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A Novel Fuzzy Comprehensive Evaluation Model of Construction Safety Risk of Inclined Shaft in Underground Mine

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Abstract

To evaluate the safety risk of inclined shaft construction effectively, a safety risk evaluation model of inclined shaft construction based on fuzzy comprehensive evaluation method was proposed aiming at complex inducing factors, high risk rate, and difficult identification of safety risk in the construction stage of underground mine inclined shaft engineering. Taking the inclined shaft project of Zisheng Coal Mine in Shanxi Province of China as a study object, a total of 20 evaluation indexes that caused safety risks in inclined shaft construction were selected to construct an index system. The analytic hierarchy process (AHP) method was applied to construct the judgment matrix and calculate the weight of each index. The relative closeness between the sample and the ideal solution was calculated by combining the AHP method with the technique for order preference by similarity to an ideal solution (TOPSIS) method. The weight of each index was coupled with relative closeness to predict the safety risk level of inclined shaft construction. Results show that the safety risk level of the inclined shaft construction is Grade II. By analyzing the total ranking of weights in the prediction results, the primary and secondary relationships of the factors that affect the safety risk of inclined shaft construction is presented as follows: human factors > supervision and management > environmental factors > equipment and materials. The safety risk prediction results of inclined shaft in underground mine are consistent with the actual situation, and the prediction accuracy of this model is high. The conclusions obtained in this study have a significant reference for the early warning and prevention of inclined shaft construction hazards.

Keywords: Inclined shaft construction, Safety risk, AHP, Fuzzy comprehensive evaluation, TOPSIS

1. Introduction

China is one of the world’s largest coal mining countries because of its rich coal resources. The Chinese economy develops rapidly, thereby leading to the increasing demand for coal. In the next few decades, coal will continue to dominate China’s industrial production and modernization construction [1]. The coal industry plays a key role in China’s national economy and the people’s livelihood. Meanwhile, the safe and effective mining of coal is a long-term and arduous task that needs to be addressed. At present, most coal mine enterprises take inclined shaft rail transportation as an improvement method. As a coal mining method, inclined shaft is characterized by cost saving and high efficiency [2-3]. With the increasing improvement of China’s coal mining technologies, coal mining design theory, and construction technologies, the use of inclined shaft lifting under the conditions of medium and shallow burial depths is particularly important. According to statistics, as the world’s largest economy, the US has 80% coal mining enterprises to use inclined shaft lifting to transport coal underground, whereas the rate of transporting coal underground by inclined shafts in developed countries, such as the European Union, is 85%. By 2021, inclined shaft transportation will account for 70% of the underground transportation methods of Chinese coal mining enterprises, which is significantly lower than the level achieved by developed countries [4]. Therefore, carrying out research on inclined shaft construction in geology and mines around the world is of great significance to reduce mining costs and improve production efficiency [5].

With the increase in coal mining depth, the more complex the geological conditions of coal mines are, the more serious the disasters, such as water, fire, gas, ground temperature, and ground pressure, will be, thereby causing great challenges to the safe production of underground coal mine inclined shaft construction [6]. However, given the many advantages of inclined shaft construction, it gradually becomes a preferred construction technique in underground coal mine. At present, the inclined shaft construction and infrastructure equipment has entered into a stable development stage. The economic base determines the direction of the market. The inclined shaft construction technology will not be updated greatly in a short period of time, but it provides a good development space for future intelligent development. With the increase in the underground mining depth, geological conditions have a great impact on the inclined shaft construction, wherein safety accidents and damage in mining equipment have high chance of occurrence, which may cause major casualties and property damage and serious restriction in the rapid development of China's economy [7]. Nowadays, slurry spraying, manual support, and surface hardening treatment are mainly used to treat the inclined shaft construction safety accidents, but some blindness and dangers often exist [8]. Many factors, which are interactive and inter-restricted,

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influence the actual construction and cause complicated safety issues [9-10]. Therefore, determining the hazard location and its degree in the construction process in time is difficult. The study of the safety risk assessment of the slant shaft construction in underground mines has become a main problem to be solved in coal mine safety production in China and even around the world [11]. A large number of studies showed that the safety conditions of the inclined shaft construction could be predicted better by analyzing the unsafe factors in slant shaft construction and by using mathematical modeling, intelligent algorithms, and cloud computing. However, some disadvantages, such as requiring a large amount of raw data and the influence of subjective and objective factors, are encountered.

Therefore, by adopting scientific and effective methods to predict and evaluate safety risks during the construction of underground mine inclined shaft projects and taking corresponding measures can effectively reduce construction safety risks, which have become a hot topic of research.

2. State of the art

The construction of underground mine inclined shaft project is a complex process that consists of multiple uncertainties in space and time. Due to its construction cycle, personnel flow, and construction environment, safety accidents, which seriously threaten construction personnel safety and bring huge economic losses to the construction organization, occur frequently [12-13]. In recent years, China’s underground mine construction technology has developed rapidly and steadily because of the development hotspot of short construction term, construction efficiency, and high construction accuracy of the slant shaft project. However, the current improvement of the mechanization of shaft engineering, construction difficulties, and lack of control of construction quality result in the frequent occurrence of accidents during construction [14].

