Article

Numerical Investigation on Influence of Two Combined Faults and Its Structure Features on Rock Burst Mechanism

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Abstract: With the increase in coal mining depth, engineering geological conditions and the stress environment become more complex. Many rock bursts triggered by two combined faults have been observed in China, but the mechanism is not understood clearly. The focus of this research aims at investigating the influence of two combined faults on rock burst mechanisms. The six types of two combined faults were first introduced, and two cases were utilized to show the effects of two combined faults types on coal mining. The mechanical response of the numerical model with or without combined faults was compared, and a conceptual model was set up to explain the rock burst mechanism triggered by two combined faults. The influence of fault throw, dip, fault pillar width, and mining height on rock burst potential was analyzed. The main control factors of rock burst in six models that combined two faults were identified by an orthogonal experiment. Results show that six combinations of two faults can be identified, including stair-stepping fault, imbricate fault, graben fault, horst fault, back thrust fault, and ramp fault. The particular roof structure near the two combined faults mining preventing longwall face lateral abutment pressure from transferring to deep rock mass leads to stress concentration near the fault areas. Otherwise, a special roof structure causing the lower system stiffness of mining gives rise to the easier gathering of elastic energy in the coal pillars, which makes it easier to trigger a rock burst. There is a nonlinear relationship between fault parameters and static or dynamic load for graben faults mining. The longwall face has the highest rock burst risk when the fault throw is between 6 and 8 m, the fault dip is larger than 65°, the mining height is greater than 6 m, and the coal pillar width is less than 50 m. The stair-stepping, imbricate, horst, and ramp fault compared to the other fault types will produce higher dynamic load stress during longwall retreat. Fault pillar width is the most significant factor for different two combined faults, leading to the rise of static load stress and dynamic proneness.

Keywords: two combined faults; classification; rock burst mechanism; main control factor

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1. Introduction

As a typical dynamic disaster phenomenon, rock bursts have emerged as the most critical issue for underground engineering, which usually leads to casualties, equipment damage, and roadway destruction with the release of lots of elastic energy [1–9]. The statistics of a large number of rock bursts show that the area affected by geological fault structure is more prone to dynamic disasters [10–14]. For example, by the late 1970s, there had been at least a thousand fault-induced rock bursts at the Witwatersrand gold mine in South Africa [15]. In Longfeng Coal Mine, faults induced rock burst 36 times (50 times in total), 62% of which occurred when the roadway was close to the faults [8]. 3 November

2011 witnessed that 10 people were killed and 75 were trapped underground in the Qianqiu Coal Mine due to the fault activation [16]. Otherwise, multiple rock bursts triggered by faults were recorded in many other countries, including the USA, Poland, Australia, South Africa, Germany, Russia, and Canada [17–23].

Considerable efforts have been expended to obtain a comprehensive understanding of rock burst mechanisms triggered by faults or fault slipping. Keneti et al. [11] investigated the influence and mechanism of rock burst corresponding to geological discontinuities (e.g., faults, geological contacts, etc.). The nature of a deformation zone and fault rock related to a rock burst in South Africa was investigated by Stewart, et al. [24]. Uskov et al. [23] investigated the relationship between the tectonic features of faults and rock burst risk in the Norilsk Region, Russia. Li, et al. [25] introduced the concept of the fault coal pillar and suggested that fault-induced rock burst be categorized as fault slip, coal pillar instability, and their coupling type. Cai, et al. [26] verified two types of fault rock burst through similar simulation experiments: mining-induced quasi-static stress-dominated and seismic-based dynamic stress-dominated. Wang, et al. [27] investigated the stress distribution characteristics and instability mechanism of fault surfaces under mining conditions. However, the present works only are focused on the relationship between fault slip and rock burst. There is less attention paid to combined geological structures, such as combined faults. Recently, severe several rocks bursts triggered by two combined faults have been reported in China, such as “2.22” rock burst in the Xinjulong Coal Mine (four people killed), “8.2” rock burst in the Tangshan Coal Mine (seven people killed and five people injured), “6.9” rock burst in the Longjiapu Coal Mine (nine people killed and 12 people injured), “10.20” rock burst in the Longyun Coal Mine (21 people killed and four people injured), and “3.27” rock burst in the Qianqiu Coal Mine (six people killed and 13 people injured) [28]. However, the influence of two combined faults and its structure features on the rock burst mechanism is not understood. A systematical investigation on the rock burst mechanism caused by two combined faults is indispensable to conduct the targeted prediction and prevention.

