

Research Article

Mechanism of Vibration Energy Action on Dynamic Instability of Shock-Type Rockburst Carrier System

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In coal mining, the rockburst intensity triggered by the mine earthquake is often greater in the mining area, and the precursor information is more difficult to capture. In this paper, this kind of rockburst is called shock-type rockburst and studied as the research object. Based on the evolution process and the theoretical model of the carrier system, the energy criterion of the occurrence of shock-type rockburst was deduced based on the theories of mathematics and statistical physics. The results showed that the process of shock-type rockburst can go through four stages: inoculation stage, occurrence stage, development stage, and termination stage, and the secondary triggering phenomenon may occur in the occurrence stage. The theoretical model of the shock-type rockburst carrier system was constructed, and the key characteristic parameter of shock-type rockburst was put forward. Then, the energy of mine earthquake was quantitatively characterized in the form of kinetic energy of rock block. Through the combination of the two parameters, the energy criterion of shock-type rockburst was obtained as follows: once the energy of mine earthquake acting on the rockburst source area was 2%–9% of the static energy, shock-type rockburst can occur. Then, this criterion was verified by three typical cases. Finally, based on the distribution conditions of "red seam" overburden in the Yanzhou mining area of China, the secondary triggering principle of rockburst was formed. This study provides a theoretical system for judging the instability of the shock-type rockburst carrier system was formed. This study provides a theoretical system for judging the instability of the shock-type rockburst carrier system was formed. This study provides a

1. Introduction

Rockburst is one of the serious mine dynamic disasters [1-5]. According to the time of stress action, it can be divided into creep-type rockburst caused by static load stress and shock-type rockburst caused by mine earthquake action [6-10]. Before the occurrence of shock-type rockburst, the stress concentration in the coal rock near the excavation region is sometimes not obvious, and the rockburst risk is difficult to be detected by drilling cutting method and online stress monitoring. Due to the sudden release of external vibration disturbance, the rockburst intensity is hard to predict, and the precursor information is hard to capture. In a word, the prediction and prevention of shock-type rockburst is a difficult issue in engineering [11-15]. Figure 1

shows the actual situation of shock-type rockburst in a coal mine of Xinjiang under a mining depth of 317 m. It can be seen that under the relatively shallow coal seam depth and small self-weight loads, a strong mine earthquake still has the possibility of inducing catastrophic rockburst. Therefore, it is of great significance to study the mechanism of shock-type rockburst and directly obtain its occurrence criterion.

At present, certain research and application achievements have been made on the shock-type rockburst. Jiang et al. [16, 17] established the mechanical model of dynamic disaster induced by mine earthquake in composite coal seam mining and analyzed the interaction between them. Aiming at the frequent occurrence of rockburst under the complex conditions of fault structure, coal pillar, and hard roof, Pan et al. [18–20] established the disturbance response instability theory of rockburst. It was reported that once the critical index of the interaction between disturbance subsystem, response subsystem, and control subsystem in the coal rock deformation system is reached, rockburst is caused. Besides, the quantitative criterion of the system in the unstable equilibrium state was also obtained. Wang et al. [21, 22] established the stress control theory of rockburst characterized by gradient stress and revealed the coupling inducing mechanism of rockburst including original rock stress, tectonic stress, and mining stress through the similar simulation and numerical calculation. Lyu et al. [23] established the "disturbance-rockburst" dynamic system of the coal rock, discussed the mechanism and criterion of shock-type rockburst disaster, and carried out verification analysis by numerical calculation. Rong Hai et al. [24-26] put forward the concept of coal rock dynamic system and developed quantitative calculation method for each region of the coal rock dynamic system based on Mises yield criterion. These results have been effectively applied in the Laohutai coal mine. To a certain extent, the above studies have concluded the criterion of shock-type rockburst disaster and quantitatively revealed the mechanism of rockburst. However, most of the methods are based on the stress angle, and the error is usually large.

In recent years, scholars have found that occurrence conditions of rockburst may be accurately characterized by taking energy as the occurrence criterion of rockburst, and they have carried out relevant research on energy discrimination of rockburst. On the basis of shale loading test, Wen et al. [27] obtained the energy evolution characteristics in the rock fracture process under different constraints and analyzed the energy release law of the transformation from plastic failure to brittle failure. These research results can be used as the energy criterion of rockburst and the inspection standard of rockburst prevention of hydraulic fracturing. Wang et al. [28, 29] revealed the triggering mechanism, triggering conditions, and prevention ideas of unstable energy of rockburst through theoretical analysis and microseismic monitoring. It is found that the rockburst will be triggered when both the unstable energy accumulated in coal rock and the disturbance energy of mine earthquake reach the critical value.

