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Mechanism of Rock Burst Induced by Hard Roof and Discussion on Hydraulic Fracturing Prevention and Control Technology

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Abstract. The dynamic load released after hard roof fracture, which superimposes with the static load inside the coal and rock mass, is an important force source condition causing rock burst disasters in domestic coal mines. According to two dimensions of rock stratum combination form and spatial position, this paper divides hard roofs into four categories: single/composite and near-field/far-field, and sorts out the disaster-inducing mechanisms corresponding to each type of roof. On this basis, it explains the essence of energy regulation of hydraulic fracturing, which realizes "reducing static load - weakening dynamic load - blocking transmission path" through artificial fracture network. In view of the current practical bottlenecks, such as the lack of quantitative criteria for collaborative disaster induction of composite roofs and the fact that main control stratum identification mostly relies on engineering experience, this paper proposes a prevention and control technology framework of "accurate identification of main control strata - three-dimensional collaborative fracturing above and below the mine - intelligent effect evaluation". The research results show that promoting the prevention and control work from "experience-based rock burst prevention" to "science-based rock burst prevention" is the key path to improve the prevention and control effect of hard roof rock burst.

Keywords: rock burst, hard roof, hydraulic fracturing, superposition of dynamic and static loads, multiple key strata

1. Introduction

Rock burst is a type of dynamic disaster with extremely strong destructive force in the process of deep coal mining. As shallow coal resources in China are gradually depleted, the mining focus continues to shift to deep coal fields in the west such as Shanxi-Shaanxi-Inner Mongolia-Xinjiang. The occurrence conditions of hard roof and its fracture and instability behavior have become the main force source conditions triggering impact disasters, and roof-related impact accidents account for a high proportion [1, 2]. Therefore, clarifying the mechanical mechanism of rock burst induced by hard roof and sorting out the development context of hydraulic fracturing prevention and control technology have strong theoretical research value and engineering practical significance.

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In terms of geological occurrence characteristics, the geological conditions in the Meng-Shaan mining area are very special. Controlled by continental sedimentation, there are often 2 to 3 or even more thick sandstone layers developed above the coal seam, forming a multi-key-stratum overburden structure with low-position, medium-position and high-position combinations [3, 4]. Under such conditions, roof fracture behaviors no longer occur independently, and obvious synergistic effects will appear between strata. Direct application of single roof prevention and control experience from eastern mining areas makes it difficult to achieve ideal governance effects. At the mechanism research level, the superposition of dynamic and static loads has become the mainstream theory for analyzing rock burst [5]. However, the energy amplification effect caused by synchronous fracture of upper and lower key strata under composite roof conditions brings new research challenges to the existing theoretical system. In terms of engineering prevention and control, hydraulic fracturing technology has gradually replaced deep-hole blasting and become the mainstream means of hard roof treatment [6, 7]. However, facing multi-key-stratum overburden, there is no unified quantitative criterion for which layer to select as the fracturing target stratum and whether to carry out multi-layer collaborative fracturing (Figure 1) [4, 8, 9].

Based on the above practical background, this paper mainly carries out four aspects of work: ① Sorting out the mine distribution characteristics and accident features of hard roof rock burst in China; ② Classifying and analyzing the disaster-inducing mechanisms of different types of roofs; ③ Summarizing the energy regulation principle of hydraulic fracturing and the current status of process development; ④ Summarizing the existing core problems and putting forward the technical framework for follow-up research.

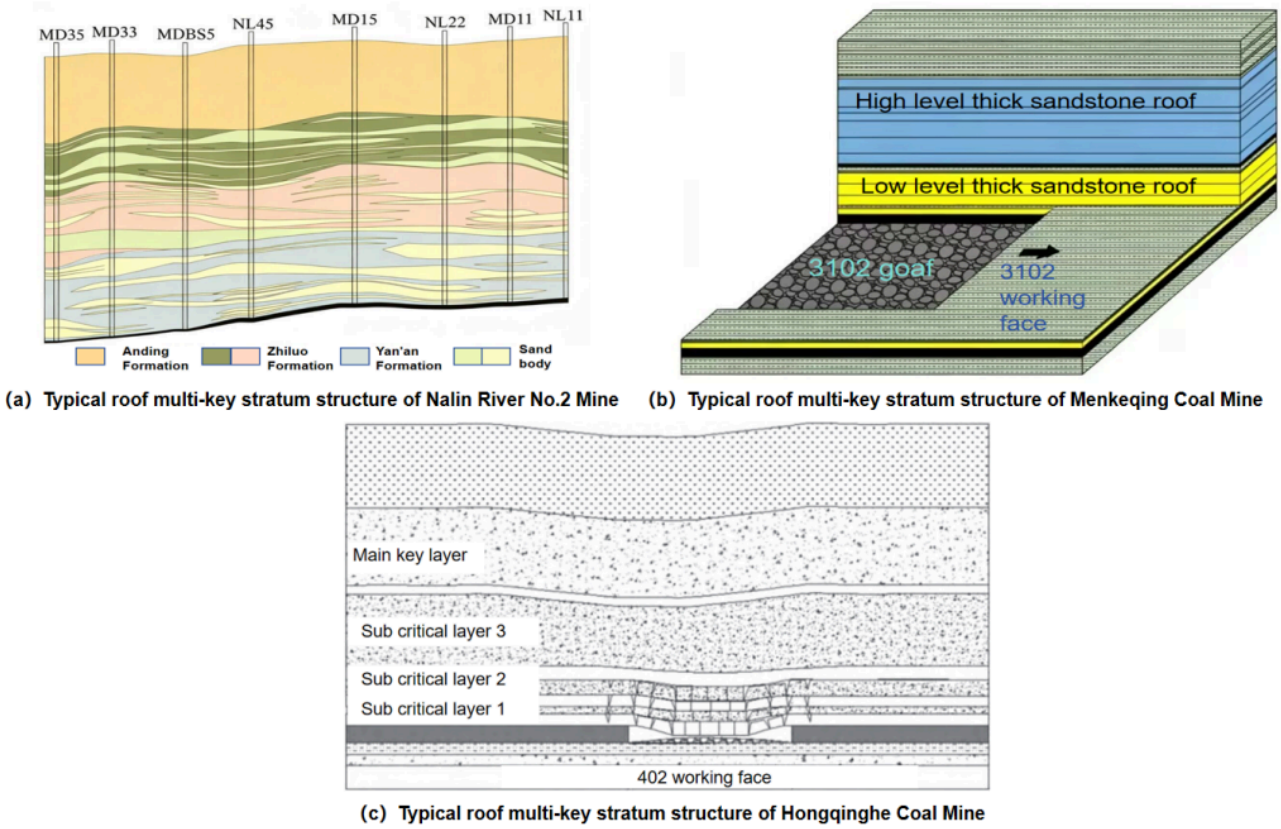
2. Distribution and accident characteristics of hard roof rock burst in China

