

Research on Comprehensive Evaluation Method of Hydraulic Fracturing Gas Drainage Effect in Underground Coal Mine and its Engineering Application

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Abstract

Aiming at the engineering problems of current single evaluation of underground coal mine hydraulic fracturing effect, low quantification accuracy, lack of multi-dimensional coupling evaluation, which makes it difficult to accurately characterize the comprehensive effects of fracturing crack creation, pressure relief and permeability enhancement, this paper systematically sorts out the existing fracturing effect monitoring and evaluation technology system, and summarizes the technical characteristics and applicable scenarios of each evaluation method. Combined with different engineering scenarios such as hard roof pressure relief, coal seam permeability enhancement and rock burst prevention and control, a multi-dimensional quantitative evaluation index system covering fracture development characteristics, stress relief effect, surrounding rock deformation control, gas control effect and construction efficiency is constructed. The entropy weight-analytic hierarchy process coupling model is introduced to realize the scientific assignment of evaluation index weights, and a five-level comprehensive evaluation method for hydraulic fracturing effect is established. The engineering application results show that this evaluation system can accurately quantify the effect of underground hydraulic fracturing reconstruction, effectively avoid the one-sidedness of a single evaluation method, and the evaluation results are highly consistent with on-site mine pressure monitoring and fracture detection data. It can provide theoretical support and technical basis for parameter optimization, process improvement and accurate judgment of engineering effect of underground coal mine hydraulic fracturing.

Keywords

Underground Coal Mine; Hydraulic Fracturing; Effect Evaluation; Index System; Engineering Application.

1. Introduction

With the continuous increase in coal mining depth and intensity in China, deep mines are generally confronted with a series of disaster challenges, such as difficult caving of hard roofs, low coal seam permeability, concentrated abutment stress, and frequent rock bursts[1]. Hydraulic fracturing technology, with its advantages of high efficiency, low cost and minor disturbance, has been widely applied in underground coal mine engineering fields including roof pressure relief, coal seam permeability enhancement, stress release and gas extraction, making it a core prevention and control technology for safe deep coal mining[2-4]. Underground hydraulic fracturing fractures coal and rock masses through high-pressure water flow to construct an artificial fracture network, so as to realize stress release and permeability

improvement of coal and rock masses[5]. Its reconstruction effect directly determines the engineering outcomes of mine pressure disaster prevention and control as well as gas control. At present, scholars at home and abroad have carried out extensive research on coal mine hydraulic fracturing technology, and have achieved fruitful results in aspects such as fracture propagation laws, fracturing parameter optimization, and process improvement[6-10]. Most existing fracturing effect evaluations adopt a single monitoring method, which mainly relies on single data from microseismic monitoring, borehole peeping, mine pressure observation, etc. for qualitative analysis, and has obvious technical shortcomings. First, a single monitoring dimension cannot take into account both micro-fracture development and macro mine pressure response, leading to prominent one-sidedness in evaluation. Second, there is a lack of a unified and quantitative evaluation index system, with strong subjectivity and arbitrariness in index weight assignment and no standardized evaluation grades. Third, the evaluation priorities for different fracturing engineering scenarios are not distinguished, resulting in insufficient universality and accuracy. Therefore, to solve the above problems, this paper systematically integrates existing hydraulic fracturing evaluation technologies, analyzes the advantages, disadvantages and applicable conditions of various evaluation methods by classification, constructs a multi-dimensional and all-element quantitative evaluation index system combined with different underground engineering application scenarios, establishes a coupled comprehensive evaluation model based on the entropy weight-analytic hierarchy process, formulates standardized evaluation grades, and verifies the scientificity and practicability of this evaluation method through field engineering applications, so as to provide technical support for accurate effect evaluation and iterative parameter optimization of underground coal mine hydraulic fracturing engineering.

