Research on Critical Depth of Rock Burst in Coal Mines in China

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Abstract: With increasing coal mining depths in China, the number of mines experiencing rock burst is increasing. The conditions in which a mine can reach the critical impact-mining depth remain theoretically unknown, which hampers the determination of the depth at which rock burst prevention can begin in coal mines. Based on different mining boundary conditions of rock bursts occurring in coal mines, this study proposes the concepts and calculation methods of three critical depths of rock bursts in coal mining. The strength criterion for rock mass impact of medium–hard and hard coal is used to evaluate the failure strength and stress state of the coal rock mass under dynamic loading conditions. Then, the value of the dynamic stress coefficient of the coal rock mass is determined. The research team applied this method to numerous mines in China to test rock bursts under different types of working face conditions with a coincidence rate of 100%. Results verify the rationality of the calculation formula of the critical impact depth and the value of the dynamic stress coefficient. The findings of this research can provide a basis for evaluating rock bursts.

Keywords: Coal mines; Rock bursts; Critical depth; Dynamic strength; Stress concentration; Types of working faces

1 Introduction

With the increasing demand for coal resources and the rapid depletion of shallow coal resources, coal mining depths are progressively increasing and an increasing number of coal mines is being deeply mined. However, this has led to frequent dynamic disasters associated with deep mining. Although numerous researches have been conducted on deep coal mining [1-5], research on the critical depth of rock bursts lacks a unified scientific definition and quantitative standard. Therefore, understanding the problem of the critical depth of rock bursts from a new perspective is essential.

The “Coal Mine Safety Regulations” promulgated at the end of 2015 define coal seams of rock bursts as coal seams that have experienced rock bursts within the mine field or those (including roof and floor rock seams) that have an outburst tendency and rock burst risk. Mines experiencing rock bursts within the scope of the mine development and production must be managed according to the requirements of mines with rock bursts. However, the conditions under which a mine can reach the critical mining depth of rock burst remain theoretically unknown, which makes it difficult to define the depth at which rock burst prevention can begin. That is, the problem of critical burst depth of coal mines has not been solved at the levels of theory and application. In the present study, the critical burst depths of three typical mining boundaries are discussed on the basis of the mining boundary conditions needed for the occurrence of bursts. In addition, the value of the dynamic stress coefficient of the coal rock mass is determined according to the strength criteria for the occurrence of rock bursts of medium–hard and hard coal rock and based on the analysis of factors affecting
the strength of the coal rock mass under dynamic loading. Moreover, based on the practice of prevention and control of rock bursts in multiple mines, the rationality of the calculation method for the critical burst depth and the value of the dynamic stress coefficient of the coal rock mass are verified. The results are expected to provide a theoretical basis for the prevention and control of coal mine rock bursts.

2 Definition and classification of critical depth of coal mine rock bursts

2.1 Definition of critical depth of coal mine rock bursts

Statistical data reported in previous research [4-5] indicate that the occurrences of coal mine rock bursts are unevenly distributed in the depth direction and generally begin to occur only after reaching a particular depth. In other words, rock bursts occur at a certain critical depth. This critical depth also applies to coal seams with burst tendencies. The critical depth of rock bursts is a comprehensive reflection of factors such as coal seam properties, coal mining methods, working face type, and overburden bulk density. The burst risk index widely used in engineering practice to evaluate the risk of coal mine rock bursts, $I_c$, is the ratio of the vertical stress $\sigma_y$ received in the mine against its uniaxial compressive strength $\sigma_c$, as given in the following equation:

$$
I_c = \frac{\sigma_y}{\sigma_c}
$$

(1)

When the uniaxial compressive strength of the coal body is different, the mechanism of the rock burst in the coal mass is also different. A soft coal seam burst is a structural condition, whereas a hard coal seam burst is a dynamic stress destructive burst. According to the previous research [6-8], the applicable condition of formula (1) is a medium–hard coal seam with a burst tendency in which the uniaxial compressive strength is greater than 10 MPa. Assuming that the critical value of the stress ratio for a rock burst is $I_c^1$, the corresponding critical depth of the rock burst is $H$, and the vertical stress concentration coefficient of the relevant site in the mine is $k$. Then, the vertical stress at this site $\sigma_y = k\gamma H$, and the critical depth of the rock burst can be obtained by

$$
H = I_c^1 \frac{\sigma_y}{\kappa y}
$$

(2)

2.2 Classification of different boundary conditions affecting critical depth of coal mine rock bursts

Different mining boundary conditions in the coal seam will form different stress concentrations. As shown in Figure 1, the critical depth of a coal mine rock burst is divided into the critical depths of the rock burst in mining face, stope face, and goaf-side face.