At present, studies on the safety risk evaluation of slant shaft engineering construction are relatively rare. Liu Jie [15] analyzed the safety risk of coal mine slant shaft tunnel engineering construction based on the tunnel boring machine (TBM) method to explore the feasibility and safety of slant shaft tunnel construction from four aspects, namely, personnel, machine, environment, and pipe. Hou Gongyu et al. [16] analyzed the construction risk factors of shaft engineering based on the TBM method for long inclined shafts in coal mines, established a progressive hierarchical risk assessment system, and modified the traditional set-pair analysis method by using the entropy weight method to construct an improved set-pair analysis risk prediction model for long inclined shafts in the Taigemiao Mine. By using the information monitoring technology, Xue Weipei et al. [17] researched the stability of coal mine shaft walls and analyzed the relationship among pressure, strain, and temperature of the outer wall of the shaft with the progress of construction. Yin Xin et al. [18] improved the TBM excavatability evaluation model of deep belief network based on Bayesian optimization algorithm and early stopping strategy and the accuracy of the tunneling roadway safety prediction model. An Yonglin et al. [19] established a shaft construction simulation model based on the engineering geology and analyzed the construction safety combined with field monitoring data to solve the low safety coefficient of positive cavern excavation construction. Dong Wei et al. [20] analyzed the sources of engineering construction safety risks by using Delphi method, established a safety risk evaluation model of the construction phase based on gray fuzzy theory, and distinguished and classified the risk factors in the construction process, which are convenient for managers to control safety risks dynamically.

The prediction model in the above research has their own shortcomings. For example, although the TBM method can achieve the multivariable prediction of the inclined shaft construction, its sample data acquisition has certain limitations that affect the accuracy of the evaluation results. The Bayesian optimization algorithm can overcome the influence of subjective factors on the weight, but the evaluation process is prone to causing some serious problems, such as the unclear classification of risk levels and unscientific evaluation results. In addition, some problems in the above-mentioned studies, such as relatively few influencing factors considered, uncertainty between the primary and secondary relationships of influencing factors, and strong subjectivity of evaluation results, are encountered. Therefore, discrepancies will be generated in evaluating slant shaft engineering construction safety. The adoption of fuzzy algorithms for the evaluation of underground mine slant shaft construction safety risks is relatively rare. This paper adopts the AHP method to analyze the relative importance of each indicator and build a judgement matrix to calculate the weight of each indicator. Then, it is combined with the TOPSIS method to determine the Euclidean distance between each index and the ideal solution and calculate the relative closeness of the sample to the ideal solution. The weight of each index is coupled with relative closeness to predict the safety risk level of the inclined shaft construction in underground mines. The method avoids the impact of subjective and objective factors on the evaluation results and improves the accuracy of the model, which can be expected to lay a theoretical foundation for the safety risk evaluation of inclined shaft construction in underground mines.

The rest of this study is organized as follows. Section 3 gives the basic principle of determining weight by AHP method and safety risk evaluation model for inclined shaft construction. Section 4 gives the result analysis and discussion, and finally, the conclusions are summarized in Section 5.

3. Methodology

3.1 Basic principle of determining weight by AHP method

The AHP method is the recursive logical hierarchy model that is established on the basis of the hierarchical and methodical processing of different factors that are mutually constrained in the evaluation system [21-22]. The different attributes, from top to bottom, can be referred to as follows: target layer, criterion layer, and indicator layer. Each element of the same attribute layer is influenced by the factors above and below [23]. Finally, the weights of each element are determined by its importance to the previous layer [24]. By analyzing the intrinsic connection among factors and mathematizing a small amount of quantitative sample information in the decision deeply, the processing of disorderly multi-objective, multi-criteria complex decision is simplified and makes accurate decisions on complex problems.

3.1.1 Construction of judgment matrix
The relative importance of each index factor in the evaluation index system is analyzed by the two-by-two comparison method; its results are labeled by using the 1–9 scale method [25-26] or the importance ratio. Based on the comparison results, the judgment matrix $\boldsymbol{B}=\left(b_{ij}\right)_{n\times n}$ is established to improve the accuracy of evaluation:

$$\boldsymbol{B}=\begin{pmatrix} b_{11} & b_{12} & \cdots & b_{1j} \\ b_{21} & b_{22} & \cdots & b_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ b_{i1} & b_{i2} & \cdots & b_{ij} \end{pmatrix} \tag{1}$$

where b_{ij} is the ratio of the importance of the indicator factors after two comparisons, thereby indicating the relative importance of the i-th indicator over the j-th indicator, where i=1….n, j=1….n.

3.1.2 Consistency test of judgement matrix
The judgment matrix is constructed empirically. Thus, meeting the requirement of complete consistency is difficult. To allocate elements in the judgment matrix $\boldsymbol{B}$ reasonably, establishing the evaluation criteria is necessary. When the judgment matrix meets the requirements of the criterion, it can be approximated to have full consistency. Only when the judgment matrix $\boldsymbol{B}$ meets the requirements of full consistency can the weights of various level indicators be allocated reasonably. If not, then the judgment matrix must be revised:

$$\lambda_{\max}=\frac{1}{n}\sum_{i=1}^{n}\left(\sum_{j=1}^{n}\frac{b_{ij}\cdot W_j}{W_i}\right) \tag{2}$$

$$CR=\frac{CI}{IR} \tag{3}$$

$$CI=\frac{\left|\lambda_{\max}-n\right|}{n-1} \tag{4}$$

where CR is the consistency ratio, CI is the consistency index value, IR is the random consistency index, $\lambda_{\max}$ is the maximum eigenvalue of the matrix $\boldsymbol{B}$, n is the order of the judgment matrix, and W_i and W_j are the elements of the eigenvector.

