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Research Article

The Application of Intuitionistic Fuzzy Set-TOPSIS Model on the Level Assessment of the Surrounding Rocks

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The level assessment of surrounding rocks in underground tunnels has essential significance for the stability of surrounding rocks. Its review is affected by many factors. The intuitionistic fuzzy set-TOPSIS model is first introduced to estimate the quality of surrounding rocks accurately. Secondly, the decisive matrix of the intuitionistic fuzzy sets is established. Then, the weighed decisive matrix is obtained. Finally, the degree of membership at different levels regarding the surrounding rock quality is determined. The quality level corresponding to the maximum degree of membership is the final assessment level. The conclusions are drawn that estimating the quality level of surrounding rocks using the method is feasible compared to the actual investigations and other methods. This method can reflect the quality level of surrounding rocks accurately, providing a new route for the quality assessment of surrounding rocks in the future.

1. Introduction

With the development of underground space technology, more than two hundred tunnels with 10 km lengths have been established in different zones in many countries [1]. For example, in 1988, Tsing Hon Cross Harbour Tunnel started to run in Japan; the undersea tunnel across the English Channel ran formally in 1994; the Le Qishan tunnel in Switzerland and the Gotthard Tunnel under the Alps were, respectively, established in 2007. In China, the total length of the railway tunnels under construction and completion is currently more than 14,500 km [2]. The total length of tunnels during the planning and design phases is 10000 km [3]. And the tunnel is engineering towards more prolonged, more extensive, and more profound than before with the rapid development of infrastructure construction in the world [4]. As the magnitude of the stress increases, the differences among the geological conditions become more remarkable, and the degree of destabilization and destruction of the surrounding rocks increases gradually. The form of failure represents the diversity, complexity, and non-predictability of the deformation. The quality of surrounding rocks during the tunnel construction is applied to assess the stability of surrounding rocks and economic benefit and select the parameters of engineering structures. Therefore, the quality assessment of surrounding rocks in a tunnel is significant [5].

Many researchers have investigated the quality level assessments of surrounding rocks [6], in many countries. Many methods are applied to analyze the quality of surrounding rocks [7], especially with the development of mathematics and computer technology; the applied mathematical statistics method, clustering partition method [8], and fuzzy mathematics theory [9] have been used to partition the quality of surrounding rocks successfully, such as the Grey theory method [10], the neural network method [11], Fisher discriminant analysis method [12], the classification of probability theory [13], and extension classification method [14]. The application of these methods shown in Table 1 makes the quality assessment of surrounding rocks more reasonable, but they still have some shortcomings [15]. For example, the determination of

Table 1: The contribution list of different authors.

Serial number	Name of the author	Year	The contents of contribution
1	Bezdzk	1981	Using the clustering partition method
2	Gu	2021	Using fuzzy mathematics theory
3	Gu and Wu	2019	Using the grey theory method
4	Cao et al.	2014	Using the neural network method
5	Rao et al.	2015	Using Fisher discriminant analysis method
6	Wang et al.	2019	Using the classification of probability theory
7	He and Chen	2016	Using the extension classification method

membership degree weight in the fuzzy mathematics theory is too objective and casual; the data with the large fluctuations and dispersion in grey theory cannot be predicted accurately; for the neural network method, although the irrationality of determining weight artificially can be avoided, its quantity of training sample is limited [16]; for the Fisher discriminant analysis method, the requirement of engineering data is high, and the training samples should contain greater capacity to meet the need of precision; different classifications are required to be independent of each other in the category of probability theory, and it does not conform to actual circumstances, while for the extension classification method, the membership degree reflects insufficient for the fuzziness of evaluation factors. To overcome the above shortcomings, the intuitionistic fuzzy set-TOPSIS model is used to assess the quality level of surrounding rocks in the paper.

Relative to the traditional vague mathematical method, the non-membership function is added in the intuitionistic fuzzy sets [17], so the fuzzy concept can be expressed definitively [18–20]. Also, it is characterized by the sufficient usage of original datum, minor information loss, and wide application [21], so it is an efficient multiple attribute decision-making method [22]. A new model is constructed when the intuitionistic fuzzy set theory is combined with the TOPSIS model. In comparison with the traditional methods, the new model has higher efficiency.

The paper is organized as follows. In Section 2, the basic theory is introduced first. In Section 3, engineering background in the study area is introduced, and a quality assessment model of the surrounding rocks is established and analyzed. In Section 4, conclusions are drawn.

2. Basic Theory

2.1. The Construction of Model. The quality assessment of surrounding rock in an underground tunnel has essential significance for the objective evaluation of the stability of surrounding rocks, the design of excavation section, the selection of rational construction technology, and determination of supporting mode.

To assess the quality of surrounding rocks, a new model is provided based on the combination of intuitionistic fuzzy sets and the TOPSIS model. Its calculation frame is plotted in Figure 1.

In Figure 1, the assessment indexes are determined about the quality of surrounding rock firstly; then, the original data are handled; that is, their parameters of membership degree and non-membership degree functions are, respectively, calculated, the decisive matrix of the initial datum is constructed, the optimal weight coefficients are determined, and then weighted decisive matrix is determined; finally, ranking sequences of the degree of membership are determined, and the quality levels of the surrounding rock are judged according to the maximum degree of membership criterion.

2.2. The Establishment of Evaluation Index Systems about the Quality of Surrounding Rocks. The geological environment in the underground engineering is very complex. The detection of the stress of original rocks and the parameters of rock mechanics is challenging, and the distribution of mechanical parameters of the rock mass has apparent inhomogeneity. So, the reasonable selection of the evaluation index is significant.

The uniaxial compression strength of rocks at the saturation states (R_c), the rock quality index (RQD), the water seepage of groundwater (Q), the acoustic velocity of rock mass (V), and the orientation of structural plane (θ) are selected as the quality assessment indexes of rock mass in the paper. These indexes are all qualitative indexes. The five assessment indexes are divided into five levels: perfect (I), good (II), common (III), bad (IV), and very bad (V), as shown in Table 2.

2.3. The Entropy Weight Theory. Its calculation process is as follows.

(1) Normalization of different indexes: their expression is shown as

$$r_{ij} = \frac{x_{ij} - x_{i\min}}{x_{i\max} - x_{i\min}}, \tag{1}$$

$$r_{ij} = \frac{x_{i\max} - x_{ij}}{x_{i\max} - x_{i\min}}, \tag{2}$$

where x_{ij} is the corresponding magnitude of the jth assessment index in the ith scheme ($i = 1, 2, 3, \ldots, m$; $j = 1, 2, 3, \ldots, n$).

