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Research Article

Quantitative Calculation of Critical Depth in Typical Rockburst Mine

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In order to calculate the critical depth of a typical rockburst coal mine quantitatively, which is helpful in rockburst prevention and control, in this paper, the concept of typical rockburst coal mine and atypical rockburst coal mine is put forward, energy characteristics of a coal-rock dynamic system is identified, and the relationship between rockburst and the coal-rock dynamic system is analysed by the model of the coal-rock dynamic system. Energy characteristics of the coal-rock dynamic system in the gravity stress field, tectonic stress field, and mining stress field are determined, respectively, and corresponding calculation methods are put forward at the same time, and the calculation method of the coal-rock dynamic system energy can forecast the occurrence of rockburst, with an accuracy of 80%. The calculation method of the critical depth in a typical rockburst coal mine is put forward, and the accuracy of which is validated in one typical rockburst coal mine. The degree of coincidence for the result of this method is 93.1%, which shows that the calculation method of a critical depth in a typical rockburst mine is highly reliable and practical, which could be widely used in forecasting the hazard of rockburst in typical rockburst mines. This method will be validated in more coal mines, and the calculation method of the critical depth in an atypical rockburst mine will be further researched in the future.

1. Introduction

Rockburst, a serious and destructive dynamic disaster in coal mines, poses a great threat to the safety of coal production and human life [1–12]. If there is one coal seam with rockburst risk in a mine at least, the coal mine will be named as a rockburst mine. When rockburst begins to occur after reaching a certain mining depth, we will define this mining depth the critical depth of this rockburst mine [13]. The critical depth varies with the geological conditions, and the risk of rockburst increases with the increase in the mining depth. For different rockburst mines, it is extraordinarily important to judge the critical depth quantitatively for rockburst prevention and control effectively. Hu et al. [14] researched on the high earth temperature, strata bumping, gas emission, the water inrush from the lime stone in the Ordovician Period, the mining effect, and other issues which occurred from the deep mining operations in China coal mines and proposed the deep mine conception and classification principle, thus providing a basis for the study of the critical mining depth of rockburst. Li et al. [15] proposed a method to judge quantitatively the mechanical behavior of the mining disturbed rock mass with the apparent constitutive relation of rock sand, the characteristics of microfractal geometry of the rock brittle fracture, and the special dynamic phenomenon that does not happen at shallow. Li et al. [16] put forward the concept of anomalously low friction rockburst, and the anomalously low friction effect was introduced. With the vertical impact load and crustal stress, a theoretical block model of anomalously low friction rockburst was established, and the variation of the normally dynamic load on the interface of coal-rock mass was deduced. They indicated that the normally dynamic load on the interface of deep rock mass periodically changes under the vertical impulse load, and the generating of a rockburst had a critical depth zone, when the depths were 400 m–600 m, 800 m–1000 m, and 1200 m. Qi and Dou [17] studied the occurrence mechanism and control technology of rockburst; they considered that the critical mining depth of rockburst in coal mines in China was 200 m–540 m, and the average depth was 380 m. Qin and Mao [18] used UDEC simulation software to simulate the influence of roadway depth and disturbed stress intensity on the stability of surrounding rock, and the critical depth and disturbed stress intensity value of rockburst was obtained. Vazaios et al. forecasted the hazard of rockburst and coal and gas outburst in different mining depths based on the finite-discrete element method and other methods. [19–25].

However, there is no consensus on the critical depth of rockburst mines, and the research results are mostly focused on the depth at present, and few on the typical rockburst mines. In this paper, in order to provide more evidence for the effective prevention and control of rockburst, the concept of typical rockburst coal mine and atypical rockburst coal mine is put forward, energy characteristics of the coal-rock dynamic system and the relationship between rockburst and the coal-rock dynamic system were analysed. Energy characteristics of the coal-rock dynamic system in the gravity stress field, tectonic stress field, and mining stress field were determined, and the corresponding calculation method was put forward and validated, respectively. Calculation method of the critical depth in a typical rockburst coal mine was put forward, and the accuracy of which was validated in one coal mine of China.

