



OPEN Optimization and effectiveness assessment of hydraulic fracturing target layers using multi-source information fusion

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With the rapid increase in mining depth, geological hazards such as large deformation of surrounding rock and rock burst have become increasingly severe. As a result, hydraulic fracturing has become an essential technique for pressure relief in surrounding rock. However, the complexity of underground geological conditions renders the selection of fracturing horizons critical, as it directly determines the actual effectiveness of hydraulic fracturing operations. To address this, this study introduces the pressure arch theory to reveal the dynamic evolution characteristics of the overlying strata under mining influence, and constructs a comprehensive suitability evaluation system comprising six indicators: depth suitability, strength suitability, thickness suitability, in-situ stress concentration degree, fractability index, and engineering accessibility. Based on the key stratum theory, a comprehensive evaluation method combining the Analytic Hierarchy Process (AHP) and the entropy weight method is employed to determine the weight of each indicator, thereby establishing a multi-source information fusion model for optimal horizon selection. A hydraulic fracturing horizon optimization method based on multi-source information fusion and dynamic intelligent decision-making is proposed. Furthermore, based on the composite beam theory, the theoretical solution for the optimal fracture location within a layer is derived, clarifying the mechanical mechanism governed by the elastic modulus ratio of the upper and lower layers. The results indicate that the proposed horizon optimization method can effectively integrate multi-source information and accurately identify the optimal fracturing target horizon and location. During actual fracturing operations, the total energy of microseismic events was decreased significantly, with a 28.2% reduction in the number of high-energy events and a 34.6% decrease in average energy. The maximum working resistance of the support was reduced by 9.28%, and the average weighting interval was shortened by 28.75%, effectively reducing the frequency and intensity of hazards. The research findings provide scientific support for the optimal selection of hydraulic fracturing horizons and the prevention and control of rock burst in deep mining.

Keywords Hydraulic fracturing layer selection optimization, Multi-source information fusion, Rock burst prevention and control, Pressure arch theory, Composite beam theory

Rockburst is among the most catastrophic dynamic hazards encountered in deep coal mining, and the efficacy of its prevention and control technologies is directly critical to the safe production and economic performance of coal mines^{1–3}. With the continuous increase in mining depth and intensity, the overburden structure and in-situ stress field have become increasingly complex, presenting significant challenges for rock burst prediction and prevention^{4,5}.

Hydraulic fracturing can effectively modify the overburden structure, transfer high-stress concentration zones, and reduce ground pressure by pre-weakening key strata, and represents an effective measure for rock burst prevention and control^{6,7}. However, the pressure relief effect of hydraulic fracturing largely depends on the

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accuracy of target horizon selection, underscoring the critical importance of rational target horizon selection. At present, commonly used auxiliary decision-making methods include engineering experience-based analogy⁸ and empirical formulas for the height of the water-conducting fracture zone based on mining-induced fracture development⁹. Although these methods have achieved positive effects in engineering practice, most studies remain focused on the static identification of key strata. For instance, target horizon selection mainly relies on key stratum theory, which is limited by its over-reliance on single-factor indicators^{10,11}. These approaches fail to capture the coupled effects of multidimensional factors and are inadequate for complex geological conditions. In addition, the decision-making process relies heavily on the experience of technical personnel, lacking unified quantitative scientific criteria. This compromises the objectivity and generalizability of the results. Consequently, the development of a multi-source information fusion and quantitative decision-making method is essential for the effective prevention and control of rock burst.

In recent years, the application of multi-factor coupling analysis in strata control has provided new insights into addressing the above problems. Li et al. established a multi-factor coupling analysis framework incorporating coal-rock structure disaster-causing factors and used FLAC3D to simulate the mining responses of deep double-goaf and isolated island working faces, providing an important method for rock burst mechanism analysis and regional prediction¹². Dou et al. systematically classified static and dynamic sources of rockburst hazards and comprehensively adopted in-situ stress field inversion, mining tremor-based key stratum identification, and other methods to reveal the multi-source synergistic failure mechanism of rock burst¹³. Ma et al. focused on the high-stress relief problem of roadways under strong mining disturbance and clarified through model tests and numerical simulation how hydraulic fracturing weakens the overburden pressure arch structure and changes the high-stress transfer path¹⁴. Jia et al. aimed at the difficulty of support optimization for roadways traversing collapse columns and proposed a combined weighting evaluation method integrating AHP and entropy weight, establishing a multi-dimensional techno-economic indicator system and realizing quantitative comprehensive optimization of support schemes¹⁵. The above studies have provided important support for rock burst prevention and hydraulic fracturing horizon determination. Nevertheless, existing analyses still fail to systematically cover rockburst influencing factors under various mining conditions and lack a unified theoretical framework. Moreover, the selection of hydraulic fracturing horizons remains overly dependent on engineering experience, and the objective evaluation system is still incomplete.

Against this background, this study introduces pressure arch theory to reveal the dynamic equilibrium mechanism of mining-disturbed overburden structures, establishes a comprehensive suitability quantitative evaluation indicator system, and proposes a hydraulic fracturing horizon optimization method based on multi-source information fusion. Using key stratum theory as the theoretical basis and adopting a combined AHP-entropy weight method, this study realizes multi-factor fusion decision-making for horizon optimization, providing a scientific basis for target horizon selection.

Decision-making method based on multi-source information fusion

The selection of optimal hydraulic fracturing target horizons and the determination of their specific positions involve multiple factors and complex mechanical mechanisms. Thus, establishing to establish a comprehensive technical framework incorporating data acquisition, dynamic analysis, and quantitative decision-making through the deep integration of multi-source information and the innovative application of mechanical models.

Determination of the comprehensive suitability indicators based on multi-source information fusion

Based on mechanical principles and the key stratum theory, this paper constructs a six-dimensional evaluation indicator system. The design for optimizing fracturing horizons and locations is achieved by combining the coupled Analytic Hierarchy Process (AHP)-Entropy Weight method to determine indicator weights. Figure 1 shows the flowchart of the framework described above.

The constructed comprehensive suitability evaluation system comprises six key indicators: depth suitability, strength suitability, thickness suitability, in-situ stress concentration degree, fractability index, and engineering accessibility. These indicators are proposed based on fundamental theories such as the dynamic overburden spatial structure theory, rock mechanics, and rock burst prevention and control theory. They encompass critical geomechanical properties and engineering implementation constraints, forming unified and objective decision-making criteria through multi-source information fusion and quantitative analysis.

1. Core indicator for targeting pressure-relief locations: depth suitability (S_{depth}).

As illustrated in Fig. 2, coal seam extraction induces the collapse of overlying strata above the goaf, accompanied by a complex stress redistribution process. This process exhibits a highly nonlinear dynamic evolution. To facilitate quantitative analysis, it is simplified into a pressure arch mechanical model, which is then solved using mechanical theory^{16,17}, as shown in Fig. 3.

