calculate the injection time, the seepage equation on both sides of the gas and water interface must be solved.

Considering the circular formation, the outer radius is  $R$ . The pressure remains unchanged as the original pressure  $P_g$ , and the water injection pressure  $P_w$  is also constant on the outer boundary  $r = R$ . Assume that the formation is homogeneous and isotropic with the permeability  $k$ . The viscosity of water is  $\mu_w$ , and the viscosity of gas is  $\mu_g$ . Due to the internal and external boundary pressures remaining unchanged, the injection volume  $Q$  generally remains stable. So, it can be considered that the two-phase flow of water and gas is stable seepage. The  $P_c$  on the water interface can be obtained as follows:

$$P_c = \frac{\mu_g P_g \ln(r_c/r_w) + \mu_g P_w \ln(R/r_c)}{\mu_w \ln(r_c/r_w) + \mu_g \ln(R/r_c)}. \quad (14)$$

According to Darcy's law, the equations of water and gas seepage velocity are obtained, respectively:

$$\nu_w = \frac{k}{\mu_w} \times \frac{dP1}{dr} = \frac{k}{\mu_w} \times \frac{P_w - P_c}{\ln(r/r_w)} \times \frac{1}{r}, \quad (15)$$

$$\nu_g = \frac{k}{\mu_g} \times \frac{dP2}{dr} = \frac{k}{\mu_g} \times \frac{P_c - P_g}{\ln(R/r_c)} \times \frac{1}{r}.$$

Based on the Dupuit–Forchheimer equation, the motion law of the water and gas interfaces can be obtained by the seepage velocity  $V$ :

$$V = -\phi \frac{dr_c}{dt}, \quad (16)$$

$$\begin{aligned} dt &= -\frac{\phi}{V}, \\ dr_c &= \frac{\phi}{k(p_w p_c)} \left( \mu_g \ln \frac{R}{r_c} + \mu \ln \frac{r_c}{r_w} \right) r_c dr_c. \end{aligned} \quad (17)$$

The integral of Equation (17) can be obtained:

$$\begin{aligned} t &= \frac{\phi}{2k(p_w - p_c)} \left[ \left( \mu_w - \mu_g \right) \left( r_c^2 \ln r_c - \frac{r_w^2}{R} \ln r_w - \frac{r_c^2}{2} + \frac{r_w^2}{2} \right) \right. \\ &\quad \left. + \mu_g \ln R \left( r_c^2 - r_w^2 \right) - \mu_w \ln r_w \left( r_c^2 - r_w^2 \right) \right]. \end{aligned} \quad (18)$$

The radius of the water injection hole  $r_w$  is very small compared with the outer radius  $R$  of the water injection area. Equation (18) can be simplified as follows:

$$t = \frac{\phi}{2k(p_w - p_k)} \left[ \mu_w r_c^2 \left( \ln \frac{r_c^2}{r_w^2} - \frac{1}{2} \right) + \mu_g r_c^2 \left( \ln \frac{R}{r_c} - \frac{1}{2} \right) \right]. \quad (19)$$

Through Equation (19), the time needed for water injection in the coal seam with a certain radius  $R$  can be calculated. At the same time, we can calculate the radius of water injection according to a certain injection time, which can act as an important basis for determining the layout of boreholes. It is also shown that the length of water injection for the same area depends on the pressure gradient. And the greater the pressure gradient, the less time it takes. When the water injection pressure increases, the coal seam is liable to failure and permeability increases, thus shortening the injection time and improving the water injection efficiency. Water injection time can be determined through the laboratory water injection test.

**4.3. Rock Outburst System and Water Injection into Coal Seam in Yuejin Mine.** At 10:09:59 AM, March 1, 2011, the lower lane of the 25110 working interface of Yuejin Mine had a rock burst with a magnitude of 2.071. When the rock burst happened, 210 m~410 m away from the lower lane was affected. In total, the lane with a length of 200 m was affected, and 3 workers were slightly injured. The incidence had extensive influence as the 23130 working interface and

aboveground had tremors. The location where rock burst happened was 1014 m away from the ground and 268 m away from the working interface. According to Equations (8) and (9), the energy  $\Delta U$  and the system dimensional radius of the Yuejin Mine “3.1” rock burst dynamic system can be obtained.

According to  $U = 10^{1.695ML+3.18}$ , the energy  $\Delta U = 4.9 \times 10^6$  J released by the rock burst dynamic system can be obtained. Dimensional radius of the rock burst dynamic system is 312.84 m.

In Figure 8, it can be seen that “3.1” bursts ground pressure in the rock burst dynamic system with a radius of 312.84 m, and from December 14, 2006, when the 25090 working interface had a rock burst when the lower lane extraction adopted 159 m to March 1, 2011, the lower lane of the 25111 working interface had 14 rock bursts, among which there were 8 rock bursts in the lower lane of the 25090 working interface within the rock burst dynamic system and 6 rock bursts on the 25111 working interface. The occurrence of rock bursts was affected and controlled by system energy. After a rock burst, system energy can exchange, supplement, and store within a certain period. When energy reaches the critical point of rock burst, rock burst will happen again. Therefore, it can be demonstrated that the implementation of the preventive measures of rock burst is of timeliness. It is safe to mine within the period during which preventive measures are implemented. When the period is gone, safety production will be threatened when system energy supplements to a certain extent to which rock burst might occur.