In conclusion, it is more accurate and effective to reveal the occurrence mechanism of rockburst from the perspective of energy, and the interaction between the disturbance energy of mine earthquake and the apparent energy of rockburst is the research focus. In this paper, the evolution process of shock-type rockburst was first analyzed, and then the rockburst carrier system model was established. Subsequently, based on the relevant theories of mathematics and statistical physics, the energy criterion for the occurrence of shock-type rockburst was deduced, and the quantitative relationship between the energy of mine earthquake and the apparent energy of rockburst was revealed. The research results can provide the basis for the identification and prevention of shock-type rockburst.

2. Evolution Process and Carrier System Model of Shock-Type Rockburst

The evolution of shock-type rockburst experienced four stages: incubation stage, triggering stage, development stage, and

termination stage. In the development stage, there may be multiple cycles: rockburst-mine earthquake-rockburst-rockburst development, as shown in Figure 2:

- (1) Incubation stage: the initial stress balance of surrounding rock is broken by mining activities, and stress concentration is formed near the coal seam; then, the surrounding rock structure is changed, which is manifested in the roof failure of hard rock and the aggravation of fault activation. Then, the conditions for the occurrence of mine earthquake are prepared.
- (2) Triggering phase: the stress and deformation of coal rock in the incubation stage are close to the critical condition of failure. The far-field mine earthquake causes dynamic load on the surrounding rock near the working face, triggering its fracture. As a result, the bearing capacity of surrounding rock is lost partially, resulting in rockburst instability. At the same time, the elastic properties of coal rock are released rapidly, the unstable coal rock is thrown to the free surface, and then the rockburst holes are initially formed.
- (3) Development stage: after the rockburst is triggered, a stable structure is not formed in the surrounding rock instantaneously. The initial formation of the rockburst hole results in the sudden unloading of the stress in the inner wall, and the broken coal rock is severely damaged and thrown to the free surface, and the rockburst hole expands; at the same time, the expansion of the rockburst hole also provides a good channel for the stress release and coal rock fragmentation. There is another possible situation. Most of the concentrated stress transfers and releases to the free surface of the rockburst holes, but some of the stress moves back to the free surface due to the rebound effect. When the stress transferred from the back to the free surface is too large, the rockburst holes break along the longitudinal direction. This kind of situation usually occurs in the concentration of surrounding rock structures.

In the later development stage, if the longitudinal fracture occurs in the surrounding rock, especially under the condition of fault development and hard roof, the mine earthquake may be induced again by the reverse force. Once the mine earthquake occurs, the triggering stage of rockburst is returned. In this way, the mine earthquake and rockburst can induce each other; only if the reverse stress cannot induce the mine earthquake and the mine earthquake cannot trigger the rockburst, this process is suspended.

(4) Termination phase: after the suspension of rockburst, the structure of coal rock tends to be stable, and the stress returns to equilibrium again. At this stage, there is no large-scale breakage and structural instability in the coal rock.

According to the evolution process of shock-type rockburst and the interaction between mine earthquake and



FIGURE 1: Actual situation of shock-type rockburst. (a) Toppling of shearer; (b) folding of single pillar.



FIGURE 2: Evolution process of shock-type rockburst.

rockburst, it is considered that the disturbance area of mine earthquake and rockburst behavior area should be taken as the research object, instead of the single rockburst source area in the study of shock-type rockburst. Besides, the individual role and the quantitative relationship with the whole system should be clarified. Therefore, the shock-type rockburst carrier system model is established, as shown in Figure 3.