2. Concept of Typical Rockburst Mine and Model of Coal-Rock Dynamic System

2.1. Concept of Typical Rockburst Mine. Coal-rock dynamic system, composed of coal and rock mass, provides energy for the occurrence of rockburst [26, 27]. The forms of energy accumulation and release for coal and rock are different, and the characteristics of rockburst are different, under different geodynamic environment and mining conditions. A rockburst mine can be divided into typical rockburst mine and atypical rockburst mine, according to the evaluation method of geodynamic environment.

The occurrence of rockburst is the result of the interaction of geodynamic environment and mining disturbance and also the process of energy accumulation and release of the coal-rock dynamic system [26, 27]. If the energy accumulated in the coal-rock dynamic system can support the occurrence of rockburst, rockburst will occur under the influence of mining activities, and this kind of mine is a typical rockburst mine. When the energy accumulated in the coal-rock dynamic system could not support the occurrence of rockburst, other engineering conditions to supply energy are needed, and rockburst is likely to occur under the influence of mining activities, and this kind of mine is an atypical rockburst mine.

2.2. Model Construction for Coal-Rock Dynamic System. Coal-rock dynamic system will be in a balanced and stable state under the natural geological conditions. Under the disturbance of mining activities, the stress of the coal and rock mass will increase and the energy will accumulate. When the strength limit of the coal and rock mass is exceeded, the balanced and stable state will break, the energy will be released, and the rockburst would occur. The difference in energy depends on the relative spatial relationship between mining work and the coal-rock dynamic system, which leads to the different dynamic appearance of rockburst. We constructed the model of the relationship between the rockburst and the coal-rock dynamic system and formulated the corresponding relationship criteria, as shown in Figure 1.

The energy of the dynamic system is mainly concentrated in the dynamic nuclear zone, and the dynamic nuclear zone is the power source of rockburst. When rockburst occurs, the energy released by the coal-rock dynamic system is provided by the dynamic nuclear zone, and the total energy of the coal-rock dynamic system is composed of the basic energy and the released energy. The radius "R" of the "dynamic nuclear zone" of the dynamic system is shown in the following formula [26, 27]:

$$R = \sqrt[3]{\frac{3E(1-\mu)\Delta U}{2\pi\left[2\mu^2\left(k_1k_2 + k_1k_3 + k_2k_3 + 1\right) - \mu\left(2k_1k_2 + 2k_1k_3 + 2k_2k_3 + k_1^2 + k_2^2 + k_3^2 - 1\right) + k_1^2 + k_2^2 + k_3^2 - 1\right]\gamma^2 H^2}}. \quad (1)$$

3. Energy Characteristic of Coal-Rock Dynamic System

3.1. Energy Source and Energy Composition of Coal-Rock Dynamic System. The energy factor controls the occurrence of rockburst and affects the stability of the whole coal-rock dynamic system. Natural geological condition and mining effect are the two sources that the energy of the coal-rock dynamic system comes from. The coal-rock dynamic system is located in the tectonic environment and the modern stress field, with dynamic conditions for forming energy accumulation. Through the work such as mining and excavation, the stress of the system will be increasing. When the strength limit of the coal and rock mass is exceeded, the balanced and stable state will break, the energy will be released ($>10^4$ J–10^6 J), and the rockburst is likely to occur, as shown in Figure 2. Without tectonic movement, there is no geological dynamic environment for the occurrence of rockburst, no formation of a coal-rock dynamic system, and no energy conditions for the occurrence of rockburst.

