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Intelligent Quality Evaluation System for Vertical Shaft Blasting and Its Application

XINMIN MA[1], ZHENYU CHEN[2,3], PAN CHEN[1], YUAN JIN[1], YUE WANG[4], LIYUN YANG[1], AND ZHAORAN ZHANG[5]

[1]School of Mechanics and Civil Engineering, China University of Mining and Technology, Beijing 100083, China
[2]Big Data Center, State Grid Corporation of China, Beijing 100031, China
[3]China Electric Power Research Institute, Beijing 100192, China
[4]School of Management, China University of Mining and Technology, Beijing 100083, China
[5]School of Civil Engineering, North China University of Technology, Beijing 100141, China

Corresponding author: Zhenyu Chen (czy9907@gmail.com)

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ABSTRACT Blasting quality is a key factor in determining the productivity and total cost of the shaft blasting excavation construction, so it is of great engineering and theoretical importance to evaluate blasting quality rationally. The existing evaluation methods rely more on previous experience and the knowledge level of technicians, which are more subjective and cannot be judged by quantitative or unified standards, so the evaluation results have limitations. This paper proposes the Analytic Hierarchy Process (AHP) based on Particle Swarm Optimization (PSO) to obtain the weights of each index for evaluating the blasting quality of shafts, then combine expert knowledge, field engineering experience and statistical data for a comprehensive analysis to determine the quantitative interval of blasting quality evaluation index levels and construct a blasting quality evaluation index system, which makes the evaluation indexes more accurate and more in line with reality. The PSO-AHP combined with fuzzy comprehensive evaluation technique has constructed a blasting quality evaluation matrix more in line with the engineering reality and established a shaft blasting quality evaluation model adapted to different geological conditions. Finally, the established blasting quality evaluation model is combined with computer programming and artificial intelligence technology to develop a visualized shaft blasting quality intelligent evaluation system, which meets the practical needs of front-line operators in the field to evaluate the blasting quality objectively and reasonably, and achieves the accuracy, objectivity and intelligence of shaft blasting quality evaluation.

INDEX TERMS Particle swarm optimization (PSO), analytic hierarchy process (AHP), fuzzy mathematics, shaft blasting, result assessment.

I. INTRODUCTION

Blasting is an important coal mining method, and in practice, the level of technology, construction techniques, worker operations and geological conditions are the four main factors that affect the effectiveness of blasting. For example, these factors may cause serious over-excavation, low excavation speed, high powder factor and high concussion of blasting. Under the same level of technology, only good construction management can better play the advanced technology. Therefore, it is of great significance to improve the quality of blasting by establishing quantitative evaluation index system for shaft blasting to reduce project cost, improve construction speed and ensure construction safety.

A large number of scholars have carried out in-depth and extensive research on technical issues such as how to evaluate and improve the blasting efficiency in mines. In 1986, M. A. Kayupov and M. G. Abuov [1] studied the evolution of dynamic stress in rock masses during blasting. Based on the transportation cost as the main parameter, H Taherkhani and R Doostmohammadi [2] conducted a surface mine blasting quality evaluation studying at Angouran mine. And through sensitivity analysis, it was found that the uniaxial compressive strength of the rock, the inclination of the working face and joint have the greatest influence on blasting, which in turn influence the transportation cost. Shapiro V Y [3] studied a method for evaluating the effect of roadway

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shaping in drifting blasting based on the multi-criteria optimization principle, by calculating and analyzing the relevant parameters form a theoretical point of view. D. Jahed Armaghani *et al.* [4] improved the traditional empirical method to predict blasting fly-rock in mine stopes and used an Artificial Neural Network (ANN) and Adaptive Neural Fuzzy Inference System (ANFIS) to predict and evaluate blasting fly-rock V. N. Tyupin and Rubashkin [5] determined the stress of the rock by blast energy and obtained the theoretical equation for calculating stress based on the size of the fracture zone and fissured zone, the physical and mechanical properties of the rock and the explosive characteristics of the explosive. Yari M. *et al.* [6] used the AHP-TOPSIS method to sort the blasting styles of the Sungun copper mine and determined the most suitable blasting scheme. Shen *et al.* [7] conducted extension evaluation of the blasting quality extension of jointed rock tunnel by entropy assignment weight method. Zou *et al.* [8] established a three-dimensional visual digital model for tunnel blasting quality and proposed a comprehensive evaluation method. Li *et al.* [9] adopted a Systematic Engineering Approach to comprehensively evaluate blasting safety, quality and economy in surface mines, and established a comprehensive evaluation model to realize the management of blasting quality in surface mines. Yi *et al.* [10] systematically analyzed and demonstrated the sampling, image recognition, quality conversion, error correction and distribution function calculation involved in the evaluation process of blockiness evaluation system of blasted pile in surface mines, and established a systematic method for quantitative evaluation system of blast blockiness accordingly. Wang *et al.* [11] developed a BP neural network model to predict the blasting effect of shaft. Zhang [12] carried out comprehensive evaluation research, and analysis of the impact factors of drilling drift excavation. Jiang *et al.* [13] established the blasting effect's comprehensive evaluation system of surface mines by using the theory of the Analytic Hierarchy Process. Zou *et al.* [14] developed a handheld mobile platform to propose the evaluation and control the performance of the tunnel smooth blasting quality. M. Hasanipanah *et al.* [15] developed a blasting prediction and evaluation model, and applied it to an engineering case in Iran. Yang *et al.* [16] developed a rock drifting blasting parameter optimization system.

The above analysis has better promoted the development of blasting quality evaluation and predictive management technology in different fields, but for the evaluation of the shaft blasting, there are certain limitations in both technical means and applicability. The main limitations are listed as follows: The first is that there are few reports in the literature on blasting quality evaluation of vertical shafts, a few kinds of literature can be applied for reference. The second is that in other blasting engineering fields, such as surface mines tunneling blasting, etc, the importance of parameter selection for evaluation is often ignored, or key evaluation indicators are arbitrarily selected without scientific and reasonable derivation and verification, which to a certain extent will affect the accuracy and rationality of evaluation quality. The third is that the influencing factors of blasting engineering effects in different fields are complex, but the blasting quality evaluation parameters chosen are all very single, which cannot fully reflect and objectively evaluate the true blasting quality.

With the advancement of science and technology, artificial intelligence technology has been widely used in many fields [17], [18]. In this study, a fuzzy mathematics evaluation method based on PSO improved AHP is proposed, and an intelligent evaluation system for the shaft blasting quality is developed accordingly. Compared with the traditional blasting quality evaluation methods, the method proposed in this paper better achieves the objectivity and accuracy of blasting quality evaluation. The advantages are mainly reflected in the following aspects. First, the AHP based on PSO is used to obtain the weight values of factors affecting blasting effect, and the key technical indexes of shaft blasting quality evaluation are determined by considering blasting theory and expert experience, which provides a reliable basis for objective and accurate blasting quality evaluation. Second, based on blasting theory and engineering practice statistics, blasting experts' experience and knowledge in the field of blasting are integrated to propose the quantification method of blasting quality evaluation indexes and establish the quantification interval of each evaluation index level to make the standard of blasting quality evaluation more objective. Third, the AHP based on PSO and a fuzzy mathematical method are proposed to establish a shaft blasting quality evaluation model, which makes the evaluation results more accurate. Fourth, the combination of computer development and artificial intelligence technology has established an intelligent evaluation system for the shaft blasting quality, which realizes objective, accurate and intelligent evaluation of the shaft blasting quality, and the application in engineering proves the reliability and feasibility of the method in this paper.

II. INTELLIGENT QUALITY EVALUATION SYSTEM STRUCTURE OF VERTICAL SHAFT BLASTING

The structural design of the shaft blasting quality inspection system is based on modularization and flow, which is conducive to achieving the high efficiency, stability and hermeticity of the system. The structure design of the whole system mainly covers the functions of the human-machine interaction interface (user login), project creation, data management, standards development, knowledge base, database, inference engine, interpretation mechanism, and so on. The system structure design is shown in FIGURE 1.

III. ESTABLISHMENT OF EVALUATION INDEX SYSTEM FOR SHAFT BLASTING QUALITY

A. STUDY ON INFLUENCING FACTORS OF VERTICAL SHAFT BLASTING QUALITY

Determining key influencing factors and establishing evaluation index system are prerequisites for blasting quality evaluation. In the current research by experts and scholars, there are

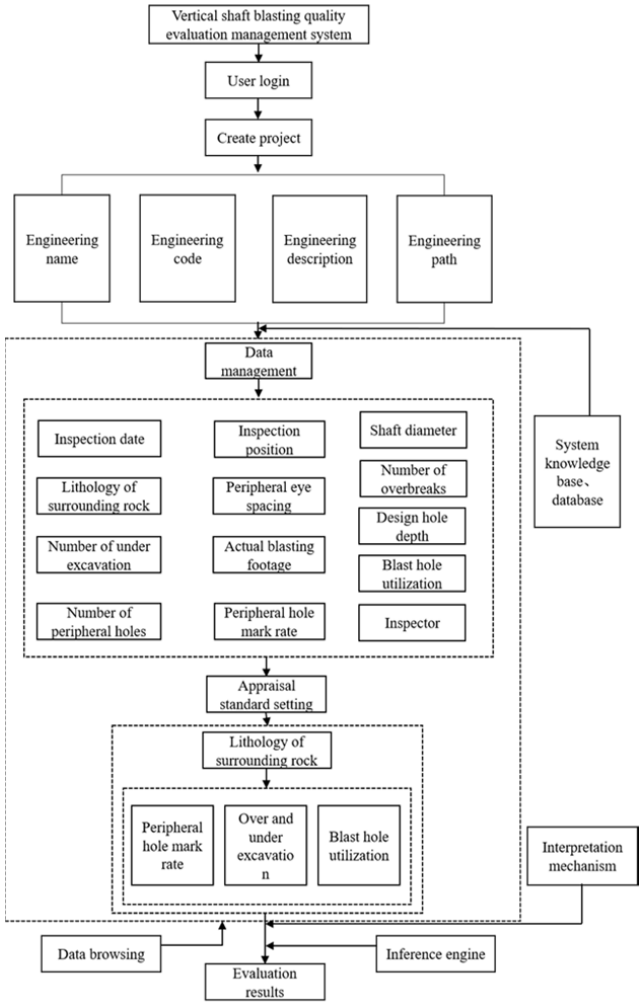

FIGURE 1. Quality inspection system structure flow chart.

few studies on the determination of key influencing factors and specific indicators for the evaluation of shaft blasting quality. In this paper, based on a comprehensive analysis of blasting theory, engineering practice cases, experts' experience and research results of experts and scholars in the field the main influencing factors of the shaft blasting quality. are innovatively determined, and classify the influencing factors according to the factors of tunneling speed, blasting effect, construction safety and construction cost, which contain several subfactors under each factor. The classification system of indexes affecting blasting quality is shown in FIGURE 2.