When the consistency ratio CR < 0.1, the judgment matrix established after two-by-two comparison meets the consistency requirement. If not, then it needs to be revised.

3.1.3 Weight calculation
The maximum eigenvalue $\lambda_{\max}$ method is used to calculate the eigenvectors of the judgment matrix, and each indicator can be ranked by it hierarchically. However, given the difficulty in calculating the eigenvector value of $\lambda_{\max}$ accurately, the geometric mean method is used to calculate its approximate value. The weight w_i is calculated as follows:

$$w_i=\frac{\left(\prod_{i=1}^{n}\left(b_{ij}\ /\sum_{i=1}^{n}b_{ij}\right)\right)^{\frac{1}{n}}}{\sum_{i=1}^{n}\left(\prod_{j=1}^{n}\left(b_{ij}\ /\sum_{j=1}^{n}b_{ij}\right)\right)^{\frac{1}{n}}},\quad i=(1,2,\cdots,n);\ j=(1,2,\cdots,n) \tag{5}$$

3.2 Safety risk evaluation model for inclined shaft construction
To eliminate the influence of the dimension of each indicator on the evaluation results, the TOPSIS method is used to construct the judgment matrix for the evaluation of the closeness of the construction safety risk of the slant shaft engineering [27]. In the meantime, the fuzzy comprehensive evaluation model is constructed by coupling the judgement matrix with the index weights obtained by the AHP method. Finally, the model is used to evaluate the construction safety risk of slanting shaft engineering comprehensively. The specific steps are presented as follows:

Step 1) Establishing the initial evaluation matrix $\boldsymbol{A}$. Assuming the sample set $\boldsymbol{A}=\left\{A_1,A_2,\cdots A_m\right\}$, and the vector $A_i=\left(a_{i1},a_{i2},\cdots a_{in}\right)$ is composed of n indicator values of every research object in $\boldsymbol{A}$; a_{ij} is the indicator value of the evaluation indicator j of evaluation sample i.

$$\boldsymbol{A}=\left(a_{ij}\right)_{n\times n}=\begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1j} \\ a_{21} & a_{22} & \cdots & a_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ a_{i1} & a_{i2} & \cdots & a_{ij} \end{pmatrix} \tag{6}$$

Step 2) Standardized processing matrix $\boldsymbol{A}$. The dimensional differences among the evaluation indicators make their direct comparison and analysis impossible. To eliminate the differences, the indicator data must be processed by the standard of the benefit and cost type indicators. Indicator data are converted into the value of [0,1] to obtain the standardization matrix $\boldsymbol{D}=\left(d_{ij}\right)$ of $\boldsymbol{A}$.

$$d_{ij}=a_{ij}\ /\sqrt{\sum_{i=1}^{n}a_{ij}^2}\quad \text{benefit type} \tag{7}$$

$$d_{ij}=(1/a_{ij})\ /\sqrt{\sum_{i=1}^{n}(1/a_{ij})^2}\quad \text{cost type} \tag{8}$$

Step 3) Calculating sample closeness. Closeness refers to the degree of approximation of every indicator in the sample to the optimal solution [28-29]. In calculating sample closeness, the positive and negative ideal solutions are calculated first, and then the Euclidean distance between every indicator and the ideal solution are determined subsequently.

$$\begin{aligned} D^+&=\left\{\left(\max d_{ij}\ \middle|\ j\in J^+\right),\left(\min d_{ij}\ \middle|\ j\in J^-\right)\right\} \\ D^-&=\left\{\left(\min d_{ij}\ \middle|\ j\in J^+\right),\left(\max d_{ij}\ \middle|\ j\in J^-\right)\right\} \end{aligned} \tag{9}$$

$$C_i^+ = \left(\sum_{j=1}^{n} w_i (d_{ij} - d_j^+) \right)^{\frac{1}{2}}$$
$$C_i^- = \left(\sum_{j=1}^{n} w_i (d_{ij} - d_j^-) \right)^{\frac{1}{2}} \quad (10)$$

$$f_i^+ = C_i^- / \left(C_i^+ + C_i^- \right) \quad (11)$$

where D^+ is the positive ideal solution, and D^- is the negative ideal solution. J^+ is the benefit type indicator, and J^- is the cost type indicator. C^+ is the Euclidean distance between the indicator and the positive ideal solution, and C^- is the Euclidean distance between the indicator and the negative ideal solution. f_i^+ is the relative proximity, usually $f_i^+ \in (0,1)$. The farther the evaluation indicator is from the positive ideal solution, the smaller the f_i^+ value will be, that is, the worse the evaluation object is.

Step 4) Establishing a fuzzy comprehensive evaluation model. Based on the principle of fuzzy evaluation, the weight matrix of each index obtained by the AHP method is coupled with the closeness judgment matrix constructed by the TOPSIS method to obtain the evaluation result vector [30-31].

$$L = w \times \boldsymbol{F} \quad (12)$$

where L is the comprehensive evaluation result, w is the index weight matrix, and $\boldsymbol{F}$ is the closeness judgment matrix.