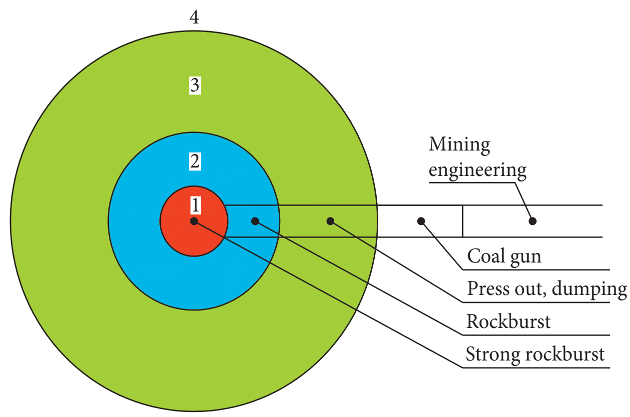

Figure 1: Model of the relationship between the rockburst and the coal-rock dynamic system: 1, dynamic nuclear zone; 2, damage zone; 3, injury zone; 4, influence zone.

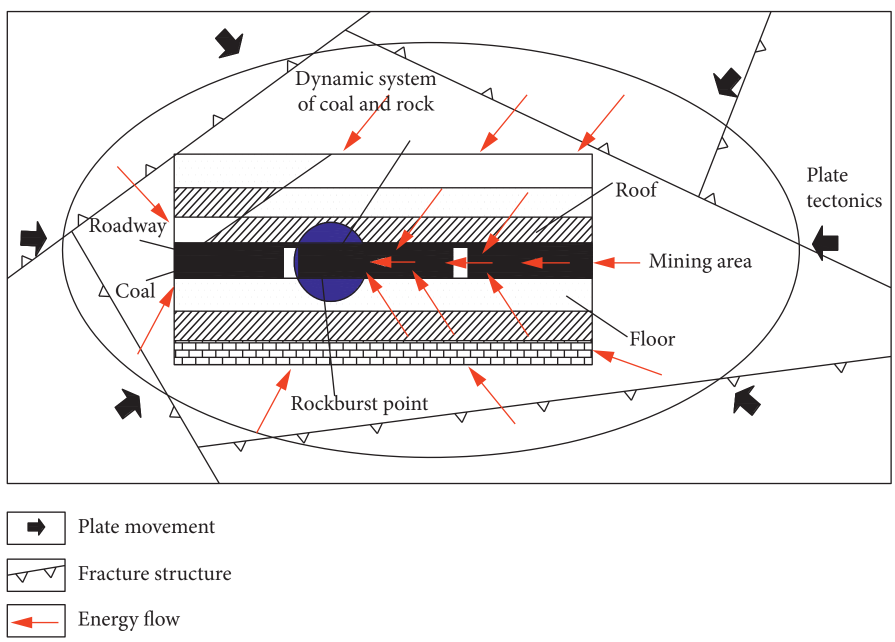

Figure 2: Energy sources of the coal-rock dynamic system.

$$E_\varepsilon = \left[\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\mu\left(\sigma_1\sigma_2 + \sigma_1\sigma_3 + \sigma_2\sigma_3\right)\right] \times \frac{1}{2E}. \quad (3)$$

The total energy of a dynamic system is made up of the energy under the gravity stress field U_Z, energy under the tectonic stress field U_G, and energy under the mining induced stress field U_C, as shown in the following formula:

$$U = U_Z + U_G + U_C. \quad (2)$$

Energy calculation of a coal-rock dynamic system is obtained from the volume integral of energy density to the "dynamic nuclear zone", as shown in formula (1). When the energy released by the coal-rock dynamic system is different, the radius of the dynamic nuclear zone is different and the volume of the dynamic nuclear zone is different. In order to facilitate the comparative analysis and calculation, the energy density of the coal-rock dynamic system was employed to reflect the energy characteristics. The unified calculation formula for energy density of the coal-rock dynamic system is shown in the following formula:

3.2. Energy Characteristic of Coal-Rock Dynamic System under Gravity Stress Field. The stress value is related to the burial depth and unit weight under the gravity stress field, unit volume of coal and rock mass was selected for study, and the energy density under the gravity stress field is shown in formula (4). According to A.H.K hypothesis, the influence of gravity stress on the energy of the coal-rock dynamic system is considered only under the gravity stress field, the lateral stress is equal to the product of gravity stress and lateral pressure coefficient, and the accumulated energy in the coal-rock dynamic system increases with the increase in the mining depth. Energy of the gravity stress field is defined as the basic energy of the coal-rock dynamic system:

$$E_Z = \gamma^2 H^2 \times \frac{1 - 2\mu - \mu^2 + 2\mu^3}{(1-\mu)^2} \times \frac{1}{2E}. \quad (4)$$

3.3. Energy Characteristic of Coal-Rock Dynamic System under Tectonic Stress Field. The energy of the coal-rock dynamic system is decided by the tectonic stress field under the gravity stress field, and the energy accumulated in coal and rock mass is related to three-dimensional stress. Unit volume of coal and rock mass was selected for the study, and the energy density can be derived from formula (3) and further from formula (5) ~ (7), as shown in formula (8). The accumulated energy in the coal-rock dynamic system increases with the increase in tectonic stress.

As the stress value measured by tectonic stress includes the stress under the gravity stress field, the energy calculated under the tectonic stress field also includes the energy of the gravity stress field:

$$\sigma_1 = k_1 \gamma H, \quad (5)$$

$$\sigma_2 = k_2 \gamma H, \quad (6)$$

$$\sigma_3 = k_3 \gamma H, \quad (7)$$

$$E_G = \gamma^2 H^2 \times \left[\left(k_1^2 + k_2^2 + k_3^2\right) - 2\mu\left(k_1k_2 + k_2k_3 + k_1k_3\right)\right] \times \frac{1}{2E}. \quad (8)$$

3.4. Energy Characteristic of Coal-Rock Dynamic System under Mining Stress Field. The energy of the coal-rock dynamic system is decided by the mining stress field under the gravity stress field, and the accumulated energy in the coal-rock dynamic system is related to the degree of mining stress concentration. The gravity stress will further increase under the condition of the mining stress field. A unit volume of coal and rock mass was selected for the study, and the energy density under the mining stress field is shown in formula (9). The accumulated energy in the coal-rock dynamic system increases with the increase in stress concentration:

$$E_C = \left[\sigma_1^2 + k^2\sigma_2^2 + \sigma_3^2 - 2\mu\left(k\sigma_1\sigma_2 + \sigma_1\sigma_3 + k\sigma_2\sigma_3\right)\right] \times \frac{1}{2E}. \quad (9)$$

The existing research results show that the mining stress can be 2–5 times of the original rock stress; therefore, the value of k is usually 2–5 [28]. The energy density of a typical rockburst mine is mainly depending on the tectonic stress field, the energy accumulated in the coal-rock dynamic system can support the occurrence of rockburst, and the mining activity only induced the rockburst. In this paper, the critical depth in a typical rockburst mine was quantificationally determined and calculated under the condition of the tectonic stress field.

4. Relationship between Energy Evolution of Coal-Rock Dynamic System and Dynamic Behavior of Rockburst

4.1. Energy Calculation Method of Coal-Rock Dynamic System

4.1.1. Energy of Coal-Rock Dynamic System under Gravity Stress Field. The calculation method of the energy under the gravity stress field is shown in formula (10), and the calculation result is shown in (11). Energy of the gravity stress field is defined as the basic energy of the coal-rock dynamic system:

$$U_Z = \int_{i=1}^{i=n}\left[\gamma_i^2 H_i^2 + 2\frac{\mu^2}{(1-\mu)^2}\gamma_i^2 H_i^2 - 2\mu\left(2\frac{\mu}{(1-\mu)}\gamma_i^2 H_i^2 + \frac{\mu^2}{(1-\mu)^2}\gamma_i^2 H_i^2\right)\right] \times \frac{1}{2E_i}, \quad (10)$$

$$U_Z = \frac{4\pi R^3}{3} \times \gamma^2 H^2 \times \frac{1 - 2\mu - \mu^2 + 2\mu^3}{(1-\mu)^2} \times \frac{1}{2E}. \quad (11)$$