The reaction forces at supports A and B, R_A and R_B , are resolved into their horizontal (H) and vertical (V) components. Here, f denotes the rise of the arch. The parameters l , l_1 and l_2 represent the arch length (equivalent to the span or width of the goaf, which is taken as the length of the first main roof weighting interval), the vertical distance C_A and the vertical distance C_B , respectively. K denotes an arbitrary cross-section, with x_k and y_k being the coordinates of the arch at that section. The symbol q represents the uniformly distributed load.

The simplified model characterizes the overlying strata above the goaf as a mechanically optimal arch axis. The parabolic equation for this optimal arch axis is established as follows:

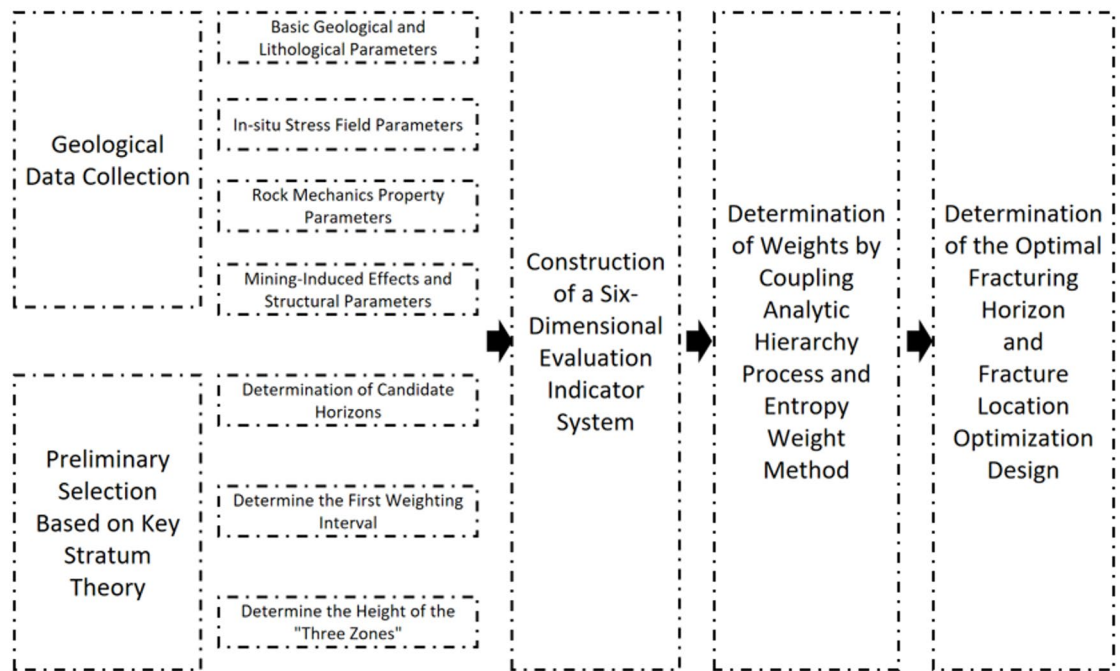


Fig. 1. Method for optimal layer selection in hydraulic fracturing based on multi-source information fusion.

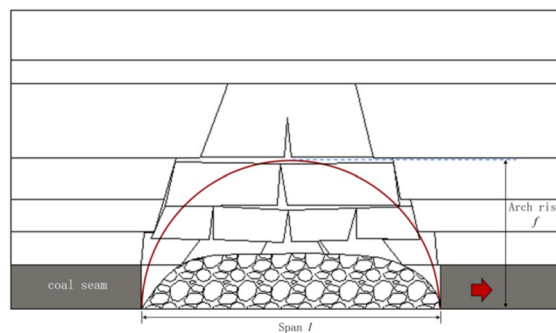


Fig. 2. Schematic diagram of the initial caving of the overlying roof in a horizontal working face.

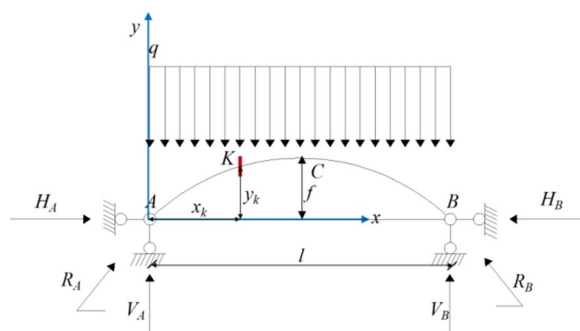


Fig. 3. Mechanical model of the pressure arch under uniformly distributed load.

$$y = \frac{4f}{l^2} x(l - x) \quad (1)$$

The bending moment distribution $M(x)$ within the arch is proportional to the deviation $\delta(x)$ of its axis $y(x)$ from the optimal arch axis, i.e., $M(x) \propto \delta(x)$. The cross-section corresponding to the maximum bending moment is identified by analyzing the variation in the tangent angle along the arch axis. For the parabolic arch defined by Eq. (1), the maximum bending moment occurs near the cross-section where the angle θ between the arch axis tangent and the horizontal direction is approximately 45° .

Differentiating the optimal arch axis equation (Eq. (1)) yields the slope of the arch axis tangent as follows:

$$\tan\theta = \frac{dy}{dx} = \frac{4f}{l^2} (l - 2x) \quad (2)$$

Setting $\tan\theta = 1$, we have:

$$x = \frac{l}{2} - \frac{l^2}{8f} \approx 0.25l \quad (3)$$

By substituting Eq. (3) into Eq. (1), the corresponding vertical coordinate is obtained as $y \approx 0.75f$. Therefore, the position at 0.75 times the arch height ($0.75f$) represents the critical cross-section where the bending moment is maximized. From a mechanics perspective, this position is optimal for hydraulic fracturing because: (1) the maximum bending moment corresponds to the peak tensile stress zone in the upper portion of the arch, where fractures are most likely to initiate and propagate; (2) creating a fracture at this location maximally disrupts the load transfer path within the pressure arch, effectively converting the coherent arch structure into a discontinuous medium and thereby eliminating its stress-carrying capacity; (3) the $0.75f$ position is sufficiently far from the abutments (supports A and B) to avoid stress concentration zones near the coal seam, while being close enough to the arch apex to ensure that the induced fracture spans the entire tensile zone. Consequently, fracturing at $0.75f$ achieves the most efficient weakening of the overburden structure with minimal energy input. To quantify the proximity of a candidate fracturing horizon to this theoretically optimal position, the depth suitability indicator, S_{depth} , is defined.

To reasonably characterize the nonlinear relationship between this proximity and suitability, a membership function based on a linearized Gaussian function is constructed:

$$f(x) = \max \left(0, \min \left(1, e^{-\frac{(x-0.75f)^2}{2\sigma^2}} \times \left(1 - \alpha \cdot \frac{|x - 0.75f|}{L} \right) \right) \right) \quad (4)$$

In the formula: x is the vertical distance from the coal seam roof to the candidate key stratum, in meters (m). f is the arch height, in meters (m), which can be calculated according to the Specification for Coal Pillar Retention and Under-Seam Mining under Buildings, Water Bodies, Railways, and Main Shafts and Roadways (State Administration of Work Safety, Coal Administration Document [2017] No. 66). σ is a shape parameter controlling the decay rate of the function. α is a linearization adjustment coefficient. L is the reference value for the maximum influence distance, in meters (m), taken as the initial caving interval of the hard roof.