(1) The tunneling speed includes two indicators, namely the single-cycle footage and blast hole utilization rate. Single-cycle footage is one of the most important indicators reflecting the excavation speed, and the utilization rate of the blast hole reflects the energy utilization of explosives, both of which are important parameters during blasting.

(2) The blasting effect mainly refers to the quality of blasting excavation. The half-hole marks rate reflects the quality of smooth blasting, and the oversize yield rate is a quantitative index for the reasonable use of blasting energy.

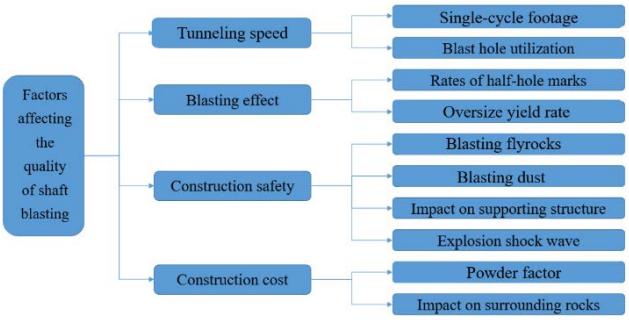

FIGURE 2. Factor classification system.

(3) The safety construction is the first prerequisite for vertical shaft blasting, blasting flyrocks, blasting fume, dust and blasting damage to the support structure can reflect the blasting safety situation, but also an important indicator of single-cycle blasting technology.

(4) The construction cost is one of the core indicators of the production of mining enterprises. High powder factor and overbreak or underbreak will cause the increase of direct and indirect costs, which is not conducive to the safe and efficient production and operation of coal enterprises.

B. DETERMINING THE EXCAVATION INDEX WEIGHT OF BLASTING QUALITY BASED ON PSO-AHP

In multi-objective decision-making [19], scientifically and rationally determining the key indicators is one of the core tasks in the evaluation of shaft blasting quality. In this paper, we use the improved AHP to analyze the weights of 10 factors affecting the quality of shaft blasting, so as to determine the key indicators for blasting quality evaluation. Analytic Hierarchy Process (AHP) in systems engineering theory is a good method to determine the weights, which is a multi-objective and multi-criteria decision-making method that can divide the factors in a complex problem into an orderly hierarchy of related factors and makes them organized. The AHP has a wide range of applications, in many fields, but there are few reports on weight analysis of the blasting influencing factors, which is the main content of this study. As the scoring of various factors has the limitation of the subjective tendency, the determination of key indicators needs to be more scientific and reasonable. The specific implementation steps are as follows:

1) ESTABLISHMENT OF THE HIERARCHICAL MODEL

The target is set to the highest level of the model, that is the target layer. Factors with common characteristics are divided into the same group, and the four groups of factors composed the criterion layer, which is also called the transition layer. The factors for weight analysis are the bottom layer, also called the indicator layer. Using the AHP to analyze the ten factors affecting shaft blasting effectiveness identified from our study, a hierarchical structure model of the shaft blasting effect index is established, as shown in FIGURE 3.

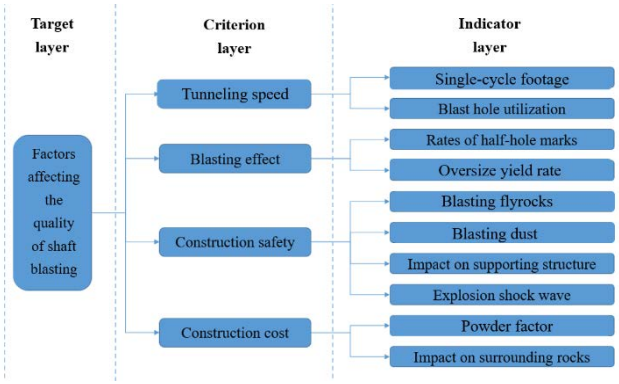

FIGURE 3. Hierarchical model.

2) THE ESTABLISHMENT OF A COMPARISON MATRIX

There are many factors involved in the process of shaft blasting quality evaluation, and different factors are closely related to each other but are independent and representative of each other. Therefore, in the actual blasting quality evaluation, it is necessary to distinguish the differences between various factors and objectively evaluate the impact of various factors on blasting quality.

After fully considering the characteristics of shaft blasting quality evaluation factors, we select the more suitable 9-scale method, when analyzing the weights of the influencing factors using the AHP. The 9-scale method is more finely divided and can reflect the nuances between factors. The uniformity of its scales and the memorability and perceptibility of the scale values are the best. In addition, this method not only can clearly evaluate and judge the importance and importance magnitude among the functions, but also can check and maintain the consistency of the evaluation process. Therefore the 9-scale method is the most commonly used scale in the AHP, which uses nine numbers between 1 and 9 (and their reciprocals) as evaluation elements to scale the relative importance of each function and form a judgment matrix. The judgment matrix is a comparison of the relative importance of all factors in this layer against a factor in the previous layer.

Experts in the blasting field are invited to score the importance of the factors in the comparative structural model and obtain the corresponding comparison matrix R, as shown in equation (1).

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nn} \end{bmatrix} \tag{1}$$

where, $r_{ij} = \frac{1}{n}\sum_{k=1}^{n}(a_{ik} + a_{kj})$, a_{ik} is the value of the i-th row and k-th column in the comparison matrix, a_{kj} is the value of the k-th row and j-th column in the comparison matrix, and n is the number of rows or columns of the value in the comparison matrix, where, r_{ij} is the result of the inter-factor importance comparison between the i-th and j-th factors using the 9-level method, which can be classified as ''absolutely important'', ''very important'', ''relatively important'', ''slightly important'', ''equally important'', ''absolutely unimportant''. The comparison table between factors is shown in TABLE 1. When determining the weights between factors at each layer, it is not easy to be accepted if the results are only qualitative. Therefore, two-by-two comparisons of factors of different natures are made instead of comparing all factors together to minimize the difficulty of comparison and thus ensure accuracy of the results. The comparison results in TABLE 1 provide expert-level suggestions for the reasonable determination of the importance weights of each influencing factor which ensures the accuracy and reasonableness of the weight values of each factor.

TABLE 1. Importance comparison table between factors.

Factor contrast importance	F(i, j)
i is just as important as j	1
i is slightly more important than j	3
i is more important than j	5
i is more important than j	7
i is absolutely more important than j	9
i is slightly less important than j	1/3
i is less important than j	1/5
i is less important than j	1/7
i is never more important than j	1/9

We invite six experts in the field of blasting to compare and evaluate the relative importance between the above indicators. Because in the traditional single-level analysis method, the subjectivity of the experts has a large influence on the results of the evaluation, which is an adverse influence on the construction of the judgment matrix. Therefore, we use a Particle Swarm Optimization algorithm to correct the original matrix of experts' scoring.

IV. PSO-AHP MODEL ESTABLISHMENT

A. BASIC THEORY OF PSO

The Particle Swarm Optimization (PSO) originated from the study of birds flock predation behavior and was proposed by Eberhart and Kennedy in 1995[21]. It originated from the study of birds swarm predation behavior [22]. The PSO is initialized as a group of random particles (random solutions). The optimal solution is then found through iteration. In each iteration, the particles update themselves by tracking two ''extreme values'' (pbest, gbest).

The PSO uses the following equation to update the particle state, the dth dimensional velocity update equation of particle i [23], [24]:

Suppose that in an N-dimensional search space, a population of m particles is formed, each particle has two attributes: position and velocity, and let the position of the i-th particle

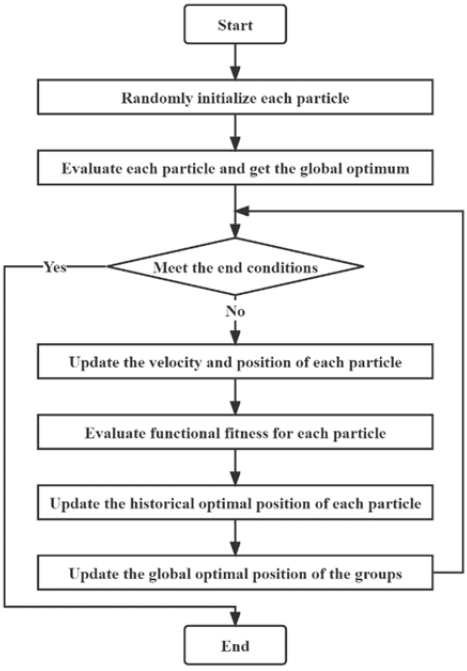

FIGURE 4. POS algorithm flow.

be denoted as $X_i = (x_{i1}, x_{i2}, \ldots, x_{id})$, $i = 1, 2, \ldots, m$; The velocity of the i-th particle is expressed as $V_i = (v_{i1}, v_{i2}, \ldots, v_{id})$, $i = 1, 2, \ldots, m$. As the position and velocity are updated, the global optimal solution and the local optimal solution are continuously updated, and the current fitness of the objective function is calculated using each particle property, and the optimal fitness value is found by iterative updating.The velocity and position of each particle is updated by Eq:

$$v_{id}^{k+1} = wv_{id}^{k} + c_1 r_1 (pbest_{id} - x_{id}^{k}) + c_2 r_2 (gbest_{id} - x_{id}^{k}) \tag{2}$$

The dth dimensional position of particle i is updated by Eq:

$$x_{id}^{k+1} = x_{id}^{k} + v_{id}^{k} \tag{3}$$

C_1 and C_2 is the learning factor, usually taken $C_1 = C_2 = 2$.