3. Action Condition of Vibration Energy for Dynamic Instability of the Shock-Type Rockburst Carrier System

3.1. Analogy Analysis. The essence of bullet shooting from the gun body to hitting a target is the process of momentum and energy exchange between gun body, bullet, and target at high speed. The "impact energy factor" of the bullet is the key characteristic parameter that causes different deformation of the target. The motion equation of this process is expressed by

$$m_D h'' = -F_D,$$

 $h_{t=0} = 0,$ (1)
 $h'_{t=0} = v_0,$

where m_D is the mass of the bullet, g; h is the deformation of the target, mm; F_D is the resistance of the target, MPa; t is the contact time, ms; and v_0 is the initial velocity of the bullet, m/s. Equation (2) is obtained by the integral of equation (1):

$$\frac{1}{2}m_D v_0^2 = \int_0^{h_{\text{max}}} F_D(h) dh,$$
 (2)

where h_{max} is the maximum deformation of the target, mm. Equation (3) can be obtained by dimensionalizing

equation (2):

$$\int_{0}^{h_{\text{max}}} \overline{F_D} d\overline{h} = \frac{m_D v_0^2}{2\sigma_R d^3} = \frac{2\pi\rho_D v_0^2}{3\sigma_R} = I_B,$$
(3)

where \overline{h} and $\overline{F_{D}}$ are dimensional parameters of h and F_{D} ; σ_{R} is the dynamic yield strength of target and can be replaced by



FIGURE 3: Shock-type rockburst carrier system model.

3-D compressive strength, MPa; *d* is bullet diameter, mm; and ρ_D is bullet density, kg/m³.

In the above equations, impact energy factor $I_{\rm B}$ is an important parameter in ballistic engineering to measure the deformation effect caused by bullet ejection hitting the target. In essence, the impact energy factor reflects the transmission capacity of bullet impact energy. This provides enlightenment for large deformation or rockburst damage of coal rock in high-stress area of underground coal mine engineering due to external vibration disturbance. As shown in Figure 4, the two principles have similarities. Next, the ballistic ejection principle is used to analyze the rockburst triggered by the mine earthquake.

3.2. Proposal and Analysis of Vibration Energy Factor

3.2.1. Impact Energy Factor of the System. According to the above principle, the shock-type rockburst is analyzed, and the equation of rock block motion can be written as

$$m_R u'' = -F_R,$$

 $u_{t=0} = 0,$ (4)
 $u_{t=0}' = v_{R0},$

where m_R is the mass of rockburst source rock mass, g; u is the displacement of rockburst source rock mass, mm; and F_R is the failure resistance of rockburst source rock mass, MPa.

Assuming that the system is composed of several block cubes, the occurrence of rockburst is the friction movement of rock blocks along with its weak structure or free surface in the rockburst source area; then, the failure resistance F_R of rockburst source is the friction force of rock block interaction, as shown in equation (5). Figure 5 shows the interaction movement mode between rock blocks:

$$F_R = (\mu_R \sigma_R + C_R)S = (\mu_R \sigma_R + C_R) \text{mnl}^2, \qquad (5)$$

where $\mu_{\rm R}$ is the friction factor of rock block; $\sigma_{\rm R}$ is the normal stress on the contact surface of rock block, MPa; $C_{\rm R}$ is the cohesion force of rock block, MPa; *S* is the interaction area between rock blocks, m³; *l* is the side

length of cubic rock block, *m*; and mn is the number of interacting rock blocks.

Assuming that at the time of $t = t^*$, the rock mass reaches the limit displacement of rock failure under the action of mine earthquake disturbance and $u_{t=t*} = u^*$, and the average velocity of block movement of rockburst source rock mass before the failure is \overline{v} , as shown in the following equation:

$$\overline{\nu} = \frac{1}{t^*} \int_0^{t^*} \nu \mathrm{d}t. \tag{6}$$

The displacement of the rockburst source u is expanded according to the second-order partial derivative, that is, $u'' = (\partial^2 u/\partial t^2)(\partial/\partial u) = (\partial/\partial u)[(\partial u/\partial t)^2] = \partial v^2/2 \partial u$, which is substituted into equation (4) and integrated. Let $\varepsilon^* = u^*/l$ be the limit strain, and its physical significance is the parameter of the maximum deformation capacity of the rockburst source, as shown in the following equation:

$$\varepsilon^* = \frac{m_R \overline{\nu}^2}{2n(\mu_R \sigma_R + C_R) l^3} = \frac{\rho_R \overline{\nu}^2}{2R_C},\tag{7}$$

where ρ_R is the rock mass density of the disturbance source, kg/m³, and $R_C = n(\mu_R \sigma_R + C_R)$ is the motion impedance of rockburst source rock mass (MPa).