Figure 1 Three typical types of faces of coal mining

(1) Critical depth of rock burst in the driving face

The driving face is affected by the support pressure formed by roadway excavation. The stress concentration coefficient of the driving face is $k_1$. Substituting it into formula (2) can solve the critical depth of rock bursts in the driving face as

$$
H_1 = I_c^1 \frac{\sigma_y}{k_1\gamma}
$$

(3)

(2) Critical depth of rock burst in the stope face


The stope face is affected by the mining stress of the face and the lateral support pressure formed by roadway excavation. The stress concentration coefficient of the stope face is $k_2$. Substituting it into formula (2) can solve the critical depth of the rock bursts of the stope face as

$$H_s = \frac{L \sigma}{k_2 \gamma}.$$  

(4) Critical depth of rock burst in the goaf-side face

The goaf-side face is affected by the lateral support pressure formed by roadway excavation, the advance support pressure of the working face, and the transfer stress in the goaf of the adjacent working face. The stress concentration coefficient of the goaf-side working face is $k_3$. Substituting it into formula (2) can solve the critical depth of the rock burst in the goaf-side working face as

$$H_s = \frac{L \sigma}{k_3 \gamma}.$$  

(5) Complex conditions and critical depth of rock burst in multiple coal seam mining faces

The stress concentration coefficient of multi-layer coal mining, disturbed by multi-face mining, is $k_4$. Substituting it into formula (2) can solve the multi-layer coal mining as

$$H_s = \frac{L \sigma}{k_4 \gamma}.$$  

(6)

3 Analysis of influencing factors of critical depth of rock bursts of coal mines

Based on the definition of the critical depth of coal mine rock bursts, factors such as coal seam properties, working face type, and overburden bulk density affect the critical depth of rock bursts. According to formula (2), the factors determining the critical depth of coal mine rock bursts include the dynamic stress coefficient, the uniaxial compressive strength of the coal seam, the value of the stress concentration coefficient, and the bulk density of the overburden rock. In general, the overburden bulk density can be approximated as 25 kN/m$^3$. The effects of the uniaxial compressive strength of the coal seams, the coal seam thickness, and the stress concentration coefficient on the critical depth of rock bursts are discussed below.

3.1 Relationship between the critical burst depth of the coal mine and the uniaxial compressive strength of the coal seam

The overburden bulk density $\gamma$ is 25 kN/m$^3$, and the range of the uniaxial compressive strength of the coal seam is [10 MPa, 30 MPa]. The stress concentration coefficients of the coal seams for the driving, stope, and goaf-side faces, i.e., 1.5, 2.0, and 2.5, respectively, were substituted into formulas (3)–(5) to obtain the critical burst depth of the uniaxial compressive strength of different coal seams under these face conditions, as shown in Figure 2. When the uniaxial compressive strength of the coal seam was fixed, the critical burst depth of the driving face was greater than that of the stope face, and the critical burst depth of the goaf-side face was greater than that of the goaf-side face. As the uniaxial compressive strength of the coal seam increased, the growth rate of the critical burst depth of the driving face became greater than that of the stope face, and the growth rate of the critical burst depth of the stope face was greater than that of the goaf-side face. Therefore, for the same coal seam, no risk of rock bursts was indicated during driving; however, the risk could be present during stoping.
3.2 Stress concentration coefficients: working face types
The support pressure is redistributed after mining of the working face. This pressure is a comprehensive reflection of the overburden stratum structure and dynamic evolution process. The concentration coefficient of the support pressure of the working face is a comprehensive reflection of the properties of the coal seam, face type, coal seam strength, and mining depth [9-11]. The strength criterion for the occurrence of rock bursts can be expressed by formula (7):

\[
\frac{\sum \sigma_i}{\sigma_1} \geq 1,
\]

where \(\sigma_i\) is the stress of the ith influencing factor on the formation of the coal rock system.