4.1.2. Energy of Coal-Rock Dynamic System under Tectonic Stress Field. The calculation method of the energy under the tectonic stress field is shown in formula (12), and the calculation result is shown in (13). The energy under the tectonic stress field includes the energy of the gravity stress field:

$$U_G = \int_{i=1}^{i=n}\left[\left({k_1}^2 + {k_2}^2 + {k_3}^2\right){\gamma_i}^2{H_i}^2 - 2\mu\left(k_1k_2 + k_2k_3 + k_1k_3\right){\gamma_i}^2{H_i}^2\right] \times \frac{1}{2E_i}, \quad (12)$$

$$U_G = \frac{4\pi R^3}{3} \times \gamma^2 H^2 \times \left[\left(k_1^2 + k_2^2 + k_3^2\right) - 2\mu\left(k_1k_2 + k_2k_3 + k_1k_3\right)\right] \times \frac{1}{2E}. \quad (13)$$

Due to the interaction between structural fault blocks and the difference of rock mechanical properties, high stress area, stress gradient area, and low stress area will naturally form within the scope of the coal mine field.

In the high stress area, under the action of high stress, the accumulated elastic energy of rock mass is much higher than that in the normal stress area. Part of the rock has reached the critical point of steady state to unsteady state transition, which is most likely to lead to roadway failure.

In the stress gradient area, the stress and deformation modulus increase greatly, the brittleness of rock increases, the failure strength decreases, and it is easy to form a geological structure. Under the action of structural stress, it is easy to cause roadway failure.

The rock located in the low stress area has little change in its characteristics, which is not easy to produce energy accumulation, and the risk of roadway damage is the lowest [29–31].

In general, when the stress concentration coefficient k > 1.2, the range of the corresponding main stress equivalent coil is the high stress area. When k < 0.8, the range of the corresponding main stress equivalent coil is the low stress area. The stress gradient area is usually located between the normal stress area and the high stress area [29–31]. The system energy located in different stress areas can be calculated by using corresponding stress values and stress concentration factors.

4.1.3. Energy of Coal-Rock Dynamic System under Mining Stress Field. The calculation method of the energy under the mining stress field is shown in formula (14). The relationship between energy and the mining stress concentration coefficient of the coal-rock dynamic system in different mines is different. Laohutai coal mine in the Fushun mining area, China, and Wudong coal mine in the Shenhua Xinjiang mining area, China, were selected for study in this paper, and relationship between the multiple of energy increase and the coefficient of mining stress concentration was calculated. The calculation results are shown in formulas (15) and (16), Figures 3 and 4.

$$U_C = \frac{4\pi R^3}{3} \times \left[\sigma_1^2 + k^2\sigma_2^2 + \sigma_3^2 - 2\mu\left(k\sigma_1\sigma_2 + \sigma_1\sigma_3 + k\sigma_2\sigma_3\right)\right] \times \frac{1}{2E}, \quad (14)$$

$$y = 0.3091k^2 - 0.3505k + 1.0414, \quad (15)$$

$$y = 0.3105k^2 - 0.4954k + 1.1849. \quad (16)$$

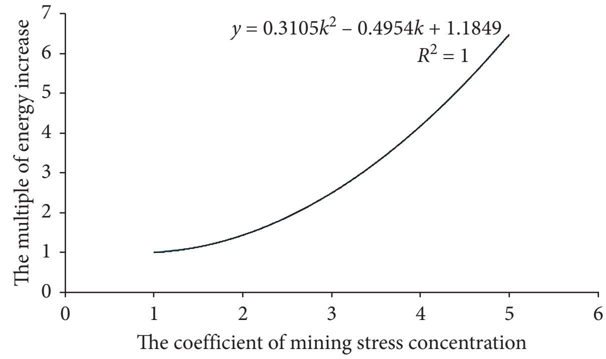

FIGURE 3: Relationship between the multiple of energy increase and the coefficient of mining stress concentration in the Wudong coal mine.