4. Results analysis and discussion

4.1 Application of safety risk prediction in inclined shaft construction

4.1.1 Establishment of hierarchical structure and evaluation grade of safety risk assessment

The main factors that cause the occurrence of construction safety risks in underground mine slant shaft engineering can be concluded on the basis of previous research results [32-33]. Based on accident causation cross theory and relevant national standards and specifications, 20 factors that affect the safety status of slant shaft engineering, which includes the aspects of human factors, equipment and materials, supervision and management, and environment, were summarized [34-35] [36]. According to the principle of the AHP method, a two-level recursive hierarchical structure evaluation model of the construction safety state of the slant shaft project was established to analyze its current situation comprehensively. Table 1 shows the relationship among the indicators of each level, where the indicators of each level and their initial data values were selected by the standard of relevant regulations [37].

For the characteristics of the construction safety management of the inclined shaft project [38], safety risk is divided into five levels: level I (minimum), level II (low), level III (medium), level IV (high), and level V (maximum). The critical values of each level are expressed by L_1, L_2, L_3, and L_4, respectively; the risk level classification guidelines are shown in Table 2 [39]. If $L > L_1$, then it is judged as low construction safety risk; if $L \in [L_1, L_2)$, then it is judged as low construction safety risk; if $L \in [L_2, L_3)$, then it is judged as medium construction safety risk; if $L \in [L_3, L_4)$, then it is judged as high construction safety risk; and if $L \leqslant L_4$, then it is judged as high construction safety risk.

Taking the underground inclined shaft project of Zisheng coal mine in Shanxi Province of China as an example, the fuzzy comprehensive evaluation model is used to evaluate the safety risk of the slant shaft construction process of the mine.

Table 1. Comprehensive evaluation index of construction safety risk

Objectives	Primary index	Secondary index
Safety risk assessment of inclined shaft construction (*R*)	**Human factors (R_1)**	Violation rate of construction operation (R_{11})
		Personnel technical level (R_{12})
		Personnel safety awareness level (R_{13})
	Equipment and materials (R_2)	Component production quality (R_{21})
		Selection of equipment and tools (R_{22})
		Strength of hoisting connection part (R_{23})
		Regular safety inspection of equipment (R_{24})
		Bearing strength of temporary support (R_{25})
		Material properties (R_{26})
	Supervision and management (R_3)	Security management institution and system (R_{31})
		Safety education and training (R_{32})
		Safety supervision (R_{33})
		Accident prevention and emergency management (R_{34})
		Component stacking and hazard source management (R_{35})
	Environmental factors (R_4)	Adverse conditions of natural environment (R_{41})
		Operating environment adverse conditions (R_{42})
		Transportation and stacking conditions of components (R_{43})
		Construction period requirements (R_{44})
		Adverse factors around the site (R_{45})
		Adverse factors of economic policy (R_{46})

Table 2. Evaluation criteria of construction safety risk level

Index	I	II	III	IV	V	Sample
R_{11}	(0,4]	(4,8]	(8,12]	(12,16]	(16,100)	2.5
R_{12}	(9,10)	(7,9]	(5,7]	(3,5]	(0,3]	7.5

R_{13}	(10,100)	(6,10]	(4,6]	(2,4]	(0,2]	5.4
R_{21}	(95,100)	(90,95]	(85,90]	(80,85]	(0,80]	95
R_{22}	(95,100)	(90,95]	(85,90]	(80,85]	(0,80]	93
R_{23}	(95,100)	(90,85]	(85,90]	(80,85]	(0,80]	85
R_{24}	(95,100)	(90,95]	(85,90]	(80,85]	(0,80]	89
R_{25}	(95,100)	(90,95]	(85,90]	(80,85]	(0,80]	77
R_{26}	(95,100)	(90,85]	(85,90]	(80,85]	(0,80]	90
R_{31}	(0,8]	(8,25]	(25,45]	(45,75]	(75,100)	19
R_{32}	(0,20]	(20,180]	(180,600]	(600,1200]	(1200,+∞)	1830
R_{33}	(9,10)	(7,9]	(5,7]	(3,5]	(0,3]	5
R_{34}	(95,100)	(90,95]	(85,90]	(80,85]	(0,80]	81
R_{35}	(0,4]	(4,6]	(6,8]	(8,10]	(10,+∞)	5
R_{41}	(0,0.5]	(0.5,1]	(1,2]	(2,3]	(3,+∞)	9.5
R_{42}	(90,100)	(80,90]	(70,80]	(60,70]	(0,60]	82
R_{43}	(90,100)	(80,90]	(70,80]	(60,70]	(0,60]	79
R_{44}	(90,100)	(80,90]	(70,80]	(60,70]	(0,60]	81
R_{45}	(90,100)	(80,90]	(70,80]	(60,70]	(0,60]	89
R_{46}	(90,100)	(80,90]	(70,80]	(60,70]	(0,60]	92

4.1.2 Establishment of index weight

Based on the AHP method and crossover theory, experts with rich experience and outstanding theory knowledge and field technicians were invited to consult on the construction of slant shaft engineering and construct the judgment matrix, which is shown in Tables 3–7.