The physical experiment is a powerful tool for assessing the rock burst potential. However, due to the limitations of model size, complex mechanical properties of coal and rock mass, and excavation sequence of a longwall face, a large-scale parametric investigation cannot be carried out. In comparison, the numerical technique has proved to be a powerful tool for studying the mechanics of underground rock [29]. A large-scale discrete model was established by Wei, et al. [30] to assess the influence of faults on peak abutment stress, the distribution characteristics of strain energy of coal seam, and the energy released by fault slip. An explicit Finite Element Method (FEM) was developed by Manouchehrian and Cai [6] to perform a parametric study with different fault positions, length, and dip relating to the deep tunnel. An FLAC^{3D} model was built up by Jiang et al. [31] to analyze the influence of fault parameters on fault behavior and the possibility of rock burst induced by fault slip. Therefore, it is accepted that numerical simulation has unique advantages in large-scale excavation simulation and rock burst risk assessment [32,33].

In this paper, a numerical investigation is conducted to understand the rock burst mechanism and parameter-influenced mechanical response triggered by two combined faults. The types of two combined faults were first introduced based on the types of two embedded faults and the movement direction of the upper and lower walls of the faults. Two FLAC^{3D} models, i.e., the base model and two combined fault models, were set up to investigate the mechanical response difference between them and the rock burst mechanism triggered by combined faults. Subsequently, a series of parametric tests (including fault throw, dip, mining height, and fault pillar width) were performed to research the influence of different parameters of two combined faults on rock burst potential. In addition, the orthogonal experiment method with four factors and three levels (3⁴) was adopted to identify the main control factors of rock burst triggered by combined faults.

2. Classification of Two Combined Faults under Mining Background

2.1. Classification of Two Combined Faults

A slip fault is a geological phenomenon characterized by a fracture zone existing between two rock blocks, in which two blocks can slip along the fracture [34]. The angle between the fault plane and horizontal surface (known as the dip) and the direction of slip along the fault are used by earth scientists to classify faults. It is widely accepted that faults could be classified as dip-slip and strike-slip types depending on whether they move along the dip direction or move horizontally. Especially for dip-slip faults, two types are commonly adopted: (1) normal fault—The hanging wall of the fault moves downward relative to the footwall of the fault; (2) thrust fault—The hanging wall of the fault moves upward relative to the footwall of the fault.

However, in reality, a fault does not exist independently in nature, which means that a fault combined with other faults or folds could form new composite structures [35,36]. Particularly for two adjacent faults, several two combined faults types were systematically proposed by HU [35]: The scheme of the different two combined faults is depicted in Figure 1, and the detailed identification is shown in Table 1.

Figure 1. The scheme of the different two combined faults. (a) Plane view represents stair-stepping fault. (b) Plane view represents imbricate fault. (c) Plane view represents graben fault. (d) Plane view represents horst fault. (e) Plane view represents back thrust fault. (f) Plane view represents ramp fault. The red arrows represent the moving direction of the fault block. The black fill represents coal seams and others represent other sedimentary formations.

Table 1. The detailed identification of two combined faults (as referred to HU [35]).

Types of Two Combined Faults	Types of Two Embedded Faults	Identification
Stair-stepping fault	Two normal faults	The stair-stepping fault is formed by two parallel normal faults, the hanging walls of which descend in the same direction, resembling a staircase.
Imbricate fault	Two thrust faults	The imbricate fault is formed by two parallel thrust faults, the hanging walls of which descend in the same direction, resembling a roof tile on the house.
Graben fault	Two normal faults	The graben fault is composed of two symmetrical and inclined normal faults with fault walls rising on both sides and a common descending wall in the middle.
Horst fault	Two normal faults	The horst fault is composed of two symmetrically inclined normal faults with fault walls descending on both sides and common uplifting walls in the middle.
Back thrust fault	Two thrust faults	It is similar to the graben fault, but the back thrust fault consists of two thrust faults.
Ramp fault	Two thrust faults	It is similar to the horst fault, but the ramp fault consists of two thrust faults.

2.2. Influence of Two Combined Faults Types on Coal Mining

Over the decades, with the coal resources in China rapidly getting exhausted, the mining depth has increased substantially, e.g., the Huafeng Coal Mine, a typical rock burst coal mine in eastern China, has reached −1300 m below the surface [37]. It was observed that the increasingly complicated engineering geological conditions had posed a great threat to the safety production of Chinese coal mines. Considerable efforts have been expended to acquire a comprehensive understanding of mechanism of the dynamic failure induced by different factors, including roof rupture [38–40], fault slip [8,26,41], fold structure [42,43], coal pillar [7,44,45], etc. However, more complex geotechnical conditions are characterized by composite geological structures that have been threatening the safety in underground mining.

Recently, especially for the aforesaid two combined faults, several catastrophic accidents have occurred in China. For example, the “2.22” rock burst disaster (occurred on 22 February 2020) of the Xinjulong Coal Mine in Shandong Province, China, trapped a total of 14 people, four of whom died [46]. Meanwhile, the investigation report [46] indicated that the wedge-shaped graben fault structure (GFS) is one of the direct causes of rock burst.