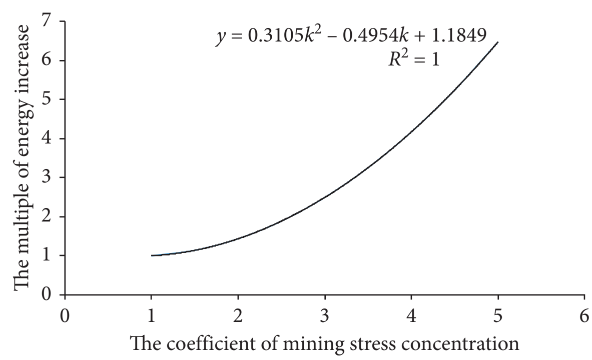

FIGURE 4: Relationship between the multiple of energy increase and the coefficient of mining stress concentration in the Laohutai coal mine.

4.1.4. Total Energy of Coal-Rock Dynamic System. Total energy of the coal-rock dynamic system consists of energy under the gravity stress field, under the tectonic stress field, and under the mining stress field, which can be divided into basic energy and released energy.

4.2. Calculation Method of Critical Depth in Typical Rockburst Mine. The released energy of the coal-rock dynamic system is equal to the difference between total energy and basic energy. If the released energy is higher than 10^4 J ~ 10^6 J, rockburst is likely to occur. The apparent strength of rockburst is positively related to the released energy of the coal-rock dynamic system.

The research shows that the initial velocity of the broken coal and rock mass thrown into the free space is an important indicator of the occurrence of rockburst. When the initial velocity is less than 1 m/s, rockburst cannot occur. When the initial velocity is greater than 10 m/s, rockburst is more likely to occur [32]. When rockburst occurs, the required energy should not only reach the energy consumed by the unit coal and rock mass broken, but also reach the minimum kinetic energy accumulated when rockburst occurs. When the elastic energy accumulated by unit coal and rock mass exceeds these two conditions, rockburst may occur.

Therefore, when the rockburst occurs, the calculation result of the energy density released by the coal-rock dynamic system is expressed in formula (17), and the calculation result of the energy released by the coal-rock dynamic system is expressed in formula (18):

$$E_{\min} = \frac{\rho v_0^2}{2} + \frac{\sigma_c^2}{2E}, \quad (17)$$

$$U_S = \frac{4\pi R^3}{3} \times \left(\frac{\rho v_0^2}{2} + \frac{\sigma_c^2}{2E}\right). \quad (18)$$

When rockburst occurs in a typical rockburst mine, the released energy is the difference between the structural stress field energy and the basic energy, and the released energy is equal to the energy released in formula (18). The calculation

Table 1: Physical mechanical parameter characters of coal and rock in one coal mine.

Lithology	Natural apparent density ($kg.m^{-3}$)	Uniaxial compressive strength (MPa)	Uniaxial tensile strength (MPa)	Modulus of elasticity (MPa)	Poisson ratio
Rock A	2189	5.5	1.01	1170	0.24
Coal	1243	15.3	2.71	6330	0.29
Rock B	2712	40.1	4.60	44768	0.22
Rock C	2552	23.0	1.52	17885	0.18

Table 2: Release energy by the coal-rock dynamic system in part rockburst of one coal mine.