Grasping the mine distribution law and accident characteristics of hard roof rock burst is the basis for carrying out mechanism research and formulating targeted prevention and control schemes.

Statistics by Qi Qingxin et al. [1] show that as of 2023, the total number of rock burst mines in China is about 180, distributed across 13 provincial administrative regions. As mining work continues to advance to the Shanxi-Shaanxi-Inner Mongolia-Xinjiang region, the problem of rock burst disasters in deep western mining areas such as Inner Mongolia and Shaanxi has become increasingly prominent [10]. According to different disaster-inducing causes, rock burst mines can be divided into five categories: shallow type, deep type, structural type, hard roof type and coal pillar type [11].

Among the five types of mines, hard roof type mines, or mines where hard roof and deep high static load act together, account for more than half [1]. The occurrence conditions of roofs in different mining areas vary significantly (Table 1), which directly determines the disaster mode and prevention and control ideas. The particularity of the Meng-Shaan mining area is especially prominent. Affected by the lateral migration of continental distributary channels in Jurassic coal fields, thick hard sandstone layers inside the strata are repeatedly superimposed, forming a multi-key-stratum overburden structure [3], which provides a geological basis for the occurrence of high-intensity rock burst.

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(a) Typical roof multi-key stratum structure of Nalin River No.2 Mine (b) Typical roof multi-key stratum structure of Menkeqing Coal Mine

(c) Typical roof multi-key stratum structure of Hongqinghe Coal Mine

Figure 1. Examples of typical multi-key-stratum roof structures in multiple locations in the Meng-Shaan mining area (a modified from reference [4], b [8], c [9])

Table 1. Characteristics of hard roofs in typical mining areas

Mining area	Representative mine	Roof characteristics	Key stratum structure	Main rock burst type
Shandong mining area	Tangshan Coal Mine	Single-layer thick hard sandstone	Single key stratum	Single roof fracture type [12]
Meng-Shaan mining area	Nalinhe No.2 Coal Mine	Superimposed thick sandstone layers	Double key strata	Composite roof collaborative type [13]
Meng-Shaan mining area	Menkeqing Coal Mine	Medium-high position thick hard sandstone	Single thick hard key stratum	Medium-high position dynamic load trigger type [14]
Xinjiang mining area	Liuhuanggou Coal Mine	Extra-thick conglomerate roof	Single extra-thick key stratum	Far-field strong dynamic load type [15]

By sorting out typical rock burst accident cases in recent years (Table 2), it can be found that all accidents are directly related to the fracture of thick hard rock strata. Three rules can be summarized from them: First, hard roof is a universal geological factor inducing impact accidents. Second, the

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disaster-inducing mode in the Meng-Shaan mining area is more complex, and most accidents stem from the collaborative fracture of double key strata or multi-layer strata [2, 16]. Third, disasters are concentrated in operation areas with deep mining and high-intensity stoping.

Table 2. Typical rock burst accidents in recent five years

Time	Coal mine name	Location	Inducing cause
2023	Shuangyang Coal Mine	Shuangyashan, Heilongjiang	Hard roof fracture [17]
2023	Liuhuanggou Coal Mine	Changji, Xinjiang	Extra-thick conglomerate roof [15]
2023	Menkeqing Coal Mine	Ordos, Inner Mongolia	Medium-high position thick hard sandstone roof [14]
2022	Tangshan Coal Mine	Tangshan, Hebei	Thick hard rock stratum of roof [12]
2022	Nalinhe No.2 Coal Mine	Ordos, Inner Mongolia	Collaborative fracture of composite hard roof [13]

3. Types of hard roof and mechanism of rock burst induced by them

Hard roofs with different occurrence conditions and rock stratum combinations have obvious differences in energy accumulation and release paths. Combined with two dimensions of rock stratum combination form (single/composite) and spatial position (near-field/far-field), this section elaborates the internal mechanism of rock burst induced by each type of roof respectively.