(2) The determination of index weights: based on the normalized index matrix, the index weights can be calculated as follows:

$$\omega_j = \frac{1 - s_j}{n - \sum_{j=1}^{n} s_j}, \tag{3}$$

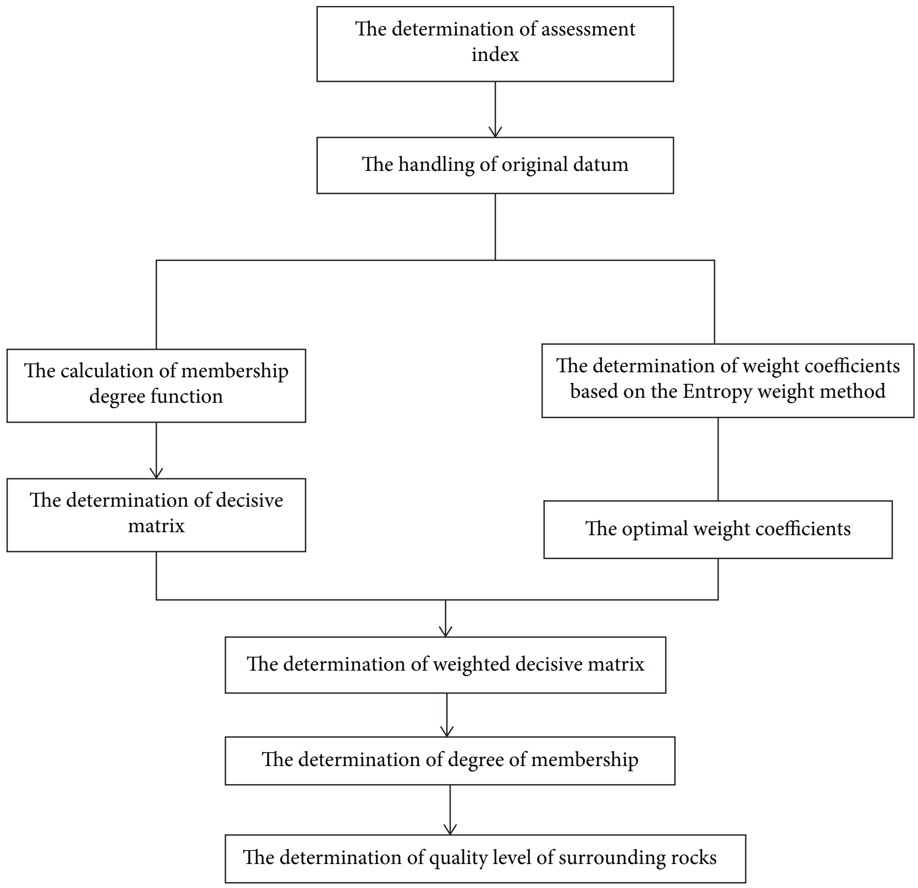


Figure 1: The assessment process of quality of surrounding rocks.

Table 2: The quality level of surrounding rocks and assessment standard.

The quality level of surrounding rocks	R_c (MPa)	RQD (%)	Q ($l.$ (min. 10 m))$^{-1}$	V (m/s)	θ (°)
Very good (I)	150~200	90~110	0~25	5000~7500	75~90
Good (II)	125~150	75~90	25~50	4000~5000	60~75
Common (III)	90~125	50~75	50~100	2500~4000	45~60
Bad (IV)	40~90	25~50	100~125	2000~2500	30~45
Very bad (V)	10~40	0~25	125~200	100~2000	0~30

where

$$s_j = -k \sum_{i=1}^{n} b_{ij} \ln(b_{ij}),$$
$$b_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}}. \quad (4)$$

2.4. The Establishment of a Decisive Matrix. The intuitionistic fuzzy set model originated form the fuzzy set theory. It was provided by Atanassov [23]. In the theory, two scales are applied to define the fuzziness (membership degree and non-membership degree), and three states (support, opposition, and neutrality) can be described, so it has wide application prospect.

x is assumed as a non-empty set, and X is given domain; an intuitionistic fuzzy set in X can be defined as [9]

$$A = \{\langle x, \mu_A(x), \nu_A(x) | x \in X\rangle\}, \quad (5)$$

where μ_A and ν_A represent, respectively, the membership degree and non-membership degree of the element $x \in A$ in X; it should meet the following condition: $\pi_A(x) = 1 - \mu_A(x) - \nu_A(x) \le 1, x \in X$, and $\pi_A(x)$ is called the degree of hesitation of $x \in A$.

To establish the intuitionistic fuzzy matrix, the corresponding determined parameters about the membership and non-membership degrees can be expressed as

$$\mu_{nk} = \exp\left[-\frac{\left(x_n - c_{\mu k}\right)^2}{2\sigma_{\mu k}^2}\right], \tag{6}$$

$$\nu_{nk} = 1 - \exp\left[-\frac{\left(x_n - c_{\gamma k}\right)^2}{2\sigma_{\gamma k}^2}\right], \tag{7}$$

$$c_{uk} = c_{\gamma k} = \frac{\underline{S_k} + \overline{S_k}}{2}, \tag{8}$$

$$\sigma_{\mu k}^2 = -\frac{\left(\overline{S_k} - c_{\mu k}\right)^2}{2\ \ln(1 - \alpha/2)}, \tag{9}$$

$$\sigma_{\gamma k}^2 = -\frac{\left(\overline{S_k} - c_{\gamma k}\right)^2}{2\ \ln(\alpha + (1 - \alpha/2))}, \tag{10}$$

where $c_{\mu k}$, $c_{\gamma k}$, $\sigma_{\mu k}$, and $\sigma_{\gamma k}$ are, respectively, correlated parameters and α is the hesitating degree (it is equal to 0.2 in the paper).

According to the intuitionistic fuzzy number $A_{\mathrm{nk}} = \langle \mu_{nk}, \nu_{nk} \rangle$, the decisive matrix can be obtained as

$$F_P = \begin{bmatrix} (\mu_{11}, \nu_{11}) & (\mu_{12}, \nu_{12}) & \cdots & (\mu_{1K}, \nu_{1K}) \\ (\mu_{21}, \nu_{21}) & (\mu_{22}, \nu_{22}) & \cdots & (\mu_{2K}, \nu_{2K}) \\ \cdots & \cdots & \cdots & \cdots \\ (\mu_{N1}, \nu_{N1}) & (\mu_{N2}, \nu_{N2}) & \cdots & (\mu_{NK}, \nu_{NK}) \end{bmatrix}. \tag{11}$$

2.5. The Procedure of Model. Its specific procedure is as follows.

(1) The assessment index of surrounding rocks' quality is analyzed first, and classification standards of surrounding rocks are constructed.

