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Construction of Safety Assessment System based on Risk Closed-Loop Management of Underground Mine Blasting Stage

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Abstract: Aiming at the dynamic safety control problems caused by the instantaneous release of high energy and the coupling of multi-source risks in blasting operations in underground mines, a safety assessment system based on closed-loop risk management is constructed. Through the three-dimensional framework of "risk source-impact path-accident consequence", we integrate the four-dimensional indicators of blasting parameters, operating environment, personnel behavior and monitoring response, integrate the Delphi method and coefficient of variation (CV) method to screen the key factors, and combine the hierarchical analysis method to realize the subjective and objective empowerment. A five-level risk threshold standard and a weighted fuzzy comprehensive evaluation

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model are established to quantify the high coupling risk relying on the triangular subordinate function. The engineering validation shows that the response time of the system is lower than 0.8 seconds, and the accuracy of risk level discrimination is 27.8% higher than that of the traditional method, which effectively supports the dynamic risk warning and closed-loop control of underground blasting.

Keywords: underground mine; blasting safety; risk closed-loop management; index system

1 Introduction

Underground mine blasting operation is characterized by instantaneous release of high energy and multi-source coupling interference, presenting high-risk attributes such as strong suddenness, fast propagation speed and significant secondary disaster chain effect. The superposition of shock wave, toxic gas diffusion and geological disturbance in the enclosed space can easily lead to catastrophic accidents, and the existing static assessment methods are difficult to meet the dynamic risk management and control needs. Aiming at the high coupling degree, strong uncertainty and real-time response bottleneck of the risk in the blasting phase, there is an urgent need to build a closed-loop management system that integrates risk perception, quantitative assessment and early warning feedback [1]. This study focuses on the systematic decoupling of risk conduction paths and multi-dimensional index fusion mechanism, aiming to break through the lagging constraints of traditional safety management, and provide theoretical support and practical paradigm for intelligent safety prevention and control in mines.

2 Characterization of risk analysis of underground mine blasting stage

Underground mine blasting operations stage there is a significant high-energy instantaneous release and multi-source coupling interference characteristics, the risk of showing a strong suddenness, fast propagation speed and secondary disaster correlation of high significant features. The main risk factors in this stage include the risk of perimeter rock fragmentation and topping caused by the non-standardized management of blasting equipment, errors in the assembly of pyrotechnic products, disturbance of the ventilation system, and uneven geological structure [2]. In the enclosed or semi-enclosed workspace, the shock wave, seismic wave and toxic gas diffusion path is complex, and it is very easy to cause casualties and equipment damage. In addition, the transient stress changes caused by blasting may also stimulate the collapse of the old empty area or induce microseismic activity, forming a coupled disaster chain. In summary, the risk of blasting phase of underground mines presents multiple characteristics of high coupling, high dynamics and high uncontrollability, which puts forward higher requirements for the dynamic response ability of the safety management system.

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3 Blasting stage safety assessment index system construction

3.1 Assessment index screening method

On the basis of clarifying the multi-dimensional risk characteristics of the blasting phase of underground mines, the design of the indicator screening method needs to take into account the systematic, representative and quantifiable, to ensure that the assessment system constructed has engineering adaptability and implementability. The three-dimensional framework of "risk source-impact path-accident consequence" is adopted as the logical main line, and the initial indicator library is constructed by combining the fusion analysis of multi-source data and the judgment of experts' experience and knowledge. On this basis, the Delphi method and the coefficient of variation (CV) method are used to screen and optimize the indicators, in which the Delphi method is used to eliminate the redundant indicators with insufficient engineering relevance, and the CV method is used to measure the degree of dispersion and differentiation of the indicators in the sample data, so as to achieve the complementary fusion of objectivity and subjectivity [3]. Table 1 lists the content of the indicator database and its source types established in the preliminary screening stage, including the four dimensions of the operating environment, blasting parameters, personnel behavior and monitoring response.

Table 1 Preliminary indicator database and data source type

Indicator name	Dimension	Data Source	Type of data source
Blasting Charge	Blasting Parameters	Construction Records + Measured Data	Quantification
Perforation density	Blasting Parameters	Design drawings	Quantification
Operational ventilation	Operating environment	Online monitoring system	Quantitative
Explosives storage compliance	Personnel Behavior	Safety inspection records	Qualitative
Toxic Gas Dispersion Response Time	Monitoring Response	Gas sensor + alarm system	Quantitative

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3.2 Hierarchical structure of assessment index system