3.1. Classification of hard roof

Hard roof generally refers to overburden rock with uniaxial compressive strength greater than 60 MPa, thickness more than 10 m, good rock mass integrity, and difficulty in natural caving under mining disturbance. This paper adopts two groups of independent conditions for roof classification. According to rock stratum combination, it is divided into single hard roof (only 1 key stratum exists) and composite hard roof (the number of key strata is ≥2, the interlayer spacing is no more than 30 m, and there is mechanical interaction between rock strata). The fracture process of single roof is relatively independent; there will be synergistic fracture effect between each rock stratum of composite roof [2, 18]. Referring to the "three zones" division of overburden to define spatial position: the roof within the caving zone and fracture zone, with a distance of no more than 60 m from the coal seam, is defined as near-field roof, and disasters are mainly manifested as direct disturbance; the roof within the bending subsidence zone, with a distance of more than 60 m from the coal seam, is defined as far-field roof, and disasters are mainly characterized by long-distance disturbance of stress waves.

3.1.1. Mechanism of fracture-induced disaster of single hard roof

As the key stratum of overburden, single roof will suffer sudden fracture when the overhanging area reaches the limit condition, releasing a large amount of elastic energy and forming dynamic load [19]. Based on the superposition theory of dynamic and static loads, Guo Li [20] constructed a mechanical model of rock burst induced by roof fracture, and derived the calculation formulas of

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average stress and dynamic load increment caused by roof fracture. Yu Bin et al. [21] established a refined calculation method for periodic fracture of thick hard roof based on Timoshenko variable-section tapered beam model, and found that the limit periodic weighting step distance and rock stratum trend coefficient satisfy the Lorentzian peak function relationship. The fracture of single roof is periodic, corresponding to the periodic weighting phenomenon of the working face, and the dynamic load coefficient of the stope will increase significantly.

3.1.2. Mechanism of collaborative fracture-induced disaster of composite hard roof

The core of disaster induced by composite roof comes from the collaborative fracture effect of multi-layer hard rock strata. Zheng Kaige et al. [2] observed that "large-small" periodic weighting phenomenon will appear in thick hard roof with composite key strata, and the acoustic emission frequency and microseismic energy during the weighting period are 5.3 times and 7.3 times of those in non-weighting period respectively. The synergistic fracture effect is reflected in three aspects: rock stratum fracture time coincides or is close, resulting in energy superposition; upper rock stratum fracture changes the mechanical boundary conditions of lower rock strata, forming a spatial linkage relationship; stress waves couple with each other during propagation, making dynamic load energy more easily transmitted to the stope area [18]. Li Yanjun [22] carried out analysis based on the engineering conditions of Nalinhe No.2 Coal Mine, and pointed out that the internal mechanical interaction relationship of composite hard roof is complex, so it is difficult to directly determine the main control stratum that should be treated by hydraulic fracturing. Guo Wenhao et al. [23] revealed the "step-by-step differentiation" periodic weighting characteristics of multi-layer thick roof, and measured the large cycle of 141.6 m, the medium cycle of 43.2~49.6 m, and the small cycle of 17.6~27.2 m.

3.1.3. Mechanism of dynamic-static load coupling disaster of near-field and far-field hard roof

Near-field roof takes direct disturbance as the main disaster-inducing form: the dynamic load generated by roof fracture directly acts on the stope, superimposes with the high static load inside the coal body, and then triggers impact disasters [24]. Far-field roof disasters are manifested as remote disturbance: rock stratum fracture forms strong mine tremors, and energy propagates outward through stress waves, which still retain strong destructive ability even when transmitted to the excavation space. Gao Mingshi et al. [25] established a mechanical model of seismic source layer fracture, and the results show that the energy released by the seismic source is positively correlated with mining height, fracture scale and fracture step distance, and negatively correlated with the buried depth of the seismic source layer. Near-far field coupling is an important disaster-inducing mode: periodic fracture of near-field rock strata generates conventional dynamic load, and far-field rock stratum fracture brings high-intensity dynamic load. When the two types of dynamic loads occur at similar times, energy superposition will occur [25].

3.2. Mechanism of rock burst induced by hard roof — three-element unified framework

Combined with the disaster-inducing characteristics of various types of roofs, the mechanism of rock burst induced by hard roof can be uniformly classified into the theoretical framework of dynamic-static load superposition. The occurrence of disasters requires three elements: static load accumulation, dynamic load excitation, and spatiotemporal coupling, which match each other in time and space (Figure 2).

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(1) Static load accumulation is the material basis for disaster occurrence. Hard roof rock mass has high strength and good integrity, which can efficiently transfer the overlying stratum load to the lower coal body, resulting in the increase of static load level inside the coal body. Under different roof conditions, the dominant factors controlling the magnitude of static load are different (Table 3).