(2) The determination of weight coefficients: the weights of membership degree are $\alpha = (\alpha_1, \alpha_2, \ldots, \alpha_n)$, the weights of non-membership degree are $\beta = (\beta_1, \beta_2, \ldots, \beta_n)$, and the combination weight coefficients can be expressed as [9]

$$\omega_{\mathrm{n}} = \langle \chi_{n}, \gamma_n \rangle = \langle \min\left(\alpha_{n}, \beta_n\right), 1 - \max\left(\alpha_{n}, \beta_n\right) \rangle, \tag{12}$$

where ω_n represent the combination weights and χ_n, γ_n represent, respectively, the important and non-important degrees (they should meet $0 \leq \chi_n + \gamma_{\mathrm{n}} \leq 1$).

(3) According to equations (11) and (12), the weighted decisive matrix is depicted as

$$\overline{F_P} = \omega_n F = \langle \chi_n \mu_{nk}, \gamma_n + \nu_{nk} - \gamma_n \nu_{nk} \rangle_{n \times k}. \tag{13}$$

(4) The determination of plus and negative ideal solutions: they can be expressed as

$$\begin{aligned} B^+ &= \left[\langle \mu_1^+, \nu_1^+ \rangle, \langle \mu_2^+, \nu_2^+ \rangle, \ldots, \langle \mu_{\mathrm{n}}^+, \nu_n^+ \rangle\right], \\ B^- &= \left[\langle \mu_1^-, \nu_1^- \rangle, \langle \mu_2^-, \nu_2^- \rangle, \ldots, \langle \mu_{\mathrm{n}}^-, \nu_n^- \rangle\right], \end{aligned} \tag{14}$$

where $\mu_n^+ = \max_{1 \leq k \leq n} (\overline{\mu_{nk}})$; $\nu_n^+ = \max_{1 \leq k \leq n} (\overline{\nu_{nk}})$; $\mu_n^- = \min_{1 \leq k \leq n} (\overline{\mu_{nk}})$; $\nu_n^- = \max_{1 \leq k \leq n} (\overline{\nu_{nk}})$; $n = 1, 2, \ldots, n$.

(5) The determination of Euclidean distance: the Euclidean distance of plus and negative ideal solutions is calculated as

$$D\left(\mathrm{s}_k, B^+\right) = \sqrt{\frac{1}{2} \sum_{n=1}^{N} \left[\left(\overline{\mu_{nk}} - \mu_n^+\right)^2 + \left(\overline{\nu_{nk}} - \nu_n^+\right)^2 + \left(\mu_n^+ + \nu_n^+ - \overline{\mu_{nk}} - \overline{\nu_{nk}}\right)^2 \right]}, \tag{15}$$

$$D\left(\mathrm{s}_k, B^-\right) = \sqrt{\frac{1}{2} \sum_{n=1}^{N} \left[\left(\overline{\mu_{nk}} - \mu_n^-\right)^2 + \left(\overline{\nu_{nk}} - \nu_{\mathrm{nk}}^-\right)^2 + \left(\mu_n^- + \nu_n^- - \overline{\mu_{nk}} - \overline{\nu_{nk}}\right)^2 \right]}, \tag{16}$$

$$\eta_{\mathrm{k}} = \frac{D^2\left(\mathrm{s}_k, B^-\right)}{D^2\left(\mathrm{s}_k, B^-\right) + D^2\left(\mathrm{s}_k, B^+\right)}, \tag{17}$$

where $D(s_k, B^+)$ and $D(s_k, B^-)$ are, respectively, the Euclidean distances of plus and negative ideal solutions and η_k is the degree of membership at scheme S_k.

(6) The determination of surrounding rock level: when the membership degrees are determined, the maximum membership degree is determined as the assessment levels of corresponding surrounding rocks' quality.

3. Engineering Application

3.1. Study Area. Bulunkou-Gonggeer Hydropower Project is located in Akto County, Kizilsu Kyrgyz Autonomous Prefecture, Xinjiang Province. It is the first hydroelectric station in the upper and middle sections of the Ganzi River basin. Its locations are plotted in Figure 2. Its distance from VIII in the upper reaches of the dam axis line is 240 m, the mountain is steep along the tunnel, and the terrain is high in the west and low in the east. The highest elevation of the peak is 4750 m.

Figure 2: The location of survey area.

The general height is between 3500 and 5000 m; the tunnel extends downstream to 1600 km along 314 National Highway, and the length of the tunnel is 17.36 km.

The lithology of strata along the division tunnel includes the middle Devonian system in Silurian, Cenozoic quaternary, and Caledonian intrusive rock. The ancient crystalline schist, foliation and gneissic development, and the fault and structural fracture development are distributed widely in engineering. So, the water gushing originated from defects, crevices, and rockburst often occur, and the quality assessment of surrounding rocks in the underground hydraulic tunnel has great significance.

3.2. The Establishment of Level Assessment Model about the Surrounding Rocks. The level of surrounding rocks in the underground hydraulic tunnel is divided into five types according to the correlating influential index. To testify the feasibility, according to the design geological survey report in the underground tunnel in the Bulunkou-Gonggeer Hydropower Project, the reference values of quality indexes of surrounding rocks in 4 classic pile numbers section are given in Table 3.

Based on Table 2, according to equations (6)–(10), for $1^{\#}$ pile section, the parameters of membership and non-membership degree functions can be shown in Table 4.

The membership degree function and non-membership degree function are, respectively, plotted in Figures 3 and 4.

Based on Figures 3 and 4, surrounding rocks at $1^{\#}$ pile section are selected as an example to assess and analyze; according to equation (11), the decisive matrix F of intuitionistic fuzzy sets can be expressed as follows:

$$F = \begin{bmatrix} (0.0341, 0.8479) & (0.5238, 0.3026) & (0.3206, 0.4697) & (0.0036, 0.9568) & (0, 1) \\ (0.0366, 0.8418) & (0.9604, 0.0202) & (0.1344, 0.6734) & (0, 0.9979) & (0, 1) \\ (0.0009, 0.9796) & (0.589, 0.2555) & (0.3168, 0.4731) & (0, 1) & (0, 0.9921) \\ (0.5239, 0.3026) & (0.166, 0.6326) & (0.002, 0.9684) & (0, 1) & (0, 0.9999) \\ (0.002, 0.9684) & (0.719, 0.168) & (0.1659, 0.6326) & (0, 0.9973) & (0, 0.9947) \end{bmatrix}. \quad (18)$$

According to equations (1)–(3), the membership degree weights of decisive matrix can be obtained as follows:

$$\alpha = (0.1569, 0.2214, 0.1911, 0.208, 0.2226). \quad (19)$$

Likewise, the non-membership degree weights can be expressed as follows:

$$\beta = (0.198, 0.1119, 0.1728, 0.2578, 0.2596). \quad (20)$$

Finally, according to equation (12), the intuitionistic fuzzy weights can be obtained as follows:

$$\omega = [(0.1569, 0.802), (0.1119, 0.7786), (0.1728, 0.8089), (0.208, 0.7422), (0.2226, 0.7404)]. \quad (21)$$

