Research Article

The Application of Variable Fuzzy Sets Theory on the Quality Assessment of Surrounding Rocks

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The quality assessment of surrounding rocks has tremendous influences on engineering construction, so its investigation is significant. The uniaxial compressive strength of rocks $\sigma_c$, the integrity coefficients of rock mass $K_V$, the conditions of the structural plane $S$, the seepage amount of groundwater $W$, and the intersection angle $\theta$ between the axis line and structural plane are selected as the quality assessment index of surrounding rocks at first. Then, the entropy weight-variable fuzzy sets model is introduced. Second, the relative membership degree matrix about the variable fuzzy sets is established, and the weight coefficients are determined based on the entropy weight method. Finally, the fracture behavior level of surrounding rocks is determined using the mean ranking feature value. The conclusions demonstrate that the results obtained based on the variable fuzzy sets method are consistent with the current specification; its accuracy arrives at 80%. Compared with the traditional way, its assessment process has higher reliability and efficiency. So, it could provide a new alternate way to assess the risk level in civil engineering accurately.

1. Introduction

Many factors affect the stability of surrounding rocks in reality [1, 2], for example, the construction level, timbering opportunity, and the geometric deformation of cross-section [3, 4]. In essence, these factors are relevant to the quality of surrounding rocks [5, 6], so the quality of surrounding rocks during the construction process of the tunnel is adopted to assess the stability of the tunnel. Moreover, it is also used to select the engineering structure parameters and evaluate the economic benefit [7]. So, the quality assessment of surrounding rocks in the tunnel has great significance.

Many researchers in many countries have provided many methods to assess the quality of surrounding rocks [8] in recent years. The fractal theory is supplied by Du et al. [9] and Point et al. [10] to assess the surrounding rocks’ quality based on the fractal characteristics of the rock structure face. The fractal dimension about over and under excavation of rock mass is calculated by Boadu, etc., [11] to seek the relationship between structural features and the category of surrounding rocks. The probability and statistical method for rock mass classification are suggested by Boadu and Long [12] to determine the rock strength and deformation parameters based on the classification index of surrounding rocks. Gao et al. [13] perform an artificial intelligence expert system to classify the tunnel’s surrounding rock level. Then, a fuzzy information analysis model is suggested by Zhou et al. [14] to establish the classification of surrounding rocks in the road tunnel. The Fuzzy comprehensive evaluation method is provided by Bieniawski and Balkema [15] to classify the level of the rock mass. Zhang et al. [16] suggested the hierarchy analytical method to determine the weight distribution of different influential indices about the surrounding rocks. The grey optimization theory about the stability classification of surrounding underground rocks was established by Bai et al. [17] based on the correlated grey analysis. Ruan and Wei [18] and He and Chen [19] showed the BP neural
network model to deal with the nonlinearity and uncertainty of the classification of the surrounding rocks. Li et al. [20] solved the actual category of surrounding rocks in the hydraulic tunnel based on the artificial neural network theory. The matter-element model of surrounding rock evaluation in underground engineering is applied by Ye et al. [21] according to the procedure of extension method. The support vector machine theory is used to assess the quality of rock mass by Zhao et al. [22], and its higher accuracy is improved; besides, the distance discriminant analysis method is applied to determine the classification of surrounding rock quality in the tunnel by Gu et al. [23] and Chen and Zhou [24]. Wong et al. apply the efficacy coefficient method to destabilization risk assessment of surrounding rocks in the tunnel [25, 26].

Although the above method has promoted the development of the assessment theory of surrounding rock quality, some shortcomings still exist [27–29]. For example, the calculative process is complex, and the assessment process in many methods is often quantitative or qualitative. To overcome the shortcomings of the above methods, the entropy weight-variable fuzzy sets are introduced to assess the quality level of surrounding rocks in the tunnel. It has many virtues, such as the preciseness of the algorithm and operability in practice, and it can well solve the grading standards, which are interval forms. The method is a tremendous improvement on the traditional fuzzy sets model.

The paper is organized as follows: in Section 2, the study overview is introduced at first; in Section 3, the theory and methodology based on the entropy-weight variable fuzzy sets model are introduced; in Section 4, the assessment model about the surrounding rock quality is established, and the assessment results of the proposed model are compared and discussed; in Section 5, conclusions are drawn.

