

Research and Application of Multi-dimensional Feasibility Evaluation Method for Protective Layer Decision-Making in Coal and Gas Outburst Seam Groups

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Abstract: Coal and gas outbursts are prone to triggering cascading disasters and rank among the most severe dynamic hazards in coal mines. Mining protective seams is a fundamental measure for achieving regional gas control. Based on the theory of mining-induced pressure relief and the effective mechanical criteria for protective seams, and following the logic of "necessary threshold–core constraints–practical selection," this study constructs a multi-dimensional feasibility evaluation method for protective seam selection in outburst coal seam groups, comprising "three levels and ten indicators." Taking a mine in Yangquan, Shanxi Province as the engineering background, the method is applied to conduct layer-by-layer evaluation and quantitative analysis of six potential protective seams: No.6, 8, 9, 12, 13 and 15. The results show that: (1) Seams No.6, 8 and 9 fail to meet the spatial position conditions and do not satisfy the requirements for protective seam selection. (2) Seams No.12 and 13 meet the theoretical feasibility but exhibit issues in safety feasibility, including discontinuous pressure relief and high disaster coupling risks, as well as constraints in technical-economic feasibility, such as high mining difficulty and poor economic viability. (3) Seam No.15 performs well across all dimensions and indicators and is identified as the preferred protective seam. This method successfully identifies the hidden risks of using thin and unminable seams as protective seams, addressing the limitations of traditional single-parameter verification, and can serve as a reference for scientific decision-making on protective seam selection in outburst coal seam groups under similar complex conditions.

Keywords: Coal and gas outburst; Protective layer selection; Multi-dimensional feasibility evaluation; Outburst-prone coal seam group; Pressure relief mining.

1. Introduction

Gas, primarily composed of methane and existing in adsorbed and free states within the pores and fractures of coal, is a by-product gas generated during the coalification of plant material [1]. During coal resource extraction, gas acts as a major disaster-causing factor; its abnormal emission frequently triggers various types of safety and production accidents, among which coal and gas outbursts represent one of the most destructive dynamic hazards [2,3]. A coal and gas outburst refers to the phenomenon in which the coal mass surrounding a mining or excavation face instantaneously loses stability under the coupled action of mining-induced stress and gas pressure, ejecting large quantities of coal, rock, and gas into the excavation space [4]. This hazard is characterized by strong suddenness, great destructive power, and a wide disaster-affected area, and it readily forms a disaster chain typically represented by "coal and gas outburst–gas explosion–dust explosion–asphyxiation," posing a serious threat to mine safety production and the lives of miners [5]. China is one of the countries most severely affected by coal and gas outburst disasters [6-8]. As shallow resources are gradually depleted, the depth of coal mining is extending at a rate of approximately 20m/year. Ground stress, gas pressure, and gas content are increasing significantly, structural complexity is intensifying year by year, the risk of coal and gas outbursts is escalating, and the difficulty of disaster prevention and control is progressively rising.

Regarding the prevention and control of coal and gas outbursts, decades of research and experience have led China

to gradually establish a disaster prevention technology system centered on "regional measures as primary, supplemented by local measures." The Detailed Rules for Prevention and Control of Coal and Gas Outbursts explicitly require that outburst-prone mines must adhere to the principle of "regional comprehensive outburst prevention measures first, supplemented by local comprehensive outburst prevention measures." Among various regional outburst prevention measures, mining protective seams is the most effective and fundamental approach [9]. Its mechanism is as follows: by preferentially mining a seam with no outburst risk or relatively low outburst risk, the combined action of the mining-induced stress field and fracture field causes the protected seam to undergo pressure relief, expansion deformation, and a substantial increase in permeability. Adsorbed gas is fully desorbed and migrates along fractures, after which it is extracted by the gas drainage system, thereby fundamentally eliminating the outburst risk of the protected seam [10-12].