(2) Dynamic load excitation is the trigger condition for disaster occurrence. Roof fracture is sudden, and dynamic load energy is released outward in the form of pulses. Single roof brings periodic pulse dynamic load; composite roof belongs to multi-source energy superposition, with larger dynamic load amplitude and more complex temporal changes; far-field roof is mainly manifested as remote disturbance.

(3) Spatiotemporal coupling is the critical condition for disaster occurrence. The existence of static load and dynamic load alone will not directly trigger rock burst. Only when the two are coupled in time and space will disasters occur. Near-far field coupling disaster is a typical case: far-field rock fracture outputs strong dynamic load, which may promote the early failure of near-field roof, forming a disaster amplification effect of "far-field trigger + near-field intensification" [25].

Table 3 compares the differences of the three elements among four types of roofs. From single near-field roof to composite far-field roof, the static load level rises from medium to high, the dynamic load amplitude increases synchronously, and the coupling risk continues to increase. The more complex the roof overburden structure and the higher the stratum position, the stronger the concealment of disaster-inducing behavior, and the more difficult the governance work will be accordingly.

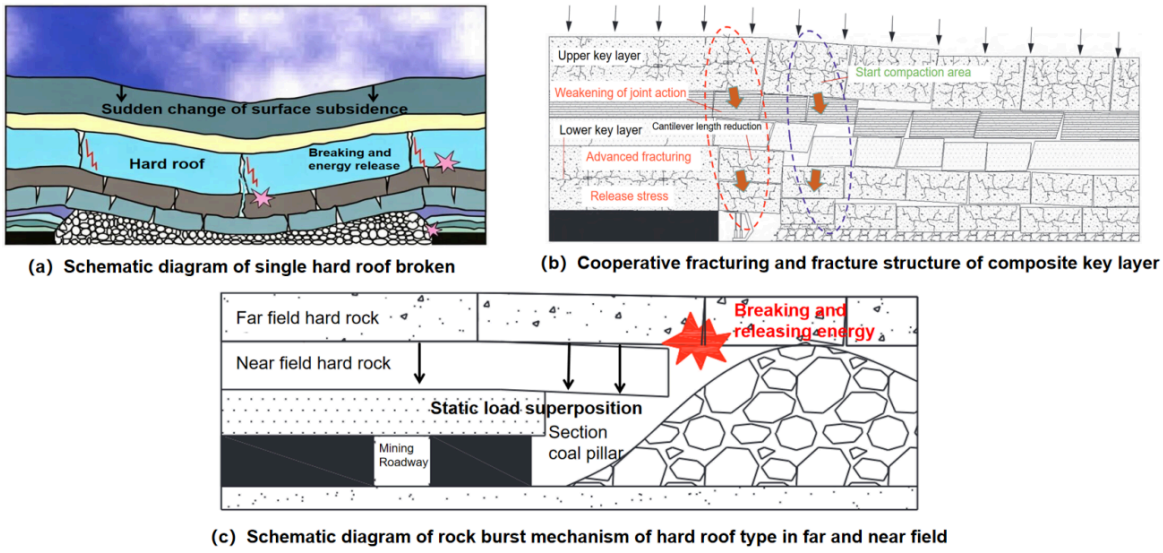


Figure 2. Schematic diagram of disaster-inducing mechanism of different types of hard roof fracture (a modified from reference [26], b [2], c modified from reference [1])

Table 3. Unified comparison of three disaster-inducing elements of different types of hard roofs

Comparison dimension	Single near-field roof	Single far-field roof	Composite near-field roof	Composite far-field roof
Static load level	Medium	Medium	High	High

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Table 3. (continued)

Dominant factor of static load	Advanced abutment pressure	Overall load of high-position overburden	Cumulative load transmitted by multi-layer collaboration	High-position load + multi-layer transmission
Dynamic load amplitude	Medium	Medium-high	High	High
Temporal characteristics of dynamic load	Obvious periodic weighting	Strong suddenness	"Large-small cycle" composite	Dominated by large cycle
Action range of dynamic load	Local stope	Large range	Stope and adjacent areas	Regional wide area
Coupling mode	Overlap of periodic weighting and high static load area	Remote wave reaches high static load area to trigger	Spatiotemporal superposition of collaborative fracture and multi-layer energy	Double superposition of far-field trigger + near-field intensification
Coupling risk	Medium	Medium-high	High	Extremely high
Early warning difficulty	Medium	High	Medium-high	High
Prevention and control target	Weakening of low-position roof	Fracturing of high-position area	Identification of main control stratum + collaborative fracturing	Three-dimensional collaboration above and below the mine

4. Hydraulic fracturing prevention and control technology system and core progress

The core idea of hydraulic fracturing to prevent and control rock burst is to carry out artificial transformation on the disaster force source of hard roof, so as to intervene the three disaster-inducing elements of static load accumulation, dynamic load excitation and spatiotemporal coupling mentioned above.

4.1. Mechanical principle and energy regulation mechanism of hydraulic fracturing for rock burst prevention

The reason why hydraulic fracturing can prevent and control rock burst is essentially to transform the original energy field of the stope, and the transformation process corresponds to the three disaster-inducing elements one by one.