After completing the systematic screening of risk indicators in the blasting stage, it is necessary to scientifically classify and categorize the indicators in order to build an assessment framework with clear logical relationships and operability. In this regard, based on the theory of hierarchical analysis, a three-layer structure model of "target layer - guideline layer - indicator layer" is designed to ensure that the weights of different dimensional indicators in the system are clearly transferred and the attribution relationship is clear [4]. The target layer is set as "underground mine blasting stage operation safety status", the criterion layer covers the four core dimensions of operating environment safety, blasting parameter control, personnel behavioral norms and monitoring and response capabilities, and the indicator layer is specifically developed by the quantifiable factors obtained from the aforementioned screening. Figure 1 shows the complete hierarchical model, in which the layers are connected by a unidirectional decision path, and the aggregation effect of the input variables of the comprehensive assessment is realized through the weight transfer mechanism. The structural design of the subsequent hierarchical weights and assessment algorithms provide the basis for the construction of data mapping support, with good module independence and expansion compatibility.

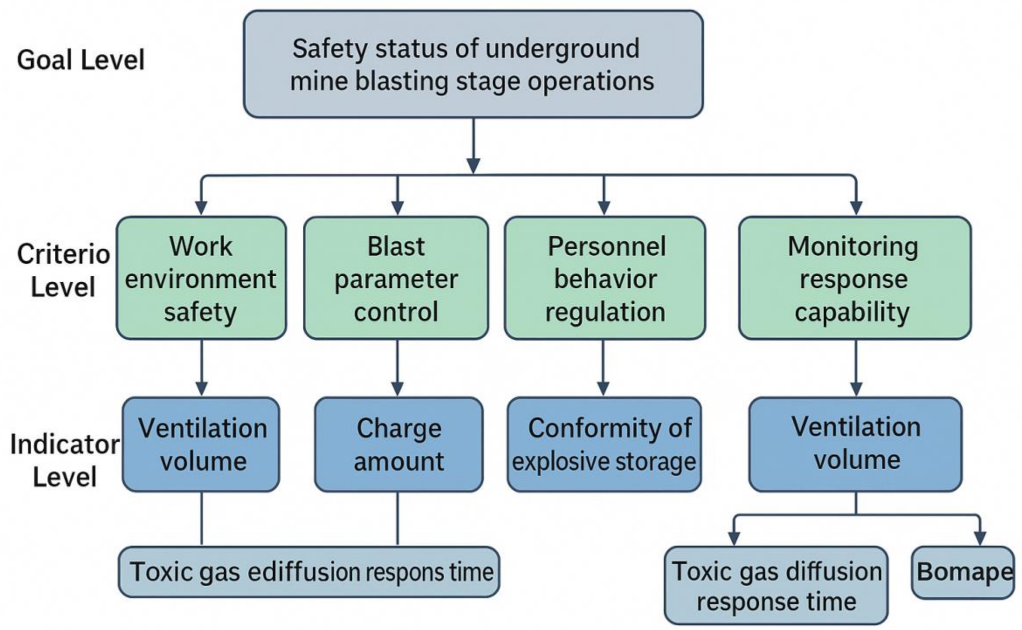

Figure 1 Schematic diagram of the three-layer structure model of the safety assessment indexes in the blasting phase of underground mines.

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3.3 Determination of indicator weights

3.3.1 Expert scoring method

After the establishment of the structure of the indicator system, assigning the relative importance of each indicator becomes a key link in the construction of the assessment system. In order to achieve the preliminary assignment of subjective weights among indicators, the expert scoring method is introduced, and 10 senior engineers who have long been engaged in mine safety management, blasting engineering design and risk assessment research are organized to form an expert group to carry out three rounds of anonymous scoring based on the idea of the Delphi method [5]. The scoring standard is based on the 9-level scale method, and the scoring content is centered on the direct influence of the indicators on the "safety status of blasting phase operations". In order to ensure the stability and consistency of the scoring data, the weighted average method is used to make iterative corrections to the scoring of each round, and finally form the expert scoring matrix of each indicator (Table 2). This method not only realizes the systematic integration of expert knowledge, but also provides the basic data input of the initial judgment matrix for the hierarchical analysis method, which effectively enhances the credibility of the model structure and the reasonableness of decision-making.

Table 2 Expert scoring matrix for each assessment indicator

Indicator name	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Average Score
Blasting Charge	8	9	9	8	8.6	8.6
Ventilation air volume	7	6	7	7	6	6.6
Explosives storage compliance	6	7	6	6	6	6.2
Toxic Gas Diffusion Response Time	9	8	9	9	9	8.8

3.3.2 Hierarchical analysis method (AHP)

On the basis of completing the expert scoring, in order to further realize the systematic quantification of the weights of the assessment indicators, the hierarchical analysis method (AHP) is introduced to construct the judgment matrix and carry out the weight extraction and consistency test.