In coal and gas outburst mines, coal seams predominantly occur in the form of coal seam groups. For multi-layered superimposed outburst coal seam groups, preferentially mining protective seams is the fundamental measure for achieving regional gas control. The selection of a protective seam is critically important, as it affects the mine's mining sequence, disaster prevention planning, production capacity targets, and even the safety and economic benefits over the entire life cycle of the mine [13]. However, protective seam selection involves multidisciplinary cross-cutting issues spanning mining engineering, safety technology and engineering, geological engineering, mine rock mechanics,

and fluid–solid coupling. It is not a simple process of parameter comparison but rather a complex decision-making process involving multiple constraints including safety, technology, economics, and spatiotemporal factors. Existing research has largely focused on single-parameter compliance checks represented by "protective vertical distance calculation and inter-seam spacing verification," lacking a systematic evaluation framework that can address the practical engineering demands of large numbers of coal seams with varying outburst risks and complex occurrence conditions. In particular, when thin seams at close range or unminable seams exist within a coal seam group, selecting them as protective seams often leads to a practical dilemma: theoretically feasible but engineering-infeasible. There is an urgent need to establish an evaluation method capable of considering multi-dimensional constraints [14]. Therefore, this study aims to construct a multi-dimensional feasibility evaluation method applicable to protective seam decision-making for outburst coal seam groups. Grounded in the theory of mining-induced pressure relief and the effective mechanical criteria for protective seams, and guided by disaster prevention and control as the core orientation, the method establishes a three-tier constraint framework of "theoretically feasible, safely feasible, and technically feasible," refines ten core indicators, and forms a progressively layered, quantitatively screened evaluation approach. Taking a mine in Yangquan, Shanxi Province as the engineering background, the method is applied to conduct layer-by-layer evaluation and quantitative analysis of multiple potential protective seams in the mine, verifying its scientific validity and practical applicability. The research findings can provide a theoretical basis and methodological reference for the scientific decision-making on protective seam selection in outburst coal seam groups under similar complex conditions.

2. Theoretical Basis of Protective Seam Mining

2.1. Mechanism of Mining-Induced Pressure Relief

Prior to protective seam mining, both the protective seam and the protected seam are in their in-situ stress state. For highly outburst-prone coal seams, the gas stored within them resides in primary fractures and pores, forming a relatively stable mechanical system with the coal-rock mass. During protective seam mining, influenced by the unloading–reloading effect induced by mining activities, the coal-rock mass within the mining influence zone undergoes progressive

failure: primary fractures open, secondary fractures continuously develop, and a caving zone, a fracture zone, and a bending subsidence zone gradually form above the protective seam, while a floor heave fracture zone forms below it. When the protected seam is located within the aforementioned fracture development zones, the following mechanical and seepage responses occur.

(1) Stress and elastic strain energy release: Stress decreases significantly and redistributes, with the coal mass transitioning from a triaxial stress state to a biaxial or uniaxial state. The stress reduction can reach 60%–80% of the original stress, accompanied by the instantaneous release of elastic strain energy stored in the coal mass.

(2) Dilatant deformation: Under mining-induced pressure relief, the coal mass expands in volume and progressively generates pressure-relief fractures. The permeability coefficient can increase by several hundred to several thousand times, providing channels for gas desorption and migration.

(3) Gas desorption–migration: Adsorbed gas is converted into free gas, and driven by the gas pressure gradient, it migrates along the newly formed fractures toward the gob of the protective seam, enabling effective drainage of the pressure-relieved gas.

2.2. Effective Mechanical Criteria for Protective Seams

According to elastoplastic mechanics and the evolution laws of mining-induced fractures, whether a protective seam can effectively protect the protected seam is governed by the following mechanical criteria:

(1) Spatial position condition: The protected seam must be located within the effective protective vertical distance of the protective seam. According to the Technical Specifications for Protective Seam Mining (AQ 1050-2008), the effective protective vertical distance is related to the mining thickness of the protective seam, mining depth, working face length, and inter-seam lithology:

$$S = S' \beta_1 \beta_2 \quad (1)$$

where: S' is the base protective vertical distance, related to mining depth and working face length. β_1 is the mining thickness influence coefficient: when $M \leq M_0$, $\beta_1 = M/M_0$; when $M > M_0$, $\beta_1 = 1$; where M_0 is the minimum effective thickness of the protective seam, selected according to Fig. 1. β_2 is the inter-seam hard rock content coefficient, where η denotes the percentage of hard rock in the inter-seam strata: when $\eta \geq 50\%$, $\beta_2 = 1 - 0.4\eta/100$; when $\eta < 50\%$, $\beta_2 = 1$.