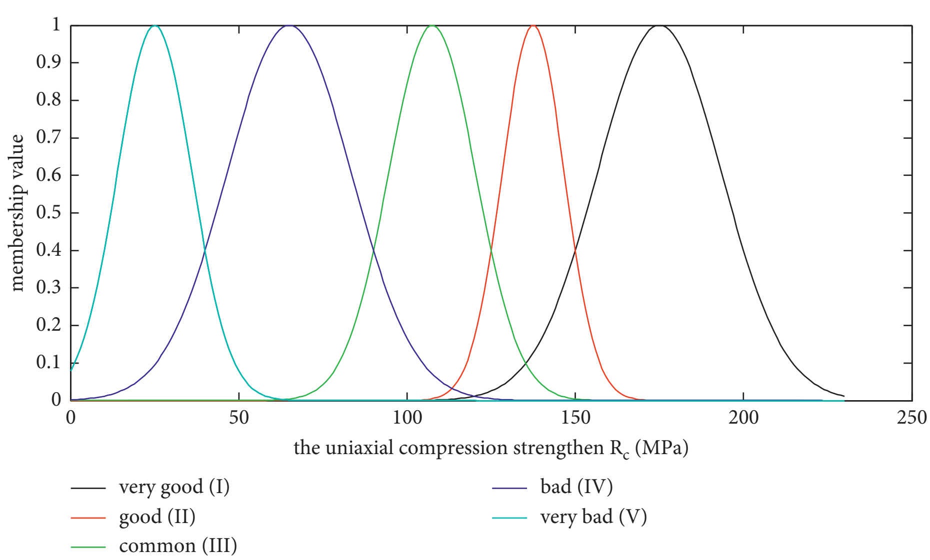
Substituting F and into equation (13), the weighted decisive matrix can be expressed as

Table 3: The actual value of the index in the classic surrounding rock section.

Pile number section	R_c (MPa)	RQD (%)	Q ($l.$ (min. 10 m)$^{-1}$)	V (m/s)	θ (°)
1#	127	81	47	5200	63
2#	106	68	73	3500	54
3#	78	51	112	2900	41
4#	83	49	105	3200	32

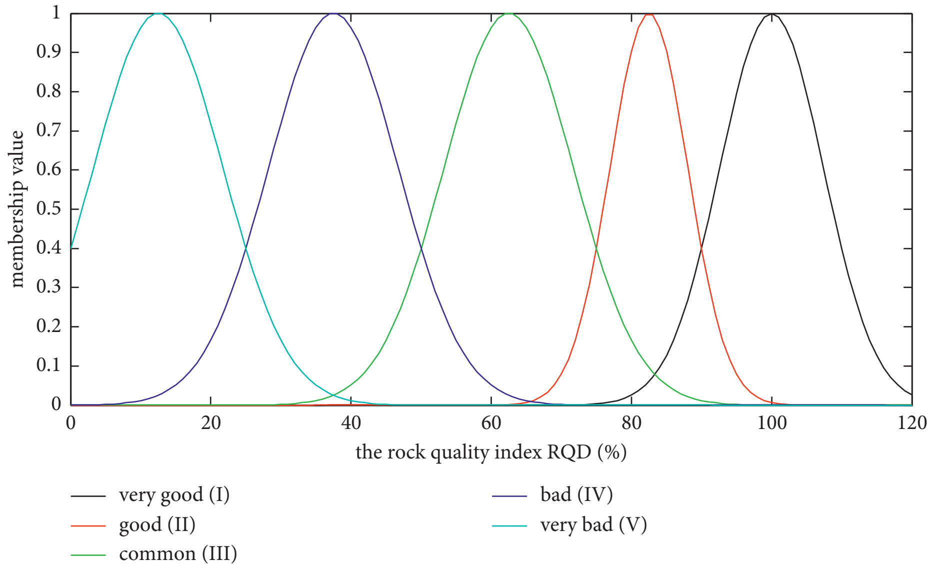
Table 4: The parameters of membership and non-membership degree functions.

Index	Level				
	I	II	III	IV	V
R_c (MPa)	$c_{\mu1}=c_{\gamma1}=175$, $\sigma^2_{\mu1}=341.05$, $\sigma^2_{\gamma1}=611.75$	$c_{\mu2}=c_{\gamma2}=137.5$, $\sigma^2_{\mu2}=85.26$, $\sigma^2_{\gamma2}=152.94$	$c_{\mu3}=c_{\gamma3}=107.5$, $\sigma^2_{\mu3}=167.114$, $\sigma^2_{\gamma3}=299.76$	$c_{\mu4}=c_{\gamma4}=65$, $\sigma^2_{\mu4}=341.05$, $\sigma^2_{\gamma4}=611.75$	$c_{\mu5}=c_{\gamma5}=25$, $\sigma^2_{\mu5}=122.78$, $\sigma^2_{\gamma5}=220.23$
RQD (%)	$c_{\mu1}=c_{\gamma1}=100$, $\sigma^2_{\mu1}=54.57$, $\sigma^2_{\gamma1}=97.88$	$c_{\mu2}=c_{\gamma2}=82.5$, $\sigma^2_{\mu2}=30.69$, $\sigma^2_{\gamma2}=55.06$	$c_{\mu3}=c_{\gamma3}=62.5$, $\sigma^2_{\mu3}=85.26$, $\sigma^2_{\gamma3}=152.94$	$c_{\mu4}=c_{\gamma4}=37.5$, $\sigma^2_{\mu4}=85.26$, $\sigma^2_{\gamma4}=152.94$	$c_{\mu5}=c_{\gamma5}=12.5$, $\sigma^2_{\mu5}=85.26$, $\sigma^2_{\gamma5}=152.94$
Q ($l.$ (min. 10 m)$^{-1}$)	$c_{\mu1}=c_{\gamma1}=12.5$, $\sigma^2_{\mu1}=85.26$, $\sigma^2_{\gamma1}=152.94$	$c_{\mu2}=c_{\gamma2}=37.5$, $\sigma^2_{\mu2}=85.26$, $\sigma^2_{\gamma2}=152.94$	$c_{\mu3}=c_{\gamma3}=75$, $\sigma^2_{\mu3}=341.05$, $\sigma^2_{\gamma3}=611.75$	$c_{\mu4}=c_{\gamma4}=112.5$, $\sigma^2_{\mu4}=85.26$, $\sigma^2_{\gamma4}=152.94$	$c_{\mu5}=c_{\gamma5}=162.5$, $\sigma^2_{\mu5}=767.36$, $\sigma^2_{\gamma5}=1376.4$
V (m/s)	$c_{\mu1}=c_{\gamma1}=6250$, $\sigma^2_{\mu1}=852620$, $\sigma^2_{\mu1}=30.69$, $\sigma^2_{\gamma1}=1529400$	$c_{\mu2}=c_{\gamma2}=67.5$, $c_{\mu2}=c_{\gamma2}=4500$, $\sigma^2_{\mu2}=136420$, $\sigma^2_{\gamma2}=244700$	$c_{\mu3}=c_{\gamma3}=52.5$, $c_{\mu3}=c_{\gamma3}=3250$, $\sigma^2_{\mu3}=306940$, $\sigma^2_{\gamma3}=550580$	$c_{\mu4}=c_{\gamma4}=37.5$, $c_{\mu4}=c_{\gamma4}=2250$, $\sigma^2_{\mu4}=136420$, $\sigma^2_{\gamma4}=244700$	$\sigma^2_{\mu5}=122.78$, $c_{\mu5}=c_{\gamma5}=1050$, $\sigma^2_{\mu5}=492470$, $\sigma^2_{\gamma5}=883370$
θ (°)	$c_{\mu1}=c_{\gamma1}=82.5$, $\sigma^2_{\gamma1}=55.06$	$\sigma^2_{\mu2}=30.69$, $\sigma^2_{\gamma2}=55.06$	$\sigma^2_{\mu3}=30.69$, $\sigma^2_{\gamma3}=55.06$	$\sigma^2_{\mu4}=30.69$, $\sigma^2_{\gamma4}=55.06$	$c_{\mu5}=c_{\gamma5}=15$, $\sigma^2_{\gamma5}=220.23$