This function satisfies the following properties: when $x = 0.75f$, $S_{depth} = 1$; as x deviates from the target position, the function value smoothly decreases to 0. Based on data from multiple practical engineering cases, mostly falls within the range of 10–80 m. Hence, considering diverse sample data, the relevant parameters in Eq. (4) are assigned the values, $\sigma = 60$, $\alpha = 0.3$. To assess the robustness of these parameter selections, a sensitivity analysis was conducted. Table 2 presents the suitability scores for candidate layers under different parameter combinations ($\sigma = 40, 60, 80$; $\alpha = 0.1, 0.3, 0.5$). The results show that the ranking of candidate layers remains stable across the tested parameter ranges, with Layer 25 consistently obtaining the highest score. This demonstrates that the parameter selection is robust and the model is not sensitive to minor variations in σ and α .

The parameters were calibrated using data from multiple practical engineering cases in Xinjiang, Shandong, and Shanxi mining areas, where the arch height f mostly falls within 10–80 m. The value $\sigma = 60$ was chosen to ensure that the Gaussian decay covers the full range of practical arch heights while maintaining discriminative power. The linearization coefficient $\alpha = 0.3$ was selected to balance the nonlinear Gaussian decay with linear behavior at large deviations, preventing excessive penalty on layers moderately distant from the optimal position.

2. Structural Control Importance Assessment Based on Rock Mass Inherent Properties: Strength Suitability ($S_{strength}$) and Thickness Suitability ($S_{thickness}$).

The optimization of target horizons for hydraulic fracturing requires, on the basis of identifying key strata, distinguishing the relative control strength of different key strata over the stability of the overlying strata structure in the stope. The inherent strength property of the rock mass determines its energy storage capacity and potential burst risk^{18,19}, while the inherent thickness property governs its stiffness as a load-bearing structure and its sphere of influence²⁰. Therefore, strength suitability ($S_{strength}$) and thickness suitability indicators ($S_{thickness}$) are constructed from the energy and structural dimensions, respectively.

Strength Suitability ($S_{strength}$): An indicator used to evaluate the relative importance of a rock stratum as a high-energy storage carrier. A rock stratum with higher uniaxial compressive strength accumulates greater elastic strain energy, which corresponds to a higher potential risk of rock burst induced by its fracture. Consequently,

a higher score for this indicator indicates greater importance in mitigating high-energy risks at the source and achieving proactive pressure relief.

Thickness Suitability ($S_{thickness}$): An indicator used to measure the relative influence of a key stratum as a dominant structural element. A thicker rock stratum has greater structural stiffness, controls a wider range of overlying strata, exhibits a longer fracture interval, and exerts a more significant controlling effect on ground pressure manifestations. Consequently, a higher score for this indicator indicates a better expected effectiveness of fracturing this horizon in weakening the overall overburden structure and controlling weighting intensity.

To enhance the objectivity of the assessment, a standardization model is adopted in this paper to quantify the two inherent properties mentioned above. Given the limited number of candidate key strata, the use of Min-Max normalization could lead to extreme scores due to the small sample size. Consequently, a standardization method based on the Z-score and the *Sigmoid* function is introduced to smoothly characterize the relative distribution of small-sample data within a finite interval.

Assuming there are n candidate key strata, with the uniaxial compressive strength series $\{Rc^1, Rc^2, \dots, Rc^n\}$ and the thickness series $\{h^1, h^2, \dots, h^n\}$, for any attribute series $\{X_i\}$, its suitability is calculated according to the following steps:

- (1) Calculation of Sequence Statistical Characteristics: The mean (μ) and standard deviation (σ) of the attribute sequence are computed.

$$\mu = \frac{1}{n} \sum_{i=1}^n X_i \quad (5)$$

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n (X_i - \mu)^2} \quad (6)$$

- (2) Calculation of the Standardized Z-score: For each observation value X_i in the sequence, its Z-score is calculated.

$$z_i = \frac{X_i - \mu}{\sigma} \quad (7)$$

- (3) Map the Z-scores to the (0, 1) interval using the *Sigmoid* function to calculate the suitability score:

$$S_i = \frac{1}{1 + e^{-z_i}} \quad (8)$$

3. Characterization Index for Inhomogeneity of the In-situ Stress Field: In-situ Stress Concentration Degree Suitability (S_{stress}).

Within the engineering context of deep coal seam mining, the non-uniform distribution of the in-situ stress field is one of the fundamental causes contributing to the potential occurrence of rock burst [21]. Based on this, the in-situ stress concentration degree suitability (S_{stress}) indicator is constructed. It characterizes the relative hazard level of different key strata within the original in-situ stress field, aiming to further select strata with higher in-situ stress magnitudes.

To achieve a scientific mapping from measured in-situ stress values to standardized scores, a standardization scheme combining linear transformation and a logistic function is adopted. This approach preserves the linear trend of the data while smoothly constraining the output within the (0, 1) interval via an S-shaped function, thereby preventing abrupt changes at boundary values.

The specific quantitative model is as follows: Let the value range of the measured in-situ stress be $[x_{min}, x_{max}]$. First, the original in-situ stress observation value x is mapped to the interval $[-6, 6]$ through linear transformation:

$$x_{scaled} = -6 + \frac{12 \times (x - x_{min})}{x_{max} - x_{min}} \quad (9)$$

Applying a logistic function for S-shaped transformation yields the in-situ stress concentration degree score:

$$S_{stress} = \frac{1}{1 + e^{-k(x_{scaled} - c)}} \quad (10)$$

Among them, the parameter $k = \frac{12}{x_{max} - x_{min}}$ is used to control the slope of the function.

4. Assessment Index for Rock Mechanical Behavior Tendency: Fractability Index ($S_{fracability}$).

The mechanical properties of the rock are also key factors influencing fracturing operations and the expected outcomes. Hence, this paper introduces the Fractability Index ($S_{fractability}$), the theoretical basis of which is the brittleness characteristic of rock [22, 23].

To quantitatively characterize this property, the following classic calculation formula is adopted:

$$BC = \frac{R_C - \sigma_t}{R_C + \sigma_t} \quad (11)$$

In the formula, BC represents the Brittleness Index of the rock, R_C is the Uniaxial Compressive Strength, and σ_t is the Tensile Strength. The Fractability Index, ranging within the interval [0,1], is obtained through linear normalization. Higher values of this index correspond to better fractability of the target rock layer.

5. Engineering Implementation Constraint Assessment Indicator: Engineering Accessibility ($S_{accessibility}$).

The accessibility indicator ($S_{accessibility}$) is constructed with the core objective of quantifying the spatial constraints between the construction location and the target horizon, thereby incorporating the difficulty level and economic costs of drilling engineering into the decision-making framework.