Figure 2a shows the panel layout and seismic events distribution (captured and calculated by seismic monitoring system) from the time the longwall started to retreat until rock burst occurred on longwall (LW) 2305S in the Xinjulong Coal Mine. To facilitate the understanding of roof strata of LW2305S, the A-A cross-section in Figure 2a is shown in Figure 2b, and the stratigraphic column of LW2305S is shown in Figure 2c. Two faults, i.e., FD6 and FD8 run through LW2304S and extend into LW2305S. As shown in Figure 2b, the two faults form a typical GFS. A tremendous amount of seismic events occurred near the LW2305S between the fault FD6 and FD8. Particularly, there were several high-magnitude events that exceeded 10^5 J, distributing at the area between two faults. It means that the area between the two faults has a significantly higher dynamic disaster risk than the other areas. On the one hand, the existed GFS will lead to specific roof structures (seen in Figure 2b) and further abnormal roof activity. Moreover, the GFS will reduce mine system stiffness and result in unstable failure of the mine system [6].

Similarly, there are stair-stepping faults detected in Xuzhuang Coal Mine, which is a typical burst-prone coal mine in Jiangsu Province, China [8]. As shown in Figure 3a, two faults, the F_{113} fault and F_{115} fault, existed on both sides of the retreat direction of LW7335. Moreover, the dip cross-section of coal mass formed a stair-stepping structure (seen in Figure 3b). Since 2014, the Xuzhuang Coal Mine was equipped with a seismic monitoring system called “SOS” developed by the Central Institute of Mining in Poland to continuously monitor seismicity related to mining activities. Lots of seismic events were detected during the LW7335 retreat between 2018/09/08 and 2019/01/31. As depicted in Figure 3d, many seismic events were distributed near the solid coal area and F_{115} fault rather than the goaf area. An extraordinary phenomenon also indicated that the special roof with stair-stepping faults could lead to an increasingly dynamic disaster potential.

It follows from the above statement that the two combined faults have been a common geological structure and threaten the safety of coal mines. When there is longwall face mining near the faults, the interaction between faults and coal extraction is a key factor leading to the fault reactivation [26]. Otherwise, in order to minimize the disturbance of operation to the faults, longwall panels are usually separated from the faults by fault pillars. Especially for two combined faults (as shown in Figures 2 and 3), the advance of the longwall face is usually consistent with the strike of the fault to reduce the disturbance to the faults. However, in this case, the fault parameters (i.e., throw, dip, and the width of fault pillars) are usually distinct everywhere due to the complex geological surroundings. Especially rock burst could be triggered by the instability of the fault pillar and disturbance from fault reactivation proposed by Cai et al. [26]. Therefore, the influence of two combined faults and their structure features on the mechanism of rock burst should be further systemically investigated in order to guide the monitoring and prevention of two combined faults-triggered rock bursts.

Figure 2. Cont.

(b)

Thickness/m	Column	Lithology
2.30		Mudstone
7.70		Medium sandstone
11.10		Siltstone
5.60		Medium sandstone
7.50		Mudstone
3.10		Coarse sandstone
3.00		Mudstone
37.90		Sandstone group
6.50		Medium sandstone
6.10		Siltstone
16.50		Fine sandstone
3.60		Siltstone
9.20		NO.3 Coal
4.60		Fine sandstone

(c)

Figure 2. (a) Seismic events distribution (from the time the longwall started to retreat until rock burst occurred) of LW2305S. Purple crosses represent events with energy from 0 to 10^3 J, blue filled circles represent events with energy from 10^3 to 10^4 J, pink unfilled rhombuses represent events with energy from 10^4 to 10^5 J, pink filled rhombuses represent events with energy from 10^5 to 10^6 J, and red filled circles represent events with energy over 10^6 J. (b) A-A cross-section of LW2305S in (a). The red arrows represent the moving direction of the fault block. (c) Stratigraphic column of LW2305S. (It is noticed that the stratigraphic column of a longwall face is usually plotted by comprehensively considering the strata distribution around the longwall face rather than for specific sites. The same applies to similar descriptions elsewhere in this work).

Figure 3. Cont.

Figure 3. (a) Seismic events distribution of LW7335 between 2018/09/08 and 2019/01/31. (b) E-E cross-section of the mining coal seam in (a). (c) Stratigraphic column of LW7335. (d) The seismic events frequency distribution on the dip position of the LW7335. Green filled circles represent events with energy from 0 to 10^3 J, yellow filled circles represent events with energy from 10^3 to 10^4 J, and red filled circles represent events with energy over 10^4 J.

3. Influence of Two Combined Faults on Rock Bursts

Obviously, understanding the triggering mechanism of two combined faults on rock bursts is an essential task for the improvement of mine safety. In recent years, considerable hypotheses have been expended to acquire a comprehensive understanding of rock burst

mechanisms, such as strength [47], rigidity [48,49], burst liability [50,51], stability [52,53], and energy theory [54,55], in which stress, strain, and energy are mainly considered. To further understand the links among the three parameters and explain the rock burst mechanism, a theory that integrated the stress, energy, and displacement (i.e., stiffness) of the roof–coal–floor system was proposed by Zhang, et al. [56]. Therefore, it is critical to systematically research the triggering mechanism of two combined faults on dynamic hazards according to stress, energy, and displacement.