It can be seen that equations (7) and (3) are extremely similar, and the physical meaning of the function can represent the energy transmission capacity. Therefore, the "impact energy factor I_S " is defined for the rock block in the movement, as follows:

$$I_{S} = \frac{m_{R}\overline{\nu}^{2}}{2n(\mu_{R}\sigma_{R} + C_{R})l^{3}} = \frac{\rho_{R}\overline{\nu}^{2}}{2R_{C}}.$$
(8)

In conclusion, when the impact energy factor I_s of the moving rock exceeds its critical threshold value ε^* , rockburst will occur. Of course, the physical meaning of I_s is the same as the impact energy factor in ballistic engineering; that is, I_s reflects the ability of a disturbing body to release energy in the motion.

3.2.2. Proposal and Analysis of System Vibration Energy Factor. In the study of rockburst disaster in metal mines, although the dimensionality condition of rockburst under blasting disturbance is obtained in equation (9) [20], the physical meaning is not clear since this condition is based on a large number of blasting tests. It is concluded that the stability of the structure in underground excavation will be lost if $k \ge (1 \sim 4) \times 10^{-11}$ or $k = (1 \sim 4) \times 10^{-9}$. In other words, when k satisfies the above conditions, rock block overcomes the friction force and run away; then, the rockburst occurs:

$$k = \frac{W}{MC_P^{2}},\tag{9}$$

where *W* is the disturbance energy of the blasting center, *J*; *M* is the mass of the blasting center, kg; and C_P is the velocity of longitudinal wave of blasting, m/s.



FIGURE 4: Analogy analysis chart. (a) Bullet hitting projectile target; (b) rockburst triggered by mine earthquake.



FIGURE 5: Rock block action mode.

The above equation can be written as equation (10) for the rockburst triggered by disturbance of the mine earthquake:

$$k = \frac{U_{\rm DZ}}{MC_{\rm P}^{\ 2}} = \frac{\alpha U_{\rm JZ}}{MC_{\rm P}^{\ 2}},\tag{10}$$

where U_{DZ} is the energy generated by vibration disturbance, *J*; U_{JZ} is the static load energy (i.e., the accumulated elastic energy of rock mass after excavation), *J*; and α is the mine earthquake action coefficient.

By comparing the impact energy factor I_S and the above expression of k value, it is found that the relationship between them is shown as follows:

$$I_S = \frac{k}{R_C / \rho c_P^2}.$$
 (11)

If $R_C/\rho c_P^2 = \varepsilon *$, then equation (11) is changed into $I_S = k/\varepsilon^*$. Let the equivalent average strain $\overline{\varepsilon} = \overline{\nu}/c_P$, and the

further relationship between the two can be deduced as follows:

$$k = \frac{\overline{\varepsilon}^2}{2} = (\varepsilon *)^2 = I_S^2.$$
(12)

According to the above analysis, the expression of k value is defined as the "vibration energy factor" of the rockburst carrier system, which is the key characteristic parameter of the system. It can be seen that its physical meaning also represents the density of disturbed energy flow. However, another key problem is the expression of $U_{\rm DZ}$. Only by establishing the value or expression of $U_{\rm DZ}$, we can judge whether the system is unstable.

3.3. Equivalent Homogenization Kinetic Energy of Mine Earthquake Disturbance. The essence of rockburst is the "continuous-discontinuous" transformation process of coal rock. However, the movement mode of rock mass under the disturbance of mine earthquake is not fixed, detailed parameters are difficult to be obtained by conventional force analysis, and the number of rock blocks involved in the movement is huge. As a result, an unsolvable mechanical problem is constituted. By the statistical physical method, homogenization processing is performed for the rock block of particle motion, and the equivalent homogenization kinetic energy expression of mine earthquake is constructed from the perspective of kinetic energy of the particle motion.

The energy accumulation is forced by mining activities near the mining face, including the self-weight energy field, tectonic energy field, and mining energy field [30, 31]. The fracture and fault activation of hard roof in the overburden can disturb the stationary field. The stress of rock mass under the action of mine earthquake can be expressed by

$$f_i = f_{i1} \cos(\omega_r t) + f_{i2} \sin(\omega_r t), \qquad (13)$$

where f_1 and f_1 represent the amplitude of the shear wave and longitudinal wave, m; ω_r is the frequency of vibration wave, Hz; and t is the time of periodic function, s. The periodic function of equation (13) is expressed by the sine cosine Fourier series as

$$f_i(t) = \sum_{n=1}^{\infty} \left[f_{i1n} \cos\left(n\omega_r t\right) + f_{i2n} \sin\left(n\omega_r t\right) \right].$$
(14)