2. Study Area

The Mandarin Duck intersection tunnel is located between the Mandarin Duck intersection village and Dong Niu Po village in Suozhou city, Shanxi province, China. Its locations are plotted in Figure 1. It belongs to the Shanyin to Pinglu districts of National Highway in Shanxi province. It is a two-way and four-lane separated tunnel. The space between the left and right lines is 40 m. The import mileage at the left line is LK178 + 102; the exit mileage is LK182 + 830, and its total length is 4728 m. The longitudinal slope is 1.931%. The import mileage at the right line is RK178 + 044; its total length is 4787 m, and the longitudinal gradient is 1.98%. The maximum depth of the bottom plate in the tunnel at the left line is 316 m, and one at the right line is 317 m; it belongs to the extralong tunnel. The inclined shaft is placed in the middle of the tunnel. The tunnel passes through the tectonic and denudation strip in the mountain; its altitude height is 1400–2000 m, the cutting depth is 100–300 m, the slope angle is significant, and the mountain peak is steep. The lithology is mainly carbonate rock; the Archean metamorphic rock is beneath the carbonate rock. The different thicknesses of loess are covered at its upper. The maximum depth is 317 m. Its geomorphology is the bedrock ridge and gully slope.

The cross-section LK178 + 713–733, LK182 + 085–115, K0 + 320–350, and RK182 + 017–047, are selected as the classic surrounding rock sections. According to the

![Figure 1: The geographical location of the survey area.](image-url)
geological survey reports, the correlated geological parameters are determined. The geological conditions of the classical cross-section are plotted in Figure 2.

3. Theory and Methodology

3.1. The Basic Principle. It is assumed that \( A \) is a fuzzy variable in the domain \( U \), for any \( u \in U \), a determined number \( \mu_A^0(u) \) can be found in the closed interval. The relation between \( u \) and \( A \) is called as the absolute membership relationship, its mapping is [30]:

\[
\mu_A^0: U \rightarrow [0, 1]  \\
u | \rightarrow \mu_A^0(u).
\]

It is called as the absolute membership degree function of \( A \).

In the domain \( U \), \( u \) is a variable of \( U \), \( u \in U \), two opposite fuzzy parameters in the variable \( u \) are, respectively, \( A, A_c \), for the variable \( u \), two number \( \mu_A(u), \mu_{A_c}(u) \) can be determined at any position in two continuous closed intervals, they are called as the relative membership degree relation of \( u \) to \( A \) and \( A_c \), the mapping is as follows:

\[
\mu_A, \mu_{A_c}: U \rightarrow [0, 1]  \\
u | \rightarrow \mu_A(u), \mu_{A_c}(u) \in [0, 1].
\]

It is called as the relative membership degree of \( F \) and \( F_c \).

The schematic diagram of dynamic variable about any number in the closed interval can be plotted in Figure 3.

\[
\begin{array}{c|c|c|c}
\hline
P_1 & P_2 & P_3 \\
\hline
\mu_A(u)=1 & \mu_{A_c}(u)=0 & \mu_A(u)=0 \\
\mu_{A_c}(u)=0 & \mu_A(u)<\mu_{A_c}(u) & \mu_A(u)=0 \\
\mu_A(u)<\mu_{A_c}(u) & \mu_{A_c}(u)=0 & \mu_A(u)=0 \\
\hline
\end{array}
\]

Figure 3: Dynamic change diagram.

Two fuzzy variables \( A \) and \( A_c \) are, respectively, within two closed intervals, their relative membership degree can be defined as \( \mu_A(u) \) and \( \mu_{A_c}(u) \), and \( \mu_A(u) + \mu_{A_c} = 1 \), \( 0 \leq \mu_A(u) \leq 1 \), \( 0 \leq \mu_{A_c}(u) \leq 1 \).

\[
A = \{ u , \mu_A(u), \mu_{A_c}(u) | u \in U \},
\]

where, \( A \) is defined as the opposite fuzzy sets. It is plotted in Figure 4.