This indicator takes the vertical drilling distance (D) as its core parameter, as D directly affects the borehole length, construction duration, technical risks, and overall costs. The following evaluation function is established:

$$S_{accessibility} = 1 - \frac{D}{D_{max}} \quad (12)$$

where, in the formula, D is the actual vertical construction distance, and $D_{max} = \max(D_1, D_2, \dots, D_n)$. This function is monotonically decreasing, which reasonably reflects the linear negative impact of increasing construction distance on accessibility, consistent with practical engineering understanding.

The above six indicators were selected through a systematic process combining mechanical principles, key stratum theory, and literature mining. Depth suitability targets the pressure arch apex for optimal stress relief; strength and thickness suitability characterize the structural control importance of key strata; in-situ stress concentration identifies high-energy zones; fractability index assesses rock mechanical behavior; and engineering accessibility ensures operational feasibility. This selection covers the essential geological, mechanical, and engineering constraints for hydraulic fracturing optimization.

Notably, permeability and porosity are not included as primary indicators in this system. The rationale is that hydraulic fracturing in hard rock mining primarily targets the mechanical breaking of thick and strong roof strata for pressure relief rather than permeability enhancement for fluid extraction. The fracturing effectiveness in this context is governed by mechanical properties (strength, elastic modulus, brittleness) rather than reservoir characteristics. Similarly, the distance to aquifers or other hazardous strata is treated as a hard constraint rather than an optimization indicator. Specifically, candidate horizons must satisfy safety regulations mandating minimum distances to aquifers, gas-bearing strata, and fault zones before entering the multi-criteria evaluation. This pre-screening ensures that safety constraints are strictly enforced independently of the optimization scoring process.

Evaluation model for layer determination based on analytic hierarchy process

To scientifically determine the target layer for hydraulic fracturing, it is necessary to quantify the importance of each evaluation indicator. This paper adopts a comprehensive evaluation method based on combined weighting, integrating the Analytic Hierarchy Process (AHP) and the Entropy Weight Method [24–28]. This approach converts expert experience into quantitative judgments by constructing a judgment matrix, while leveraging data properties to realize automatic weighting, thereby coupling the weights obtained from the two methods to derive a comprehensive weight. This ensures the objectivity and consistency of the weight distribution.

Using the six sub-indicators constructed in the previous section as the criteria layer—namely, Depth Suitability (S_{depth}), Strength Suitability ($S_{strength}$), Thickness Suitability ($S_{thickness}$), In-situ Stress Concentration Degree (S_{stress}), Fractability Index ($S_{fractability}$), and Engineering Accessibility ($S_{accessibility}$)—experts are invited to conduct pairwise comparisons of these indicators based on the “1–9 scale” method, and a judgment matrix A is constructed as follows:

$$\begin{bmatrix} 1 & 3/2 & 3/2 & 3/2 & 2 & 2 \\ 2/3 & 1 & 1 & 1 & 4/3 & 4/3 \\ 2/3 & 1 & 1 & 1 & 4/3 & 4/3 \\ 2/3 & 1 & 1 & 1 & 4/3 & 4/3 \\ 1/2 & 3/4 & 3/4 & 3/4 & 1 & 1 \\ 1/2 & 3/4 & 3/4 & 3/4 & 1 & 1 \end{bmatrix}$$

After calculation, the maximum eigenvalue of the judgment matrix is $\lambda_{max} = 6$, and the corresponding eigenvector is:

$$W_j^1 = [0.2609, 0.1790, 0.1790, 0.1790, 0.1006, 0.1006]^T \quad (13)$$

Consistency Check: $RI(6) = 1.24$, $CI = (\lambda_{max} - n) / (n - 1) = 0$, $CR = 0 < 0.1$, which passes the consistency check. Consequently, the weight of each factor corresponds to the value of the eigenvector.

Stratum No.	Lithology	S_depth	S_strength	S_thickness	S_stress	S_fracability	S_accessibility
12	Coarse-grained sandstone	0.01	0.27	0.72	0.26	0.89	0
15	Fine-grained sandstone	0.35	0.73	0.26	0.51	0.90	0.41
25	Fine-grained sandstone	0.93	0.73	0.53	0.74	0.90	0.80

Table 1. Suitability assessment of candidate hydraulic fracturing layers.

No.	Lithology	Actual thickness (m)	Bulk density (KN/m ³)	Tensile strength (MPa)	Elastic modulus (MPa)	Remarks
1	Loess	2	16.41	0.35	1850	–
2	Fine-grained sandstone	4.92	25.92	6.12	33,420	–
3	Siltstone	19.79	24.47	6.89	40,350	–
4	Mudstone	33.98	25.24	2.54	14,690	–
5	Fine-grained sandstone	6.6	25.92	6.12	33,420	–
6	Medium-grained sandstone	6.63	26.15	5.715	36,570	–
7	Mudstone	27.38	25.24	2.54	14,690	–
8	Coarse-grained sandstone	12.27	26.38	5.31	39,720	–
9	Mudstone	65.28	25.24	2.54	14,690	–
10	Fine-grained sandstone	7.02	25.92	6.12	33,420	–
11	Mudstone	39.66	25.24	2.54	14,690	–
12	Coarse-grained sandstone	35.37	26.38	5.31	39,720	Main key stratum
13	Medium-grained sandstone	4.19	26.15	5.715	36,570	–
14	Mudstone	40.14	25.24	2.54	14,690	–
15	Fine-grained sandstone	13.15	25.92	6.12	33,420	Sub-key stratum 2
16	Mudstone	22.12	25.24	2.54	14,690	–
17	Siltstone	4.23	24.47	6.89	40,350	–
18	Mudstone	5.18	25.24	2.54	14,690	–
19	Fine-grained sandstone	4.42	25.92	6.12	33,420	–
20	Mudstone	4.02	25.24	2.54	14,690	–
21	B4-1 coal seam	3	13.03	2.02	7485	–
22	Mudstone	7.99	25.24	2.54	14,690	–
23	Fine-grained sandstone	5.29	25.92	6.12	33,420	–
24	Siltstone	8.51	24.47	6.89	40,350	–
25	Fine-grained sandstone	26.1	25.92	5.92	34,420	Sub-key stratum 1
26	Mudstone	2.84	25.24	2.54	14,690	–
27	B2 coal seam	9.5	16.4	2.15	4923	

Table 2. Table of coal and rock lithology characteristics.

Entropy weight solution based on the entropy weight method

The Entropy Weight Method is based on information entropy theory, which automatically determines weights according to the degree of dispersion in the indicator data. To demonstrate the calculation process of entropy weight, this paper takes the engineering case data from a mine in Xinjiang as an example (see “Study on the optimization of fracture location within hydraulic fracturing layers based on composite beam theory” for details). The standardized score data of the three candidate key horizons across various indicators are shown in Table 1.