From Equations (2) to (4), $\lambda_{\max}=4.01$, $IR=0.89$, and $CR=0.004<0.1$ can be presented, and the judgment matrix meets the consistency requirements. Combined with Equation (5), the first-level index weight $w=(0.42, 0.23, 0.12, 0.23)$ can be calculated. Similarly, the second-level index judgment matrix $CR<0.1$ can be obtained. The results above can meet the consistency requirements. Thus, the index weights of index layer are: $w_1=(0.55, 0.27, 0.18)$, $w_2=(0.09, 0.06, 0.09, 0.26, 0.17, 0.34)$, $w_3=(0.12, 0.16, 0.34, 0.22, 0.16)$, and $w_4=(0.08, 0.15, 0.23, 0.16, 0.07, 0.31)$. The weights of each indicator and its overall ranking are shown in Table 8.

Table 3. Judgement matrix of *R-Ri*

R-R_i	***R*₁**	***R*₂**	***R*₃**	***R*₄**
R_1	1	2	3	2
R_2	1/2	1	3/2	1
R_3	1/3	2/3	1	2/3
R_4	1/2	1	3/2	1

Table 4. Judgement matrix of R_1-R_{1i}

R_1-R_{1i}	R_{11}	R_{12}	R_{13}
R_{11}	1	2	3
R_{12}	1/2	1	3/2
R_{13}	1/3	2/3	1

Table 5. Judgement matrix of R_2-R_{2i}

R-R_{2i}	R_{21}	R_{22}	R_{23}	R_{24}	R_{25}	R_{26}
R_{21}	1	4/3	1	1/3	1/2	1/4
R_{22}	3/4	1	3/4	1/4	3/8	3/16
R_{23}	1	3/4	1	1/3	1/2	1/4
R_{24}	3	3	4	1	3/2	3/4
R_{25}	2	8/3	2	2/3	1	1/2
R_{26}	4	16/3	4	4/5	2	1

Table 6. Judgement matrix of R_3-R_{3i}

R-R_{3i}	R_{31}	R_{32}	R_{33}	R_{34}	R_{35}
R_{31}	1	3/4	1/3	1/2	2/3
R_{32}	4/3	1	4/9	2/3	9/8
R_{33}	3	9/4	1	3/2	2
R_{34}	2	3/2	2/3	1	4/3
R_{35}	3/2	8/9	1/2	3/4	1

Table 7. Judgement matrix of R_4-R_{4i}

R-R_{4i}	R_{41}	R_{42}	R_{43}	R_{44}	R_{45}	R_{46}
R_{41}	1	1/2	1/3	1/2	1	1/4
R_{42}	2	1	2/3	1	2	1/2
R_{43}	3	3/2	1	3/2	3	3/4
R_{44}	2	1	2/3	1	2	1/2
R_{45}	1	1/2	1/3	1/2	1	1/4
R_{46}	4	2	4/3	2	4	1

Table 8. Index weight and total ranking

Index layer	***R-R_i***				**Total weight sort**
	R_1	R_2	R_3	R_4	
R_{11}	0.55	—	—	—	0.14
R_{12}	0.27	—	—	—	0.07
R_{13}	0.18	—	—	—	0.04
R_{21}	—	0.09	—	—	0.02
R_{22}	—	0.06	—	—	0.01
R_{23}	—	0.09	—	—	0.02
R_{24}	—	0.26	—	—	0.06
R_{25}	—	0.17	—	—	0.04
R_{26}	—	0.34	—	—	0.08
R_{31}	—	—	0.12	—	0.03
R_{32}	—	—	0.16	—	0.04
R_{33}	—	—	0.34	—	0.08
R_{34}	—	—	0.22	—	0.05
R_{35}	—	—	0.16	—	0.04
R_{41}	—	—	—	0.08	0.02
R_{42}	—	—	—	0.15	0.04
R_{43}	—	—	—	0.23	0.06
R_{44}	—	—	—	0.16	0.04
R_{45}	—	—	—	0.07	0.02
R_{46}	—	—	—	0.31	0.08

4.1.3 Construction of TOPSIS approach matrix

According to Equations (7) and (8), the data in the sample are normalized to obtain a standardized matrix of consistent indicators:

$$\boldsymbol{D}_1=\begin{pmatrix} 0.17 & 0.13 & 0.06 & 0 & 0.19 \\ 0.04 & 0.03 & 0.02 & 0 & 0.03 \\ 0.02 & 0.01 & 0.004 & 0 & 0.07 \end{pmatrix}$$

$$\boldsymbol{D}_2=\begin{pmatrix} 0.02 & 0.01 & 0.006 & 0 & 0.02 \\ 0.01 & 0.008 & 0.004 & 0 & 0.01 \\ 0.02 & 0.01 & 0.006 & 0 & 0.006 \\ 0.07 & 0.05 & 0.04 & 0 & 0.05 \\ 0.02 & 0.02 & 0.01 & 0 & 0.002 \\ 0.11 & 0.10 & 0.08 & 0 & 0.05 \end{pmatrix}$$

$$D_3 = \begin{pmatrix} 0.10 & 0.06 & 0.03 & 0 & 0.07 \\ 0.07 & 0.04 & 0.02 & 0 & 0.04 \\ 0.02 & 0.02 & 0.008 & 0 & 0.02 \\ 0.02 & 0.01 & 0.006 & 0 & 0.02 \\ 0.05 & 0.03 & 0.02 & 0 & 0.05 \end{pmatrix}$$

$$D_4 = \begin{pmatrix} 0.01 & 0.008 & 0.005 & 0 & 0.01 \\ 0.07 & 0.06 & 0.05 & 0.02 & 0 \\ 0.02 & 0.02 & 0.007 & 0 & 0.007 \\ 0 & 0.008 & 0.005 & 0.003 & 0.001 \\ 0.006 & 0.004 & 0.002 & 0 & 0.005 \\ 0.13 & 0.12 & 0.11 & 0.1 & 0 \end{pmatrix}$$