K is the current number of iterations; r_1 and r_2 are random numbers with values between (0,1); ω is the inertia factor, non-negative; *pbest* denotes the local optimal solution; *gbest* denotes the global optimal solution; $v_{id} \in$ [-*vmax*,*vmax*], *vmax* is a constant.

The algorithm flow is as follows:

B. IMPLEMENTATION OF PSO-AHP ALGORITHM

The weights obtained by AHP are optimized using PSO [25]–[27].

(1) PSO-AHP model operation prep

Step 1. To establish a hierarchical structure model of key indicators affecting blasting effect, three levels are established in this paper, which are recorded as A, B and C in order. Layer A is the target layer with only one factor, B and C are the criterion layer and the indicator layer respectively, and the number of their factors are recorded as n_b and n_c respectively.

Step 2. Using the 1 to 9 scale method, the judgment matrix of each layer is constructed. For layers B and C, the elements of the previous layer are used as guidelines for two-by-two comparison, and the scale method of 1∼9 is used to describe the relative importance among the factors, taking the judgment matrix of layer B as an example, which can be expressed as $R = (r_{ij})nb \times nb$.

Step 3. The key parameters of the PSO are determined, mainly including the number of particle swarms m, the maximum number of iterations K, the learning factors c_1 and c_2, the variation range of the inertia coefficient v_{in} [-*vmax*, *vmax*], etc.

(2) PSO for weight optimization

Step 1. Generate initial solutions of particles: generate random numbers in the solution space within (0,1) and normalize them.

Step 2. The values in Step 1 are brought into the objective function of equation (5) to calculate the fitness of the initial particles, and the global optimal particles are selected from them.

$$\sum_{i=1}^{n_b} \left| \sum_{k=1}^{n_b} (a_{ik} w_k) - n_b w_i \right| = 0 \tag{4}$$

$$MinCIF\ (n_b) = \sum_{i=1}^{n_b} \left| \sum_{k=1}^{n_b} (a_{ik} w_k) - n_b w_i \right| / n_b \tag{5}$$

where CIF(n_b) is the consistency index function; w_k is the single ranking weight of each factor in each layer, $k = 1 \sim n_b$.

Step 3. Iterate the particle update according to equations (2) and (3).

Step 4. Judge whether the updated particles satisfy the equation (6), if not, the particles should be normalized.

$$\begin{cases} \sum_{k=1}^{n_b} w_k = 1 \\ w_k > 0\ (k = 1 \sim n_b) \end{cases} \tag{6}$$

Step 5. Calculate the fitness value of the particle, find the individual optimal *pbest* that each particle can find by continuously updating the position, compare the optimal value with each new *pbest*, which optimal is updated to the global optimal *gbest*, and update the global optimal *gbest* step by step with the update iteration of one particle.

Step 6. Determine whether the optimal solution found meets the convergence condition, if not, skip to Step 3. If it is satisfied, output the result.

(3) Output the global optimal position and the corresponding weight values and consistency index function values.

The modified weight matrix obtained based on PSO-AHP is as follows:

(1) Key factors of the shaft blasting quality evaluation—blasting effect.

The key factor of the shaft blasting quality evaluation blasting effect corrected weight matrix for calculation.

Six experts in the field of blasting were invited to score the importance of pairwise comparison of the key indexes of the shaft blasting quality evaluation. Each expert forms their comparison matrix after scoring, and then checks the consistency according to equation (19), and corrects the unqualified matrix according to the PSO. The comparison matrices of experts 1 to 6 are as follows: Where R''5 are modified matrices.

$$R_1' = \begin{bmatrix} 1 & 1 & 5 & 7 \\ 1 & 1 & 7 & 7 \\ \frac{1}{5} & \frac{1}{7} & 1 & 1 \\ \frac{1}{7} & \frac{1}{7} & 1 & 1 \end{bmatrix} \tag{7}$$

$$R_2' = \begin{bmatrix} 1 & 1 & 7 & 7 \\ 1 & 1 & 7 & 7 \\ \frac{1}{7} & \frac{1}{7} & 1 & 1 \\ \frac{1}{7} & \frac{1}{7} & 1 & 1 \end{bmatrix} \tag{8}$$

$$R_3' = \begin{bmatrix} 1 & 1 & 5 & 3 \\ 1 & 1 & 7 & 7 \\ \frac{1}{5} & \frac{1}{7} & 1 & 1 \\ \frac{1}{3} & \frac{1}{7} & 1 & 1 \end{bmatrix} \tag{9}$$

$$R_4'' = \begin{bmatrix} 1 & 1.1347 & 7.6712 & 8.1429 \\ 0.8813 & 1 & 3.4899 & 10.1391 \\ 0.1304 & 0.2865 & 1 & 5.9896 \\ 0.1228 & 0.0986 & 0.167 & 1 \end{bmatrix} \tag{10}$$

$$R_5'' = \begin{bmatrix} 1 & 0.424 & 5.0329 & 4.9468 \\ 2.3587 & 1 & 6.9162 & 5.0423 \\ 0.1987 & 0.1446 & 1 & 2.8867 \\ 0.2022 & 0.1983 & 0.3464 & 1 \end{bmatrix} \tag{11}$$

$$R_6' = \begin{bmatrix} 1 & \frac{1}{5} & 5 & 5 \\ 5 & 1 & 7 & 7 \\ \frac{1}{5} & \frac{1}{7} & 1 & 1 \\ \frac{1}{5} & \frac{1}{7} & 1 & 1 \end{bmatrix} \tag{12}$$

Because the six experts are of the same level, the importance of scoring is equal. According to the comparison matrix or modified comparison matrix passed by the consistency test of the six experts, the geometric average of the corresponding positions is calculated to form the degree of membership matrix R_1. The specific implementation process of geometric average is as follows:

Calculate the $1/n$ power of the numerical product of the corresponding positions of n comparison matrices, where $n = 6$. The degree of membership matrix is denoted as R_1.

$$R_1 = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nn} \end{bmatrix}_{(n=6)} \tag{13}$$

The geometric mean of the parameters at each position in the matrix is obtained, as equation (14) shows.

$$r_{ij} = \sqrt[n]{R_{(1)ij} \cdot R_{(2)ij} \cdot \ldots \cdot R_{(n)ij}} \tag{14}$$

Among them, $R_{(1)ij}, R_{(2)ij}, \ldots\ldots R_{(n)ij}$ represents the comparison matrices obtained by each of the six experts.

Finally, the group composition matrix is obtained as follows:

$$R_1 = \begin{bmatrix} 1 & 0.6769 & 5.6857 & 5.562 \\ 1.4773 & 1 & 6.2209 & 7.0497 \\ 0.1759 & 0.1607 & 1 & 1.6081 \\ 0.1798 & 0.1418 & 0.6219 & 1 \end{bmatrix} \tag{15}$$

where, $\lambda_{(n)ij} = 4.0303$, $CR = 0.0113$, $CI = 0.0101$, $0.010<0.1$. It meets the requirements of consistency. The weight of each factor of the blasting effect: {*single cycle footage, blast hole utilization rate, half-hole marks rate, oversize yield rate*}={0.3706, 0.4888, 0.0795, 0.0611}. Matrix R_1 normalize by columns.

The specific calculation method is as follows:

$$\overline{r_{ij}} = \frac{r_{ij}}{\sum_{k=1}^{n} r_{kj}} (i, j = 1, 2, \cdots\cdots, n) \tag{16}$$

$$G_1 = \begin{bmatrix} \overline{r_{11}} & \overline{r_{12}} & \cdots & \overline{r_{1n}} \\ \overline{r_{21}} & \overline{r_{22}} & \cdots & \overline{r_{2n}} \\ \vdots & \vdots & \ddots & \vdots \\ \overline{r_{n1}} & \overline{r_{n2}} & \cdots & \overline{r_{nn}} \end{bmatrix} \tag{17}$$

The specific calculation process is as follows:

$$\begin{aligned} \overline{r}_{11} &= \frac{\overline{r}_{11}}{\overline{r}_{11} + \overline{r}_{21} + \overline{r}_{31} + \overline{r}_{41}} \\ &= \frac{1}{11.4773 + 0.1759 + 0.1798} = 0.353 \\ \overline{r}_{12} &= \frac{\overline{r}_{12}}{\overline{r}_{12} + \overline{r}_{22} + \overline{r}_{32} + \overline{r}_{42}} \\ &= \frac{0.6769}{0.6769 + 1 + 0.1607 + 0.1418} = 0.342 \end{aligned}$$

And so on:

$$G_1 = \begin{bmatrix} 0.353 & 0.342 & 0.4203 & 0.3654 \\ 0.5215 & 0.5052 & 0.4598 & 0.4632 \\ 0.0621 & 0.0812 & 0.0739 & 0.1057 \\ 0.0635 & 0.0717 & 0.046 & 0.0657 \end{bmatrix} \tag{18}$$

No matter the weight distribution obtained above is reasonable, it is also necessary to perform a consistency check on the judgment matrix.