Similarly, for any variable \( u \), there exists, respectively, attractive and repelled sets \( \mu_A(u) \) and \( \mu_{A_c}(u) \), then

\[
D_A(u) = \mu_A(u) - \mu_{A_c}(u),
\]

where when \( \mu_A(u) > \mu_{A_c}(u) \), \( 0 \leq D_A(u) \leq 1 \); when \( \mu_A(u) = \mu_{A_c} \), \( D_A(u) = 0 \); when \( \mu_A(u) < \mu_{A_c}(u) \), \( -1 \leq D_A(u) \leq 0 \). \( D_A(u) \) is called as the relative difference function of \( u \) to \( A \). The mapping is as follows:
where $x_{ij}$ denotes the eigenvalue of the index $i$ of sample $j$, $i = 1, 2, ..., m; j = 1, 2, ..., c$. $c$ means level of index; the attractive domain $I_{ab}$ is expressed as follows:

$$I_{ab} = \left[ a_{ij}, b_{ij} \right].$$

(7)

When the sets $I_{de}$ is enlarged based on the upper and lower bound of its adjacent intervals, it is depicted as follows:

$$I_{de} = \left[ d_{ij}, e_{ij} \right].$$

(8)

According to the physical meaning of assessment index, the level standard of index can be determined by the matrix $A$:

$$A = \begin{bmatrix}
A_{11} & \cdots & A_{1j}
\vdots & \ddots & \vdots
A_{n1} & \cdots & A_{nj}
\end{bmatrix}. $$

(9)

Based on $a_{ij}$ and $b_{ij}$, the parameter $A_{ij}$ is shown as follows:

$$A_{ij} = \frac{c - j}{c - 1} a_{ij} + \frac{j - 1}{c - 1} b_{ij},$$

(10)

where $j = 1, A_{1j} = a_{ij}$; when $j = c$, then $A_{cj} = b_{ij}$; when $j = (c + 1)/2$, then $A_{ij} = (a_{ij} + b_{ij})/2$.

It is assumed that $X_{0}(a, b)$ is the attractive domain of fuzzy variable sets $V$, namely, $0 \leq D_A(u) \leq 1$, $X = [d, e]$ is included in the upper and lower domain intervals of $X_{0}(X_{(a, b)} \subset X)$, it is plotted in Figure 6 as follows.

According to relevant physical analysis, their relative membership degree can be expressed as follows:

$$
\mu_A(u) = 0.5 \left[ 1 + \left( \frac{x - a}{A - a} \right)^{\beta} \right] \quad x \in [a, A]
$$

(11)

$$
\mu_A(u) = 0.5 \left[ 1 - \left( \frac{e - a}{x - a} \right)^{\beta} \right] \quad x \in [a, e],
$$

$$
\mu_A(u) = 0.5 \left[ 1 + \left( \frac{x - b}{A - b} \right)^{\beta} \right] \quad x \in [A, b]
$$

(12)

$$
\mu_A(u) = 0.5 \left[ 1 - \left( \frac{x - b}{e - b} \right)^{\beta} \right] \quad x \in [b, e],
$$

$$
D: U \longrightarrow [0, 1]
$$

(5)

$|u| \longrightarrow D_A(u) \in [-1, 1]$.

It is called as the relative difference function of $u$ to $A$. It is plotted in Figure 5.

3.2. The Determination of the Relative Membership Degree.

To assess the quality of surrounding rocks, the sample sets can be expressed as follows:

$$X = (x_{ij}).$$

(6)

3.3. The Determination of Index Weights

(1) Assuming that there are $m$ cases of surrounding rock and $n$ assessment indices, so the original matrix can be expressed as follows:

$$X = \begin{bmatrix}
x_{11} & x_{12} & \cdots & x_{1m}
x_{21} & x_{22} & \cdots & x_{2m}
\vdots & \vdots & \ddots & \vdots
x_{n1} & x_{n2} & \cdots & x_{nm}
\end{bmatrix}. $$

(13)

(2) Normalization treatment is conducted for the main indices $X_{ij}$. The positive indicator is as follows:

$$x'_{ij} = \frac{x_{ij} - \min \{x_{ij}, \cdots, x_{nj}\}}{\max \{x_{ij}, \cdots, x_{nj}\} - \min \{x_{ij}, \cdots, x_{nj}\}}$$

(14)

The negative indicator:

$$x''_{ij} = \frac{\min \{x_{ij}, \cdots, x_{nj}\} - x_{ij}}{\max \{x_{ij}, \cdots, x_{nj}\} - \min \{x_{ij}, \cdots, x_{nj}\}},$$

(15)

where $i$ is assessment scheme; $j$ is assessment index; and $x_{ij}$ is the corresponding magnitude of the $j$th assessment index in the $i$th scheme.