The ideal solution of each index is calculated from Equation (9). The positive and negative ideal solutions of each index are shown in Table 9. The Euclidean distance vector between each index and the ideal solution is calculated from Equation (10):

$$C_1^+ = (0.02, 0.08, 0.14, 0.16, 0.01)$$
$$C_1^- = (0.18, 0.12, 0.06, 0, 0.19)$$

$$C_2^+ = (0, 0.03, 0.05, 0.07, 0.06)$$
$$C_2^- = (0.14, 0.11, 0.09, 0.07, 0.08)$$

$$C_3^+ = (0, 0.04, 0.08, 0.13, 0.04)$$
$$C_3^- = (0.13, 0.09, 0.04, 0.003, 0.098)$$

$$C_4^+ = (0.15, 0.14, 0.12, 0.103, 0.028)$$
$$C_2^- = (0.022, 0.018, 0.033, 0.06, 0.15)$$

Table 9. Positive and negative ideal solutions of each index

Index	Positive ideal solution	Negative ideal solution
R_{11}	0	0.19
R_{12}	0.044	0
R_{13}	0.068	0
R_{21}	0.019	0
R_{22}	0.012	0
R_{23}	0.017	0
R_{24}	0.066	0
R_{25}	0.024	0
R_{26}	0.112	0
R_{31}	0.095	0
R_{32}	0.065	0
R_{33}	0.024	0
R_{34}	0.017	0
R_{35}	0.045	0
R_{41}	0	0.011
R_{42}	0	0.069
R_{43}	0.033	0
R_{44}	0.008	0
R_{45}	0	0.006
R_{46}	0	0.131

The closeness matrix F is formed by the closeness of Equation (11) index and positive ideal solutions f_i^+.

$$F = \begin{pmatrix} 0.89 & 0.57 & 0.30 & 0 & 0.93 \\ 1 & 0.82 & 0.64 & 0.47 & 0.58 \\ 0.93 & 0.87 & 0.74 & 0.59 & 0.78 \\ 1 & 0.67 & 0.35 & 0.02 & 0.74 \end{pmatrix}.$$

4.2 Analysis of evaluation results

Equation (12) shows that the comprehensive evaluation result can be obtained by coupling each index weight w with the closeness matrix F: (L_1, L_2, L_3, L_4, L)=(0.95, 0.70, 0.44, 0.18, 0.79), in which L=0.79∈(0.95, 0.70). Therefore, the inclined shaft construction safety risk level of the test sample is Level II (relatively low), which is consistent with the actual safety risk level of the inclined shaft construction of Zisheng coal mine. The fuzzy comprehensive evaluation model is a scientific and effective way to evaluate the inclined shaft construction safety risk. According to analysis, the factors that affect the construction safety risk of inclined shaft engineering are ranked by its importance as: human factors > supervision and management > environmental factors > equipment and materials, in which the inclined shaft construction equipment and materials are the key factors that affect sample safety risk. On the basis of the index standardization matrix D_2 of equipment and materials, the production quality of components (0.02), the selection of equipment and machines (0.01), the strength of hoisting connection parts (0.002), the regular safety inspection of equipment (0.06), the bearing strength of temporary support (0.004), and the material performance (0.08) can be determined. Therefore, the selection of equipment and machines should be optimized, the strength of hoisting connection parts should be strengthened, and the component production quality should be improved. The strength of the hoisting joint part and the production quality of components have relatively large safety risks.

5. Conclusions

To solve the problem of complexity, high risk rate, and difficulty in identifying the inducing factors of construction safety risk in the inclined shaft engineering of underground mines in the construction stage, the evaluation model of the construction safety risk in the inclined shaft engineering of underground mines is proposed on the basis of a fuzzy comprehensive evaluation method. By introducing the Euclidean distance function to optimize the decision-making model, the AHP method and the TOPSIS method are combined to reduce the influence of subjective and objective factors on the evaluation results. The following conclusions were obtained:

1) Aiming at the complex inducing factors of construction safety risk in inclined shaft engineering of underground mines, high risk rate, and difficulty in identifying during the construction stage, a fuzzy comprehensive evaluation model is established. Meanwhile, the AHP method couples with the TOPSIS method to reduce the error of evaluation results caused by a single weighting method.

2) Based on the critical value of the construction safety risk influencing factors of inclined shaft engineering, the safety risk evaluation criteria are constructed, and each index closeness is calculated to obtain the safety risk level of the test sample: II (lower). The evaluation results are consistent

with the actual situation, thereby verifying the correctness of the model.

3) The factors that affect the construction safety risk of inclined shaft engineering from priority to subordinate are presented as: human factors > supervision and management > environmental factors > equipment and materials, in which the inclined shaft construction equipment and materials are the key factors that affect the sample safety risk. The selection of equipment and tools, the strength of hoisting joints, and the bearing strength of temporary supports are the weak links of the construction safety risk of inclined shaft engineering, and its management should be strengthened.