For the whole rockburst carrier system, the Lagrange function can be expressed as

$$L = \frac{1}{2} \sum_{i,k=1}^{m} b_{ik}(q) q'_{i} q'_{k} - U_{JZ}(q), \qquad (15)$$

where q_i is the *i*th moving particle, b_{ik} is the function of the moving particle, $(1/2) \sum_{i,k=1}^{m} b_{ik}(q) q'_i q'_k$ is the system kinetic energy, *J*; and $U_{\text{IZ}}(q)$ is the steady static load field.

In the Lagrange function, the partial derivative of q_i is obtained and the system motion equation is established as

$$\sum_{k=1}^{m} b_{ik} \left(q_k'' \right) = \frac{\partial U_{\rm JZ}}{\partial q} + f_i. \tag{16}$$

If the motion form of the rock block in the system is equivalent to the combination of a relatively stable vibration and a small amplitude vibration, that is, $q_k(t) = Q_k(t) + \xi_k(t)$, then $Q_k(t)$ is the stable vibration with relatively small change; $\xi_k(t)$ is the small vibration with certain change, and then the average value $q_k(t)$ can be approximately expressed as $\overline{q_k(t)} = \overline{Q_k(t)}$. Equation (17) can be obtained through substitution of $\overline{q_k(t)} = \overline{Q_k(t)}$ into Equation (16):

$$\sum_{k} b_{ik} \left(Q_k'' + \xi_k'' \right) = -\frac{\partial U_{JZ}}{\partial Q_i} - \sum_{k} \xi_k \frac{\partial^2 U_{JZ}}{\partial Q_i \partial Q_k} + f_i(Q, t) + \sum_{k} \xi_k \frac{\partial^2 f_i}{\partial Q_k}.$$
(17)

It can be seen that equation (17) consists of a stable vibration term and an unstable vibration term. Equation (18) can be obtained by homogenizing the stable vibration term, and Equation (19) can be obtained by integrating the unstable vibration term:

$$\begin{cases} \sum_{k} b_{ik} Q_{kk}'' = -\frac{\partial U_{JZ}}{\partial Q_i} - \frac{1}{2\omega^2} \frac{\partial}{\partial Q_i} \left(\sum_{k,n} a_{kn}^{-1} \overline{f_1 f_k} \right) = -\frac{\partial U_{val}}{\partial Q_i}, \\ U_{val} = U_{JZ} + \frac{1}{2} \sum_{i,k} b_{ik} \overline{\xi_i} \overline{\xi_i'}, \end{cases}$$

$$(18)$$

where U_{val} is the equivalent effective total energy of the system, *J*:

$$\sum_{k} b_{ik} \xi_{k} = -\frac{1}{\omega^{2}} f_{i}(Q, t).$$
(19)

As shown in equation (18), the energy of the static load energy field $U_{\rm JZ}$ is the average value of rock vibration kinetic energy caused by mine earthquake disturbance, and the equivalent homogenization kinetic energy of vibration disturbance $U_{\rm DZ}$ is shown as follows:

$$U_{\rm DZ} = U_{\rm val} - U_{\rm JZ} = \frac{1}{2\omega^2} \sum_{i,k} a_{ik}^{-1} \overline{f_i f_k} = \sum_{i,k} \frac{a_{ik}}{2} \overline{\xi_i \xi_k'}.$$
 (20)

If the particle rock during the mine earthquake moves in a straight line towards the rockburst source, the above expression can be reduced to

$$U_{DZ} = M_R \overline{\nu}^2 / 2 = \overline{f}^2 / \left(2M_R \omega^2 \right), \tag{21}$$

where $M_{\rm R}$ is the mass of the disturbance subsystem, kg; $\bar{\nu}$ is the equivalent average velocity of the particle in the disturbed subsystem, m/s; and ω is the equivalent unstable small vibration frequency, Hz.

It can be seen that after the equivalent homogenization of the disturbance kinetic energy of mine earthquake, the static load energy field $U_{\rm JZ}$ is visually added to another steady-state field, which is proportional to the square of the equivalent unstable small vibration frequency. In other words, it is the steady field of the equivalent disturbance $U_{\rm DZ}$ applied to the static load energy field $U_{\rm JZ}$ that triggers the rockburst disaster.