The test is performed using equation (19):

$$CR = CI/RI \tag{19}$$

equation (19) is a common equation in the AHP, which is used to calculate the consistency ratio after calculating the consistency index *CI*. When *CR*<0.1, the consistency of the judgment matrix is generally considered acceptable. Where *CR* is the random consistency ratio of the judgment matrix, *CI* is the general consistency index of the judgment matrix and can be expressed as equation (20).

$$CI = (\lambda_{max} - n) / (n - 1) \tag{20}$$

For the multi-order judgment matrix, the average random consistency index *RI* (Random Index) is introduced, which is obtained by taking the arithmetic average after repeating the calculation of the characteristic roots of the random judgment matrix several times. According to equation (19), to perform the consistency test, it is necessary to give the *RI* value, which needs to be obtained by calculating. The *RI* values of the judgment matrix of order 1-9 calculated according to the literature [28] are shown in TABLE 2.

TABLE 2. Judgment matrix *RI* value.

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46

When the *CR* of the judgment matrix *P* is less than 0.1 or $\lambda_{max} = n$, *CI*=0, it is considered that *P* has satisfactory consistency. Otherwise, the elements in *P* need to be adjusted to make it have satisfactory consistency.

λ_{max} is the maximum eigenvalue of a matrix the following main functions.

1) According to the judgment matrix, the feature vector *w* corresponding to the maximum eigenvalue λ_{max} is obtained. The calculation equation is as follow:

$$P_w = \lambda_{max} \cdot w \tag{21}$$

The feature vector *w* is normalized to rank the importance of each evaluation factor, that is, the weight distribution.

2) According to the maximum eigenvalue, the consistency of the matrix is checked. The calculation equation is:

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(Aw)_i}{\mathrm{n}w_i} \tag{22}$$

In the equation (22), $(Aw)_i$ Represents its *n*th element is the matrix dimension, and $Aw=R\cdot W_i$, *R* is the judgment matrix.

$$\lambda_{max} = (\sum(Aw/w))/n = 4.0303, \quad n = 4$$

For a fourth-order matrix, according to TABLE 2, *RI*=0.89.

$$CI = (\lambda_{max} - n)/(n-1) = (4.0303 - 4)/(4-1) = 0.0101$$
$$CR = CI/RI = 0.0101/0.89 = 0.0113$$

(2) Key factors of the shaft blasting quality evaluation—construction safety.

The key factors affecting the safety of blasting construction include blasting flyrock, blasting dust, impact on support structures and blasting shock waves.

The scoring matrix of experts 1 to 6 is as follows (all passed the consistency test):

$$R_1' = \begin{bmatrix} 1 & 5 & 1 & 1 \\ \frac{1}{5} & 1 & \frac{1}{3} & \frac{1}{3} \\ 1 & 3 & 1 & 3 \\ 1 & 3 & \frac{1}{3} & 1 \end{bmatrix} \tag{23}$$

$$R_2' = \begin{bmatrix} 1 & 3 & 1 & 1 \\ \frac{1}{3} & 1 & \frac{1}{3} & \frac{1}{3} \\ 1 & 3 & 1 & 3 \\ 1 & 3 & \frac{1}{3} & 1 \end{bmatrix} \tag{24}$$

$$R_3' = \begin{bmatrix} 1 & 3 & 1 & 1 \\ \frac{1}{3} & 1 & \frac{1}{3} & \frac{1}{3} \\ 1 & 3 & 1 & 1 \\ 1 & 3 & 1 & 1 \end{bmatrix} \tag{25}$$

$$R_5' = \begin{bmatrix} 1 & 3 & 1 & 1 \\ \frac{1}{3} & 1 & \frac{1}{3} & \frac{1}{3} \\ 1 & 3 & 1 & 3 \\ 1 & 3 & \frac{1}{3} & 1 \end{bmatrix} \tag{26}$$

$$R_6' = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix} \tag{27}$$

The six experts have the same level, and their scoring weights are equal. Therefore, based on the six comparison matrices passed by the consistency test, the geometric mean of the corresponding positions is calculated and the degree of membership matrix R_2 is obtained.

$$R_2 = \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} \\ r_{21} & r_{22} & r_{23} & r_{24} \\ r_{31} & r_{32} & r_{33} & r_{34} \\ r_{41} & r_{42} & r_{43} & r_{44} \end{bmatrix} \tag{28}$$

According to the equation (14), R_2 is calculated as follows:

$$R_2 = \begin{bmatrix} 1 & 3.1326 & 1.3077 & 1 \\ 0.3192 & 1 & 0.4003 & 0.4003 \\ 0.7647 & 2.4981 & 1 & 1.7321 \\ 1 & 2.4981 & 0.5773 & 1 \end{bmatrix} \tag{29}$$

where, $\lambda_{max} = 4.0644$, *CR*=0.0241, *CI*=0.0215, the weights of each index affecting the safe construction of blasting can be calculated as: {*blasting flyirock, blasting dust, impact on support* structures, *blasting shock waves*}={0.3276, 0.1095, 0.3106, 0.2523}. The results matrix G_2 of R_2 normalized by

column is as follows:

$$G_2 = \begin{bmatrix} 0.3243 & 0.3432 & 0.398 & 0.242 \\ 0.1035 & 0.1095 & 0.1218 & 0.0969 \\ 0.248 & 0.2736 & 0.3044 & 0.4191 \\ 0.3243 & 0.2736 & 0.1757 & 0.242 \end{bmatrix} \quad (30)$$

The random consistency ratio CR of the matrix is calculated as follows:

$$\lambda max = (\sum (Aw/w))/n = 4.0644, RI = 0.89, \quad n = 4 \quad (31)$$

$$CI = (\lambda max - n)/(n-1)(4.0644-4)/(4-1) = 0.0215$$

$$CR = CI/RI = 0.0215/0.89 = 0.0241. \quad (32)$$

The random consistency ratio CR<0.1 means that the consistency of the total ranking results of the hierarchy is satisfactory, and the weight of the influencing factors is considered to be reasonable.

(3) Key factors of the shaft blasting quality evaluation—Construction cost.

The main factors influencing the cost include the powder factor and the impact on the surrounding rocks.

Similarly, the comparison matrix R_3 is synthesized based on the scoring matrix of six experts. The score comparison matrix of six experts (all passed the consistency test) is as follows:

$$R_1' = \begin{bmatrix} 1 & 9 \\ \frac{1}{9} & 1 \end{bmatrix} \quad (33)$$

$$R_2' = \begin{bmatrix} 1 & 7 \\ \frac{1}{7} & 1 \end{bmatrix} \quad (34)$$

$$R_3' = \begin{bmatrix} 1 & 7 \\ \frac{1}{7} & 1 \end{bmatrix} \quad (35)$$

$$R_4' = \begin{bmatrix} 1 & 7 \\ \frac{1}{7} & 1 \end{bmatrix} \quad (36)$$

$$R_5' = \begin{bmatrix} 1 & 7 \\ \frac{1}{7} & 1 \end{bmatrix} \quad (37)$$

$$R_6' = \begin{bmatrix} 1 & 7 \\ \frac{1}{7} & 1 \end{bmatrix} \quad (38)$$

The six experts have the same level, and their scoring weights are equal. Therefore, based on the six comparison matrices passed by the consistency test, the geometric mean of the corresponding positions is calculated and the affiliation matrix R_3 is obtained. Using equation (14) to calculate $R_3 = \begin{bmatrix} r_{11} & r_{12} \\ r_{21} & r_{22} \end{bmatrix}$, the specific calculation process is as follows:

$$r_{11} = (1 \times 1 \times 1 \times 1 \times 1 \times 1)^{\frac{1}{6}} = 1$$

$$r_{12} = (9 \times 7 \times 7 \times 7 \times 7 \times 7)^{\frac{1}{6}} = 7.2995$$

$$r_{21} = \left(\frac{1}{9} \times \frac{1}{7} \times \frac{1}{7} \times \frac{1}{7} \times \frac{1}{7} \times \frac{1}{7}\right)^{\frac{1}{6}} = 0.137$$

$$r_{22} = (1 \times 1 \times 1 \times 1 \times 1 \times 1)^{\frac{1}{6}} = 1$$

Therefore, the modified weight matrix R_3 is as follows:

$$R_3 = \begin{bmatrix} 1 & 7.2995 \\ 0.137 & 1 \end{bmatrix} \quad (39)$$

Among them, λ_{max} =2, CR=0, CI=0, the weights of each index affecting blasting cost can be calculated as t: {*the powder factor, the impact on surrounding rocks*}={0.8795, 0.1205}. The results matrix G_3 of R_3 normalized by column is as follows:

$$G_3 = \begin{bmatrix} 0.8795 & 0.8795 \\ 0.1205 & 0.1205 \end{bmatrix} \quad (40)$$

The random consistency ratio CR of the matrix is calculated as follows:

$$\lambda_{max} = (\sum (Aw/w))/n = 2, RI = 0, n = 2,$$
$$CR = 0.0 (\text{when matrix dimension } n <= 2, CR = 0.0.)$$

(4) Group Decision (All Factors) Weights

The group decision weights were calculated based on the weights of the respective influencing factors corresponding to the three key indicators of blasting effect, construction safety and cost. The main objective of calculating the group decision weights is to calculate the mutual weight values of all the 10 factors affecting the blasting quality evaluation and to provide a reference for determining the key influencing factors. The calculation results and consistency tests are as follows:

1) The group decision middleweight is shown in TABLE 3.