(1) Regulating static load accumulation and reducing the energy storage level of rock mass. Hydraulic fracturing generates artificial fracture network inside the roof, cutting the complete thick roof into several small rock masses, realizing "turning long beams into short beams and large blocks into small blocks", and the overall stiffness and energy storage capacity of the roof decrease accordingly [27]. Existing measured data show that after fracturing treatment, the additional disturbance stress caused by overburden movement decreases by 76.0% compared with the unfractured condition, and the impact danger influence range is reduced by 47.8% [28].

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(2) Regulating dynamic load excitation and weakening the intensity of energy release. Artificial fractures act as pre-set weak structural planes, and the roof no longer suffers centralized sudden fracture, but gradually fails in a progressive manner. In terms of monitoring, it is manifested as high-frequency and low-energy microseismic events, and the number and released energy of large-energy mine tremor events are significantly reduced [29, 30].

(3) Intervening in spatiotemporal coupling and blocking the transmission path of dynamic load. The fracture network can change the propagation path of stress waves, and the fracture surface produces scattering and reflection effects on elastic waves. The dynamic load energy attenuates significantly after passing through the fracture zone [31], realizing the decoupling of near-field and far-field dynamic load effects. In summary, the essence of hydraulic fracturing prevention and control of rock burst is to complete the comprehensive energy regulation of "reducing static load - weakening dynamic load - blocking transmission path" by means of artificial fracture network.

4.2. Identification and selection of fracturing target strata

For single thick hard roof, the fracturing target stratum is relatively clear, and fracturing construction can be carried out directly on the main control key stratum. The situation is much more complicated under the condition of composite hard roof. The interlayer coupling effect interferes with judgment, and it is difficult to lock the main control stratum simply relying on engineering experience [22]. Zheng Kaige et al. [32] constructed a "geology-stress-energy" three-dimensional identification model, realizing quantitative discrimination of fracturing target strata.

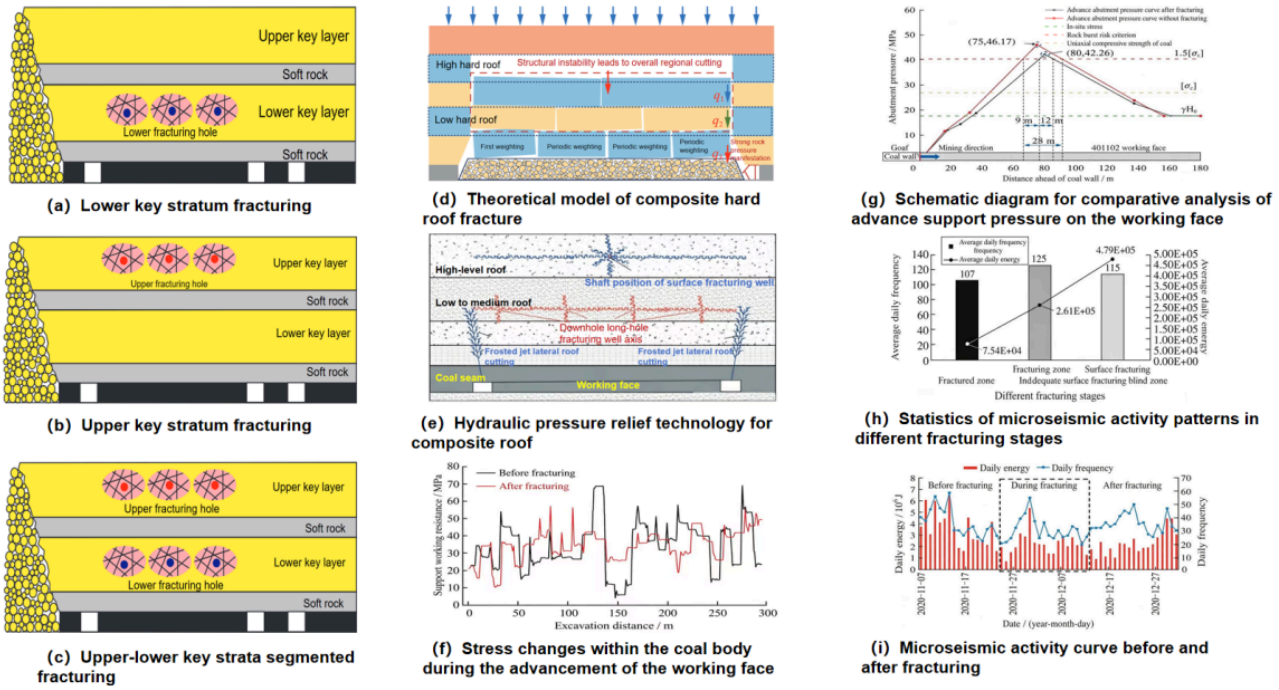


Figure 3. Comparison of overburden structure regulation and rock burst prevention effects under different fracturing modes (a, b, c modified from reference [2], d [22], e [33], f [34], g [28], h [29], i [34])

Combined with the discrimination results of main control strata, three types of fracturing modes can be divided [18, 32]: ① Lower key stratum fracturing mode, with simple construction process, but unable to suppress the large energy impact risk brought by upper key stratum; ② Upper key

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stratum fracturing mode, which directly acts on the highest main control key stratum, equivalent to controlling total energy release from the source; ③ Upper-lower key strata collaborative fracturing mode, which simultaneously controls total energy magnitude and energy release rhythm, is the optimal rock burst prevention means under composite roof conditions (Figure 3).