In this section, numerical modeling was performed to investigate the mechanism of rock burst triggered by two combined faults by simplifying to some extent. However, it is not straightforward to recognize stable and unstable rock failure (i.e., rock burst) in numerical modeling. Usually, the judgment of unstable failure in numerical modeling is performed via comparing the model response with a known model response, which is regarded as a stable failure [6]. In longwall excavation modeling, the failure mode in a model without geological structures can be considered stable (base model). On this basis, the stress, displacement, and energy responses of geological models are compared with those of non-geological models to investigate the triggering mechanism of rock burst.

3.1. Model Setup and Material Properties

Taking the graben fault as an example, FLAC^{3D} numerical modeling was performed to investigate the mechanical response caused by two combined faults. In the process, two numerical models (a base model and a graben fault model (GFM)) were established. The only difference between the base model and GFM is the presence of faults, as shown in Figure 4. Figure 4a,c show the numerical model without faults (base model) and with faults (GFM model), respectively. To show the longwall layout more clearly, the grids hyalinized over the longwall face in Figure 4a,c are shown in Figure 4b,d, respectively. The strata were simplified into floor, coal seam, immediate roof, main roof, and overburden according to the classical mining overburden movement theory [57] due to the model not being targeted to a specific engineering context.

Figure 4. Numerical model of base model and graben fault model. (a) Grid model of base model. (b) Schematic of longwall face layout in base model. (c) Grid model of graben fault model. (d) Schematic of longwall face layout in graben fault model. The rock layers above the longwall face in (b,d) were made transparent in order to display the layout of the longwall.

Figure 4 displays the numerical models with the size of 500 m × 400 m × 130 m. This paper aims to obtain the mechanical response characteristics of a specific fault structure rather than to do a parametric study on the rock strata and faults. Therefore in this process, the mechanical parameters of strata and faults are obtained according to reliable literature. The origin (i.e., elastic) mechanical parameters of strata are referred from the literature [58], as seen in Table 2. In addition, to obtain the stress distributions in the model, the static displacement boundary is applied around the models. The horizontal displacements around the model and the vertical displacements at the model's bottom are fixed in the normal direction. At the top of the models, a vertical load ($P = \gamma H = 15.0$ MPa, approximately equal to the hydrostatic pressure when the coal seam buried 600 m) was applied to simulate the in situ stress, while stress coefficients along the x- and y-directions were set to 0.8 and 1.5, respectively.

Table 2. Model mechanical parameters and thickness of the fault and strata. /: The interface elements do not have thickness assignments.

Items	Thickness (m)	Bulk Module (GPa)	Shear Module (GPa)	Cohesion (MPa)	Internal Friction Angle (°)	Density (kg·m ⁻³)
Overburden	37	1.31	0.42	0.30	33	2500
Main roof	20	2.30	1.52	1.7	38	2700
Immediate roof	5	1.31	0.42	0.30	33	2500
Coal seam	3	0.15	0.08	0.11	25	1400
Floor	65	1.97	1.14	0.40	35	2600
Interface elements	/	interfacial cohesion = 2.0 MPa, interfacial friction angle = 30°, $k_n = k_s \approx 2.16 \times 10^{10}$ Pa/m.				

Please note that only the normal stress and tangential stress of the fault are considered here without the effect of pore water pressure, which means that the mechanical parameters here do not consider the effect of pore water.

In addition, to simulate the excavation of the longwall face, the coal blocks in the mined area were set to the null model. Moreover, the boundary between the longwall panel and the model boundary should be 50 m to eliminate the boundary effect during the excavation of the longwall face. On this basis, the strain-softening model was adopted to simulate the weakening effect of rock mass after mining. The softening coefficient method suggested in the FLAC^{3D} manual [59] was adopted due to the absence of reliable measurements for the strata after excavation. Moreover, the fault was simulated using the interface elements (seen in Figure 4d). Since the mechanical parameters of the faults cannot really be measured, they were determined by trials in a reasonable range. Thereby, the common values of interfacial cohesion and interfacial friction angle were adopted herein as referred to Karakaş [60]; the normal stiffness (k_n) and shear stiffness (k_s) suggested in the FLAC^{3D} manual were adopted (seen in Table 2). Among these, k_n and k_s were primarily estimated to be greater than ten times the equivalent stiffness of the stiffest neighboring zone, which can be expressed as:

$$k_n = k_s \approx 10 \cdot \max \left[\frac{K + 4G/3}{\Delta Z_{\min}} \right] \quad (1)$$

where K and G are the bulk and shear moduli, respectively, and $\Delta Z_{\min}$ is the smallest width of a zone in the normal direction of the interfacing surface.