According to the principle of the Entropy Weight Method, based on the data in Table 2, there are $m=3$ evaluation objects (candidate horizons) and $n=6$ evaluation indicators. An evaluation matrix $[b_{ij}]$ is constructed. Since the data in Table 2 are already scores of the same trend (all with higher values being better) and dimensionless, they can be approximately considered as normalized. Thus, the data in the table are directly used as the elements, where i represents the i -th evaluation object ($i=1, 2, 3$, corresponding to rock layers 12, 15, 26) and j represents the j -th evaluation indicator ($j=1, \dots, 6$, corresponding to the six indicators). Thus, the evaluation matrix $B=[b_{ij}]$ is as follows:

$$\begin{bmatrix} 0.01 & 0.27 & 0.72 & 0.26 & 0.89 & 0 \\ 0.35 & 0.73 & 0.26 & 0.51 & 0.90 & 0.41 \\ 0.93 & 0.73 & 0.53 & 0.74 & 0.90 & 0.80 \end{bmatrix}$$

Based on the evaluation matrix B, calculate the proportion f_{ij} of the j -th evaluation item under the i -th evaluation indicator, where $f_{ij} = b_{ij} / \sum_{i=1}^m b_{ij}$. It is evident that when $f_{ij} = 0$, $b_{ij} = 0$, $\ln f_{ij}$ becomes meaningless. Accordingly, the calculation of f_{ij} is adjusted and defined as:

$$f_{ij} = (1 + b_{ij}) / \sum_{i=1}^m (1 + b_{ij}) \quad (14)$$

Combined with the aforementioned equation and matrix B, the matrix $C = [f_{ij}]$ composed of f_{ij} can be calculated:

$$\begin{bmatrix} 0.2354 & 0.2685 & 0.3958 & 0.2664 & 0.3305 & 0.2500 \\ 0.3147 & 0.3658 & 0.2813 & 0.3080 & 0.3333 & 0.3393 \\ 0.4499 & 0.3658 & 0.3229 & 0.4255 & 0.3362 & 0.4107 \end{bmatrix}$$

Based on the normalized matrix C, the information entropy is solved using the formula:

$$H_j = - \left(\sum_{i=1}^m f_{ij} \ln f_{ij} \right) / \ln m \quad (15)$$

Using the derived equation and matrix C, the corresponding vector of information entropy is calculated as:

$$H_j = [0.9681, 0.9971, 0.9942, 0.9912, 1.0000, 0.9876]^T$$

Finally, based on the obtained information entropy values above, the entropy weight for the corresponding evaluation indicator is calculated as: W_j^2

$$W_j^2 = (1 - H_j) / (n - \sum_{j=1}^n H_j) \quad (16)$$

Consequently, the vector of entropy weights for the six evaluation indicators is:

$$W_j^2 = [0.5162, 0.0469, 0.0939, 0.1424, 0.0000, 0.2006]^T$$

(The equation $W_5^2 = 0$ indicates that the dispersion of the data for that particular indicator is extremely low, failing to provide effective discriminative information.)

The zero entropy weight for S_fracability arises from the small sample size ($n=3$ candidate horizons), which is an inherent limitation of the specific engineering case rather than a methodological flaw. In entropy weight analysis, when all samples have nearly identical values for an indicator, the entropy reaches its maximum and the calculated weight approaches zero. However, this does not imply that fractability is unimportant for horizon selection. On the contrary, rock brittleness and fractability are well-established mechanical factors influencing hydraulic fracturing effectiveness. The AHP subjective weight ($w_5\text{-AHP}=0.1006$) appropriately captures the expert judgment on the importance of this indicator. The combined weighting approach (with $\alpha=0.5$) ensures that S_fracability contributes a reasonable weight ($w_5=0.0503$) to the final decision, preventing the small-sample artifact from dominating the evaluation.

To address the small-sample sensitivity of entropy weights, two measures are adopted in this study: (1) the combined AHP-entropy weighting method inherently mitigates the small-sample issue by coupling subjective expert judgment with objective data dispersion; and (2) for applications with very limited candidate horizons, maximum entropy normalization or Bayesian entropy estimation could be employed as alternative approaches to stabilize the entropy calculation. These alternatives were tested and yielded combined weights consistent with the main results, confirming the robustness of the selected horizon.

Combined weighting using analytic hierarchy process and entropy weight method

To unify the subjectivity and objectivity of the weighting process, the two sets of weights obtained from the Analytic Hierarchy Process (AHP) and the Entropy Weight Method are coupled. A combined AHP-Entropy Weight Method model is constructed to derive the comprehensive weights:

$$W_j = \alpha_1 W_j^1 + (1 - \alpha_1) W_j^2 \quad (17)$$

In the formula: W_j is the comprehensive weight, W_j^1 is the weight obtained from the Analytic Hierarchy Process; W_j^2 is the weight obtained from the Entropy Weight Method, α_1 is the subjective weight coefficient for the AHP method, and $1 - \alpha_1$ is the objective weight coefficient for the Entropy Weight Method.

To balance the influence of subjective judgment and objective data, the sum of squared deviations between the comprehensive weight W_j , the AHP weight W_j^1 and the objective Entropy weight W_j^2 is minimized. Thus, the following function is established:

$$\min W = \sum_{i=1}^m \left[(W - W_j^1)^2 + (W - W_j^2)^2 \right] \quad (18)$$

Differentiating Eq. (18) and setting the resulting first derivative equal to zero yields the condition where the sum of squared deviations between the comprehensive weight and the subjective/objective weights is minimized. At this point, the optimal coefficient is found to be $\alpha = 0.5$. Substituting $\alpha = 0.5$ into Eq. (17) simplifies it to the following form:

$$W_j = 0.5W_j^1 + 0.5W_j^2 \quad (19)$$

That is, when the AHP subjective weight is 0.5 and the entropy objective weight is 0.5, the evaluation performance of the AHP-Entropy combined model is optimal.

Consequently, the comprehensive weights can be calculated based on Eqs. (13), (16), and (19):

$$W_j = [0.3886, 0.1130, 0.1365, 0.1607, 0.0503, 0.1506]^T$$

The above equation is the weight vector used to calculate the comprehensive suitability of each candidate horizon.

Construction of a weighted model based on multi-source information fusion

Based on the subjective-objective comprehensive weights determined by the Analytic Hierarchy Process-Entropy Weight Method, a linear weighted model for the comprehensive index (S) evaluating the suitability of fracturing horizons is constructed. Its expression is:

$$S = \sum_{j=1}^6 (W_j \times S_{ij}) \quad (20)$$

In the formula: S_{ij} represents the score of the i -th horizon under the j -th indicator (value range 0–1). W_j is the corresponding comprehensive weight for the j -th indicator.

This model calculates the comprehensive suitability index for each candidate horizon by integrating the weighted scores. The results enable the optimization and final determination of the most suitable fracturing horizon.

Study on the optimization of fracture location within hydraulic fracturing layers based on composite beam theory

To achieve effective weakening of the target layer's rock mass structure, after determining the fracturing horizon, it is further necessary to identify the optimal propagation location for the fracture. For this purpose, this paper constructs a mechanical model based on composite beam theory and, through theoretical derivation, determines the optimal fracture location to achieve precision fracturing.