3.4. Vibration Energy Action Conditions of System Instability. The main reason for the dynamic instability of the system is the mining disturbance of the working face. The mine earthquake caused by a working face is assumed:

$$F_{\rm RD} = -\sigma_c S e^{-t} \cos\left(\omega t\right),\tag{22}$$

where σ_c is the initial in situ stress, MPa; S is the excavation chamber surface area, m²; β is the mine seismic wave attenuation coefficient; and ω is the mine seismic wave frequency, Hz.

If equation (22) is substituted into equation (21), the mine vibration load caused by mining is expressed by

$$\begin{cases} U_{\rm DZ} = \frac{F_{\rm RD}^2}{4M_F \omega^2}, \\ F_{\rm RD} = \sigma_c S, \end{cases}$$
(23)

where M_F is the mass of the zone involved in surrounding rock failure (kg).

By substituting equation (23) into the expression of vibration energy factor, equation (24) can be obtained by combining $\omega = C_P / (2r_0)$:

$$\sqrt{k} = \frac{F_{\rm RD}}{2M_F \omega C_P} = \eta \frac{\sigma_c}{\rho C_P^{-2}} \frac{M_0}{M_F},\tag{24}$$

where M_0 is the mass of the excavated chamber, kg, and η is the shape coefficient.

Equation (25) can be obtained by connecting Equation (24) with the vibration energy factor, where V_h is the volume of the excavation roadway, m³, and V_s is the volume of the coal and rock involved in the destruction,m³:

$$\alpha U_{\rm JZ} = \eta^2 \frac{\sigma_c^2}{\rho C_P^2} V_h \frac{V_h}{V_S}.$$
 (25)

Taking the excavation of circular roadway as an example, the static load elastic energy $U_{\rm JZ}$ formed by excavation can be expressed by equation (26), where Poisson's ratio is $\nu = 0.2$:

$$U_{\rm JZ} = \iiint_{\nu} U' dV = \left[1 + \frac{2(1+\nu)}{3(1-2\nu)} \left(\frac{V_h}{V_h + V_{\rm S}} \right) \right] \frac{3(1-2\nu)}{2E} \sigma_c^{\ 2} V_{\rm S}.$$
(26)

Then, equation (27) can be deduced according to equations (10), (23), and (26):

$$\alpha = \frac{2}{3 + (2 + 2\nu/1 - 2\nu) \left(V_h / V_h + V_S \right)} \left(\frac{1 + \nu}{1 - \nu} \right) \left(\frac{\sqrt{k}}{\sigma_0} \rho C_p^2 \right)^2.$$
(27)

It can be seen that the α is affected by the vibration energy factor and the initial energy density. At this time, the energy factor of carrier at the rockburst occurrence is brought into equation (27), and the value range of α is 0.0235–0.0893. Therefore, it is concluded that the occurrence condition of shock-type rockburst is that the disturbance energy acting on the source area should reach about 2%–9% of the static load energy in the source area.

3.5. Calculation Examples. In this section, three shock-type rockbursts in Dongtan Coal Mine, Hongyang No.3 Coal Mine, and Zhaolou Coal Mine were taken as examples. In calculation, the energy transmission of mine earthquake vibration is in accordance with the attenuation form in reference [32], as shown in equation (28). The calculation process and results are shown in Table 1:

$$E = E_0 e^{\eta L},\tag{28}$$

where E_0 is the energy of the mine earthquake, *J*; *E* is the mine earthquake energy acting on the rockburst source, *J*; η is the seismic energy attenuation index; and *L* is the distance between the source and the shock source, *m*.

Through calculation and analysis, under the background of the three shock-type rockbursts occurred in Dongtan Coal Mine, Hongyang No.3 Coal Mine, and Zhaolou Coal Mine, the values of α are 0.0734, 0.0356, and 0.0597 respectively. Therefore, the calculation results are consistent with the theoretical derivation and the accuracy of theoretical derivation is verified.

4. Mechanism of Suspension, Secondary Triggering, and Termination of Shock-Type Rockburst

4.1. Background of "Red Seam" Overburden. Research has shown that after a high-energy mine earthquake, in most cases, a second high-energy mine earthquake sometimes occurs within the next 24–36 hours, and the magnitude is similar to that of the first one. The second earthquake event also has the risk of triggering rockburst [33]. Therefore, it is still debatable whether the first mine earthquake or rockburst means the termination or suspension of the disaster. Therefore, it is necessary to study the mechanism of suspension, secondary triggering, and termination of shock-type rockburst.