Number	Depth of focal point (m)	Total energy of coal-rock dynamic system (J)	Basic energy of coal-rock dynamic system (J)	Released energy of coal-rock dynamic system (10^6 J)	Microseismic monitoring energy (10^6 J)
1	662	318837686	154856876	163.98	32.00
2	676	134495703	65323471	69.17	38.00
3	697	137024948	66551905	70.47	3.80
4	673	9083727	4411893	4.67	2.50
5	643	73437125	35667816	37.77	21.00
6	818	1074673691	521960288	552.71	110.00
7	580	15179125	7372378	7.81	17.00
8	540	5263827	2556598	2.71	20.00
9	697	70156774	34074575	36.08	81.00
10	670	2531922	1229734	1.30	2.90
11	627	20689740	10048839	10.64	24.00
12	667	8030928	3900557	4.13	9.40
13	655	96886360	47056919	49.83	27.00
14	550	1018885	494864	0.52	1.20
15	673	236900214	115060511	121.84	660.00
16	822	284481197	138170208	146.31	29.00
17	823	1168071829	567323006	600.75	120.00
18	698	38996382	18940226	20.06	11.00
19	720	47144244	22897577	24.25	13.00
20	694	41119941	19971622	21.15	12.00

process is shown in formulas (19) and (20), and the critical depth calculation method of a typical rockburst mine is obtained, as shown in formula (21):

$$\Delta U = U_G - U_Z, \tag{19}$$

$$\Delta U = U_S, \tag{20}$$

$$H_{\min} = \sqrt{\frac{\rho v_0^2 E + \sigma_C^2}{\left[\left(k_1^2 + k_2^2 + k_3^2\right) - 2\mu\left(k_1 k_2 + k_2 k_3 + k_1 k_3\right) - 1 - 2u - u^2 + 2u^3/(1-\mu)\right] \times \gamma^2}}. \tag{21}$$

5. Application of the Research Results

Physical mechanical parameters of coal and rock in one coal mine of China are shown in Table 1. 20 times the focal point depth of rockburst, from January 2011 to November 2013, were selected to calculate, and released energy by the coal-rock dynamic system is shown in Table 2. The calculated results of the released energy are 0.52×10^6 J ~ 6.01×10^8 J, all of which are higher than the critical energy.

According to the monitoring results of mine microseism, the released energy of rockbursts is 1.20×10^6 J ~ 6.6×10^8 J, as shown in Table 2. The second group of data are taken as an example to show how to use the equations. Microseismic monitoring energy is 38 MJ, the depth of the focal point is 676 m, the values of k_1, k_2, and k_3 are 1.97, 1.00, and 0.79, respectively, bulk density of coal and rock is 27000 kN/m^3, modulus of elasticity is 6330 MPa, and Poisson ratio is 0.29. According to formula (1), the radius of the dynamic nuclear zone of the coal-rock dynamic system is 5.36 m. According to formulas (11) and (13), Uz is 65323471 J, which is the basic energy as given in Table 2, and U_G is 134495703 J, which is the total energy. So, we can get the released energy of the

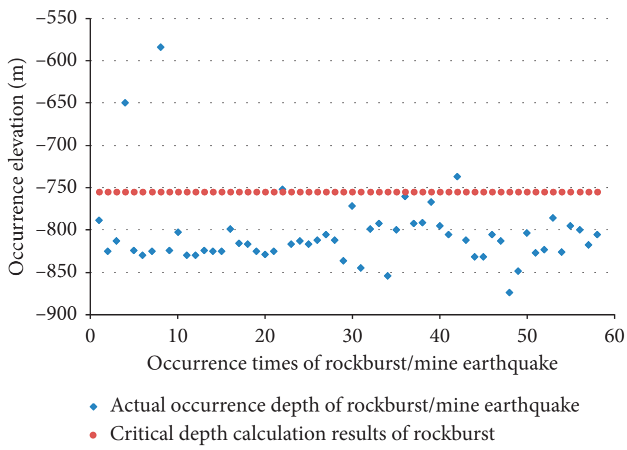

FIGURE 5: Calculation results for critical depth of rockburst in panel A01.

coal-rock dynamic system which is 69.17 MJ. To compare the microseismic monitoring energy with released energy of the coal-rock dynamic system, 38 MJ and 69.17 MJ are in the same level.