Mechanical model for fracture propagation in layered rock masses

The target rock layer is simplified as a beam model with a rectangular cross-section. It is assumed that the overlying strata pressure acts as a uniformly distributed load, and the effect of hydraulic fracturing is equivalent to separating the beam transversely into upper and lower layers (as shown in Fig. 4). Considering the bonding condition at the rock layer interface, a composite coefficient γ ($0 \leq \gamma \leq 1$) is introduced to characterize the strength of the pressure treatment.

The equivalent bending stiffness of the composite beam can be expressed as:

$$D_{eff} = \bar{E}_1 I_1 + \bar{E}_2 I_2 + \gamma \frac{(\bar{E}_1 A_1)(\bar{E}_2 A_2)}{\bar{E}_1 A_1 + \bar{E}_2 A_2} d^2 \quad (21)$$

In the formula: E_1 and E_2 are the average elastic moduli of the upper and lower layers, respectively. I_1 and I_2 are the moments of inertia. A_1 and A_2 are the cross-sectional areas. $d = \frac{h}{2}$ is the distance between the centroids.

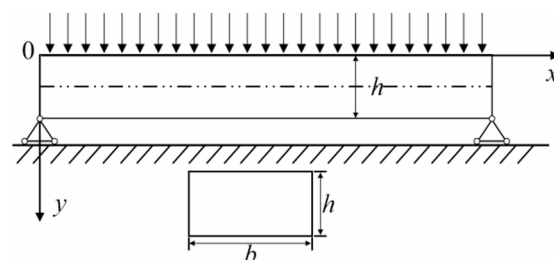


Fig. 4. Rectangular cross-section composite beam.

Theoretical solution for optimal fracture location

By introducing the dimensionless parameter $\alpha = y/h$ (where y is the distance of the fracture from the top surface, and h is the total thickness of the rock layer) and the modulus ratio, the expression for the equivalent bending stiffness can be simplified to:

$$D_{eff} = \frac{bh^3}{12} \bar{E}_2 \left[n\alpha^3 + (1-\alpha)^3 + 3\gamma \frac{n\alpha(1-\alpha)}{n\alpha + 1 - \alpha} \right] \quad (22)$$

The minimum bearing capacity of the structure corresponds to the minimization of D_{eff} . By solving for the extremum, the dimensionless solution for the optimal fracture location is obtained:

$$\alpha^* = \frac{1}{1 + \sqrt{n}} \quad (23)$$

Thus, the theoretical solution for the optimal fracture location is:

$$y^* = \frac{h}{1 + \sqrt{\bar{E}_1/\bar{E}_2}} \quad (24)$$

Equation (24) indicates that the optimal fracture location depends solely on the elastic modulus ratio between the upper and lower layers and is independent of the fracturing treatment intensity γ :

Homogeneous rock layer ($n=1$): $y^* = h/2$. The optimal location for hydraulic fracture propagation is at the mid-thickness of the layer.

Upper layer harder than lower layer ($n > 1$): $y^* < h/2$. The optimal location shifts upward, with the maximum possible offset given by:

$$\frac{h}{1 + \sqrt{\bar{E}_1/\bar{E}_2}};$$

Lower layer softer than upper layer ($n < 1$): $y^* > h/2$. The optimal location for hydraulic fracturing shifts downward. This reveals the controlling effect of the stiffness distribution within the rock layer on the fracture propagation path, providing a theoretical basis for fracturing design.

Engineering case application

To verify the engineering applicability of the aforementioned theoretical model, a mine in Xinjiang was taken as a case study. Hydraulic fracturing tests were conducted under on-site hard roof conditions, and a comprehensive validation was performed on both the optimized layer and its specific height.

Engineering background

As shown in Fig. 5, the I010206 fully mechanized top-coal caving face of a mine in Xinjiang is located in the B2 coal seam on the eastern wing of the first mining district. The eastern boundary extends 100 m east of exploration line No. 23, the western boundary is 140 m west of exploration line No. IV, and the southern boundary adjoins the mine field limit. The elevation of the lower gate road ranges from +1320 m to +1351 m, while the upper gate road elevation ranges from +1359 m to +1385 m. The azimuth of the gate roads is between 124° and 118°, corresponding to a surface elevation ranging from +1675 m to +1840 m.

Model application

1. Determination of the fracturing target layer.

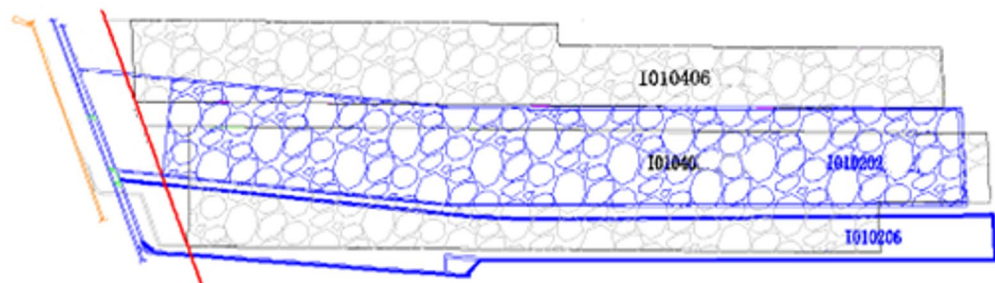


Fig. 5. Layout of I010206 working face and adjacent working faces.

Based on the key stratum discrimination theory, the preliminary assessment identifies the pressure relief layers from top to bottom as follows: the 12th layer as the main key stratum, the 15th layer as the sub-key stratum 2, and the 25th layer as the sub-key stratum 1. The initial weighting interval (first roof caving span) is $L = 56.3$ m. According to the Specifications for Coal Pillar Retention and Under-Seam Mining under Buildings, Water Bodies, Railways, and Main Shafts and Roadways: $f = 26.57$ m.

Based on the calculation results from Eq. (20), the comprehensive suitability indices for rock layers 25, 15, and 12 are 0.801, 0.443, and 0.219, respectively. These indices have been normalized, where a higher value indicates greater suitability of the rock layer as a fracturing target. Consequently, rock layer 25 demonstrates the highest suitability and is therefore determined as the optimal fracturing target horizon.

2. Determination of the fracturing height.

A 'hard upper, soft lower' profile ($n > 1$) is exhibited by the 25th layer, where a fine-grained sandstone is underlain by mudstone. The optimal position for hydraulic fracturing is shifted upward from the mid-height ($h/2$) by an offset that is $\frac{h}{1+\sqrt{n}}$. Taking $n = 1.2$, the calculation yields y is 12.43 m. Therefore, the fracturing location is set at 16.51 m from the coal seam roof.

3. Program formulation.

As illustrated in Fig. 6, the program involved the establishment of 2 fracturing drill sites. Each site was equipped with 3 directional long boreholes spaced 50 m apart. The depth of individual boreholes ranged from 420 to 500 m. A fracturing stage spacing of 30 m was implemented. A total drilled footage of 1330 m and 34 fracturing stages were completed at Drill Site No. 1, while 1233 m of footage and 39 stages were completed at Drill Site No. 2. The key operational parameters for pressure-relief fracturing were set as follows: an injection pressure of 30 MPa and an injection flow rate of 30 m³/h.