4.3. Key technologies of underground and surface hydraulic fracturing

According to the buried depth of target strata, hydraulic fracturing is divided into two technical routes: underground directional long-hole fracturing and surface horizontal well fracturing. Underground directional long-hole fracturing is mostly used for low-position roofs with buried depth ≤60 m; surface horizontal well fracturing mainly deals with high-position roofs with buried depth >60 m. The detailed comparison of the two types of technologies is shown in Table 4.

Underground directional long-hole hydraulic fracturing operation is carried out from underground roadways, with accurate target stratum positioning and controllable engineering cost. Zheng Kaige et al. [32] developed a variable-amplitude high-angle ultra-high drilling platform (drilling depth >1000 m) and low-speed large-flow fracturing pump unit, which greatly improved the coverage range and operation efficiency of underground long-hole fracturing.

Surface horizontal well hydraulic fracturing faces medium-high position roofs, and horizontal wells are arranged on the surface to implement staged fracturing, realizing large-scale advanced stratum weakening. Ma Yuzhen et al. [28] proposed the action mechanism of surface fracturing: the complete thick hard rock stratum is cut into multiple rock segments by fractures, and the rock stratum movement form changes from overall sudden fracture to rotation and slip. Wu Xueming [35] put forward the idea of collaborative fracturing above and below the mine: surface fracturing treats medium-position key strata, and underground fracturing treats low-position key strata, completing full-space prevention and control of overburden.

Table 4. Technical comparison between underground directional long-hole hydraulic fracturing and surface horizontal well hydraulic fracturing

Comparison dimension	Underground directional long-hole hydraulic fracturing	Surface horizontal well hydraulic fracturing
Target stratum	Low to medium position roof (usually ≤60 m)	Medium-high position roof (usually >60 m)
Construction site	Underground roadway	Surface
Borehole type	Directional long hole	Horizontal well ("L" type)
Fracturing scale	Staged fracturing, limited displacement	Regional volume fracturing, large displacement and large fluid volume
Fracture monitoring	Mainly underground microseism	Combined monitoring of surface microseism + underground microseism
Advantages	Accurate target, low cost, flexible construction	Wide coverage, little interference to production, regional advanced weakening
Limitations	Difficult to cover high-position roof, limited construction space	High cost, high requirements for stratum identification and fracturing design

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Table 4. (continued)

Applicable conditions	Low to medium position key stratum as the main control force source	High-position key stratum as the main control force source

5. Main problems faced by prevention and control of hard roof rock burst

At present, there are three disconnection problems in the prevention and control of hard roof rock burst: theoretical cognition, engineering implementation and effect evaluation, which are also the core obstacles restricting the prevention and control effect from effective to precise.

5.1. Theoretical level: lack of quantitative model for collaborative disaster induction of composite roof

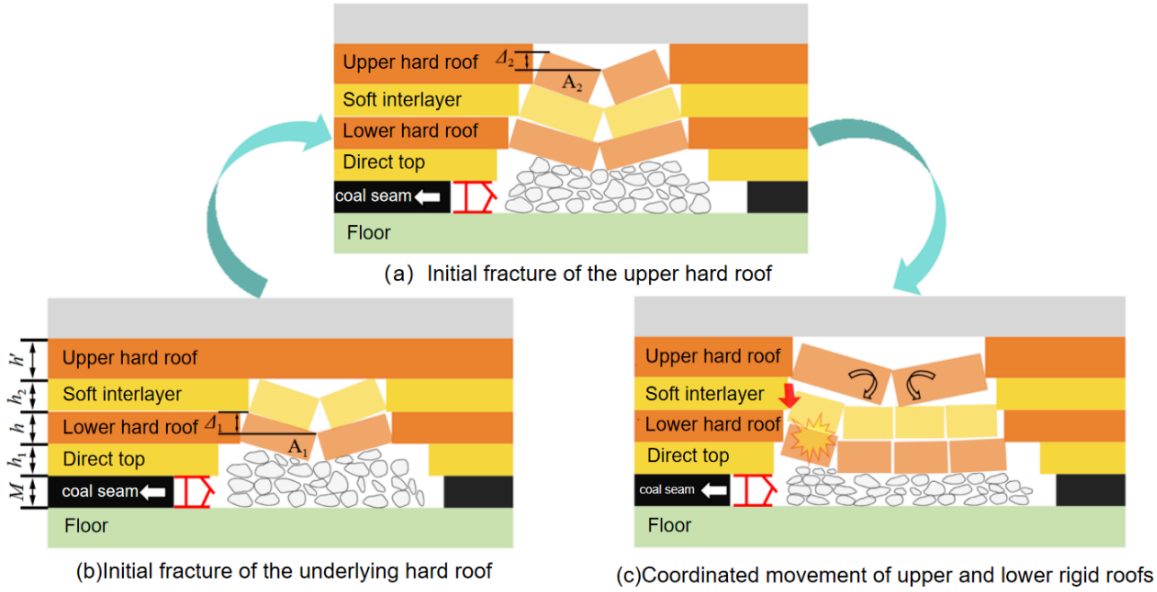


Figure 4. Three-stage evolution of composite hard roof fracture and migration under mining action [39]