3.3 Coal seam thickness
A greater thickness of the coal seam will lead to a higher frequency of rock bursts as well as an increased degree of burst. Polish statistics show that the occurrence of rock bursts in a coal seam with a thickness of 4–8 m is more than six times that with a thickness of 1–2 m [5].

4 Theoretical basis for judging the critical depth of coal mine rock burst
From a mechanical perspective, after the load or the resulting stress on the material reaches its ultimate bearing capacity (or strength limit), the material begins to fail. The underground coal rock mass is a highly complicated mechanical system, in which the following strength theory of rock burst can be applied: When rock bursts occur, the mechanical system of the coal rock mass should reach its mechanical limit equilibrium condition. The strength of the mechanical system of the coal rock mass includes the strengths of the coal mass and the rock mass as well as the strength at the junction of the coal–rock strata. Because the coal rock mass is in a complex state of stress, the strength type should generally be triaxial strength.
According to the strength criterion for medium–hard and hard coal rock masses, the failure strength of the coal rock mass under dynamic loading depends on its dynamic strength and stress state.

4.1 Dynamic strength of the coal rock mass
The strength of the coal rock mass refers to the maximum stress that can be borne by the coal rock mass before it fails under the load. This parameter is generally determined by laboratory testing. The strength index of the coal rock mass determined by the test is affected by the size, shape, three-dimensional size ratio, humidity, and loading rate of the test specimen [12-13].
According to the strength conditions under which rock bursts occur, the necessary condition for the occurrence of rock bursts is that the stress experienced by the coal rock mass exceeds the strength of the coal rock mass itself. In this study, the uniaxial compressive strength of the coal rock body positively correlated with the loading rate; that is, a greater loading rate relates to a greater measured strength index value. Figure 3 shows the stress–strain curves of carbon shale at different deformation speeds measured by in previous research [14]. When the sample was extremely pressurized at a slow rate, the process developed according to the 0-1 line. At the moment of sample breakage, the stress was low, whereas the deformation was great and the strength development process was relatively smooth. When the sample deformed faster (curve 0-2), the stress increased faster. When the sample fractured, the broken part protruded. As the speed continued to increase, the stress on the strength limit became increasingly great, the deformation became increasingly small (curves 0-3 and 0-4), and the sample cracking phenomenon became increasingly intense. Thus, the rock burst is clearly related to the deformation speed or the load of the test piece. When the deformation speed was low, no burst occurred. An increase in the deformation speed resulted in an increase in the burst intensity. In addition, greater stress on the strength limit resulted in a higher deformation rate. Therefore, the strength of the coal rock mass is not a fixed value but is instead related to the loading speed. Moreover, the practice of coal mining revealed that if the mining speed of the working face is too fast, abnormal pressure and even rock bursts can easily occur. On the contrary, slowing the mining speed can effectively control the abnormal pressure on the working face. Thus, the strength of the coal rock mass is a dynamically changing value, i.e., dynamic strength.

4.2 Determination of dynamic stress coefficient \( I \) of the coal rock mass

The laboratory test revealed that in the unidirectional state, when the maximum compressive stress sustained by the coal seam was equal to its uniaxial compressive strength, the coal seam failed. Thus, for the coal seam in the unidirectional stress state, the coal seam will fail is \( I_c = 1 \). The coal seam in which rock burst actually occurs is between uniaxial and triaxial stress states. The compressive strength of the coal seam is greater than \([\sigma_c]\). Assuming the coal seam is \( m[\sigma_c](m > 1) \), the strain described in formula (1) becomes

\[
I_c = \frac{\sigma_c}{m \sigma_c}.
\]  

Therefore, in actual engineering calculations, the risk index of rock bursts is

\[
l = ml_c = \frac{\sigma_c}{\sigma_c}.
\]  

Therefore, the calculation formula of critical burst depth for different types of working faces can be expressed as

\[
H_s = \frac{ml_c \sigma_c}{k \gamma},
\]
where \( x = 1, 2, \) and 3, representing the working faces of driving, stope, and goaf, respectively.