TABLE 3. Intermediate layer weight.

Factor	Global weight	Peer weight
Blasting effect	0.7519	0.7519
Construction safety	0.1403	0.1403
Construction cost	0.1078	0.1078

2) The process of calculating the consistency of the group decision matrix for evaluating the key factors of the shaft blasting quality is as follows:

$$CR = (0.751874 \times 0.0101 + 0.140308 \times 0.0215 + 0.107818 \times 0) / (0.751874 \times 0.89 + 0.140308 \times 0.89 + 0.107818 \times 0) = 0.0133$$

The random consistency ratio CR<0.1 means that the consistency of the total ranking results of the hierarchy is satisfactory, and the weighting of the influencing factors is considered to be reasonable.

3) Weight of each index

By calculating the respective weights of key factors such as blasting effect, construction safety and cost, the group decision weight values are obtained after verifying and adjusting

the calculation results according to the consistency test, and finally the global weight values of 10 indexes were obtained. By quantifying the weight values of each factor, the degree of influence of each index on blasting quality evaluation can be intuitively derived, and the more important indexes can be filtered out based on expert experience and engineering practice to improve the accuracy and rationality of the evaluation model. The final weight parameter calculation results are summarized in TABLE 4.

TABLE 4. Weight of affecting factor(global).

Index	SF	BHU	RMR	OYR	BF	BD	ISS	BSW	PF	ISR
Weight	0.2786	0.3675	0.0598	0.046	0.046	0.0154	0.0436	0.0354	0.0948	0.013

Note:***SF***: *Single-cycle Footage;* ***BHUT***: *Blast Hole Utilization Rate;* ***HMR***: *Half-hole Marks Rate;* ***OYR***: *Oversize Yield Rate;* ***BF***: *Blasting Flyrock;* ***BD***: *Blasting Dust;* ***ISS***: *Impact on Support Structures;* ***BSW***: *Blasting Shock Waves;* ***PF***: *Powder Factor;* ***ISR***: *Impact on the Surrounding Rocks*

C. KEY EVALUATION INDICATORS AFFECTING BLASTING QUALITY

Based on the calculation results of PSO-AHP, the top five of the indexes affecting the blasting quality are blast hole utilization rate, single-cycle footage, powder factor, half-hole marks rate, and oversize yield rate.

Considering the experience of experts, practical engineering experience and laboratory experiments, as well as the principles of clear physical meaning, easy access, strong representativeness and relative independence, five key evaluation indicators are determined from the 10 main indexes, namely, the single-cycle footage, the blast hole utilization, the half-hole marks rate, the powder factor and the oversize yield rate, which significantly affect the blasting effect of the shaft.

D. QUANTITATIVE METHODS OF BLASTING EFFECT EVALUATION INDEX

Based on the theoretical knowledge of the shaft blasting and statistical data of engineering practice, five levels were assigned to each indicator [29], which are extremely high, high, higher, average and low. The corresponding levels and scores are A (100 points), B (90 points), C (75 points), D (60 points), and E (50 points). If the level of an indicator is E, it means that the indicator is unsatisfactory.

(1) Single-cycle Footage

Single-cycle footage is the depth value of each blast in a vertical shaft, generally expressed in m. This index is an important indicator of blasting quality, and the larger the value of single-cycle footage, the higher the construction efficiency. According to the current level of blasting construction, construction equipment and experience, this index can be divided into five evaluation levels, as shown in TABLE 5.

(2) Blast Hole Utilization

Blast hole utilization is another very important indicator of blasting quality, the closer its value is to 100%, it shows that the more useful work of explosives in a blasting construction, the higher the utilization rate of explosive release energy, the more reasonable blasting parameters design, cost-saving, good blasting effect, and high blasting quality. The classification of blast hole utilization is shown in TABLE 6

TABLE 5. Classification of single-cycle footage.

	Change range (m)	Grade	Grade point (m)
A	>5.0	Excellent	5.1
B	4.0<l≤5.0	Good	4.1
C	3.5<l≤4.0	Better	3.6
D	3.0<l≤3.5	General	3.1
E	l≤3.0	Difference	2.9

TABLE 6. Classification of blast hole utilization.

	Variation range (%)	Grade	Grade point (%)
A	>95	Extremely high	96
B	90<β≤95	High	93
C	85<β≤90	Higher	88
D	80<β≤85	General	83
E	β≤80	Low	80

(3) Half-hole marks rate

The half-hole marks rate is the ratio of the number of visible hole marks to the total number of perimeter holes excluding t.lifters after the smooth blasting. When the length of the hole mark is greater than 70% of the hole length, it is considered a visible hole mark. The half-hole marks rate is one of the most important indicators for measuring and evaluating the quality of the smooth blasting [30]. The classification of the half-hole marks rate is shown in TABLE 7.

TABLE 7. Classification of half-hole marks rate.

	Variation range (%)	Grade	Grade point (%)
A	>95	Extremely high	96
B	90<γ≤95	High	93
C	85<γ≤90	Higher	88
D	80<γ≤85	General	83
E	γ≤80	Low	80

(4) Powder Factor

Powder factor is the weight of explosives required to blast each cubic meter of rock. Powder factor not only affects the quality of blasting but also directly relates to the production cost of the ore and the safety of the operation. The amount of consumption depends on the blasting nature of the rock, blasting technology and explosives performance. The grading of powder factor is shown in TABLE 8.

(5) Oversize Yield Rate

The oversize yield rate is not only an important indicator to evaluate the blasting effect, but also directly related to the gangue operation in the shaft, and in some cases, it even requires secondary blasting, which increases the production cost and operational safety. The oversize yield rate is calculated according to the volume ratio of the blasting block to the

TABLE 8. Grading of powder factor.

	Variation range (kg / m^3)	Grade	Grade point
A	a<1.0	Excellent	0.9
B	1.0≤a < 1.2	Good	1.1
C	1.2≤a < 1.4	Better	1.3
D	1.4≤a < 1.6	General	1.5
E	a≥1.6	Poor	1.6

volume of blasted rock. The classification table of oversize yield rate is shown in TABLE 9.

TABLE 9. Classification table of oversize yield rate.

	Variation range (%)	Grade	Grade point (%)
A	ε<1	Excellent	0.9
B	1≤ε<3	Good	2
C	3≤ε<5	Better	4
D	5≤ε<7	General	6
E	ε≥7	Poor	8

V. EVALUATION MODEL OF BLASTING EFFECT OF VERTICAL SHAFT

According to the characteristics of the shaft blasting construction, the fuzzy comprehensive evaluation method is selected and a fuzzy comprehensive evaluation model is established [31], [32]. The fuzzy comprehensive evaluation method is a comprehensive evaluation method based on fuzzy mathematics [33]. This comprehensive evaluation method converts qualitative evaluation into quantitative evaluation based on the affiliation theory of fuzzy mathematics, which means that fuzzy mathematics is used to make an overall evaluation of things or objects that are subject to multiple factors.

A. DETERMINING THE BLASTING QUALITY EVALUATION FACTORS AND JUDGMENT SETS

Determine the n relevant indicators or factors of the blasting quality evaluation object, and the five indicators in the aforementioned determined blasting quality evaluation index system constitute the set of factors or the set of indicators, record $U = \{$*single-cycle footage, shot hole utilization rate, half-hole marks rate, powder factor, oversize yield rate*$\}=\{u_1, u_2, \ldots, u_5\}$, the difference in the degree of influence of different factors is represented by the set of weights $A = \{a_1, a_2, \ldots, a_n\}$, let all possible evaluation results be m, remember $V = \{$*excellent, good, better, average, poor*$\}$, can be expressed as $V = \{v_1, v_2, \ldots, v_5\}$ are comment sets or judgment sets.

B. CONSTRUCTION OF BLASTING QUALITY EVALUATION MATRIX

On the basis of establishing a good set of factors of the judged object $U = \{u_1, u_2, \ldots, u_5\}$ and establishing a set of judgments $V = \{v_1, v_2, \ldots, v_5\}$, a single factor judgment is established and the affiliation vector $r_i = (r_{i1}, r_{i2}, \ldots, r_{i5})$ is obtained.

The single-factor fuzzy evaluation is to determine the degree of affiliation of the evaluation object to each element of the alternative set V_j (j = 1,2,3,4,5) from a single factor $U_i(i$ = 1,2,3,4,5) in the factor set U. Let the degree of affiliation of the judging object to the j-th element V_j in the alternative set be r_{ij} when judging by the i-th factor u_i in the factor set, then the result of judging by the i-th factor u_i can be expressed as a fuzzy set:

$$R_i = r_{i1}/v_1 + r_{i2}/v_2 + \cdots + r_{im}/v_m \tag{41}$$

where, R_i represents a single-factor judgment set, which can be expressed as:

$$R_i = (r_i1, r_i2, \ldots, r_im)$$

A fuzzy relationship matrix can be formed by the different degrees corresponding to the evaluation indicators in each affiliation function (i.e., different degrees of affiliation), as in equation (42).

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & \cdots & \cdots & r_{nn} \end{bmatrix} \tag{42}$$

C. DETERMINING THE WEIGHT OF THE EVALUATION FACTOR SET

To reflect the importance of each factor, in each evaluation index u_i (i = 1,2, …, 5), all the indicators in the evaluation index set should be assigned different weights, which constitute the set of evaluation factor weights $A = \{a_1, a_2, \ldots, a_i\}$, where a_i is the weight corresponding to the i-th factor u_i. The determination of a_i is the first prerequisite and key link in the comprehensive evaluation of evaluation index weights. Based on the characteristics of the vertical blasting quality evaluation system, the evaluation index weights are determined by the hierarchical analysis method.