The research on the mechanical model of single roof fracture is relatively mature, but the collaborative disaster-inducing mechanism under the multi-factor coupling condition of composite roof still lacks quantitative description. On the one hand, the critical criterion for multi-layer collaborative fracture of composite roof has not been established. Zheng Kaige et al. [2] revealed the "large-small" periodic weighting and collaborative fracture-induced disaster phenomenon of composite roof, but most existing achievements stay at the stage of phenomenon description, capturing energy anomalies through microseismic monitoring, and have not established quantitative critical conditions for collaborative fracture under different interlayer spacings and lithology combinations [36]. For example, when the spacing between upper and lower key strata makes the synergistic effect most significant, this problem directly affects the selection of main control strata at the engineering site. On the other hand, the research on disaster mechanism under the deep "three highs and one disturbance" environment is not sufficient. The stress environment of deep stope, the fragmentation characteristics of coal and rock mass, and the energy evolution law have all changed [37], and many existing mechanism achievements are based on shallow and medium-shallow

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conditions. At the same time, rock burst often coexists with disasters such as gas outburst and water inrush [38], and the disaster-inducing mechanism under the condition of multi-disaster coexistence needs further research (Figure 4).

5.2. Technical level: identification of main control strata and fracturing parameter design lack scientific basis

(1) The engineering discrimination of main control strata still relies on experience. The deep overburden conditions are complex. Within 100 m above the coal seam, sub-key strata and even some non-key strata may participate in disaster induction [40]. Simply equating key strata with disaster-inducing strata is easy to leave prevention and control blind areas. How to lock the really dominant disaster-inducing strata from multi-layer rock strata is still an engineering difficulty [33].

(2) Fracturing parameters are not finely matched with geological conditions. The lithology, in-situ stress and primary fracture development of different mining areas and different strata vary greatly, but fracturing parameters such as displacement, fluid volume and staged spacing are generally determined by empirical value and engineering analogy methods [41]. The nature of fracturing fluid plays a key role in fracture propagation. How to customize fracturing schemes according to the brittleness coefficient and mineral composition of target rock strata has not formed a complete technical system [41].

5.3. Evaluation level: rock burst prevention effect is difficult to quantitatively characterize and verify

(1) The real expansion morphology of fracturing fractures lacks efficient observation means. At present, monitoring methods are mainly indirect methods such as microseism, borehole leakage rate and transient electromagnetism [42]. The microseismic positioning error can reach tens of meters, while the fracture expansion scale is mostly meter-level. There is a large scale gap between the two, so it is difficult to restore the three-dimensional morphology of fractures. Borehole peeping can only obtain local section information, and cannot reflect the overall development characteristics of fracture network [41].

(2) There is a lack of quantitative correlation between indirect monitoring indicators and the reduction degree of rock burst risk. On site, the decrease of microseismic frequency energy and the shortening of periodic weighting step distance are often used as evaluation criteria [32], but there is no clear quantitative relationship between the change range of indicators and how much the impact risk is reduced and how long the effect can be maintained. For example, a 50% decrease in microseismic energy does not mean a synchronous 50% decrease in rock burst risk.

6. Conclusions and prospects

6.1. Conclusions

(1) Hard roof rock burst is a very prominent dynamic disaster in deep coal mining in China. The total number of rock burst mines in China is about 180, and more than half of the disasters are directly related to hard roof fracture. The Meng-Shaan mining area is widely developed with multi-key-stratum superimposed structures due to continental sedimentation, and the problem of composite roof collaborative disaster induction is particularly prominent.

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(2) The rock burst induced by hard roof can construct a three-element analysis framework based on the dynamic-static load superposition theory, namely static load accumulation (material basis), dynamic load excitation (trigger condition) and spatiotemporal coupling (critical condition). From single near-field roof to composite far-field roof, the disaster-inducing complexity and prevention and control difficulty increase step by step. The more complex the overburden structure and the higher the stratum position, the more systematic thinking the prevention and control scheme needs to have.

(3) Hydraulic fracturing prevention and control of rock burst completes the energy regulation of "reducing static load - weakening dynamic load - blocking transmission path" by means of artificial fracture network. At present, the core bottleneck of prevention and control work is reflected in the disconnection of three links: theory, engineering and effect evaluation: collaborative fracture of composite roof lacks quantitative criteria; fracturing parameters cannot be finely matched with geological conditions; fracture monitoring accuracy is insufficient. The three types of problems restrict each other and are the directions that need to be broken through in the follow-up.