3.2. Mechanical Response of Two Combined Faults to Mining

To investigate the mechanical response characteristic and triggering mechanism of two combined faults to mining, the difference including mining stress, displacement (i.e., stiffness), and elastic energy between graben fault model (GFM) and the base model was systematically analyzed in this section.

Figure 5 denotes the vertical stress distribution difference between the graben fault model and base model (the cross-section of 10 m ahead of the longwall face is selected since the abutment pressure peak area is about 10 m ahead of the longwall face, which

means a higher rock burst potential over there). The vertical stress peak of the base model and GFM is 20.93 MPa and 27.70 MPa, respectively, which also indicates that the vertical stress peak of GFM is approximately 32% (6.77 MPa) higher than that of the base model. Moreover, abnormal stress transitions occur near faults in GFM, as seen in Figure 5b. It can be concluded that the stress transfer on both sides of the coal pillar of the fault is obstructed due to the existence of faults, which results in stress concentration near the fault area. When the fault pillar encounters high stress and a high-stress difference state at the same time, it is easy to produce high-magnitude events, which may lead to fault activation and then trigger rock bursts [26].

Figure 5. Vertical stress distribution curve (cross-section of 10 m in advance of the longwall face). (a) Base model; (b) Graben fault model.

Figure 6 shows the vertical displacement distribution difference between GFM and base model (the cross-section of 30 m behind the longwall face is selected, since the first weighting distance of the longwall can vary 20 to 60 m [61], which is accompanied by severe roof collapse and slip of goaf). The vertical displacement peak of the base model and GFM is 212 mm and 302 mm, respectively, which also indicates that the vertical displacement peak of GFM is approximately 42% (90 mm) higher than that of the base model. In addition, the mining-affected span and height of GFM are much larger than that of the base model (compare Figure 6a with Figure 6b). Especially as seen in Figure 6b, the roof displacement field presents a trend of migration from faults to the middle of the longwall face, which means that the existence of faults reduces the stiffness of the roof–coal–floor system.

Figure 6. Vertical displacement distribution contour (cross-section of 30 m behind the longwall face). (a) Base model; (b) Graben fault model.

In numerical modeling, elastic energy density W_E can be calculated as follows [58]:

$$W_E = \frac{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\mu \cdot \sigma_1 \cdot \sigma_2 - 2\mu \cdot \sigma_2 \cdot \sigma_3 - 2\mu \cdot \sigma_1 \cdot \sigma_3}{2E} \quad (2)$$

where μ and E are the Poisson ratio and elastic modulus respectively, and σ_1 , σ_2 , and σ_3 are the maximum, intermediate, and minimum principal stresses of the element body, respectively.

Figure 7 depicts the elastic energy distribution difference between the GFM and base model. The elastic energy peak of the base model and GFM is 5×10^5 J and 7.5×10^5 J, respectively, which also indicates that the elastic energy peak of GFM is approximately 42% (90 mm) higher than that of the base model. In addition, not only the energy concentration area of GFM is larger than that of the base model, but also the energy peak area of GFM is closer to the coal mass surface (Compared Figure 7a with Figure 7b). It is not hard to find that rock bursts are easily triggered in elastic energy concentration areas once the roadway and coal mass encounter instability, which may lead to catastrophic casualties and property loss.

Figure 7. Elastic energy distribution contour (cross-section of 30 m behind the longwall face). (a) Base model; (b) Graben fault model.

3.3. Mechanism of Rock Burst Triggered by Two Combined Faults

It follows from the above argument that the stress, displacement, and energy field of a longwall face mining near two combined faults are obviously different from those without faults. To explain the difference and mechanism of rock burst triggered by two combined faults, a theoretical model was established here.

According to the mechanical behavior of the roof, floor, and coal, the roof and floor can be assumed as linear elastomers, and coal can be assumed as a nonlinear material with strain-softening behavior [26]. When longwall mining is without faults, the stress of the coal can be expressed as σ_s , whose stress–strain relationship is shown on the right in Figure 8, and the corresponding roof and floor deformation behavior is shown on the left in Figure 8.

As shown in Figure 8, when the coal mass is under quasi-static loading, the strain is generated after the force is applied, and the strain generated by the cooperative deformation of roof and floor satisfies the relation:

$$k_1 \cdot \Delta \varepsilon_1 = k_2 \cdot \Delta \varepsilon_2 \quad (3)$$

where k_1 is the loading stiffness of the roof and floor, and k_2 is the unloading stiffness of the coal. The strain of the “roof–coal–floor” system can be expressed as follows:

$$\Delta \varepsilon = \Delta \varepsilon_1 + \Delta \varepsilon_2 = \frac{k_1 + k_2}{k_1} \Delta \varepsilon_2 \Rightarrow \frac{\Delta \varepsilon_2}{\Delta \varepsilon} = \frac{1}{1 + k_2/k_1} \quad (4)$$