2. Analysis of Existing Hydraulic Fracturing Effect Evaluation Methods and Their Applicability

At present, the evaluation technologies for underground coal mine hydraulic fracturing effects can be divided into four categories: on-site monitoring characterization methods, construction parameter feedback methods, micro-fracture analysis methods, and macroscopic mine pressure response methods. These methods differ significantly in monitoring dimensions, evaluation accuracy and applicable scenarios, and their specific technical characteristics and applicability are analyzed as follows.

(1) Micro-fracture monitoring and evaluation method

This method takes the fracture development characteristics of coal and rock masses after fracturing as the core evaluation basis, directly reflects the fracturing-induced fracture effect, and is a core means to characterize the micro-reconstruction effect of fracturing. Mainstream technologies include borehole peeping, high-density electrical method, and fracture fractal characterization. Borehole peeping technology can directly observe the number, opening and extension range of fractures around the borehole, featuring simple operation and strong intuitiveness, but it can only obtain local fracture information around the borehole with limited spatial coverage, and cannot realize the characterization of the full-field fracture network. Relying on resistivity tomography, the high-density electrical method can realize 3D visualized dynamic monitoring of fracturing fractures and fracturing fluid migration, making up for the poor spatial continuity defect of traditional point monitoring. However, it is greatly interfered by underground roadway environment and surrounding rock moisture content, and its quantitative accuracy needs to be improved. The fracture evaluation method based on fractal theory can quantitatively characterize the complexity of the fracture network through 2D and 3D fractal dimensions. The larger the increase of the fractal dimension of coal and rock masses after fracturing, the more sufficient the fracture development and the better the fracturing

reconstruction effect. This method has high quantitative accuracy and is suitable for laboratory sample analysis and on-site fine evaluation, but its data processing procedure is complex. Overall, the micro-fracture monitoring method is suitable for accurately determining the fracturing-induced fracture range and fracture development quality, and is a basic means for fine evaluation.

(2) Construction parameter feedback evaluation method

Parameters such as pressure, flow rate, displacement and pressure holding time during the hydraulic fracturing construction process are direct dynamic responses of fracture propagation, which can feed back the fracturing construction effect in real time. The fracturing pressure-flow curve can directly reflect the whole process of fracture initiation, propagation, penetration and pressure holding: stable fracture initiation pressure, gentle fluctuation of the pressure curve and continuous uniform flow indicate that the fractures in coal and rock masses propagate stably and the fracturing effect is good; if the pressure rises and drops sharply and the flow changes abruptly, it indicates that the fracture development is uneven, and there are problems such as hole blockage and insufficient fracturing. The advantages of this method lie in strong real-time performance, no need for subsequent complex monitoring, enabling dynamic evaluation of the fracturing process and guiding real-time adjustment of construction parameters; its shortcoming is that it can only reflect the macroscopic response of the construction process, cannot characterize the long-term stability effect of surrounding rock and the stress relief effect after fracturing, and can only be used as an auxiliary evaluation basis.

(3) Microseismic monitoring and evaluation method

Microseismic monitoring is the core technology for full-field evaluation of underground fracturing effects. By capturing microseismic events generated by the fracture of coal and rock masses during fracturing, it locates the spatial distribution of fractures, counts the number, energy and frequency of events, and accurately obtains the fracturing reconstruction range, fracture orientation and propagation scale. The densely distributed area of microseismic events is the core reconstruction area of fracturing. The lower the event energy and the more uniform the distribution, the more sufficient the fracture development and the more thorough the stress relief; the area without microseismic events is the fracturing blind zone, indicating that the fracturing reconstruction is not covered. This method can realize full-field, dynamic and 3D monitoring, and is suitable for the evaluation of large-scale roof fracturing and regional pressure relief projects. However, it has low recognition accuracy for micro-fracture development and is easily interfered by underground mining disturbances, so it needs to be combined with other methods for joint evaluation.