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Based on the three-layer structural model, the criterion layer and indicator layer are constructed into a number of two-by-two comparison matrices, and the comparison values are derived from the average scoring results of the experts, and the Saaty scaling method is used to establish matrix A. The weights of the indicators are calculated through the normalization process and the extraction of the eigenvectors, and the consistency ratio (CR) test is carried out by using the following formula [6]:

$$CI = \frac{\lambda_{\max} - n}{n-1}, \quad CR = \frac{CI}{RI}$$

Where λmax is the maximum characteristic root of the matrix, n is the matrix order, and RI is the random consistency index. If CR<0.1, the matrix consistency is judged to meet the requirements. Through MATLAB programming to calculate the normalized weight vector of each index and the consistency test results, the constructed matrix is verified to have high consistency, so as to guarantee the scientific and structural validity of the weight allocation of the assessment system.

3.4 Establishment of assessment standards

In order to realize the quantitative judgment of the risk level of underground mine blasting stage operations, a set of systematic, safe and operable assessment standards need to be constructed. On the basis of the determination of the weight of the indicators, combined with the "Safety Regulations for Metallic and Nonmetallic Mines" and typical engineering case data, the grading method is used to divide the value of each indicator into intervals and establish the corresponding safety level mapping relationship. In order to ensure that the evaluation standard has both engineering adaptability and statistical rationality, the sample data of each indicator are discrete analyzed by reference to the coefficient of variation method, and the evaluation results are divided into five categories according to the risk level: extremely dangerous, highly dangerous, moderately dangerous, mildly dangerous, and safe state, and are respectively assigned to the assessment value range of the five segments of the interval [0,1] on the affiliation range. Table 3 lists the risk threshold division criteria and scoring conversion rules for key indicators, which are used as input boundary conditions for the evaluation function of the subsequent model. Through the establishment of this standard system, the quantitative input of the security assessment model is guaranteed to be consistent and comparable, providing support for the realization of dynamic risk early warning.

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Table 3 Risk grading standards and scoring rules for some assessment indicators

Indicator Name	Safety value interval	Slight risk	Medium risk	High risk	Extremely dangerous	Corresponding rating range
Blasting powder (kg/m^3)	0-0.6	0.6-0.9	0.9-1.2	1.2-1.5	>1.5	[0.9, 0.1]
Ventilation air volume (m^3/min)	>220	180-220	140-180	100-140	<100	[0.9, 0.2]
Gas diffusion response time (s)	<10	10-20	20-40	40-60	>60	[0.95, 0.1]

4 Safety assessment model construction and validation

4.1 Assessment model construction

4.1.1 Model parameter setting

Based on the established index system and assessment criteria, the model input layer parameters are set as X=[x1,x2,... ,xn], where xi represents the ith normalized risk assessment indicator value, using a linear interval mapping function [7]:

$$x_i = \frac{v_i - v_{\min}}{v_{\max} - v_{\min}} \left(i = 1,2,\ldots,n\right)$$

Where vi is the original indicator value, and vmin,vmax are the minimum and maximum values of the indicator in the historical sample, respectively. To further improve the model's ability to perceive the sensitivity of different indicators, a weight matrix W=[w1,w2,... ,wn], provided by the results of the AHP analysis, to ensure that the risk contributions of the input vectors remain proportionally consistent within the internal structure of the model. Table 4 summarizes the magnitude normalization parameters for each input indicator and their corresponding weight assignment values. This parameter setting strategy not only strengthens the front-end controllability of the model, but also lays the data foundation for the realization of multidimensional information fusion in the subsequent algorithm construction.

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Table 4 Model input parameter standardization setting and weight allocation

Indicator name	Original scale	Normalization method	Normalization interval	Weight wi
Blasting powder (kg/m³)	Real number	Min-Max	[0,1]	0.312
Ventilation air volume (m³/min)	Actual	min-max	[0,1]	0.186
Response time (s)	Real	Min-max	[0,1]	0.241
Human-operated compliance (rating)	Grade Score	Scale Mapping	[0,1]	0.261

4.1.2 Design of evaluation algorithm

On the basis of completing the normalization of indicators and the setting of weight input structure, design the safety assessment algorithm of blasting stage based on weighted fuzzy comprehensive evaluation model. The model adopts fuzzy mathematical principles to transform multi-dimensional uncertainty information into risk level output, with strong fault tolerance and nonlinear identification ability. The assessment process is centered on the fuzzy affiliation function construction, and let the indicator vector be X=[x1,x2,... ,xn], and the corresponding weight vector is W=[w1,w2,... ,wn], the fuzzy relationship matrix R is constructed, and the fuzzy synthesized output is realized by the following operation [8]:

$$B = W \cdot R$$

Where R=[rij] denotes the degree of affiliation of indicator xi to risk level j. A triangular affiliation function is used for mapping to guarantee the smooth transition of each level interval. The final fuzzy output vector B determines the safety state level in which the system is located by the maximum affiliation principle method. The algorithm design scheme not only conforms to the high coupling and high uncertainty characteristics of the risk in the blasting operation stage, but also provides the accuracy and stability basis for the model validation stage.