(a)

Figure 3: Continued.



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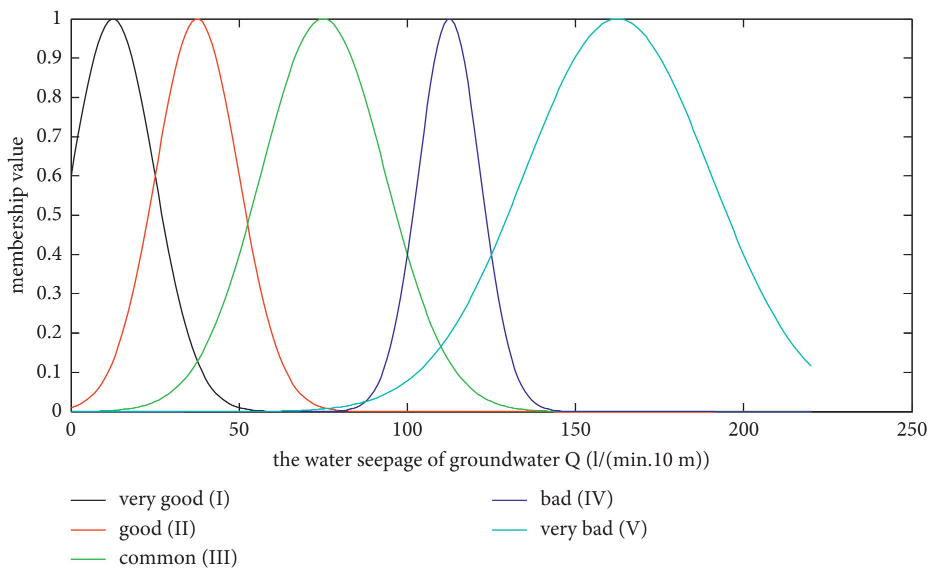

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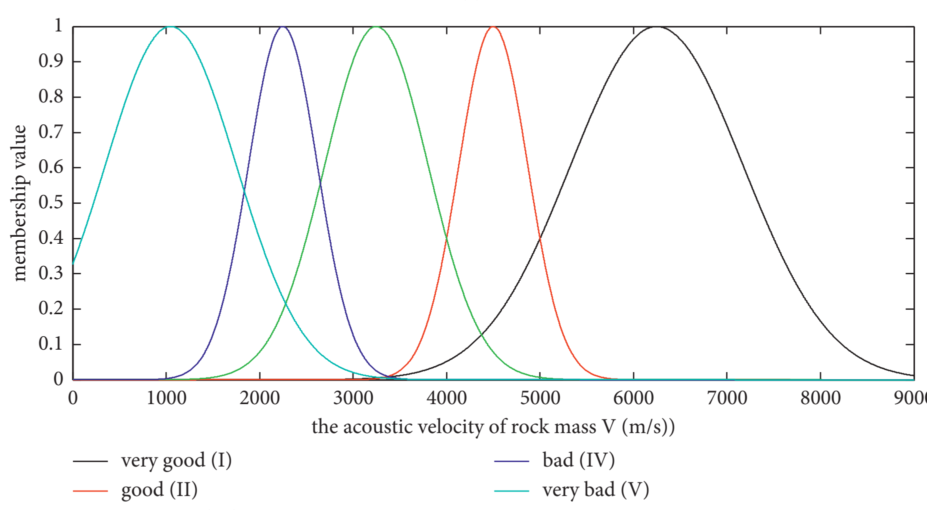