It can be seen that when $k_1 + k_2 = 0$, $\Delta \varepsilon_2 / \Delta \varepsilon \rightarrow \infty$. It means that the “roof–coal–floor” structure is in an extremely unstable state, and it is easy to induce rock burst when disturbed by the dynamic load. Furthermore, with the increase in deformation and energy release of the “roof–coal–floor” system, the whole system gradually tends to be stable (corresponding to point S), and the whole process corresponds to the complete process of rock burst. The whole system in this process follows the first law of thermodynamics. In other words, the elastic energy released from the roof and floor (E_1) is equal to the energy consumed by coal deformation (E_2) plus the elastic energy released outward (E_3), from

4. Effects of Two Combined Faults on Rock Burst Potential

It follows from the above statement that the existence of two combined faults leads to a significant increase in the rock burst potential of the longwall face. Thereby, it is necessary to carry out a systematic investigation, including the influence of different parameters of two different combined faults on rock burst potential.

4.1. Definition of Rock Burst Potential Assessment Indexes

Many case studies have proven that the occurrence mechanism of rock burst should be accounted for the static load, dynamic load, and superposition effect of them [64–69]. Moreover, when longwall face mining near the faults, fault pillar instability and fault activation are two main causes of rock burst [25,26]. Therefore, two rock burst potential assessment indexes were proposed in this section considering aforesaid static and dynamic load to investigate the response characteristics of different parameters to mining near two combined faults.

There are three types of principal stress transformation of coal and rock mass under load (as seen in Figure 9): (1) the Mohr circle remains the same size and shifts its position, i.e., $|\sigma_1 - \sigma_3|$ remains constant; (2) the Mohr circle changes in size while its position remains constant, i.e., σ_1 and σ_3 get bigger or smaller simultaneously and $|\sigma_1 - \sigma_3|$ makes changes; (3) the Mohr circle changes in size and position, i.e., $|\sigma_1 - \sigma_3|$ makes changes. In this process, according to the Mohr–Coulomb strength criterion of single discontinuity [70], rock mass failure occurs when the Mohr circle intersects or tangles the strength curve, as shown in Figure 9. It is further deduced that the smaller the distance between the Mohr circle and strength curve is, the worse the stability of the rock mass is and the more rock burst risk.

Figure 9. Normal stress transformation form based on Coulomb failure criterion where σ_1 and σ_3 are the initial maximum and minimum principal stress of rock mass respectively. σ'_1 and σ'_3 are respectively the maximum and minimum principal stresses of rock mass after transformation.

On this basis, PANG, et al. [71] considering the transformation of three principal stresses proposed the criterion of instability of complete rock mass, which can be expressed as:

$$k_{3d} = \left| \frac{\sigma'_1 - \sigma'_3}{\sigma_1 - \sigma_3} \right| \frac{2c \cdot \cot \varphi + \sigma_1 + \sigma_3}{2c \cdot \cot \varphi + \sigma'_1 + \sigma'_3} \quad (6)$$

where c and φ represent the cohesion and internal friction angle of coal and rock mass, respectively. It can be inferred that the larger the k_{3d} is, the closer to or beyond the strength limit of coal and rock mass, the stronger the disturbance state of surrounding rock, leading to the higher the rock burst risk.

In addition, it can be deduced that in the process of normal stress transformation near the fault, when the principal stress is in the nearly same direction as the fault dip, the fault is easier to be activated (which means that the stiffness of the “roof–coal–floor” system is lower). On this basis, a disturbance instability index (*DII*) was proposed here as an improvement on k_{3d} to assess the rock burst potential caused by static load transformation, which can be expressed as:

$$DII = k_{3d} \cdot f_{\sin} \quad (7)$$

where $f_{\sin}$ is the sine value of the direction of maximum principal stress at a certain point in the surrounding rock and the normal vector of the fault plane.

Furthermore, in order to evaluate risk caused by fault activation, maximum fault slip rate (F_v) is proposed to assess the rock burst potential caused by dynamic load (the faster fault slip velocity can lead to greater dynamic load and more rock burst potential [32,72]. Especially in FLAC^{3D}, the F_v of the fault plane can be recorded directly using embedded FISH language.

4.2. Influence of Different Parameters of Two Combined Faults on Rock Burst Potential

When mining longwall faces near the faults, several parameters, including fault throw, fault dip, mining height, and fault pillar width are the essential factors influencing the stability of longwall faces [26]. Thereby, in this section, a series of numerical modeling was performed to systematically research the influence of different parameters of two combined faults on rock burst potential. In this process, the control variable method was adopted. For example, when studying the effect of fault drop changes on the longwall face, five numerical models were set up, in which model parameters and the excavation mode of the longwall face were consistent with the model (as shown in Figure 4c,d), except that the fault throw was successively changed to 4 m, 6 m, 8 m, 10 m, and 12 m.