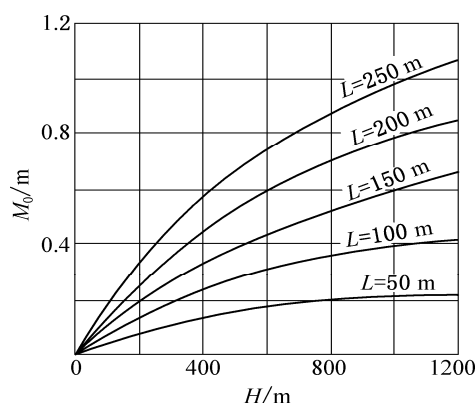


Figure 1. Relationship between the minimum effective thickness M_0 of a protective seam and mining depth H

(2) Integrity condition: The protective seam shall have good integrity and exhibit continuous and stable occurrence characteristics. When a seam with poor integrity or discontinuity is used as a protective seam, alternating zones of pressure relief and stress concentration will form in the protected seam. Excessive stress concentration not only fails to provide protection but instead intensifies the outburst risk. The core basis of this condition lies in the fact that the propagation of mining-induced pressure-relief fractures depends on continuous strata movement; the pinch-out points of the protective seam become blocking points for stress transmission, leading to a non-uniform stress field distribution in the protected seam.

(3) Minimum safe distance condition for lower protective seam: When mining a lower protective seam, it must be ensured that the overburden movement induced by mining does not damage the overall structure and mining conditions of the protected seam. When the actual inter-seam spacing exceeds H, the protected seam will undergo overall bending subsidence, with relatively few internal fractures developing, thereby weakening the protective effect.

3. Construction of Multi-Dimensional Feasibility Evaluation Method

Based on the aforementioned research, this study constructs a multi-dimensional feasibility evaluation method comprising three levels and ten core indicators. The framework follows a progressive logic of "necessary threshold → core constraints → practical selection," applying layer-by-layer screening to ensure the scientific validity and practical applicability of the evaluation results.

(1) Theoretical feasibility

Theoretical feasibility is a necessary condition for protective seam selection, primarily comprising three indicators: spatial position condition, integrity condition, and minimum safe distance. In the screening process of protective seams within a coal seam group, seams that fail to meet theoretical feasibility are directly excluded.

(2) Safety feasibility

Safety feasibility addresses the protective seam itself, mining-induced pressure relief, and disaster induction. It is the decisive factor in protective seam selection and encompasses three core indicators: inherent outburst risk, pressure relief uniformity, and disaster coupling risk.

(3) Technical-economic feasibility

In addition to theoretical and safety factors, the selection of a protective seam must also consider technical-economic feasibility. Technical-economic feasibility serves as the optimization condition for protective seam selection, comprising four core indicators: mining adaptability, system compatibility, economic rationality, and spatiotemporal matching.

4. Engineering Application

A coal mine in Yangquan, Shanxi Province, is a coal and gas outburst mine. The mineable coal seams are No.6, 8, 9 and 15, among which seams No.8, 9 and 15 all possess outburst hazards. In addition, seams No.12 and 13, with thicknesses less than 0.5 m, are also developed within the Taiyuan Formation. The mine is developed by inclined shafts, with mining carried out in two levels, and a designed production capacity of 1.2 Mt/a. The basic parameters of each coal seam are presented in Table 1.

Table 1. Basic parameters of Coal Seams in the Mine

Coal seam	Average thickness/m	Stability	Highlight the danger	Average spacing with Coal Seam 15#/m
6#	0.85	Locally recoverable	Absence	106.92
8#	0.94	Locally recoverable	Present	87.86
9#	1.74	Mostly recoverable	Present (Strongest)	75.17
12#	0.44	Unexploitable	Present	41.95
13#	0.45	Unexploitable	Present	28.26
15#	6.43	Entire recoverable area	Present (Weaker)	—

The following section employs the aforementioned multi-dimensional feasibility evaluation method to identify the optimal protective seam under the mining conditions of a coal seam group in a certain mine, through theoretical feasibility, safety feasibility, and techno-economic feasibility assessments.

4.1. Theoretical Feasibility Evaluation

According to the theoretical feasibility criteria, the spatial position condition, integrity condition, and minimum safety distance are evaluated respectively to ensure that the selected protective seam is theoretically feasible.