4.2 Assessment process design

Based on the construction of the indicator system and the design of the fuzzy comprehensive assessment algorithm, the assessment process model of the operational safety status in the blasting stage is constructed, aiming at realizing the closed-loop management from risk perception to grade

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determination. The assessment process is divided into five steps: data collection, indicator preprocessing, affiliation calculation, fuzzy comprehensive reasoning and result interpretation, in which the data collection link through the sensor real-time access to the core variables such as the amount of blasting powder, wind, response time, etc., and the preprocessing module is based on Table 4-1 for normalization and weight loading [9]. Then the system calls the above algorithm module to transform the affiliation function of each index and construct the fuzzy relationship matrix R, and then complete the fuzzy operation B=W·R through the weight vector W to output the risk level vector. The final assessment result will be determined by the maximum affiliation principle to determine the current operating state, output the assessment report and feedback to the mine safety scheduling system to realize intelligent response. Figure 2 shows the block diagram of the system structure of the complete assessment process, in which the module interfaces support later model expansion and module iteration, with good deployment versatility and engineering integration.

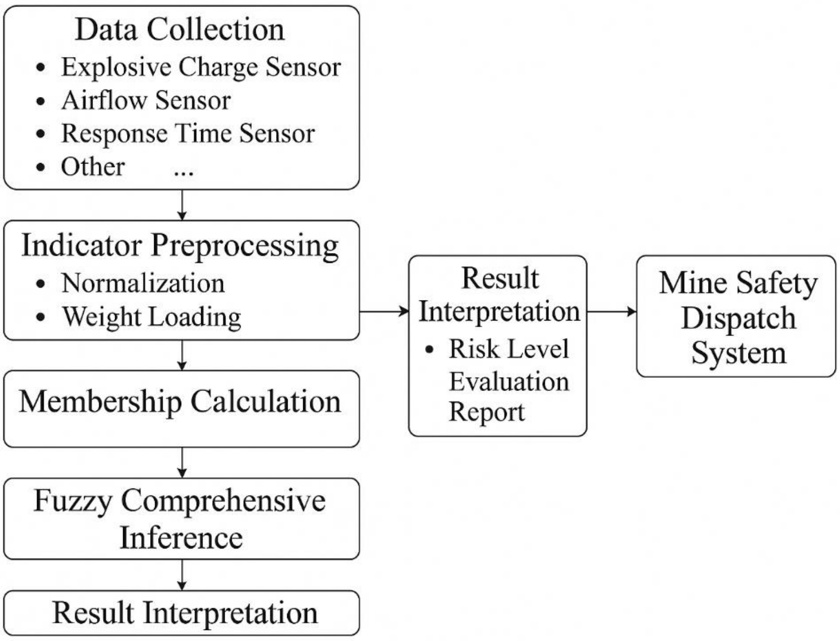

Figure 2: Flow chart of underground mine blasting stage safety assessment system.

5 case validation and analysis

5.1 an underground mine blasting project example

In order to verify the applicability and engineering responsiveness of the constructed underground mine blasting phase safety assessment system, a typical lead-zinc mine in Panxian County, Guizhou Province, is selected as an empirical object. The mine uses the horizontal segmented

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air field method for mining, the depth of the underground operation reaches 620 meters, blasting operations are mainly concentrated in the -450 m level to -500 m level between the average daily use of explosives is about 120 kg, the ventilation air volume of the operating section is maintained at 200 to 240 m³/min range, the deployment of GAS-300 series gas monitoring system and multi-channel blasting network trigger system. The blasting parameters, ventilation indicators and response time data collected on site are normalized and weighted, and then inputted into the fuzzy comprehensive model for dynamic evaluation [10]. The system automatically identifies the triangular affiliation function intervals of the input parameters and constructs the fuzzy relationship matrix; the corresponding input parameters are listed in Table 5, in which the human operation compliance is converted by the score of the operation record, reflecting the degree of standardization of the behavior of the field personnel. On this basis, the model completes multi-dimensional fuzzy inference and intermediate calculations before grade conversion, which guarantees the accuracy and controllability of the system's risk characterization in a highly dynamic blasting environment.