(4) Macroscopic mine pressure and deformation response evaluation method

This method takes the mine pressure law of the working face, surrounding rock deformation characteristics and stress distribution changes before and after fracturing as evaluation indicators to reflect the engineering application effect of fracturing, and is the final basis for verifying the disaster prevention effect of fracturing. Core monitoring indicators include the periodic weighting interval of the working face, the working resistance of supports, the dynamic load coefficient, the peak value of advance abutment stress, the convergence of roadway roof and floor, and the deformation rate of surrounding rock. After fracturing, if the weighting interval of the working face is uniform, the dynamic load coefficient is significantly reduced, the advance stress peak shifts downward and attenuates, and the surrounding rock deformation is greatly reduced, it indicates that the fracturing pressure relief and roof control effects are good. The evaluation results of this method are close to engineering practice with high reliability, but it has hysteresis and cannot realize real-time evaluation of the fracturing process, so it is suitable for long-term engineering effect verification after fracturing.

Based on the above analysis, every single evaluation method has inherent shortcomings and cannot comprehensively characterize the comprehensive effects of hydraulic fracturing in fracture generation, pressure relief and disaster control. The micro-fracture method is accurate but has a limited range, the construction parameter method is real-time but has a single dimension, the microseismic method covers the full field but has poor recognition of micro-fractures, and the mine pressure response method is close to engineering practice but has hysteresis. Therefore, it is urgent to construct a multi-dimensional coupled comprehensive evaluation system that integrates the advantages of various methods to realize all-round, quantitative and accurate evaluation of hydraulic fracturing effects.

3. Construction of Multi-dimensional Comprehensive Evaluation Index System

Table 1. Comprehensive evaluation index system for the effect of underground hydraulic fracturing in coal mines

Target layer	Criteria layer (first-level index)	Indicator layer (second-level index)
Comprehensive effect evaluation of hydraulic fracturing	Fracture development effect A1	Fracturing fracture propagation range S1
		Average fracture opening S2
		Increment of fracture fractal dimension S3
	Stress relief effect A2	Reduction of advanced abutment stress S4
		Reduction of stress concentration coefficient S5
	Mine pressure regulation effect A3	Reduction of working face dynamic load coefficient S6
		Periodic weighting uniformity S7
	Surrounding rock stability effect A4	Reduction of roof-to-floor convergence S8
		Reduction of two-side convergence S9
		Reduction of surrounding rock deformation rate S10
	Surrounding rock stability effect A5	Effective fracturing coverage rate S11
		Construction parameter stability S12

To ensure the scientific validity, comprehensiveness, and practicality of the evaluation system, the indicator selection follows these principles: 1) Systematization--covering five major dimensions, namely fracture development, stress relief, mine pressure response, surrounding rock deformation, and construction efficiency, encompassing the entire fracturing process and all effectiveness aspects. 2) Quantifiability--all indicators can be obtained as quantitative data through on-site monitoring and experimental testing, avoiding qualitative subjective

judgments. 3) Target specificity--distinguishing different fracturing engineering scenarios while balancing general applicability and special-purpose relevance. 4) Operability--the indicators are moderately difficult to monitor and are adaptable to underground coal mine field construction conditions.

In line with the functions of underground coal mine hydraulic fracturing (roof pressure relief, coal seam permeability enhancement, and burst prevention and pressure reduction), a three-level evaluation system comprising the target layer, criterion layer, and indicator layer is constructed. The target layer is the comprehensive effect of underground coal mine hydraulic fracturing, the criterion layer contains five primary indicators, and the indicator layer contains twelve secondary quantitative indicators. The specific system is presented in Table 1.

To eliminate the differences in dimension and order of magnitude of each indicator, all positive indicators are standardized by the extreme value standardization method, and the formula is as follows:

$$x'_{ij} = \frac{x_{ij} - x_{jmin}}{x_{jmax} - x_{jmin}}$$

where: x_{ij} is the original monitoring data of the j -th indicator in the i -th group of samples; x_{jmax} and x_{jmin} are the maximum and minimum values of the j -th indicator respectively; x'_{ij} is the standardized indicator value, with a value range of [0,1].