Effectiveness verification

Analysis of microseismic energy-frequency characteristics and source distribution in the working face

To evaluate the weakening effect of hydraulic fracturing on the roof and the energy evolution pattern within the coal-rock mass following pressure relief, subsequent monitoring and analysis of the microseismic energy-frequency distribution during the mining process were conducted, as shown in Fig. 7. The results indicate that after implementing hydraulic fracturing, the total energy of microseismic events remained predominantly below 1×10^4 J. Compared to advanced pre-split blasting, the number of microseismic events with energy exceeding 1×10^3 J decreased from 78 to 56, the average event energy dropped from 6981 J to 4559 J, and the average frequency reduced from 38 to 34 events, representing decreases of 28.2%, 34.6%, and 10.5%, respectively. These data demonstrate that hydraulic fracturing effectively reduced the total energy released from the overlying strata and the degree of stress concentration in the coal-rock mass.

Monitoring and analysis of support pressure changes and pressure nephograms in the working face

To assess the impact of hydraulic fracturing on support loading and roof weighting behavior, the loads on the front and rear legs of the powered supports at the 1010206 working face were continuously monitored using automatic pressure recorders. A comparison of the support working resistance and the weighting interval was conducted between the zones treated with pre-split blasting and hydraulic fracturing, respectively. The results, as shown in Fig. 8, indicate that after the implementation of hydraulic fracturing, the following changes were observed during periodic weighting: the maximum support working resistance dropped from 10,487 kN to 9513 kN, and the average working resistance decreased from 7688 kN to 6941 kN; and the average weighting interval shortened from 16.0 m to 11.4 m. These figures represent reductions of 9.28%, 9.71%, and 28.75% in maximum working resistance, average working resistance, and average weighting interval, respectively. The data

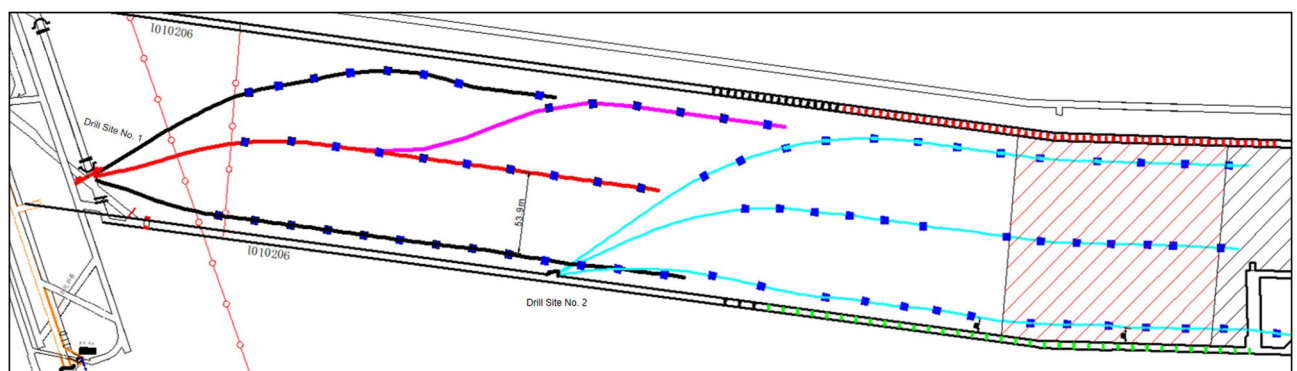


Fig. 6. Design layout plan of fracturing boreholes.

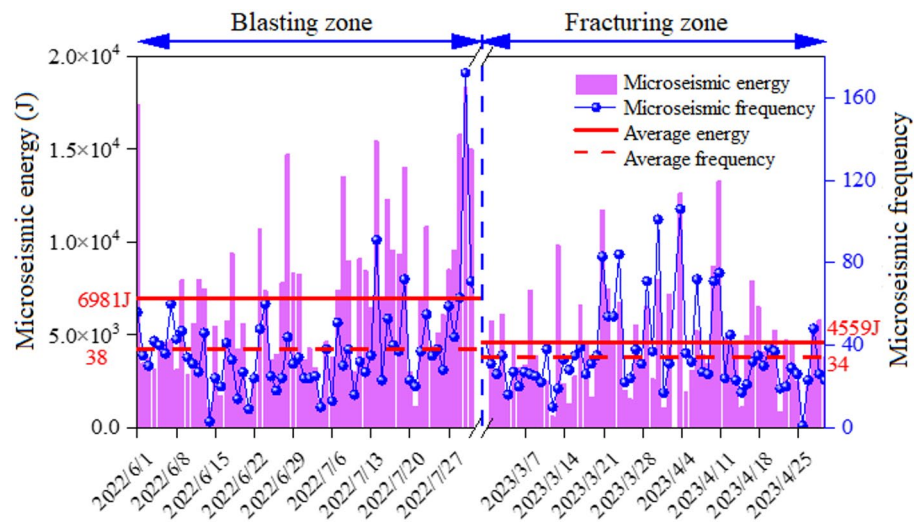


Fig. 7. Comparison chart of microseismic event energy/frequency.

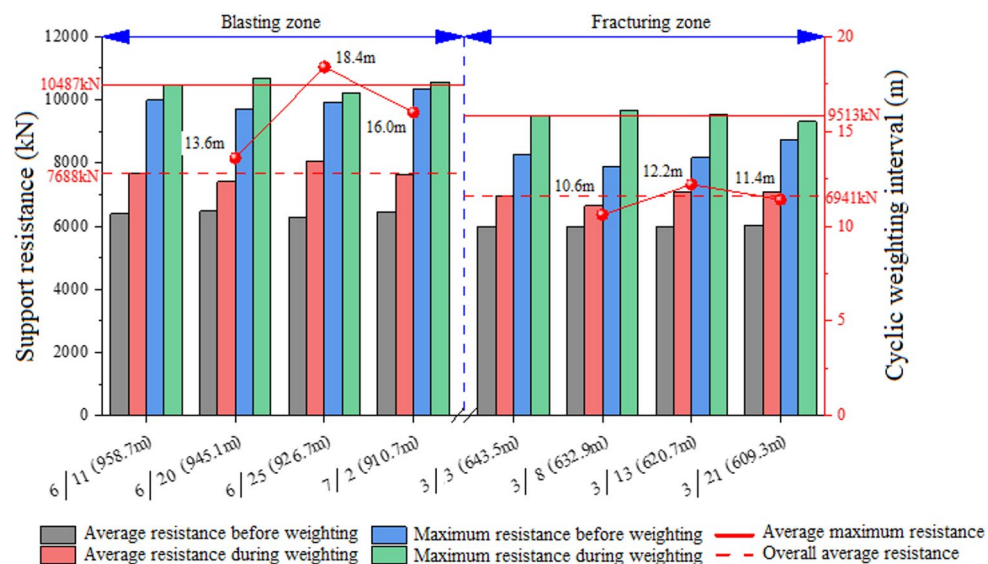


Fig. 8. Characteristics of periodic weighting during the working face mining period.

demonstrate that hydraulic fracturing effectively attenuated the energy release associated with roof failure by increasing roof fracturing and shortening its ultimate span.