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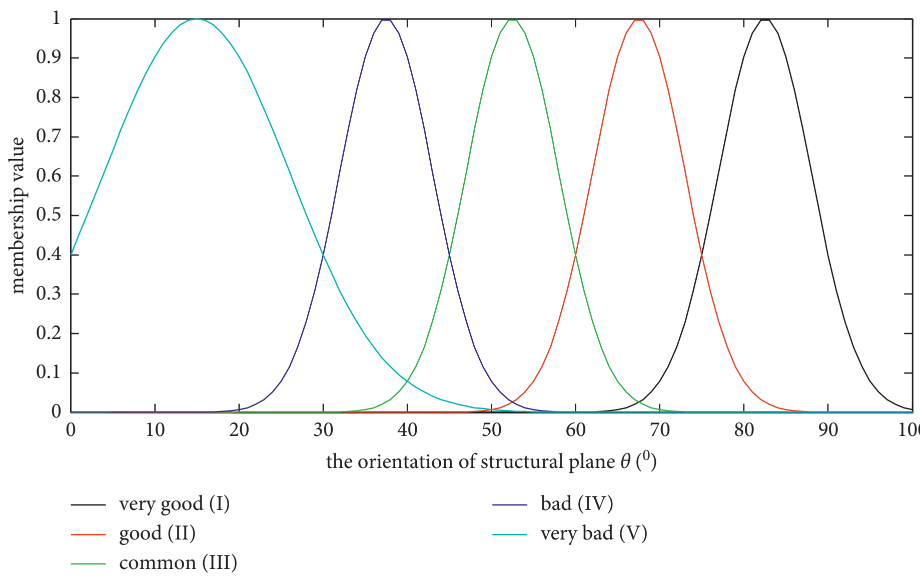
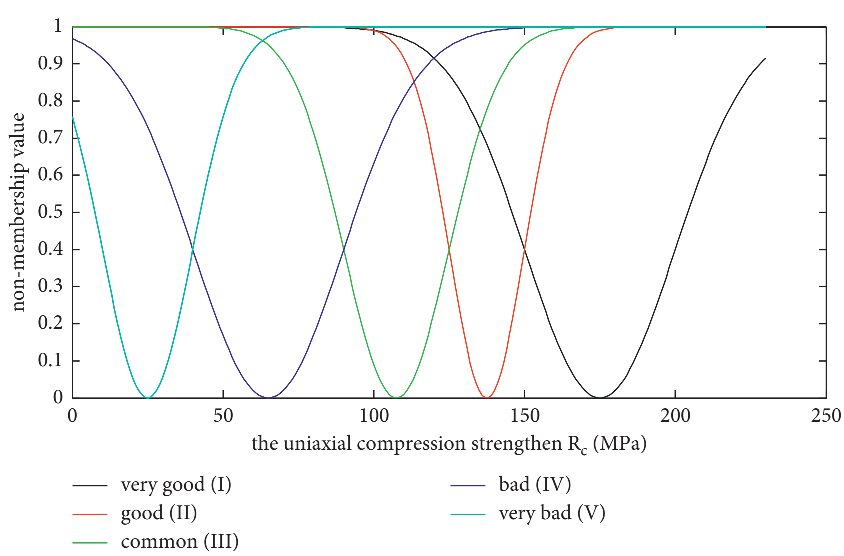


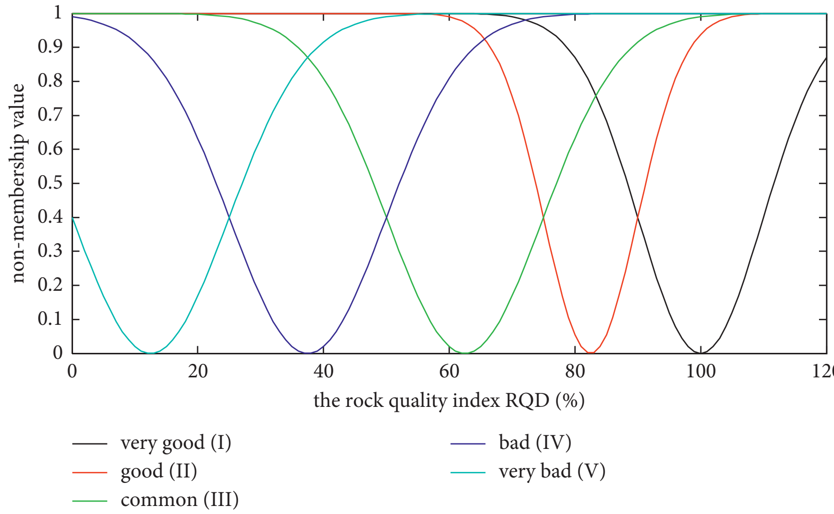
(e)

Figure 3: The membership degree function of surrounding rock quality. (a) The uniaxial compression strength of rocks at the saturation states (R_c). (b) The rock quality index (RQD). (c) The water seepage of groundwater (Q). (d) The acoustic velocity of rock mass V. (e) The orientation of structural plane θ.

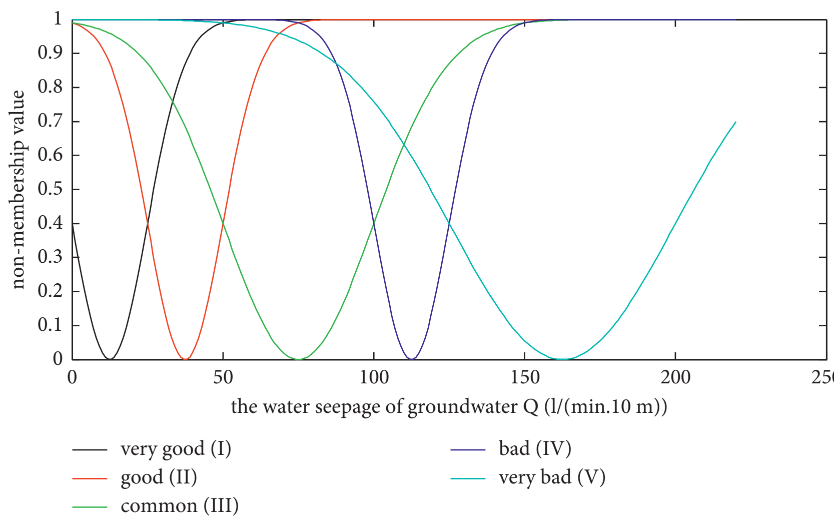


(a)

Figure 4: Continued.



(b)



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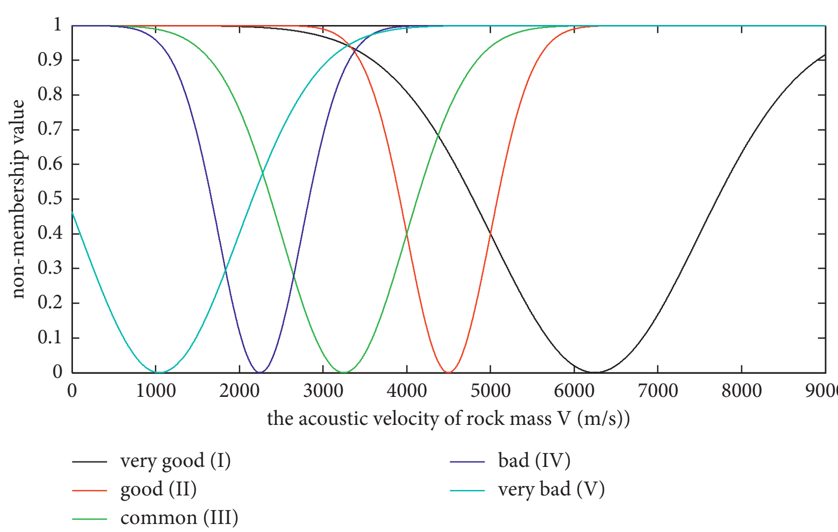
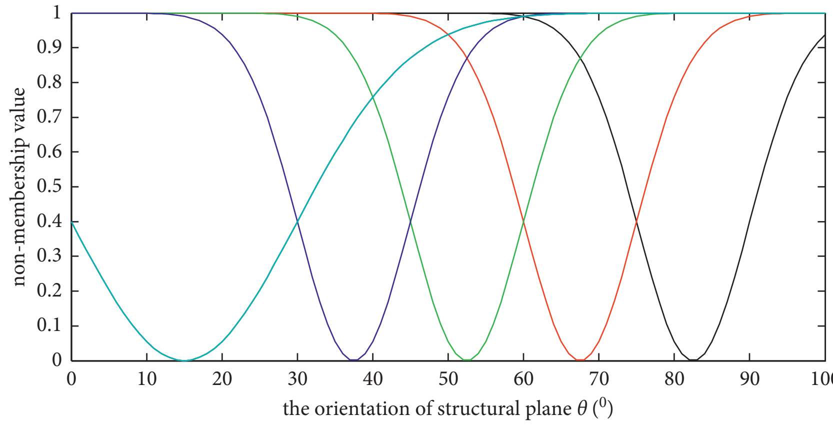


(d)

Figure 4: Continued.