(1) Establish a hierarchical model of the blasting effect index for the shaft, as shown in FIGURE 5.

(2) Establishment of the comparison matrix.

The two-way importance comparison results of each factor in the structural model were evaluated by the expert judgment method [34], and the conventional 1-9 scale was used to construct the judgment matrix, which was divided into "absolutely important", "very important", "more important", "slightly important", "equally important", "absolutely unimportant", "very unimportant", "less important" and "slightly unimportant", and the corresponding comparison matrix R' is obtained as shown below.

$$R' = \begin{bmatrix} r'_{11} & r'_{12} & \cdots & r'_{1n} \\ r'_{21} & r'_{22} & \cdots & r'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r'_{n1} & r'_{n2} & \cdots & r'_{nn} \end{bmatrix} \tag{43}$$

where r'_{ij} is the importance of factor i compared to factor j.

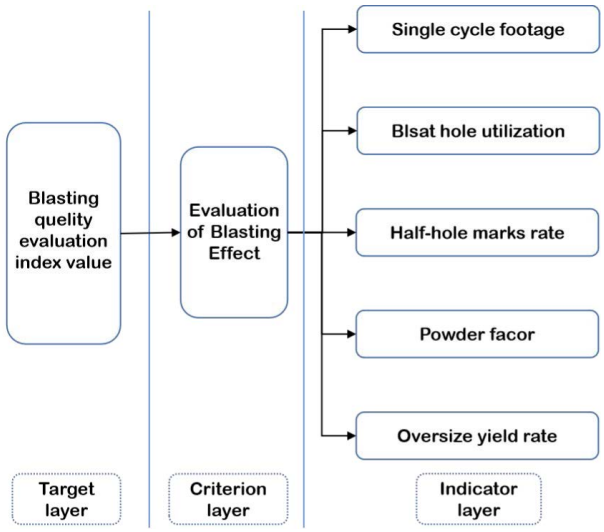

FIGURE 5. Hierarchical blasting effect index hierarchical structure model.

For the weight of key indicators that affect the evaluation of blasting quality, front-line experts are invited to compare and evaluate the relative importance of the indicators in the above hierarchical structure model. The results are averaged to obtain a comparison matrix as shown in TABLE 10. As mentioned above, the relative importance between different factors affecting blast quality is judged qualitatively, and this quantitative information obtained through judgment transformation is the information basis of the hierarchical analysis method. The quantitative information obtained by appropriate scaling is organized to obtain the judgment matrix in the following.

TABLE 10. Factors affecting judgment matrix table.

	Single-cycle Footage	Blast hole Utilization	Half-hole marks rate	Powder factor	Oversize yield rate
Single cycle footage	1	1/5	5	7	7
Blast hole utilization	5	1	7	9	7
Half-hole marks rate	1/5	1/7	1	1/5	9
Powder factor	1/7	1/9	5	1	7
Oversize yield rate	1/7	1/7	1/9	1/7	1

(3) Construction of judgment matrix.

According to the comparison matrix and the importance ranking index, the corresponding judgment matrix D is constructed, and its calculation equation is as follows:

$$r_{ij} = \frac{1}{n}\sum_{k=1}^{n}(a_{ik} + a_{kj}) \tag{44}$$

where a_{ik} is the value of the kth column of the i-th row in the comparison matrix, a_{kj} is the value of the j-th column of the k-th row in the comparison matrix, and n is the number of rows (columns) of the comparison matrix, n=10, d_{ik}=$exp(r_{ik})$, then matrix D is obtained by column normalization.

$$D = \begin{bmatrix} d_{11} & d_{12} & \dots & d_{15} \\ d_{21} & d_{22} & \dots & d_{25} \\ \vdots & \vdots & \ddots & \vdots \\ d_{51} & d_{52} & \dots & d_{55} \end{bmatrix} = \begin{bmatrix} 1 & 0.8942 & 4.9511 & 4.7861 & 7.0305 \\ 1.1184 & 1 & 5.1356 & 6.107 & 7.4287 \\ 0.202 & 0.1947 & 1 & 2.7599 & 7.4033 \\ 0.2089 & 0.1637 & 0.3623 & 1 & 4.6719 \\ 0.1422 & 0.1346 & 0.1351 & 0.214 & 1 \end{bmatrix} \tag{45}$$

$$D' = \begin{bmatrix} d'_{11} & d'_{12} & \dots & d'_{15} \\ d'_{21} & d'_{22} & \dots & d'_{25} \\ \vdots & \vdots & \ddots & \vdots \\ d'_{51} & d'_{52} & \dots & d'_{55} \end{bmatrix} = \begin{bmatrix} 0.3743 & 0.3746 & 0.4274 & 0.3219 & 0.2553 \\ 0.4186 & 0.4189 & 0.4433 & 0.4108 & 0.2698 \\ 0.0756 & 0.0816 & 0.0863 & 0.1856 & 0.2689 \\ 0.0782 & 0.0686 & 0.0313 & 0.0673 & 0.1697 \\ 0.0532 & 0.0564 & 0.0117 & 0.0144 & 0.0363 \end{bmatrix} \tag{46}$$

(4) Weight results based on AHP

The weights of the evaluation indicators based on the analytic hierarchy process are shown in TABLE 11. The table shows the weights of the five key factors affecting blasting, and the quantified index values provide reasonable criteria for the next step in accurately evaluating blast quality.

TABLE 11. Weight of affecting factor.

Index	Single-cycle footage	Blast-hole utilization	Half-hole Marks rate	Powder factor	Oversize yield rate
Weight	0.3623	0.4052	0.1275	0.0753	0.0297

D. CALCULATION THE COMPREHENSIVE EVALUATION VECTORS

For weight vector A={a_1,a_2,…, a_n}, calculating $B = AoR$ is the comprehensive evaluation, which can be expressed as:

$$\begin{aligned} B &= AoR \\ &= (a_1, a_2, \dots, a_4) \cdot \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1m} \\ r_{21} & r_{22} & \dots & \dots \\ \dots & \dots & \dots & \dots \\ r_{n1} & \dots & \dots & r_{nn} \end{bmatrix} \\ &= (b_1, b_2, \dots b_5,) \end{aligned} \tag{47}$$

The operation symbol "o" is the operator for fuzziness. In fuzzy control, the input sampling value of the actual system is generally always the exact quantity. To use the fuzzy logic inference method, the precise quantity must be fuzzified first, and the fuzzification process is essentially realized by using

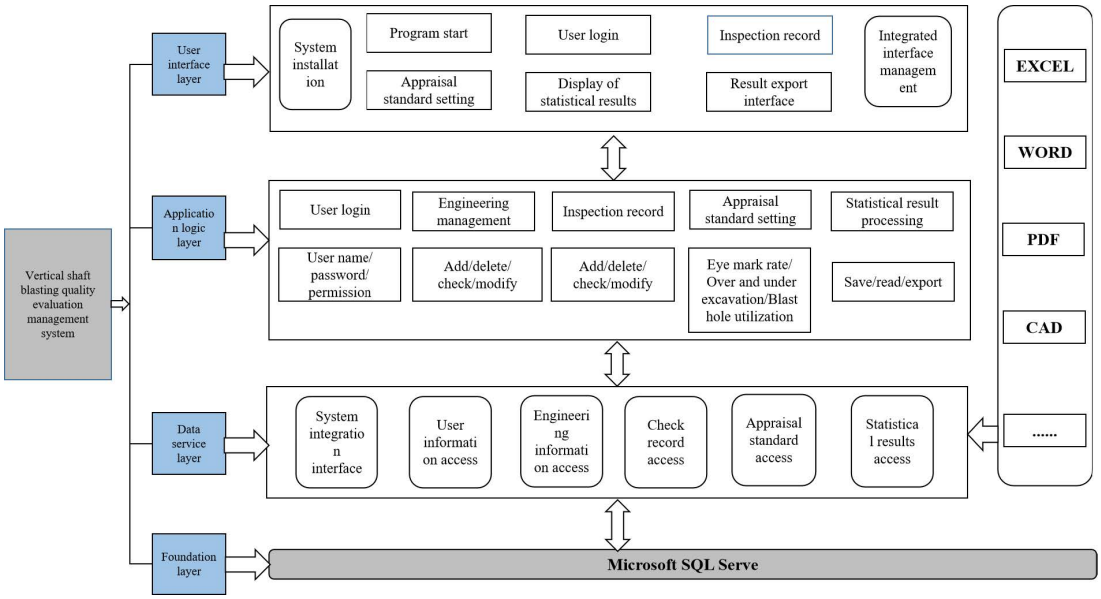

FIGURE 6. Quality management system module design flow chart.

the fuzzification operator. Therefore, it is very important to introduce the fuzzification operator. There are four commonly used fuzzy operators. Based on the characteristics of the blasting quality evaluation model, the following fuzzy operators (equation 48) are selected, whose main features are obvious embodiment of weights, strong synthesis, full utilization of information in R, and the type of weighted average type.

M $(\cdot, \oplus)$ operator: weighted average operator.

"$\cdot$" means to multiply, "$\oplus$" means summation.

$$B_k = \sum_{j=1}^{m} a_j r_{jk}, \quad k = 1, 2, \ldots, n \tag{48}$$

VI. REALIZATION OF VERTICAL SHAFT BLASTING QUALITY EVALUATION SYSTEM

A. THE SYSTEM DEVELOPMENT ENVIRONMENT AND PLATFORM

The database management system replaces the manual management of a large number of files and data, enabling intelligent data management [35], user accounts and passwords are used to log in, and different operation rights are assigned to each account to ensure the security of data. The database can store a large amount of data, and the results that meet the search conditions can be found quickly and easily using SQL language in a large amount of data.