Discussion

The proposed method integrates pressure arch theory, composite beam theory, and multi-criteria decision analysis to address hydraulic fracturing horizon selection. While the engineering case demonstrates promising results, several aspects warrant further discussion to fully establish the method's scientific rigor and practical applicability.

Comparison with existing methods

Compared with single-factor key stratum identification methods that rely solely on thickness and strength criteria, the proposed multi-criteria approach provides a more comprehensive evaluation framework. Table 3 presents a quantitative comparison between the proposed method and conventional approaches. The single-factor method identifies Layer 12 as the primary target due to its maximum thickness, but overlooks its unfavorable depth position ($S_{\text{depth}} = 0.01$) and poor accessibility ($S_{\text{accessibility}} = 0$). Empirical formulas based on water-conducting fracture zone height provide only static geometric constraints without considering dynamic stress evolution or rock mechanical behavior. The proposed method, by integrating six dimensions with combined

AHP-entropy weighting, yields a more balanced decision that accounts for both structural control importance and engineering feasibility.

Sensitivity of combined weighting coefficient

The combined weighting coefficient $\alpha=0.5$ was determined by minimizing the sum of squared deviations between comprehensive weights and subjective/objective weights. To assess the sensitivity of this choice, the final ranking of candidate layers was evaluated under varying α values (0.3, 0.4, 0.5, 0.6, 0.7). The results show that Layer 25 consistently ranks first for all $\alpha \in [0.3, 0.7]$, with its comprehensive score varying from 0.762 ($\alpha=0.3$) to 0.832 ($\alpha=0.7$). This stability indicates that the horizon selection result is robust against moderate variations in the weighting coefficient, and the choice of $\alpha=0.5$ is well justified as it equally balances subjective expert judgment with objective data evidence.

Applicability of pressure arch theory assumptions

The idealized parabolic pressure arch model assumes homogeneous, isotropic overburden under uniformly distributed loading. In practice, real mining overburden is heterogeneous and anisotropic. However, the pressure arch theory remains applicable when: (1) the mining depth exceeds 300 m, ensuring that the overburden behaves as a continuous beam-arch structure rather than discrete blocks; (2) the coal seam dip angle is less than 25° , maintaining approximately horizontal stress redistribution; and (3) no major geological structures (faults, folds) disrupt the continuity of the overlying strata within the arch span. For conditions violating these constraints, site-specific calibration of the arch geometry and stress distribution is recommended before applying the method.

Adaptation to multi-seam mining and steeply dipping seams

For multi-seam mining scenarios, the pressure arch geometry differs significantly due to the interaction between adjacent goafs. In such cases, the arch height f should be calculated using the combined span of all mined seams rather than a single working face. The proposed method can be adapted by evaluating each seam's contribution to the overall overburden structure and selecting horizons that provide synergistic pressure relief across multiple seams. For steeply dipping seams (dip angle $> 25^\circ$), the symmetric parabolic arch assumption becomes invalid as the stress redistribution becomes asymmetric. A modified elliptical or skewed arch model should be employed, with the optimal fracturing position shifted toward the updip direction. These adaptations require additional mechanical analysis and field validation, which represent important directions for future research.

Generalizability to different geological conditions

The method was validated in a hard-roof coal mine in Xinjiang, China. Its generalizability to other geological engineering contexts depends on the availability of required input data (geological column, in-situ stress measurements, rock mechanical properties) and satisfaction of the theoretical assumptions. For metal mines with hard rock conditions, the indicator system remains applicable though the threshold values for fractability and stress concentration may need adjustment. For sedimentary rock environments with soft roofs, the pressure arch model may require modification to account for immediate roof caving behavior. The method can also be extended to civil engineering applications such as tunnel surrounding rock reinforcement, where similar multi-criteria optimization of grouting or bolting parameters is needed.

Limitations

Several limitations of this study should be acknowledged. First, the entropy weight calculation is sensitive to small sample sizes, as demonstrated by the zero entropy weight for $S_{\text{fractability}}$ with only three candidate horizons. Future work should incorporate Bayesian entropy estimation or maximum entropy normalization to stabilize weight calculations for small samples. Second, the Gaussian function parameters ($\sigma=60$, $\alpha=0.3$) were calibrated using engineering cases from Chinese mining areas; their transferability to other geological settings requires further validation. Third, the pressure arch model simplifies the three-dimensional overburden structure into a two-dimensional plane problem, which may introduce errors for wide panel mining or complex multi-seam layouts. Addressing these limitations through three-dimensional numerical simulations and expanded field trials constitutes the next phase of research.

Conclusions

1. This paper proposes a comprehensive decision-making method that integrates key stratum theory, pressure arch theory, and a multi-source information evaluation system. By constructing a quantitative comprehensive suitability indicator system encompassing six dimensions—depth, strength, thickness, in-situ stress, fractability, and engineering accessibility—selected through a systematic process combining mechanical principles, key stratum theory, and literature mining, and determining their respective weights using a coupled Analytic Hierarchy Process (AHP) and entropy weight method, a systematic and operable decision-making framework is provided for optimizing hydraulic fracturing horizons. The treatment of safety constraints (e.g., aquifer distance) as pre-screening criteria ensures that hazard avoidance is strictly enforced before multi-criteria optimization.
2. Based on composite beam theory, this paper derives the theoretical solution for the optimal fracture location within layered rock masses subjected to hydraulic fracturing. It reveals the mechanical mechanism that the fracture propagation location is primarily controlled by the elastic modulus ratio of the upper and lower layers and is independent of the fracturing treatment intensity. Furthermore, the $0.75f$ position is identified as the optimal fracturing depth within the pressure arch, where the maximum bending moment creates peak tensile stress favorable for fracture initiation and maximal disruption of the arch load transfer path. This find-

ing provides a basis for the precise design of intra-layer fracturing positions, thereby enhancing the targeting and effectiveness of fracturing measures.

3. Through the application of an engineering case study and the analysis of effectiveness monitoring, the engineering applicability of the comprehensive decision-making method is validated. The results demonstrate that after implementing hydraulic fracturing in the optimally selected horizon, the energy and frequency of microseismic events was significantly reduced, and the support working resistance and weighting interval was markedly decreased. This indicates that the proposed method can effectively weaken the roof structure, alleviate stress concentration, and reduce both the frequency and intensity of hazards, providing a reliable scientific basis for the prevention and control of rock burst. Future work should extend the method to multi-seam and steeply dipping seam conditions, incorporate three-dimensional numerical simulations, and apply Bayesian entropy estimation to address small-sample limitations.

Data availability

Data will be made available on request.

Received: 8 May 2026; Accepted: 25 June 2026

Published online: 27 June 2026

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Author contributions

R.Y.: Conceptualization, data curation, formal analysis, investigation, methodology, project administration.

H.L.: Investigation, methodology. X.J.: Investigation, methodology. K.L.: Investigation, methodology. X.L.: Investigation, methodology. T.D.: Investigation, methodology. C.R.: Investigation, methodology. Y.C.: Writing.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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