4) The fuzzy comprehensive evaluation model can estimate the safety risk status of inclined shaft engineering in underground mines effectively and check the weak links based on calculation results, thereby providing a theoretical basis for the safety management of inclined shaft construction.

All in all, the evaluation model of construction safety risk in the inclined shaft engineering of underground mines proposed by the paper can effectively reduce the influence of subjective and objective factors on evaluation results and ensure the scientificity and accuracy of evaluation results, which provide a theoretical basis for the evaluation of similar problems. However, due to the enormous factors that affect the safety of the inclined shaft construction process in underground mines and the complex index system involved, the evaluation model will be revised by collecting a large amount of measured data to improve the accuracy and expand the scope of application, which can provide a more comprehensive theoretical support for the safety risk assessment of underground mine inclined shaft construction.

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References

1. Xie, H. P., Wu, L. X., Zheng, D. Z., “Prediction on the energy consumption and coal demand of China in 2025”. *Journal of China Coal Society*, 44(7), 2019, pp. 1949-1960.
2. Voloshin, V. A., Rib, S. V., Petrova, O. A., Belyaev, A. V., “The choice of the site for inclined shaft and parameters of its stage-by-stage construction in the conditions of the Tersinsky coal region”. *IOP Conference Series: Earth and Environmental Science*, 206(1), 2018, pp. 012009.
3. Kalmykov, V. N., Zubkov, A. A., Volkov, P. V., Kulsaitov, R. V., “Justification of the technology of construction of mine shafts for the conditions of the maly kuibas deposit”. *IOP Conference Series: Earth and Environmental Science*, 988(2), 2022, pp. 022014.
4. Liu, Z. Q., Song, C. Y., Ji, H. G., Liu, S. J., “Construction mode and key technology of mining shaft engineering for deep mineral resources”. *Journal of China Coal Society*, 46(3), 2021, pp. 826-845.
5. Naseri, S., Bahrani, N., “Design of initial shotcrete lining for a mine shaft using two-dimensional finite element models considering excavation advance rate”. *Geotechnical and Geological Engineering*, 39(7), 2021, pp. 1-24.
6. Fan, J. D., Feng, H., Song, C. Y., Ren, H. W., Ma, Y., “Key technology and equipment of intelligent mine construction of whole mine mechanical rock breaking in Kekegai coal mine”. *Journal of China Coal Society*, 47(1), 2022, pp. 499-514.
7. Wang, Q. C., Liu, Q. H., Song, C. Y., Li, Q., Ren, H. W., “Feasibility analysis of excavation with open full section boring machine for ultra-long distance inclined shaft in coal mine”. *Coal Science and Technology*, 50(10), 2022, pp. 1-10.
8. Yin, N., Dong, J. L., “Research on adaptability of grouting combined fluid for shield inclined shaft construction in coal mine”. *Coal Technology*, 40(11), 2021, pp. 74-77.
9. Niu, B., Zhang, L. L., Yang, M., Yang, X. W., Deng, X., “Safety management technology of TBM construction for extra long inclined shaft in Kekegai coal mine”. *Energy Technology and Management*, 47(4), 2022, pp. 145-147.
10. Ma, J. Z., Yang, M., Kang, Y. Q., Wu, B. C., “Research on key technology of open type TBM construction for extra long inclined shaft in coal mine”. *Energy Technology and Management*, 46(5), 2021, pp. 119-121.
11. Yan, Q. X., Li, B. J., Zhang, Y. Y., He, C., “In situ automatic monitoring and working state assessment of inclined shafts in coalmines”. *Proceedings of the Institution of Civil Engineers - Geotechnical Engineering*, 174(4), 2021, pp. 390-405.
12. Hu, X. Y., He, C. A., Gabriel, W., Chen, Z. Q., “A combined support system associated with the segmental lining in a jointed rock mass: the case of the inclined shaft tunnel at the Bulianta coal mine”. *Rock Mechanics and Rock Engineering*, 53(2), 2020, pp. 2653-2669.
13. Li, S. L., Guo, L. Q., Wu, R. X., Hu, X. W., Fu, M. R., “Advanced detection and analysis of inclined shaft passing through aquifer in the mine of western China”. *E3S Web of Conferences*, 206(11), 2020, pp. 03021.
14. Liu, L. L., “*Elastic-plastic Solution of TBM Inclined Shaft Surrounding Rocks Based on Unified Strength Criterion and Test Research*”. Doctoral Dissertation of China University of Mining and Technology (Beijing), China, 2017, pp. 6-26.
15. Liu, J., “Safety protection emphasis and countermeasures of TBM method in inclined shaft constuction of coal mine”. *Safety in Coal Mines*, 48(S1), 2017, pp. 128-132.
16. Hou, G. Y., Liang, R., Jin, C., Liu, X., “Risk analysis and evaluation of long slope mining construction by TBM techniques”. *Chinese Journal of Underground Space and Engineering*, 12(3), 2016, pp. 831-838.
17. Xue, W. P., Yao, Z. S., Song, H. Q., Yu, Q., “Safety monitoring analysis of coal mine shaft built by freezing method in thick clay layer”. *China Safety Science Journal*, 26(4), 2016, pp. 137-143.
18. Yin, X., Gao, F., Liu, Q. S., Wang, X. Y., Huang, X., Pan, Y. C., “Multi-algorithm fusion optimization model and its engineering application for boreability evaluation of tunnel boring machine”. *Chinese Journal of Rock Mechanics and Engineering*, 41(S1), 2022, pp. 2757-2771.
19. An, Y. L., Ouyang, P. B., Peng, L. M., Wu, B., Hu, W. X., “Construction techniques and safety analysis for a deep vertical shaft and vertical shaft shifting to main tunnel”. *Modern Tunnelling Technology*, 55(2), 2018, pp. 164-173.
20. Dong, W., “*Security Risk Research of Construction Stage of Prefabricated Housing Project Based on Grey Fuzzy Theory*”. Master Thesis of Jiangxi University of Science and Technology, China, 2018, pp. 5-20.
21. Gabriele, O., Faramondi L., Roberto, S., Marco, T., Enrico, Z., “A multi-criteria model for the security assessment of large-infrastructure construction sites”. *International Journal of Critical Infrastructure Protection*, 35(12), 2021, pp. 100460.
22. Khorrama, S., “A novel approach for ports’ container terminals’ risk management based on formal safety assessment: FAHP-entropy measure—VIKOR model”. *Natural Hazards*, 103(6), 2020, pp. 1671-1707.