(1) When No.15 seam serves as the lower protective seam:

Spatial position condition analysis: When the No.15 seam is mined as the protective seam, the mining depth ranges from 230 to 430 m, with an average of 330 m. The working face length is $L = 180$ m, and the average mining thickness of the No.15 seam is $M = 6.43$ m. From Table 1, $S'_{lower} = 121$ m. According to Figure 1, $M_0 = 0.3$ m is taken. Since $M > M_0$, β_1

$= 1$ is adopted. The interburden between seams No.8, 9 and the No. 15 seam consists of mudstone, sandstone, and limestone, among which the cumulative thickness of sandstone and limestone is approximately 33 m, accounting for less than 50% of the total interburden, so $\beta_2 = 1$. Comparing with the spatial position condition, $S = 121$ m $>$ the actual spacing of 75.2~87.9 m. Therefore, the spatial position condition is satisfied.

Integrity condition analysis: The No. 15 seam is a fully mineable seam with stable occurrence, satisfying the integrity condition.

Minimum safety distance analysis: The minimum safety distance $H = KM \cos \alpha = 10 \times 6.43 \times \cos 5^\circ = 64$ m, which is less than the actual spacing. The minimum safety distance condition is satisfied.

(2) When seams No. 6, 8, 9 serve as the upper protective seams:

Spatial position condition analysis: Using the same calculation method as for the No.15 seam, the effective

protective vertical distances for seams No. 6, 8, 9 as upper protective seams are obtained as <50 m, 56 m, and 58.5 m, respectively. However, the actual spacings between these seams and the No.15 seam are 106.92 m, 87.86 m, and 75.17 m, respectively. The spatial position condition is not satisfied.

In summary, the options of mining seams No. 6, 8, 9 as upper protective seams are excluded.

(3) When seams No.12, 13 serve as the upper protective seams:

Spatial position condition analysis: After calculation, when the No.12 seam is mined as the upper protective seam, its effective protective vertical distance $S_{upper}=55.5$ m, which is greater than the inter-seam spacing of 41.95 m with the No.15 seam. When the No.13 seam is mined as the upper protective seam, its effective protective vertical distance $S_{upper}=50$ m, which is greater than the inter-seam spacing of 28.26 m with the No.15 seam. Therefore, seams No.12 and 13 satisfy the spatial position condition.

Integrity condition analysis: Although seams No.12 and 13 are non-mineable seams, their occurrence is relatively stable, satisfying the integrity condition.

Minimum safety distance analysis: When the No.12 seam is mined as the upper protective seam, the minimum safety distance $H = KM\cos\alpha = 10 \times 0.44 \times \cos 5^\circ = 4.38$ m, which is less than the actual spacing with the No.15 seam. When the No. 13 seam is mined as the upper protective seam, $H = KM\cos\alpha = 10 \times 0.45 \times \cos 5^\circ = 4.48$ m, which is also less than the actual spacing with the No.15 seam. Therefore, seams No.12 and 13 satisfy the minimum safety distance condition.

In summary, seams No.15, 12 and 13 pass the theoretical feasibility evaluation; seams No.6, 8 and 9 are excluded.

4.2. Safety Feasibility Evaluation

Safety feasibility evaluation when the No. 15 seam serves as the lower protective seam:

(1) Self-outburst hazard analysis: Among the mineable seams, the outburst hazard ranking is No.9 > No.8 > No.15. Outburst elimination can be achieved through in-seam gas pre-drainage and other methods, satisfying the condition.

(2) Pressure relief uniformity analysis: The No.15 seam is stably mineable throughout the entire area, with a continuous pressure relief range and no blind zones, satisfying the pressure relief uniformity condition.

(3) Disaster coupling risk: No significant disaster coupling exists, satisfying the condition.

Safety feasibility evaluation when seams No.12, 13 serve as the upper protective seams:

(1) Self-outburst hazard analysis: After assessment, seams No.12 and 13 are classified as outburst-hazardous seams. The inter-seam spacing is 6~13 m. According to Document Kuang An [2022] No.68, when mining either seam, both seams must adopt corresponding outburst prevention measures, resulting in large outburst prevention engineering volumes and complex procedures.

(2) Pressure relief uniformity analysis: Seams No.12 and 13 have large-scale pinch-out zones. In these pinch-out areas, protection cannot be formed, leading to alternating pressure relief zones and stress concentration zones in the underlying No.15 seam, which may aggravate the outburst hazard.

(3) Disaster coupling risk analysis:①The overlying K3 and K4 limestones contain large amounts of free gas (measured single-hole gas emission rate: 11.7~25.9 m³/min).

Mining disturbance may induce gas blowouts. ②The spacing between seams No.12 and 13 is only 6~13 m, locally less than 10 m. According to Document Kuang An [2022] No. 68, when mining either seam, the other seam must simultaneously adopt outburst prevention measures. ③A disaster coupling of "outburst-gas blowout- inter-seam disturbance" may form.