4. Construction of Coupled Comprehensive Evaluation Model

To avoid the defects of single subjective weighting and objective weighting, the entropy weight-analytic hierarchy process (AHP-entropy method) coupled model is adopted for index weight assignment, which takes into account the subjectivity of experts' engineering experience and the objectivity of monitoring data, so as to improve the evaluation accuracy.

By constructing a hierarchical judgment matrix, experts in the field of coal mine fracturing are invited to make pairwise comparisons on the importance of indicators at each level, calculate the subjective weight of indicators, and conduct consistency tests to ensure the rationality of weight assignment and avoid subjective deviation. The objective weight is calculated based on the information entropy of each index monitoring data. The greater the dispersion of index data, the smaller the information entropy, and the higher the weight, which means that the index contributes more to the fracturing effect evaluation, and the objective law of monitoring data is fully explored.

Integrate the subjective weight and objective weight to calculate the final combined weight:

$$w_j = \alpha w_j^{AHP} + (1 - \alpha) w_j^E$$

Where: w_j is the combined weight of the j -th indicator; w_j^{AHP} is the subjective weight of the analytic hierarchy process; w_j^E is the objective weight of the entropy weight method; α is the weight coefficient.

Based on the standardized index values and the combined weights, the comprehensive evaluation score F of hydraulic fracturing is calculated:

$$F = \sum_{j=1}^n w_j x'_{ij}$$

Where: F is the comprehensive evaluation score of hydraulic fracturing.

Combined with the coal mine engineering evaluation standards and a large number of field data statistics, the fracturing effect is divided into five standardized grades, as shown in Table 2.

Table 2. Comprehensive evaluation grade standard for hydraulic fracturing effect

Evaluation score F	0~0.2	0.2~0.4	0.4~0.6	0.6~0.8	0.8~1.0
Evaluation grade	Extremely poor (Grade I)	Poor (Grade II)	Medium (Grade III)	Good (Grade IV)	Excellent (Grade V)
Engineering judgment	Fracturing failure, re-construction required	Poor effect, parameter optimization and supplementary fracturing needed	Effect up to standard with local shortcomings	Good effect, meeting engineering requirements	Excellent effect, optimal reconstruction state

5. Engineering Application Verification

5.1. Field Application

Taking the 8103 fully mechanized mining face of a certain mine as the engineering background, this working face has a mining depth of 680m, and its roof is a thick and hard sandstone roof with strong integrity and difficulty in caving. The working face has severe periodic weighting, obvious dynamic load disturbance, and rock burst hazards. To prevent and control roof disasters and release concentrated stress, the underground segmented directional hydraulic fracturing technology is adopted to pre-split and unload the roof of the working face. The fracturing hole has a depth of 80m, a diameter of 94mm, a segmented fracturing spacing of 10m, and a construction pressure of 28~32MPa.

After the fracturing construction is completed, microseismic monitoring, borehole peeping, online stress monitoring, and mine pressure observation systems are used for all-round data collection to obtain the original monitoring data of 12 secondary indicators. The dimensionless processing is completed through the extreme value standardization method, and the combined weight of each indicator is calculated relying on the constructed AHP-entropy coupling model. Finally, the comprehensive evaluation score is obtained by weighted summation, and the specific calculation process is as follows.

(1) Indicator Standardization Processing: Collect the original data of 12 evaluation indicators before and after fracturing of the working face, determine the maximum and minimum values of each indicator combined with the extreme value data of similar projects in the mining area, and normalize the original data through the extreme value standardization formula mentioned above to obtain the standardized score of each indicator. The results are all distributed in the range of 0~1, eliminating the difference in dimensions.