23. Agrawal, A., Alenezi, M., Kumar, R., Khan, R. A., "A unified fuzzy-based symmetrical multi-criteria decision-making method for evaluating sustainable-security of web applications". *Symmetry*, 12(3), 2020, pp. 448.
24. Zhang, D. J., Liu, S. X., Reng, F. Y., Zheng, Y. W., Zhang, D., "Research on optimization of goaf management method based on AHP-FUZZY". *Metal Mine*, 524(4), 2021, pp. 183-190.
25. Shanmugam, L., Joo, Y. H., "Stability criteria for fuzzy-based sampled-data control systems via a fractional parameter-based refined looped lyapunov functional". *IEEE Transactions on Fuzzy Systems*, 30(7), 2022, pp. 2538-2549.
26. Khanmohammadi, E., Barekatain, B., Quintana, A. A., "An enhanced AHP-TOPSIS-based clustering algorithm for high-quality live video streaming in flying ad hoc networks". *The Journal of Supercomputing*, 77 (3), 2021, pp. 1-35.
27. Tang, M., Kang, X. T., Gao, L., Zheng, L. L., Jiang, M. Q., Wang, Z. Y., "Study on risk assessment of coal and gas outburst based on game theory and topsis". *Journal of Shandong University of Science and Technology* (*Natural Science*), 40 (5), 2021, pp. 77-86.
28. Wang, Y. W., Li, A. C., "Safety assessment of prefabricated building construction based on grey correlation degree-TOPSIS method". *Project Management Technology*, 17(11), 2019, pp. 51-56.
29. Alzahrani, F. A., "Evaluating the usable-security of healthcare software through unified technique of fuzzy logic, ANP and TOPSIS". *IEEE Access*, 8(99), 2020, pp. 3001996.
30. Wang, W., Qi, Y., Jia, B. S., Yao, Y. L., "Dynamic prediction model of spontaneous combustion risk in goaf based on improved CRITIC-G2-TOPSIS method and its application". *PloS one*, 16(10), 2021, pp. 1-16.
31. Hezer, S., Gelmez, E., Özceylan, E., "Comparative analysis of TOPSIS, VIKOR and COPRAS methods for the COVID-19 regional safety assessment". *Journal of Infection and Public Health*, 14(6), 2021, pp. 775-786.
32. Zhang, J., "*Research on Safety Technology of Inclined Shaft Construction in Coal Mine*". Master Thesis of University of South China, China, 2018, pp. 3-28.
33. Zhang, H., "*Study of Safety Evaluation for JT Iron Mine Based on Fuzzy Comprehensive Evaluation Set Valued Statistics*". Master Thesis of Liaoning Technical University, China, 2015, pp. 7-25.
34. Ministry of Housing and Urban-Rural Development of the People's Republic of China, "*Gode for Construction of Non-ferrous Metals Mine Sinking and Drifting Engineering: GB50653-2011*". Beijing: Standards Press of China, China, 2011, pp. 78-86.
35. Zhao, S. F., Wei, M. L., Zhang, C. W., Guo, W., Lu, Z. X., "Coal mine inclined shaft advanced detection method and physical model test based on shield cutterhead moving array electrodes". *Energies*, 12(9), 2019, pp. 091671.
36. Liang, R., "*Risk Characteristic and Assessment in a Long Slope Mining Construction Excavated by TBM*". Doctoral Dissertation of China University of Mining and Technology (Beijing), China, 2016, pp. 2-22.
37. Li, W. J., "*Instruction Manual for Safety Assessment of Coal Mine and Non Coal Mine* (*Part 2*)". Xuzhou: China University of Mining and Technology Press, China, 2006, pp. 56-88.
38. Qin, G. R., "*Guide for Mine Construction Organization Design*". Beijing: China Coal Industry Publishing House, China, 2002, pp. 62-76.
39. Zhang, Z. R., "*Impact factor system analysis of blasting rock drift drivage and comprehensive evaluation research*". Doctoral Dissertation of China University of Mining and Technology (Beijing), China, 2013, pp. 8-30.