We collected coal samples from the 25110 working surface and cut them to the standard coal specimens in the laboratory. The compressive strength test of coal specimens after 3, 7, 14, and 21 days of water injection was carried out. As shown in Figure 9, the coal specimen without water injection presents a sudden brittle failure characteristic, while the coal specimen with water injection is obviously plasticized with the rapid deformation increase. With the rising moisture content, the strength of specimens decreases, despite an increase in a period of immersion time. It can be determined that when the injection and softening period is 14 days, the compressive strength is the lowest, and the specimen will not cause instability failure with the softening rate of 65%.

According to the mining practice of panel 25110 in Yuejin Coal Mine, the parallel water injection boreholes were arranged on the coal wall of the roadway, namely, the coal and rock system, to relieve geostress and prevent rock burst. The radius of the water injection borehole is 90 mm, the distance between the boreholes is 5 m, and the water injection pressure is 20 MPa, and the water injection time is 14 days. After adopting the measure of coal seam water injection, the rock burst disaster has been effectively avoided, and the safe and efficient production of coal mines has been realized.

## 5. Conclusions

- (1) By measuring and analyzing ground stress of some rock bursts in China, it can be confirmed that stress concentration coefficients of  $\sigma_1$ ,  $\sigma_2$ , and  $\sigma_3$  on the

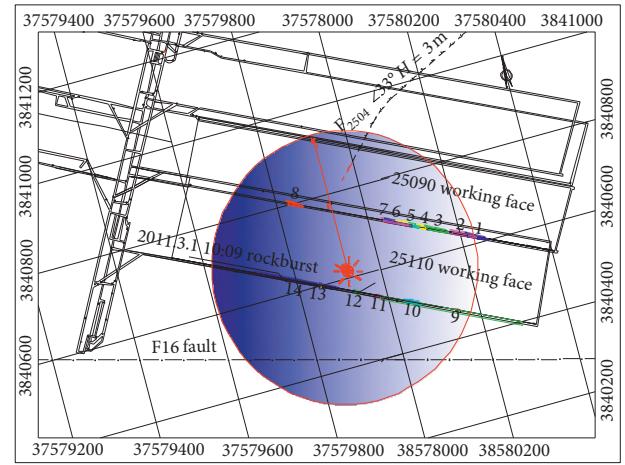


FIGURE 8: “3.1” rock burst dynamic system of the 25110 working interface of Yuejin Mine.

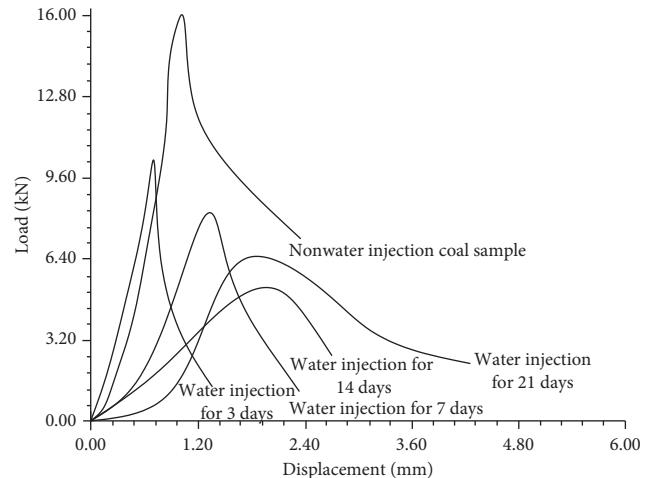


FIGURE 9: The stress-strain curve of water softening coal specimens.

tectonic stress field are  $k_1 = 2$ ,  $k_2 = 1$ , and  $k_3 = 0.7$ , respectively.

- (2) The model of the coal and rock system based on the tectonic stress is established. The relationship between the energy of the coal and rock system and the scale radius is determined, and the law of energy accumulation, release, and transfer is revealed. Rock burst is a nonlinear dynamic process of accumulating energy in a stable state and releasing energy in the unstable state.
- (3) Based on the fluid mechanics and the characteristics of the porous medium of the coal seam, the measure of water injection to relieve geostress in the coal seam was put forward and moving interface theory was used. By changing the stress state of coal and rock, the stress and energy concentration of the coal and rock system is reduced. The relationship between water injection time and flow rate and pressure is determined.
- (4) By analyzing the coal and rock system of rock burst that happened in panel 25110 of Yuejin Mine on

March 1, 2011, it can be confirmed that the energy released in the coal and rock system is  $4.9 \times 10^6$  J and spatial radius is 312.84 m. The parallel water injection boreholes were arranged on the coal wall of the roadway, namely, the coal and rock system, to relieve geostress and prevent rock burst. The radius of the water injection borehole is 90 mm, the distance between the boreholes is 5 m, and the water injection pressure is 20 MPa, and the water injection time is 14 days.

## Data Availability

The experimental data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## Acknowledgments

This research was financially supported by the National Natural Science Foundation of China (Grant no. 51604139), the State Key Research Development Program of China (Grant no. 2017YFC0804209), the Liaoning Provincial Education Department funded project (Grant no. LJYL037), the Research Fund of Research Center of Safe Exploitation and Clean Utilization Engineering of Coal Resources (Liaoning Technical University) (Grant no. LNTURCCRSMCU), and the Research Fund of State Key Laboratory Cultivation Base for Gas Geology and Gas Control (Henan Polytechnic University) (Grant no. WS2018B05).

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