Figure 10a shows the distribution of *DII* and F_v with different fall throws during longwall retreat. It can be seen that *DII* fluctuates as the fault throw increases, and *DII* reaches the peak when the fault throw is between 6 and 8 m. In addition, F_v firstly increases with the increase in fault throw and then gradually stabilizes in a relatively stable range, which means that the increase in fault throw results in a limited disturbance of dynamic load. Comprehensively considering the response of *DII* and F_v to the increase in fault throw, the longwall has a relatively high rock burst potential when the fault throw varies from 6 to 8 m.

Figure 10. Cont.

Figure 10. Change of rock burst potential under the influence of different factors based on proposed rock burst potential assessment indexes. (a) Influence of different fault throw on rock burst potential. (b) Influence of different fault dip on rock burst potential. (c) Influence of different mining height on rock burst potential. (d) Influence of different fault pillar width on rock burst potential.

Figure 10b depicts the distribution of DII and F_v with different fall dips during longwall retreat. It is noted that DII fluctuates as the fault dip increases when fault dip is less than 65° , and DII increases rapidly when fault dip is larger than 65° . F_v reaches the peak when the fault dip is equal to 55° . Moreover, when the fault dip reaches 65° , the rapid rise of DII means that the increase in fault dip will lead to a sharp increase in the stress concentration of the fault pillar.

Figure 10c displays the distribution of DII and F_v with different mining heights during longwall retreat. It is found that both DII and F_v show an obvious upward trend with the increase in mining height. It means that the increase in mining height will lead to the increase in the static and dynamic load of the longwall face, further resulting in higher rock burst risk, which is unfavorable to risk management. In addition, DII and F_v show a more obvious upward trend when the mining height is larger than 6 m. Therefore, the mining height should be reduced to below 6 m as far as possible in order to effectively reduce the rock risk potential.

Figure 10d shows the distribution of DII and F_v with different fault pillar widths during longwall retreat. Both DII and F_v increase first and then decrease with the increase in pillar width, and DII and F_v reach the peak when the pillar width is equal to 30 m and 40 m, respectively. Additionally, both DII and F_v are at extremely high levels when the fault pillar width is between 20 and 50 m. Consequently, the fault pillar width should be more than 50 m to effectively reduce the burst risk.

According to the analysis of the influence of different parameters of two combined faults on rock burst potential, it can be concluded that the change of fault throw, fault dip, mining height, and fault pillar width will make the static and dynamic load change significantly. Furthermore, none of them are linearly related to the level of static or dynamic load. It is observed that the longwall face has the highest rock burst risk when the fault throw is between 6 and 8 m, the fault dip is larger than 65° , the mining height is greater than 6 m, and the coal pillar width is less than 50 m.

4.3. Identification of Main Control Factors of Rock Burst

It has been widely acknowledged that the monitoring, warning, and prevention of rock burst must be targeted [73]. As for mining near the combined faults, the main control factors should be identified for further targeted prevention and control measures. The influenced parameters that triggered rock burst risk such as fault throw, dip, mining height, and fault pillar width have been investigated in Section 4.2. However, mining height can be adjusted flexibly when it leads to a high burst risk. Thereby, in this section, the fault throw, dip, and fault pillar width were tested to identify the main control factors of rock burst in different two combined faults models. Moreover, the DII and I_V were used to evaluate the static and dynamic burst risk, respectively.

As for the fault throw, dip, and fault pillar width, if each factor contains four parameters and the experiment is conducted using the control variable method, there will be a total of 64 schemes, which will result in a huge amount of computation and data processing and is unfavorable for data analysis. To solve the problem, the orthogonal experiment method [74] is widely adopted to study this approach of multiple factors and levels (i.e., parameters) problems. Due to three factors being considered here, an orthogonal table with four factors and three levels (3^4) is adopted, as shown in Table 3. In addition, the difference between the different parameters of each factor should be as large as possible for the more obvious results difference and facilitating the analysis (seen in Table 3). Table 4 shows the orthogonal test schemes of four factors and three levels (3^4). On this basis, several numerical models (as shown in Figure 11) corresponding to the six aforesaid two combined faults types were set up to identify the main control factors of rock burst, in which the model setups and material properties are the same as those mentioned in Section 3.1.

Table 3. Orthogonal test factor levels and model parameters.

Level	A Throw (m)	B Dip ($^\circ$)	C Pillar Width (m)
1	4	45	10
2	8	60	40
3	12	75	70

Table 4. Orthogonal test schemes of four factors and three levels (3^4).