Based on the practical requirements, scalability, efficiency, and flexibility of the blasting quality evaluation system development, Microsoft Visual Studio was selected as the development environment, and the development platform relied on was Microsoft. NET Framework, MFC (Microsoft Foundation Classes), and STL (Standard Template Library), and the development language is VC++.

The database uses Microsoft SQL Server, a relational database management system introduced by Microsoft, whose database engine provides more secure and reliable storage for relational and structured data, allowing users to build and manage high-availability and high-performance data applications for business. The quality management system is constructed using SQL Server, relational database management, the powerful database access function of ADO (ActiveX Data Objects). NET components and SQL language query functions are used to operate on database tables and are programmed in object-oriented C++ language.

Data files are stored in XML (Extensible Markup Language), which is a subset of Extensible Markup Language, a standard general-purpose markup language used to mark up electronic documents to give them structure. All raw data and inferred data are saved to achieve the need for direct recall or result viewing for the next use by the user.

The system uses VSTO (Visual Studio Tools for Office) to interface with Excel, which makes developing Office applications much easier. And using VSTO to develop office applications can use many features in the Visual Studio development environment and manage memory, recycle garbage and use other features provided by the CLR.

The selection and combined application of development environment and language make the system characterized by friendly interface, simple operation, high operational efficiency, and easy data transmission [36], while ensuring the reliable operation of the vertical shaft blasting quality evaluation system.

B. MAIN FUNCTIONAL MODULES

The quality management system module design is shown in FIGURE 6.

(1) The basic layer mainly includes the SQL Server database platform environment, which is the bottom core of the whole quality evaluation management system.

(2) The data service layer realizes the underlying data transmission service functions, including access to inspection records, assessment standards, and statistical results. It is mainly based on the system integration interface, including user account access interface, engineering information access interface, quality inspection record access interface, assessment standard access interface, results in export to excel interface, etc. it also realizes the access to office and CAD-related functions through the data interface of this layer.

(3) The application logic layer is the part of the system architecture that reflects the core values. It is located between the data service layer and the user interface layer and plays a connecting role in data exchange. It mainly deals with the specific technical problems of the system, which can also be understood as the operation of the data layer and the processing of data business logic [37]. It mainly includes user login information management, project creation, inspection record modification, assessment standard-setting, and statistical result editing.

(4) The user interface layer is a user-oriented module that corresponds to the human-computer interaction interface in the system architecture design. It mainly provides an interactive and visual operation interface for users to enter the system directly. It includes a startup interface, user login interface, project management interface, quality inspection record management interface, assessment standard setting interface, and statistical result display interface. Users select the corresponding functions as needed and give feedback to the system on the problems they need to solve through the corresponding prompts. The interface layer can directly start the corresponding functions of the application logic layer. At the same time, the application logic layer investigates the data service layer and gives the reasoning results.

C. USER LOGIN AND PROJECT CREATION

According to the system requirements, the user enters the project name, user name, and password, selects the project file path, and then clicks to enter the project. The system will automatically create a quality management project. Users can call existing projects or create new projects directly according to their actual needs. The project will be created by inputting the project name, the path to the creation file package, the project code, and the project description. The system also has buttons to add and delete projects, which makes it easier for users to manage projects. The user login screen and project creation screen are shown in Figure 7 and Figure 8, respectively.

D. DATA MANAGEMENT

The technician can view all the data entered into the system through the browser interface of the quality inspection log form. Its main fields include inspection date, inspection position, shaft diameter, surrounding rock lithology, peripheral hole spacing, overbreak number, underbreak number, design hole depth, actual blasting size, hole utilization rate, peripheral hole number, peripheral hole residue book, peripheral eye mark rate, and inspector, etc.

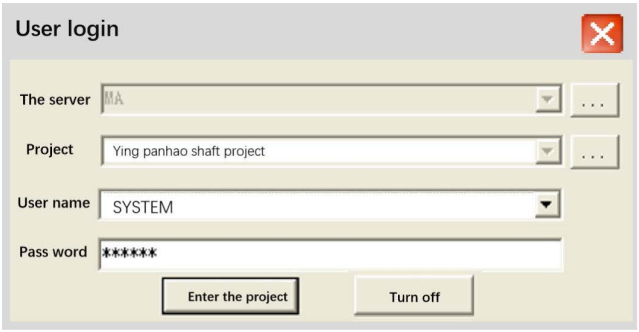

FIGURE 7. User login interface.

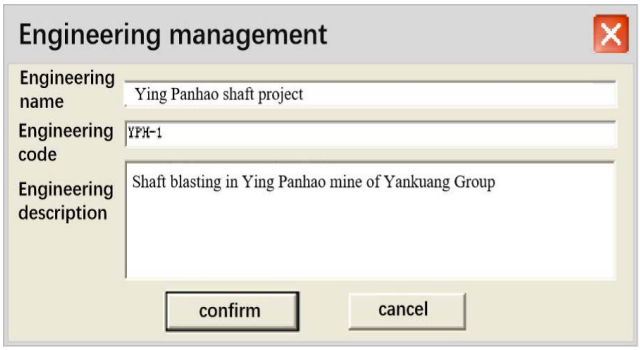

FIGURE 8. Create a project.

At the same time, you can add, delete, view, and modify data, or make queries based on the corresponding key fields. With this system, you can visualize the data at any time. The interface of shaft quality inspection records is shown in FIGURE 9. When the user selects a data item and clicks the ''view'' button, the whole data can be browsed. At the same time, you can use the ''condition query and statistics'' button to follow up the user's condition query options in real-time and to browse the data, such as period, peripheral eye mark rate, over and under excavation number, blast hole utilization rate, etc. If different options are selected, the system will give different query results. The condition query dialog box is shown in FIGURE 10.

The setting of assessment standards is based on the blasting engineering quality evaluation system formulated by the quality management department. This module mainly sets the data ranges of peripheral hole mark rate, over and under excavation, and blast hole utilization rate according to three different lithologies of the surrounding rock. Users can modify and edit the settings according to actual needs, and compare the obtained engineering blasting data with the set data. Appraisal standard setting is the core link that affects the final evaluation results, as shown in FIGURE 11.

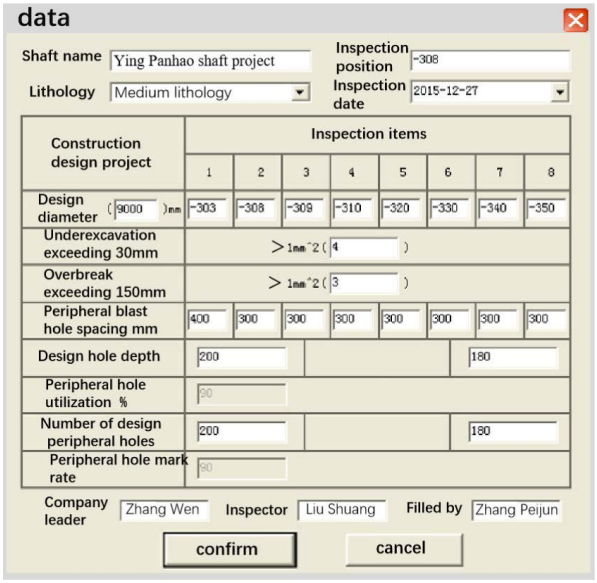

FIGURE 9. Vertical shaft quality inspection record management interface.

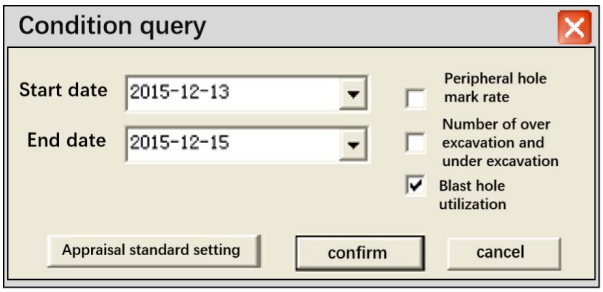

FIGURE 10. Condition query interface.

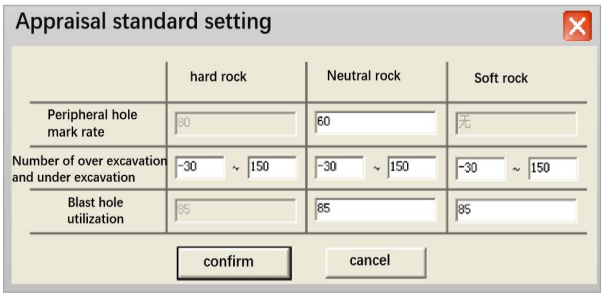

FIGURE 11. Assessment standard setting.

VII. ENGINEERING APPLICATIONS

A. PROJECT OVERVIEW

The engineering background is the return air shaft of Erfeng well in Jinzhuang Coal Mine, Datong City, Shanxi Province. The diameter of the shaft is 8m, the depth of the bedrock section is 435.3m, and the construction section is 66.48m^2.

For the same bedrock, two different blasting schemes were used to evaluate the blasting quality of the two different blasting schemes based on the fuzzy comprehensive evaluation model.

B. BLASTING PROJECT SCHEME AND EFFECT

(1) Blasting scheme I

The blasting parameters of the blasting scheme I as shown in TABLE 12.

TABLE 12. Blasting parameters of the bedrock section of the wellbore.