In summary, the No.15 seam has good safety feasibility. Seams No.12 and 13 have serious problems in both pressure relief uniformity and disaster coupling risk-two core indicators-resulting in insufficient safety feasibility.

4.3. Techno-Economic Feasibility Evaluation

Techno-economic feasibility evaluation when the No.15 seam serves as the lower protective seam:

(1) Mining adaptability analysis: With an average thickness of 6.43 m, the seam is suitable for fully mechanized top-coal caving (FMC), and the mining technology is mature.

(2) System compatibility analysis: The mine has already designed high-level gas drainage roadways and cross-seam borehole gas drainage systems, which can effectively intercept pressure-relief gas from the upper adjacent seams.

(3) Economic rationality analysis: Thick seam mining has low costs and high returns.

(4) Spatiotemporal matching: It fully matches the mine's existing development layout and can achieve the 28-month production target.

Techno-economic feasibility evaluation when seams No.12, 13 serve as the upper protective seams:

(1) Mining adaptability analysis: The average thickness of seams No.12 and 13 is less than 0.5m, far below the economic lower limit for fully mechanized mining (0.8m). Mechanized mining is difficult, and coal-gangue separation is problematic.

(2) System compatibility analysis: High-level gas drainage roadways are difficult to arrange in thin seam mining, resulting in poor gas drainage channels for pressure-relief gas.

(3) Economic rationality analysis: New equipment for thin seam mechanized mining must be procured, resulting in extremely high cost per ton of coal, low resource recovery, and poor economic performance.

(4) Spatiotemporal matching analysis: If seams No.12 and 13 are mined first, the existing development layout must be completely overhauled. Production of the No.15 seam would be delayed by several years, with enormous additional investment.

Based on the above techno-economic feasibility evaluation results, the No.15 seam demonstrates good techno-economic feasibility. Seams No.12 and 13 perform poorly across all four indicators and are techno-economically infeasible.

4.4. Comprehensive Evaluation Results

Based on the theoretical feasibility, safety feasibility, and techno-economic feasibility results obtained from the multi-dimensional feasibility evaluation method when seams No.6, 8, 9, 12, and 13 serve as upper protective seams and the No.15 seam serves as the lower protective seam, the comprehensive evaluation results for the protective seams of the mine are summarized in Table 2.

According to Table 2, the No.15 seam is the optimal protective seam for this mine and should be mined as the first-extraction seam.

Table 2. Comprehensive Evaluation Results for Protective Seam Optimization in the Mine

Candidate Protective Seam	Theoretical feasibility evaluation	Safety feasibility evaluation	Techno-economic feasibility evaluation	Comprehensive evaluation results
15#	√	√	√	First Choice
6、8、9#	×	—	—	Excluded
12、13#	√	×	×	Excluded

5. Conclusions

(1) Based on the pressure relief mechanism induced by mining and the mechanical criteria for effective protective seams, a multi-dimensional feasibility evaluation method for protective seam decision-making was established. This method encompasses three levels—theoretical feasibility, safety feasibility, and techno-economic feasibility—and ten core indicators: spatial position condition, integrity condition, minimum safety distance, self-outburst hazard, pressure relief uniformity, disaster coupling risk, mining adaptability, system compatibility, economic rationality, and spatiotemporal matching. This enables scientific decision-making for protective seam optimization in outburst coal seam groups.

(2) The proposed multi-dimensional feasibility evaluation method was applied to screen and quantitatively assess six potential protective seams in a certain mine. The results show that seams No.6, 8 and 9 do not satisfy the theoretical feasibility; seams No.12 and 13 do not satisfy safety feasibility and techno-economic feasibility; while the No.15 seam performs well across all indicators. The No.15 seam is identified as the sole feasible protective seam.

(3) The multi-dimensional feasibility evaluation method successfully identified the hidden risks of using seams No.12 and 13 as protective seams. Although the theoretical protective vertical distance of seams No.12 and 13 meets the requirements, their discontinuous occurrence leads to uneven pressure relief and exposes the mine to the multi-disaster coupling risk of "outburst-gas blowout-inter-seam disturbance." This method effectively identifies the hidden risks of thin and non-mineable seams as protective seams, compensating for the shortcomings of traditional single-parameter verification.

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