Table 5 Sampling values of key input parameters of blasting engineering

Indicator name	Original value	Unit	Normalized value	Weight (wi)
Blasting powder	1.12	kg/m³	0.733	0.312
Ventilation air volume	230 m³/min	m³/min	0.833	0.186
Gas response time	18	s	0.800	0.241
Human Operational Compliance Score	Level 4 (out of 80)	Grade Rating	0.800	0.261

5.2 Analysis of model application effect

After inputting the above data into the completed fuzzy comprehensive assessment model, the system first automatically completes the construction and weighting calculation of the affiliation matrix of each index, and outputs the fuzzy assessment results of the blasting operation status. According to the principle of maximum affiliation, the blasting operation of a mine is recognized as "medium risk", and the corresponding comprehensive assessment value is 0.524. Figure 3 shows the affiliation distribution of the fuzzy output vectors in the five risk level intervals, which reflects the sensitivity of the system under the interaction of multiple source indicators. The average single-round

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computation time of the model is less than 0.8s under the MATLAB platform, which has good real-time and adaptability. Comparing the ventilation disturbance and gas monitoring alarm records at the later stage of the blasting operation, we found that the predicted level of the model is highly consistent with the actual risk performance, which verifies the predictive validity and assessment credibility of the constructed assessment system. In addition, by comparing with the traditional empirical scoring method (Table 6), it can be found that the model has a significant improvement in risk differentiation and grade accuracy, especially in the high-dimensional coupling conditions, which shows better risk aggregation identification ability.

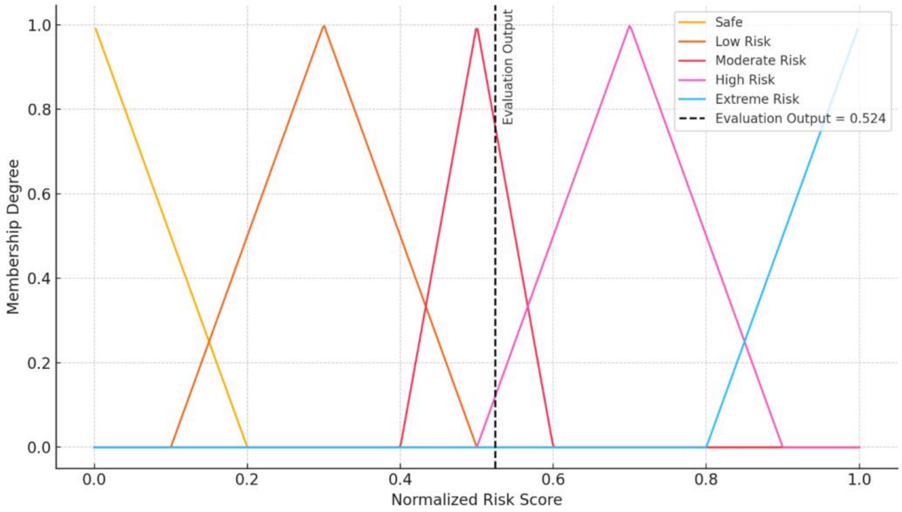

Fig. 3 Distribution of fuzzy comprehensive assessment output results in terms of affiliation degree

Table 6 Comparative analysis of model evaluation results and traditional methods

Item	Fuzzy model output grade	Comprehensive score value	Assessment response time (s)	Differentiation improvement (%)
Fuzzy comprehensive assessment system built	Moderate hazard	0.524	0.78	-
Traditional empirical method (manual scoring mean)	Slightly dangerous	0.410	10.2	+27.8%

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Conclusion

Based on the concept of risk closed-loop management, the safety assessment system of blasting stage in underground mines systematically integrates the heterogeneous risk characteristics of multiple sources through the three-dimensional framework of "risk source-impact path-accident consequence", innovatively integrates the Delphi method, the coefficient of variation method and the hierarchical analysis method to realize the scientific assignment of the indicators and establishes the five-level risk threshold standard. The weighted fuzzy comprehensive evaluation model effectively solves the problem of quantitative characterization of high coupling and strong dynamic risk in blasting operation, and empirically verifies that its assessment response speed and risk level discrimination accuracy are significantly better than traditional methods. However, the adaptability of the system to extreme geological mutations still needs to be deepened, and there are limitations in the ability of real-time dynamic monitoring of human behavior indicators. It is urgent to integrate deep learning algorithms to enhance the disaster chain prediction capability, develop underground edge computing terminals to improve the real-time in situ assessment, and expand the case base of multi-mining areas and multi-mining methods to verify the universality of the system migration.

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