Level (Scheme)	A Throw (m)	B Dip ($^{\circ}$)	C Pillar Width (m)	D /
1	4	45	10	/
2	4	60	40	/
3	4	75	70	/
4	8	45	70	/
5	8	60	10	/
6	8	75	40	/
7	12	45	40	/
8	12	60	70	/
9	12	75	10	/

Figure 11. The numerical models of the different two combined faults. (a) Stair-stepping fault model. (b) Imbricate fault model. (c) Graben fault model. (d) Horst fault model. (e) Back thrust fault model. (f) Ramp fault model. The orange blocks represent overburdens; the green blocks represent main roofs; the blue blocks represent immediate roofs; the black blocks represent coal seams; and the yellow blocks represent floors.

Figure 12a shows the DII distribution of different orthogonal experiment results. For six different combined faults, the distribution of DII is relatively high and close to each other except for some special cases, which indicates that the excavation of the longwall face in the middle of the faults leads to lateral abutment pressure, and the existence of

faults on both sides leads to stress concentration near the faults. Furthermore, the similar *DII* distribution of different combined faults indicates that the correlation between stress concentration and faults type is weak. Additionally, for a special two combined faults type, the difference of *DII* among different experimental schemes was also small except for some cases, which means that the longwall face will always be affected by high static stress when mining near the combined faults and targeted prevention and control measures should be implemented.

Figure 12b shows the I_V distribution of different orthogonal experiment results. It can be seen that the I_V distribution varies among different combined faults, in which all experimental schemes have relatively low I_V values in back thrust fault and graben fault models and the rest of the models have relatively high I_V values. Furthermore, it is noticed that the maximum I_V values all appear in scheme 9 of the other four combined faults models, in which the fault throw and dip are the maximum and the pillar width is the minimum in all experimental schemes (seen in Table 4). The larger the fault throw and dip, the smaller the pillar width when mining near the combined faults, which will lead to higher dynamic risk.

In orthogonal experimental analysis, the sample range (R) is usually used to determine the order of influence factors, which can be expressed as:

$$R = \max\{K_1, K_2, \dots, K_i\} - \min\{K_1, K_2, \dots, K_3\} \quad (8)$$

where i represents the number of influencing factors, and K_i represents the sum of the corresponding test results when the parameters of any column of orthogonal test table are the same (as shown in Table 4).

Figure 12c denotes the sample range of *DII* relating to different orthogonal experimental schemes. It can be seen that the fault pillar width is the primary control factor in the stair-stepping fault and back thrust fault model. Fault throw is the main control factor in the graben fault model, and there are few differences between the three factors in the imbricate fault model, horst fault model, and ramp fault model. It can be concluded that the main control factors are variable when mining near the different combined faults. It warns us that the exploration of fault occurrence must be strengthened, especially for the actual mining process, as faults are variable.

Figure 12. Cont.

Figure 12. Orthogonal experimental results. (a,b) represent DII and I_V distribution of different orthogonal experimental schemes, respectively. (c,d) represent the sample range of DII and I_V correspond to different orthogonal experimental schemes respectively.

Figure 12d presents the sample range of I_V corresponding to different orthogonal experimental schemes. It can be seen that fault pillar width is the primary control factor in all fault models. Especially for the stair-stepping fault, imbricate fault, and ramp fault model, the sample range of I_V of the fault pillar width is much greater than that of the fault throw and dip, which means inappropriate fault pillars should be avoided primarily to avoid triggering significant activation of the fault.

It follows from the above statement that the presence of two combined faults will result in high static load stress, and specific combined fault types will produce higher dynamic load stress (e.g., stair-stepping, imbricate, horst, and ramp fault model) during longwall retreat. As for different combined faults, the main control factors leading to the rise of static load stress of longwall are different, in which fault pillar width is the most significant factor. In addition, the fault pillar width is the primary control factor in all fault models, leading to dynamic proneness.

5. Conclusions

In underground burst-prone coal mines, the combined faults have become the critical factors that induced rock burst potential. The types of two combined faults were first classified in this work. On this basis, the rock burst mechanism and control factors were systematically investigated. The following conclusions can be drawn:

- (1) According to types of two embedded faults, six types of two combined faults can be summarized, including stair-stepping fault, imbricate fault, graben fault, horst fault, back thrust fault, and ramp fault.
- (2) The particular roof structure near the two combined faults mining preventing longwall face lateral abutment pressure from transferring to deep rock mass leads to stress concentration near the fault areas. Otherwise, a special roof structure causing the lower system stiffness of mining gives rise to the easier gathering of elastic energy in coal pillars, which makes it easier to trigger a rock burst.
- (3) The analysis of the influence of different parameters of graben faults on rock burst potential shows that none of them are linearly related to the level of static or dynamic load. It is noticed that the longwall face has the highest rock burst risk when the fault throw is between 6 and 8 m, the fault dip is larger than 65° , the mining height is greater than 6 m, and the coal pillar width is less than 50 m.
- (4) This approach of combined faults (i.e., stair-stepping, imbricate, horst, and ramp fault model) will produce higher dynamic load stress during longwall retreat. The main control factor for different two combined faults leading to the rise of static load stress and dynamic proneness is different in which fault pillar width is the most significant factor.

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