In addition, as discussed in section 4.1, the dynamic strength of rock bursts of the coal rock mass is related to the loading rate of the stress acting upon it. Therefore, \( k \) includes both static and dynamic strength effects.

Coal mine burst refers to the sudden instability and failure of the coal rock mass in the limit equilibrium position near roadways or working faces under the action of high stress [15]. One of the main characteristics of rock bursts is that the coal rock mass moves to free space, and the roadway or shallow rock mass near the working face with free space is in a uniaxial or biaxial stress state [16-17]. Thus, the stress state of the coal rock mass subject to rock bursts is between the uniaxial and triaxial stress states. In general, the triaxial compressive strength is three times the uniaxial compressive strength. Because the uniaxial compressive strength of the coal rock mass measured in the laboratory was affected by various factors in the sampling process, the uniaxial compressive strength value obtained was relatively small.

Therefore, based on the comprehensive consideration of the dynamic strength and stress state of the coal rock mass in the case of rock burst and the theoretical and practical research on the prevention and control of rock bursts in multiple mines [8,10,17-19], vertical stress 1.5 times the uniaxial compressive strength of the coal seam was used as the critical stress for rock burst. In other words, the dynamic stress coefficient \( I \) of the coal rock, at 1.5, was used as the criterion for the critical burst risk to meet the requirements of field engineering practices. Notably, the value of the dynamic stress coefficient is approximate, and the evaluation criteria need to be revised when a specific mining area is to be evaluated.

### 5 Test of three types of critical burst depths in coal mines

Based on the application to numerous of mines throughout China, statistical work was conducted on the depth of rock burst under the three types of working face conditions. On the basis of the uniaxial compressive strength of the coal seam, the stress concentration coefficients of the driving, stope, and goaf-side working faces were 1.5, 2, and 2.5, respectively, and the dynamic stress coefficient of coal seam was 1.5. As a result, the burst depths and critical depths of different mining boundaries were obtained, as shown in Table 3. The burial depth of the working face experiencing rock burst was greater than its critical depth. Moreover, 100% of the cases of rock bursts in coal mines under different boundary conditions met these conditions. Thus, the determination of rock burst critical depth in coal mines based on dynamic strength can essentially meet the requirements for determining that in coal mines under the current mining conditions.

**Table 1 Different mining boundaries and critical burst depths**

| Coal mine     | Guicheng coal mine | Liangbaosi coal mine | Zhaolou coal mine | Chaoyang coal mine | Qianqiu coal mine | Xinjulong coal mine |
|--------------|-------------------|----------------------|------------------|-------------------|------------------|---------------------|
| Type of working face with rock bursts | 3203 stopeing face | 3304 driving face | 1305 goaf-side face | 3112 goaf-side face | 21221 driving face | 1302 goaf-side working face |
| Average burial depth of working face/m | 1100 | 900 | 980 | 1100 | 800 | 800 |
| Uniaxial compressive strength of coal seam/MPa | 18.5 | 18 | 22 | 18 | 18 | 17.4 |
| Critical burst depth of working face/m | 555 | 720 | 528 | 432 | 720 | 417 |

### 6 Conclusions

In response to the engineering phenomena in which critical bursts occur at different depths in coal mining, this study proposes a formula to determine the critical burst depth based on dynamic strength and draws the following conclusions:
(1) Based on three typical boundary conditions of coal mining, three typical critical rock burst depths in coal mining are proposed to obtain the calculation formulas of critical rock burst depth under the conditions of driving, stoping, and goaf-side working faces.

(2) According to the strength criterion of medium–hard and hard coal rock bursts and based on the analysis of the factors affecting the strength of the coal rock mass under dynamic loading conditions, the value of the dynamic stress coefficient of the coal rock mass is determined.

(3) Considering the prevention and control practice of rock bursts in multiple mines in China, the rationality of the calculation method of the critical burst depth and the value of the dynamic stress coefficient of the coal rock mass were verified. The results can provide a theoretical basis for controlling rock bursts in coal mines.

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