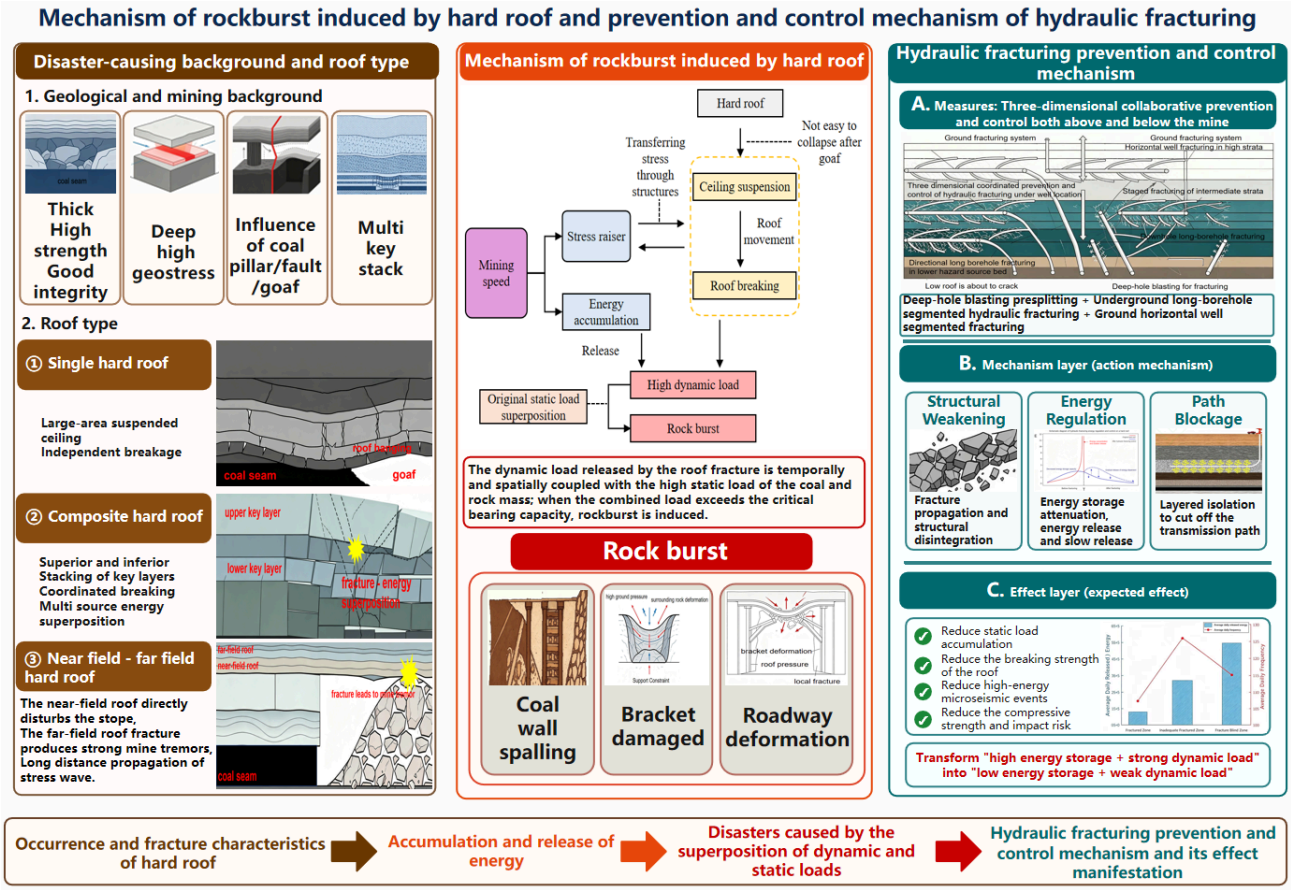


Figure 5. Discussion on mechanism of rock burst induced by hard roof and hydraulic fracturing prevention and control technology

6.2. Prospects

Future technological breakthroughs should not be limited to individual process improvement. We should promote the prevention and control mode from "experience-based rock burst prevention" to

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"science-based rock burst prevention", and advance collaboratively from three directions: monitoring and early warning, hydraulic fracturing technology and systematic governance.

(1) Monitoring and early warning shifts from passive recording of monitoring data to active identification of precursors. At present, the density of mine sensor layout is continuously increasing, and massive monitoring data are accumulated, but the proportion of effective information that can serve disaster early warning is not high. In the follow-up, it is necessary to develop intelligent identification algorithms embedded with mechanical constraints, integrate mechanical laws such as wave equation and stress balance into the deep learning model, and ensure that deduction results conforming to physical laws can still be obtained under the condition of sparse monitoring data; at the same time, carry out research on multi-physical field precursor fusion identification methods such as microseismic b-value, geophysical spectrum and stress field distortion.

(2) Hydraulic fracturing technology shifts from empirical analogy to closed-loop optimization. In fracturing engineering, "where to fracture, what scale to fracture, and how to construct" mostly rely on experience decision-making at this stage. We should establish a closed-loop work flow of "design-construction-monitoring-inversion-optimization", rely on digital twin technology to preview the effects of different fracturing schemes in a virtual environment, and dynamically adjust construction parameters combined with on-site measured data. At the same time, develop high-precision fracture monitoring means such as distributed optical fiber sensing and inter-hole electromagnetic wave CT to solve the practical problem that the fracturing effect is difficult to accurately characterize.

(3) Disaster governance shifts from single disaster governance to multi-disaster collaborative prevention and control. Under the deep mining condition of "three highs and one disturbance", rock burst often couples with disasters such as gas outburst, water inrush and spontaneous combustion. We should establish a technical path of "source identification - classified regulation - collaborative prevention and control", rely on unified geological and mechanical models to identify the common force sources and coupling nodes of various disasters, and develop governance schemes that can simultaneously suppress multiple dynamic disasters.

The Meng-Shaan mining area has prominent problems of composite roof disaster induction, which is not only a key area for disaster governance, but also can be used as a pilot test site for intelligent and precise rock burst prevention technology.

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