(e)

Figure 4: The non-membership degree function of surrounding rock quality. (a) The uniaxial compression strength of rocks at the saturation states (R_c). (b) The rock quality index (RQD). (c) The water seepage of groundwater (Q). (d) The acoustic velocity of rock mass V. (e) The orientation of structural plane θ.

$$F_P = \omega F = \begin{bmatrix} (0.0054, 0.9699) & (0.0822, 0.8619) & (0.0503, 0.895) & (0.0006, 0.9914) & (0, 1) \\ (0.0041, 0.965) & (0.1075, 0.7831) & (0.015, 0.9277) & (0, 0.9995) & , \\ (0.0002, 0.9961) & (0.1018, 0.8577) & (0.0547, 0.8993) & (0, 1) & (0, 0.9985) \\ (0.109, 0.8202) & (0.0345, 0.9053) & (0.0004, 0.9919) & (0, 1) & (0, 1) \\ (0.0004, 0.9918) & (0.16, 0.784) & (0.0369, 0.9046) & (0, 0.9993) & (0, 0.9986) \end{bmatrix}. \quad (22)$$

According to the equation (14), the minus and plus ideal solutions in 1# surrounding rock section can be expressed as follows:

$$\begin{aligned} B^{+} &= [\ (0.109, 0.8202)\ \ (0.16, 0.7831)\ \ (0.0547, 0.895)\ \ (0.0006, 0.9914)\ (0, 0.9985)\ ], \\ B^{-} &= [\ (0.0002, 0.9961)\ \ (0.0345, 0.9053)\ \ (0.0004, 0.9919)\ \ (0, 1)\ (0, 1)\ ]. \end{aligned} \quad (23)$$

According to equations (15)–(17), the Euclidean distance corresponding to the different levels for 1# surrounding rocks section can be calculated as follows:

$$\begin{aligned} &D(t_1, B^{+}) = 0.2839, D(t_1, B^{-}) = 0.1581, \eta_1 = 0.2367, \\ &D(t_2, B^{+}) = 0.17, D(t_2, B^{-}) = 0.1797, \eta_2 = 0.5278, \\ &D(t_3, B^{+}) = 0.295, D(t_3, B^{-}) = 0.1507, \eta_3 = 0.2069, \\ &D(t_4, B^{+}) = 0.016, D(t_4, B^{-}) = 0.0084, \eta_4 = 0.2135, \\ &D(t_5, B^{+}) = 0.0026, D(t_5, B^{-}) = 0.0021, \eta_5 = 0.3838. \end{aligned} \quad (24)$$

It can be found from above expressions that $\eta_2 > \eta_5 > \eta_1 > \eta_4 > \eta_3$; according to the maximum membership degree criterion, the level of 1# surrounding rock section is determined as II, and this means that the quality of 1# surrounding rock section is good; the result is consistent with the actual investigations [24].

Similarly, the Euclidean distance and degree of membership corresponding to different levels for the surrounding rock sections 2#, 3#, and 4# are, respectively, shown in Table 5.

It can be found from Table 5 that the quality of surrounding rocks can be generally divided into five levels from low to high. The final quality level of 2# and 3# surrounding rock sections is III. The quality level of the 1# surrounding rock section is II, and that of the 4# surrounding rock section is IV.. It means that the quality of 2# and 3# surrounding rock sections is common; the quality of 1# surrounding rock section is good, so no measures are needed to be taken for 1#, 2#, and 3# surrounding rock sections. But for 4# surrounding

Table 5: The assessment of surrounding rock level and comparison.

Pile number section	The assessment level I	II	III	IV	V	The text method	QC method	RMR method	Actual investigations
1#	0.2367	0.5278	0.2069	0.2135	0.3838	II	II	II	II
2#	0.2553	0.6355	0.192	0.2667	0.3917	II	III	III	III
3#	0.2017	0.2566	0.5902	0.3986	0.4252	III	IV	III	III
4#	0.2015	0.201	0.4076	0.6691	0.2761	IV	IV	IV	IV

Table 6: The advantages of intuitionistic fuzzy set method over other models.

Name of the method	The advantage of intuitionistic fuzzy set-TOPSIS model
QC model	The proposed method can not only deal with vague information but also ease our workload, and the efficiency and accuracy can be improved.
RMR method	The sufficient usage of original datum, minor information loss, and wider application.
The traditional fuzzy mathematical method	Their judgments under inherent uncertainty in the proposed model can be conveyed. More significantly, the degree of indeterminacy can be handled adequately in the evaluation.

rock section, its quality of surrounding rock is bad, so the necessary consolidation measure should be taken to prevent the collapse of 4# surrounding rock section, for example, rock bolt support, and so on.

Based on Table 5, the results obtained by four different methods [24] are consistent at different surrounding rock sections, except the 2# surrounding rock section. Its accuracy arrives at 75% in the text method. So, the conclusions are drawn that estimating the quality level of surrounding rocks using the intuitionistic fuzzy set-TOPSIS model is feasible. The model achieves accurate results and provides more details about the quality assessment levels of surrounding rocks. For example, the rock quality index (RQD) of 1# surrounding rocks is 81, which should belong to level II according to Table 1. In addition, the degree of membership of the other indexes belongs to level III, and the quality level probability of 1# surrounding rock section at level II is more significant than that of levels I, III, IV, and V. So, it only belongs to level II and almost impossibly belongs to grades I, IIII, IV, and V. The conclusions are consistent with the actual investigation. Furthermore, the level of 1# surrounding rock section is more likely to be level II than that of 3# and 4# because the maximum degree of membership of 1# surrounding rock section for level II (0.5278) is higher than that of 3# (0.2566) and 4# (0.201).

By comparing this approach with conventional QC model, RMR method, and the traditional fuzzy mathematical method, the advantages of the suggested method can be summarized in Table 6.