(2) Indicator Weight Determination: The judgment matrix of indicators at each level is constructed through the analytic hierarchy process. After consistency test ($C_R=0.083<0.1$, meeting the test standard), the subjective weight of indicators is obtained; the objective weight is calculated based on the information entropy of monitoring sample data; coupled with the weight coefficient $\alpha=0.5$, the final combined weights of 12 secondary indicators are obtained, with the total weight of all indicators being 1. The specific weight distribution: the total weight of fracture development indicators is 0.282, the total weight of stress relief indicators is 0.245, the total weight of mine pressure regulation indicators is 0.203, the total weight of surrounding rock stability indicators is 0.186, and the total weight of construction energy efficiency indicators is 0.084.

(3) Comprehensive Score Calculation: According to the comprehensive evaluation score formula, the standardized indicator values and the corresponding combined weights are weighted and summed one by one, and the scores of each criterion layer are calculated separately: fracture development effect 0.235, stress relief effect 0.212, mine pressure

regulation effect 0.178, surrounding rock stability effect 0.149, construction energy efficiency 0.052. Sum the scores of all dimensions:

$$F=0.235+0.212+0.178+0.149+0.052=0.826$$

Compared with the evaluation grade standard, the fracturing effect of this working face is excellent (Grade V).

5.2. Analysis of Evaluation Results

(1) Fracture development dimension: After fracturing, the average extension range of roof fractures was 9.2 m, with uniform fracture apertures. The fractal dimension increased by 8.7% compared with pre-fracturing levels. The fracture network was well developed with no obvious fracturing blind zones, indicating excellent fracture creation performance.

(2) Stress and mine pressure dimension: The peak advanced abutment stress in the working face decreased by 38.2%, and the stress concentration coefficient was significantly reduced. The dynamic load coefficient of the working face dropped from 1.42 to 1.08. The periodic weighting intervals were uniform, and the weighting intensity was substantially weakened, demonstrating significant stress relief and mine pressure control effects.

(3) Surrounding rock stability dimension: The roof-to-floor convergence and rib-to-rib convergence of the roadway decreased by 34.8% and 31.7%, respectively. The deformation rate of the surrounding rock slowed down considerably, and the overall roadway stability was markedly improved, effectively resolving the severe weighting problem caused by thick and hard roofs.

(4) Construction efficiency dimension: The effective fracturing coverage rate reached 98.5%. The construction pressure and flow rate parameters remained stable, with no issues such as plugging or pressure leakage, ensuring controllable construction quality.

Field engineering practice demonstrates that this comprehensive evaluation model yields accurate results and can fully reflect the overall effectiveness of fracturing-induced fracture creation, pressure relief, and disaster control. It effectively compensates for the one-sidedness of single evaluation methods and is well suited to meet the evaluation requirements of underground pressure-relief fracturing engineering in thick and hard roofs.

6. Conclusion

(1) This paper systematically analyzes the technical characteristics, advantages and disadvantages of four mainstream underground hydraulic fracturing evaluation methods, including micro-fracture monitoring, construction parameter feedback, microseismic monitoring and macroscopic mine pressure response, clarifies the applicable scenarios of various methods, and expounds the core problem that a single evaluation method is difficult to meet the requirements of accurate engineering evaluation.

(2) A comprehensive hydraulic fracturing evaluation system covering 5 dimensions of fracture development, stress relief, mine pressure regulation, surrounding rock stability and construction energy efficiency, with 12 quantitative indicators is constructed. The indicators cover the whole process and all effects of fracturing, taking into account scientificity and engineering operability. An entropy weight-analytic hierarchy process coupled evaluation model is established to realize scientific assignment of indicator weights, and a five-level standardized fracturing effect evaluation grade is formulated, which solves the problems of subjective arbitrariness and low quantitative accuracy of traditional evaluation.

(3) Engineering application verification shows that this comprehensive evaluation method can accurately quantify the effect of underground fracturing reconstruction, and the evaluation

results are consistent with engineering practice, which can provide a reliable basis for hydraulic fracturing parameter optimization, process improvement and engineering effect judgment.

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