In the Yanzhou mining area of China, the recent results of microseismic monitoring and geological data of the microseismic area have shown that the primary and secondary triggering of high-energy mine earthquake or rockburst is usually related to the extremely thick sandstone above the coal seam, namely, the "red seam." The thickness of "red seam" varies from tens of meters to hundreds of meters and is composed of many kinds of lithology. Generally, it is more than ten meters to tens of meters above the coal seam, which is the key rock strata to induce high-energy vibration events. The thickness of "red seam" is huge and hard, and the fracture of "red seam" under the influence of mining is usually incomplete. When the rockburst destroys the working face, the strong disturbance is caused to the unstable "red seam" overburden; when the rockburst occurs, the broken coal rock can be thrown out, and the formed rockburst holes and soft coal rock provide more free space for the strata movement. Therefore, under the action of the above two factors, the "red seam" may break twice and trigger the rockburst disaster twice.

Before revealing the secondary triggering principle of rockburst under the condition of "red seam," the mechanical properties of high-level "red seam" in the Yanzhou mining area were analyzed. 91 groups of typical "red seam" rock samples were collected and tested for compressive, tensile, and shear strength. The results are shown in Table 2. It can be seen that in the "red seam," the siltstone is a mediumstrength rock due to its dense and hard cementation, high compressive, and tensile strength; due to the development of pores, the medium-coarse sandstone has loose cementation and low compressive and tensile strength and belongs to soft strata, while the conglomerate in red seam belongs to hard rock strata. According to the above test results, it is considered that the "red seam" is a hard rock layer with comprehensive strength of up to 70 MPa, and its hard rock properties may attribute to the occurrence of the conglomerate.

4.2. Secondary Triggering Principle of Rockburst under "Red Seam" Condition. According to the movement relationship of overburden rock in working face under the condition of "red seam," it is considered that there are two kinds of principles for the secondary triggering of rockburst under this condition. One is the secondary rockburst triggered by shear fracture of "red seam," and the other is the secondary rockburst triggered by slip settlement of "red seam."

4.2.1. Principle of Rockburst Triggered by Shear Fracture of "Red Seam". The working face mining or roadway driving disturbs the overlying high-level "red seam," and the fracture of the "red seam" induces mine earthquake. However, due to the huge thickness of the "red seam," there is an incomplete fracture at one time, and the rock fracture or the rock block that is not completely fractured forms an articulated structure. The vibration energy generated by the first fracture of "red seam" is transferred to the vicinity of the working

No.	Mine name	Dongtan Coal Mine	Hongyang No.3 Coal Mine	Zhaolou Coal Mine
1 2	Rockburst time Rockburst position	20:26:03, February 26, 2015 Working face 43 _{Upper} 13	2:26:39, November 11, 2017 Working face 702	2:49:33, July 29, 2015 Working face1305
3	Site conditions	Coal spalling occurred in the 300–161 mm of tailentry in the working face	218.3 m in front of the coal wall of the roadway in the working face was full of coal and rock	The range of 45 m along the two sides of tailentry was moved to 3 m, and the floor heave within 40 m was between 0.5 and 1m
4	Static load energy of rockburst behavior area/ J	1.22×10^{7}	4.21×10^7	7.96×10^{7}
5	Magnitude of mining earthquake	2.02	2.4	2.3
6	Mine earthquake energy/J	2.20×10^{6}	2.61×10^{6}	$2.51 imes 10^6$
7	Distance between earthquake source and rockburst source/m	90.15	55.72	76.43
8	Seismic energy attenuation index η	-0.01	-0.01	-0.01
9	Energy of rockburst source under mine earthquake action/J	8.93×10^{5}	1.50×10^{6}	1.17×10^{6}
10	$\alpha = U_{\rm DZ}/U_{\rm JZ}$	0.0734	0.0356	0.0597

TABLE 1: Calculation process and results.

TABLE 2: Lithologic composition and parameter test results of "red seam" in the Yanzhou mining area, China.