4. Conclusions

Taking into account the uniaxial compression strength of rocks at the saturation states (R_c), the rock quality index (RQD), the seepage of groundwater (Q), the acoustic velocity of rock mass (V), and the orientation of structural plane (θ), a new estimation model is introduced to assess the quality of surrounding rocks in Bulunkou-Gonggeer Hydropower Project. The decisive matrix of the surrounding rock quality is established. Then, the weighting coefficients of different indexes were obtained by the entropy weighting method. Finally, the quality of surrounding rocks is judged.

The present method is used to estimate the quality of surrounding rocks. Finally, its results are compared with the actual investigations and other processes, and the results obtained by four various methods are approximately the same; its accurate rate arrives at 75%. The final quality level of 2# and 3# surrounding rock sections is III. The quality level of the 1# surrounding rock section is II, and that of the 4# surrounding rock section is IV.. For 4# surrounding rock section, the quality of surrounding rock is bad, so the necessary consolidation measure should be taken to prevent the collapse of 4# surrounding rock section. In total, the proposed model results are basically consistent with the actual investigations. The model demonstrates the quality level of surrounding rock accurately and further determines the quality ranking of surrounding rocks for different surrounding rock sections. New methods and thoughts for the quality assessment of surrounding rock are suggested.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] B Rajinder and G Eystein, “The use of stress-strength relationship in the assessment of tunnel stability,” *Tunnelling and Underground Space Technology*, vol. 11, no. 1, pp. 93–98, 1996.

[2] C. M Gerrard, “Equivalent elastic moduli of a rock mass consisting of orthorhombic layers,” *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, vol. 19, no. 1, pp. 9–14, 1982.

[3] X. B. Gu and Q. H Wu, “The application of nonordinary, state-based peridynamic theory on the damage process of the rock-like materials,” *Mathematical Problems in Engineering*, vol. 3, no. 8, pp. 1–9, 2016.

[4] X. P. Zhou, Y. X. Zhang, Q. L. Ha, and K. S Zhu, “Micromechanical modelling of the complete stress-strain relationship for crack weakened rock subjected to compressive loading,” *Rock Mechanics and Rock Engineering*, vol. 41, no. 5, pp. 747–769, 2008.

[5] X. B. Gu, Q. H. Wu, and Y. H Zhu, “The experimental investigation on the propagation process of crack for brittle rock similar material,” *Geotechnical & Geological Engineering*, vol. 37, no. 6, pp. 4714–4740, 2019.

[6] Q. Lan, C. Lu, D. Gautam, Q. W. Li, and Y Li, “Surface characterization and frictional energy dissipation characteristics of deep granite under high stress conditions,” *Rock Mechanics and Rock Engineering*, vol. 52, no. 5, pp. 87–90, 2019.

[7] G Lashkanpour and E. K. S Passaris, “Development of a database system on shale characterstics,” *Proceeding of 7th intemational IAEG Congress*, vol. 7, no. 6, pp. 4477–4482, 1994.

[8] J. C Bezdzk, *Pattern recognition with fuzzy objective function algorithms*, Springer, New York, NY USA, 1981.

[9] X. B Gu, “The risk assessment of debris flow hazards in banshanmen gully based on the entropy weight-normal cloud method,” *Advances in Civil Engineering*, vol. 1, no. 1, pp. 1–11, 2021.

[10] X. B. Gu and Q. H Wu, “Seismic stability analysis of waterfront rock slopes using the modified pseudo-dynamic method,” *Geotechnical & Geological Engineering*, vol. 37, no. 3, pp. 1743–1753, 2019.

[11] L. L. Cao, L. R. Xu, and S. Y Chen, “Assessment of debris flow hazard based on fuzzy network,” *Hydrogeology & Engineering Geology*, vol. 42, no. 2, pp. 26–36, 2014, (in Chinese).

[12] Y Rao, Y Zhang, and R Rao, “Sensitivity analysis on the influence factors of slope stability for ion-absorbed rare earth ore by in-situ leaching,” *Mining Research and Development*, vol. 35, no. 9, pp. 60–63, 2015, (in Chinese).

[13] X. T. Wang, S. C. Li, Z. H. Xu, J. Hu, D. D. Pan, and Y. G Xue, “Risk assessment of water inrush in karst tunnels excavation based on normal cloud model,” *Bulletin of Engineering Geology and the Environment*, vol. 3, no. 12, pp. 1–12, 2019.

[14] S He and F Chen, “Research of landslide stability assessment based on intuitionistic fuzzy sets TOPSIS multiple attribute decision making method,” *Chinese Journal of Geological Hazard and Control*, vol. 27, no. 3, pp. 22–28, 2016, (in Chinese).

[15] X. P. Zhou, X. B. Gu, and Q. H Qian, “Seismic bearing capacity of shallow foundations resting on rock masses subjected to seismic loads,” *KSCE Journal of Civil Engineering*, vol. 20, no. 1, pp. 216–228, 2016.

[16] J. Chen, Y. Shou, and X Zhou, “Implementation of the novel perfectly matched layer element for elastodynamic problems in time-domain finite element method,” *Soil Dynamics and Earthquake Engineering*, vol. 152, 2022.

[17] J. Zhou and X. B. Li, “Long-term prediction model of rock burst in underground openings using heuristic algorithms and support vector machines[J],” *Safety Science*, vol. 50, no. 4, p. 629~644, 2012.

[18] F. Xiao, “A distance measure for intuitionistic fuzzy sets and its application to pattern classification problems,” *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 51, pp. 1–13, 2020.

[19] F. Xiao, “CaFtR: a fuzzy complex event processing method,” *International Journal of Fuzzy Systems*, vol. 24, 2021.

[20] D. Xie, F. Xiao, and W. Pedrycz, “Information quality for intuitionistic fuzzy values with its application in decision making,” *Engineering Applications of Artificial Intelligence*, vol. 109, 2022.

[21] Z. H. Xu, S. C. Li, and L. P Li, “Risk assessment of water or mud inrush of karst tunnels based on analytic hierarchy process,” *Rock and Soil Mechanics*, vol. 32, no. 1, pp. 1757–1766, 2011.

[22] V. P. Singh, *Entropy theory and its application in environmental and water engineering*, John Wiley & Sons, vol. 662, Texas USA, , 2020.

[23] K. T Atanassov, *Intuitionistic Fuzzy Sets*, pp. 503–522, VII ITKR’s Session, Sofia, Bulgarian, 1983.

[24] J. Hao, *Study on Surrounding Rock Quality Evaluation and the Stability for Tunnel Construction Period in High Geostress Areas*, PhD Thesis (in Chinese), XinJiang Agricultural University, Urumqi, China, 2015.