Through the comparison of calculation results and monitoring results, all the released energy is greater than 10^5 J, which are greater than the basic energy. 16 of 20 groups of comparison data are in the same order of magnitude, which indicates that the calculation method of the coal-rock dynamic system energy can forecast the occurrence of rockburst, with an accuracy of 80%.

Panel A01 of this coal mine was located at −830 mining level, the ground elevation of the panel is +89.1 m to +95.4 m, and the underground elevation is −748.2 m to −833.5 m. The strike length of the panel is 603 m, the inclined length is 163.5 m, and the coal thickness is 11.8 m. From June 23, 2014, to January 29, 2015, 58 times of rockburst and mine shock (Energy above 10^6J) occurred in this panel. The focal point depth is −584 m to −874 m, and the average elevation is −804.93 m. According to the results of in situ stress measurement, the values of k_1, k_2, and k_3 are 1.97, 1.00, and 0.79, respectively, according to the calculation method shown in equation (21), and the critical depth of the rockburst of the panel is −754.54 m, as shown in Figure 5. Among the 58 groups of data shown in Figure 5, 54 groups of data are below the calculated critical depth, which indicates the calculation method of critical depth in a typical rockburst mine is with an accuracy of 93.1%.

6. Conclusions

(1) In this paper, concepts of typical rockburst and atypical rockburst are put forward, respectively, and the calculation method of critical depth of typical rockburst is put forward.

(2) The energy characteristics of the coal-rock dynamic system are analysed, and the energy calculation method and transformation relationship of the coal-rock dynamic system in the gravity stress field, the structural stress field, and the mining stress field are determined, respectively. The calculation method of the coal-rock dynamic system energy can forecast the occurrence of rockburst, with an accuracy of 80%, which is helpful to rockburst prevention and control.

(3) The accuracy of the research results is verified in a coal mine of China, and the degree of coincidence for the result of this method is 93.1%, which shows that the calculation method of critical depth in a typical rockburst mine is highly reliable and practical, which could be widely used in forecasting the hazard of rockburst in typical rockburst coal mines.

(4) In order to improve the calculation method continuously, more verification will be taken in more coal mines. There are many energy supplement factors for the coal-rock dynamic system of the atypical rockburst mine, such as coal pillar stress and roof movement, and the calculation method of the critical depth of the atypical rockburst mine will be further studied in the future.

Nomenclature

R: Radius of dynamic nuclear zone
U: The total energy of the coal-rock dynamic system
U_Z: The energy under the gravity stress field
U_G: The energy under the tectonic stress field
U_C: The energy under the mining stress field
γ: The density of unit bulk
H: The depth of the location of the unit
μ: Poisson's ratio of the unit
E: Modulus of elasticity of the unit
k_1: The ratio of maximum principal stress to vertical stress
k_2: The ratio of intermediate principal stress to vertical stress
k_3: The ratio of minimum principal stress to vertical stress
V: The volume of the dynamic nuclear zone
$\triangle U$: The released energy
V_S: The volume of failure fractured coal
L: The influence radius of fracture initiation
θ: The angle of the influence zone, random number between $[\pi/4, \pi/2]$
U_S: The energy required for coal and rock failure
σ_c: The uniaxial compressive strength
σ_1: Horizontal stress
σ_2: Vertical stress
σ_3: Horizontal stress
E_Z: The energy density under the gravity stress field
E_G: The energy density under the tectonic stress field
E_C: The energy density under the mining stress field
k: Stress concentration factor
y: Relationship between the multiple of energy increase and the coefficient of mining stress concentration
E_{min}: Energy density of energy released by the coal-rock dynamic system when rockburst occurs
V_0: The average initial velocity of the broken coal and rock mass

ρ: Average density of coal and rock mass thrown out after crushing
U_S: Energy released by the coal-rock dynamic system when rockburst occurs
H_{min}: The critical depth of a typical rockburst mine.

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 they have no conflicts of interest.

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