Lithology	Compressive strength (MPa)	Tensile strength (MPa)	Tensile strength (MPa)
Mudstone	19.22	1.26	3.54
Siltstone	46.40	2.02	5.50
Fine sandstone	45.29	2.19	3.70
Medium-coarse sandstone	30.22	1.10	2.96
Conglomerate	80.57	2.50	7.73

face, and a large range of cavities are formed instantly in the roadway, coal wall, or roof, and the low-level rock strata fall rapidly. In addition, the first rockburst itself is also a strong vibration disturbance to the surrounding rock, which provides effective dynamic and spatial conditions for further fracture and subsidence of the "red seam," as shown in Figure 6. It can be seen that the separation space between the "red seam" and the low-level caving strata increases (i.e., $h_2 > h_1$), the rock blocks A and B in the "red seam" have been or tended to be suspended, and the static friction force between the rock blocks is difficult to maintain its structural balance under the gravity of the upper strata. The shear fracture of rock block develops along the cracks inducing the first rockburst, and the rock falls heavily on the loose coal and rock. This process once again forms the rockburst carrier system. When the energy condition is satisfied, the rockburst may be triggered twice.

4.2.2. Principle of Rockburst Triggered by Slip Settlement of "Red Seam". As shown in Figure 7, if blocks A and B in "red seam" subside stably and their energy is not enough to trigger the rockburst twice, a separation layer with the upper rock strata is formed by the subsidence of rock blocks A and B. Rock blocks C and D can produce high-stress



FIGURE 6: Schematic diagram of rockburst principle triggered by shear fracture of "red seam."

concentration near the top of blocks *A* and *B*, forcing them to slide and stagger along the inclined direction. The larger the subsidence of blocks *A* and *B*, the stronger the displacement dislocation trend of blocks *C* and *D*. Strong stress concentration occurs at the support point near blocks *A* and *B*, resulting in inclined sliding settlement of rock blocks *C* and *D*. Finally, the rockburst carrier system is formed again. In addition, it can be seen that the sliding of rock blocks *C*



FIGURE 7: Schematic diagram of rockburst principle triggered by slip settlement of "red seam."

and D causes the support range to be smaller and smaller, which will also drive the rock blocks on both sides of blocks C and D to stagger accordingly. As a result, a more intense mine earthquake is formed, and the strata movement line is expanded accordingly.

Obviously, the two types of secondary rockburst are not independent but interact and promote each other. The shear fracture subsidence of blocks A and B increases the vertical distance between blocks C and D and aggravates the tendency of the inclined settlement of blocks C and D; meanwhile, the sliding settlement of blocks C and D squeezes blocks A and B and increases the further subsidence of blocks A and B.

5. Conclusion

Due to the high intensity and unclear precursory information, shock-type rockburst is a difficult problem to be solved urgently in mine disasters. On the basis of clarifying the relationship between mine earthquake and rockburst, the evolution process of shock-type rockburst was revealed, and the carrier system model was constructed. Based on the methods of mathematics and statistical physics, the occurrence conditions of shock-type rockburst were deduced. The main conclusions are as follows:

- (1) Based on the interaction between mine earthquake and rockburst, the evolution process of the occurrence of shock-type rockburst disaster is clarified. It is found that the explosion of shock-type rockburst needs to go through four stages: incubation stage, triggering stage, development stage, and termination stage. In the development stage, mutual inducing conditions of mine earthquake and rockburst can be achieved, resulting in multiple coal rock instability. On this basis, the theoretical model of shock-type rockburst is constructed, which lays a foundation for the follow-up study.
- (2) The vibration energy factor and its expression of the rockburst carrier system are put forward and taken as the key characteristic parameter of the occurrence of the shock-type rockburst disaster. The expression

of the equivalent homogeneous kinetic energy of the mine earthquake disturbance is derived by using the statistical physical method. Finally, the energy action condition for the instability of the rockburst carrier system is obtained; that is, the energy acting on the rockburst source area reaches 2%–9% of the static load energy of the shock source. Besides, combined with three rockburst cases, the results of theoretical derivation are verified, and the quantitative energy action conditions of rockburst are accurate.

(3) Based on the strata structure of "red seam" in China's Yanzhou mining area, the basic principle of the secondary rockburst in the shock-type rockburst carrier system is qualitatively expounded. It is concluded that there are mainly two types of secondary triggering rockburst principles, namely, shear fracture and sliding settlement of rock block in "red seam." Thus, the suspension, secondary triggering, and termination mechanism of shock-type rockburst in the instability of the shock-type rockburst carrier system is obtained.

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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