Serial number	Name	Hole Number	Holes (number)	Circle diameter (mm)	Hole depth (mm)	Distance between holes(mm)	Charge quantity		Blasting sequence
							Pcs/eye	kg/ circle	
1	Cut hole	1 ~ 8	8	1800	4500	689	8	44.48	I
2	Cut spreader hole	9 ~ 28	20	3300	4300	734	6	84	II
3	Breaking hole	29 ~ 53	25	4900	4300	531	5	87	III
4	Breaking hole	54 ~ 79	30	6400	4300	802	4	72.8	III
5	Breaking hole	80 ~ 109	39	7800	4200	789	2	42	IV
6	Perimeter hole	110 ~ 157	48	9000	4200	600	2	67.2	V
Total			157					398.3	

Two blasting operations are performed according to the blasting scheme I, and the blasting effect is shown in TABLE 13.

TABLE 13. Blasting effect of the shaft in bedrock section.

Blasting number	Blasting scheme I statistics of blasting indexes of bedrock section				
	u_1,m	u_2,%	u_3,%	u_4,kg/m^3	u_5,%
1	3.6	83.7	70	1.66	5
2	3.7	86.0	80	1.50	6

(2) Blasting scheme II

The blasting parameters of blasting scheme II as shown in TABLE 14.

Two blasting operations are performed according to blasting scheme II, and the blasting effect is shown in TABLE 15.

C. FUZZY COMPREHENSIVE EVALUATION OF BLASTING QUALITY

According to the relevant parameters that have been determined in Section 2, the blasting quality evaluation index U = {*single-cycle footage, blast hole utilization rate, half-hole marks rate,powder factor,* oversize yield *rate*}={u_1, u_2, …, u_5}, weight set of each evaluation index A={a_1, a_2, …, a_n}= (0.3623,0.4052,0.1275,0.0753,0.0297)

(1) Statistical weights of single factor indicators for the four-round blasting R_{iuv} (i = 1,2,3,4), as expressed in

TABLE 14. Blasting parameters of wellbore bedrock section.

Serial number	Name	Hole number	Holes (Number)	Circle diameter (mm)	Hole depth (mm)	Distance between holes (mm)	Charge quantity		Blasting sequence
							Pcs/eye	kg/ circle	
1	Cut hole	1 ~ 9	9	1800	4500	628	5	33.75	I
2	Cut spreader hole	10 ~ 31	22	3300	4200	471	5	82.5	II
3	Breaking hole	32 ~ 60	29	4900	4200	531	4	87	III
4	Breaking hole	61 ~ 92	32	6400	4200	628	3	72	III
5	Breaking hole	93 ~ 131	39	7800	4200	628	2	58.5	IV
6	Perimeter hole	132 ~ 189	58	9000	4200	487	2	87	V
Total			189					420.75	

TABLE 15. Blasting effect of the shaft in bedrock section.

Blasting number	Blasting scheme II statistics of blasting indexes of bedrock section				
	u_1 (m)	u_2 (%)	u_3 (%)	u_4 (kg/m^3)	u_5 (%)
1	4.0	95.2	83	1.58	4
2	3.8	90.5	86	1.67	3

equation (49)-(52).

$$(R_{1uv})_{5\times5} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix} \tag{49}$$

$$(R_{2uv})_{5\times5} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix} \tag{50}$$

$$(R_{3uv})_{5\times5} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} \tag{51}$$

$$(R_{4uv})_{5\times5} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} \tag{52}$$

(2) Affiliation Matrix

Establish single-factor evaluation, fuzzy comprehensive evaluation affiliation matrix $R' = A{\cdot}R$, Evaluation index weight vector $A = \{a_1, a_2, \ldots, a_n\}$, R Weights for single factor indicators.

R'=*(0.3623, 0.4052, 0.1275, 0.0753, 0.0297)*$\cdot(R_{iuv})_{5\times5}$ $(i = 1, 2, 3, 4)$, from which the affiliation matrix of four round blasting is obtained:

$$R' = \begin{bmatrix} r'_{11} & r'_{12} & \cdots & r'_{1n} \\ r'_{21} & r'_{22} & \cdots & r'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r'_{n1} & r'_{n2} & \cdots & r'_{nn} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0.4376 & 0.4349 & 0.1275 \\ 0 & 0.4052 & 0.3623 & 0.105 & 0.1275 \\ 0.4052 & 0 & 0.392 & 0.2028 & 0 \\ 0 & 0.4052 & 0.5195 & 0 & 0.0753 \end{bmatrix} \tag{53}$$

(3) Fuzzy comprehensive evaluation of blasting quality

Based on M(·, ⊕) operator: it is a weighted average operator, as shown below [38]:

$$B_k = \sum_{j=1}^{m} a_j r_{jk}, \quad k = 1, 2, \ldots, n \tag{54}$$

The four-round blasting is calculated based on the fuzzy comprehensive evaluation method, as shown in TABLE 16.

TABLE 16. Fuzzy comprehensive evaluation results of blasting quality.

Blasting number	Membership of each indicator					Fuzzy comprehensive score	Evaluation conclusion
	R_1	R_2	R_3	R_4	R_5		
1	0	0	0.4376	0.4349	0.1275	65.289	General
2	0	0.4052	0.3623	0.105	0.1275	76.3155	Better
3	0.4052	0	0.392	0.2028	0	82.088	Good
4	0	0.4052	0.5195	0	0.0753	79.1955	Better

It can be seen from TABLE 16 that the evaluation results of the four-round blasting effect obtained from the two different blasting schemes are average, better, good and better, respectively. Based on the fuzzy comprehensive score and evaluation results, the blasting effect of the second scheme is significantly better than that of the first scheme, which is consistent with the result in the actual blasting, because some parameters in the second blasting scheme are optimized on the basis of the first blasting scheme.

D. COMPARISON AND ANALYSIS OF BLASTING QUALITY EVALUATION

According to the introduction of Part I of this paper, there are few research results on the evaluation of the vertical shaft blasting quality, and the currently available methods for evaluating the vertical shaft blasting quality are mainly subjective determinations made by field technicians based on partial data. A comparison of the quantitative results of the conventional evaluation performed by two field technicians and the method in this paper is shown in TABLE 17.

TABLE 17. Blasting quality fuzzy comprehensive evaluation results.

Blasting number	Evaluating indicator					Evaluation by traditional methods		
	u1	u2	u3	u4	u5	Appraisal conclusion	No.1	No.2
1	3.6	83.7	70	1.66	5	General	Poor	Poor
2	3.7	86.0	80	1.50	6	Good	Good	Poor
3	4.0	95.2	83	1.58	4	Better	Better	Good
4	3.8	90.5	86	1.67	3	Good	Better	Better

From the analysis of the three evaluation results in TABLE 17, it can be seen that after four blasting constructions, the results of using the method proposed in this paper are quite different from the subjective evaluation results of the two technicians. After a comprehensive analysis the four actual blasting effects on site by experts in the field of blasting and front-line construction experts, the evaluation conclusions of this paper are considered more objective and more consistent with the actual blasting effects.

Analyzing the differences of the three evaluation results, the first technician mainly considered the half-eye trace rate because the number of half-eyes after one blast could be obtained visually, and he thought that a higher half-eye trace rate meant higher blast quality; the second technician mainly considered the bulk rate, and he considered that a lower bulk rate meant that the blast energy release was reasonable and facilitated the lifting and transportation of the debris after blasting. Both technicians made subjective qualitative determinations from a single indicator, and their results did not fully consider the influence of other factors. In fact, the quality of blasting is a comprehensive effect and requires systematic consideration of blasting efficiency, safety, cost and other aspects in order to make a more objective and accurate evaluation of blasting quality. A reasonable blasting quality evaluation can provide more reasonable reference data for blasting plan optimization and adjustment, so as to further improve blasting technology and achieve safe and efficient construction of the vertical shaft blasting.

VIII. CONCLUSION

Based on blasting theory, expert experience and field engineering practice, we have determined five key indicators that affect the evaluation of blasting quality, namely: single cycle feed, blast hole utilization rate, half-eye trace rate, explosives unit consumption, and big rock fragment rate. And we established the reference range for evaluating the quantitative grade standard of each index.

Based on the improved PSO-AHP and fuzzy mathematical hybrid algorithm technology, the weight set of five indicators A={*single cycle footage, blast hole utilization rate, half-eye trace rate, single explosive consumption, big rock fragment rate*}={0.3623, 0.4052, 0.1275, 0.0753, 0.0297} is determined for vertical shaft blasting quality evaluation. Based on the determination of blasting quality evaluation factors and judgment sets and the construction of blasting quality evaluation matrix, a mathematical model for the fuzzy comprehensive evaluation of vertical blasting quality is established.

Based on the computer development language and SQL Server database technology, an information management system for the shaft blasting quality evaluation is developed. The process-based structural design and modular functional partition provide good support for the efficient, stable, and accurate operation of the management system. The system is scientific, advanced, and easy to operate, which provides a new method for the evaluation and management of the shaft blasting quality.

The system was used to quantitatively evaluate the four-wheel blasting of two different schemes in Jinzhuang Coal Mine, Datong City, Shanxi Province. The results show that the method is feasible and reasonable for comprehensively evaluating the shaft blasting quality, and provides a reliable approach for scientific and reasonable evaluation of the shaft blasting quality, improving the level of blasting quality management and achieving safe and efficient blasting.

The main limitation of this study is the lack of a generic model that contains more input and output parameters. Since different geological conditions and lithology are encountered during the vertical shaft boring, how to obtain more construction data from different engineering backgrounds and add them to the evaluation model to enhance the applicability of the blast quality evaluation model is the next step we need to take. In addition, the accuracy of the model evaluation can also be further improved by seeking other optimization algorithms with better performance, and then, they can be compared with the model proposed in this study.

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