(3) The determination of proportion about the evaluation index in the scheme, it is expressed as follows:

$$b_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}}.$$ 

(16)

(4) The entropy of the evaluation index is shown as follows:

$$s_j = -k \sum_{i=1}^{n} b_{ij} \ln(b_{ij}).$$

(17)

(5) The weight of the evaluation index is depicted as follows:

$$\omega_j = \frac{1 - s_j}{n - \sum_{j=1}^{n} s_j}.$$ 

(18)

3.4. The Determination of the Assessment Level. Based on (11), (12) and (18), according to the relevant references [31], a synthetic membership degree can be obtained:
3.5. The Assessment Steps

(1) Based on the relevant data and assessment criterion, the eigenvalue matrix \( X \) and classification matrix \( Y \) can be determined.

(2) Determining the attractive domain \( I_{ab} \), range matrix \( I_{cd} \) and point value matrix \( A \).

(3) According to (11) and (12), the relative membership degree can be obtained.

(4) Determining the weights of different indices of the surrounding rock quality based on the entropy-weight method.

(5) Computing the level eigenvalues \( R \) according to (19)–(22), then the assessment level of surrounding rock quality can be determined on the basis of the magnitudes of \( R \), if \( 0.5 \leq H \leq n + 0.5 \), then the result is level \( n \) (\( n \) is positive integer).

4. The Establishment of Assessment Model about the Surrounding Rocks’ Quality

4.1. The Establishment of Assessment Index Systems. The uniaxial compressive strength of rocks \( \sigma_0 \), the integrity coefficients of rock mass \( K_V \), the conditions of the structural plane \( S_S \), the seepage amount of groundwater \( W \), and the intersection angle \( \theta \) between the axis line and structural plane are, respectively, selected as assessment index. These indices are all qualitative indices. The five risk assessment indices are divided into five levels: very good (I), good (II), common (III), bad (IV), and very bad (V) as shown in Table 1. Based on reference [32], the monitoring value of the assessment index of ten cross-sections can be shown in Table 2.

4.2. The Construction of the Assessment Frame. The assessment of surrounding rock quality not only influences the construction progress but also affects the life safety of construction staff. Hence, it is significant to assess the quality level of surrounding rocks.

A new quality assessment method of surrounding rock quality is suggested based on the variable fuzzy sets theory as presented in Figure 7. At first, to evaluate the quality level of...
surrounding rock quality, a complete assessment index system is established. Second, the weight of each assessment index is determined according to an entropy weight theory. Third, the relative membership degree is determined using the variable fuzzy sets theory. Then, the magnitudes of synthetic certainty degree are determined; finally, the quality level of surrounding rock is determined.

### 4.3.1. Determining the Attractive Domain, Range Matrix, and Point Value Matrix

Based on Table 1, according to (7), the attractive domain $I_{ab}$ can be expressed as follows:

\[
I_{ab} = \begin{bmatrix}
300 & 250 & 250 & 100 & 100 & 50 & 50 & 25 & 25 & 1 \\
1 & 0.75 & 0.75 & 0.55 & 0.55 & 0.35 & 0.35 & 0.15 & 0.15 & 0.0 \\
10 & 9 & 9 & 7 & 7 & 4 & 4 & 2 & 2 & 0 \\
0 & 5 & 5 & 10 & 10 & 25 & 25 & 125 & 125 & 300 \\
90 & 80 & 80 & 70 & 70 & 30 & 30 & 10 & 10 & 0
\end{bmatrix}.
\] (23)

Based on (8), the matrix $I_{de}$ can be expressed as follows:

\[
I_{de} = \begin{bmatrix}
300 & 100 & 300 & 50 & 250 & 25 & 100 & 1 & 50 & 1 \\
1 & 0.55 & 1 & 0.35 & 0.75 & 0.15 & 0.55 & 0 & 0.35 & 0 \\
10 & 7 & 10 & 4 & 9 & 2 & 7 & 2 & 4 & 0 \\
0 & 10 & 0 & 25 & 5 & 125 & 10 & 300 & 25 & 300 \\
90 & 70 & 90 & 30 & 80 & 10 & 70 & 0 & 30 & 0
\end{bmatrix}.
\] (24)

Based on (10) and (11), the point value matrix $A$ can be depicted as follows:

\[
A = \begin{bmatrix}
300 & 212.5 & 75 & 31.25 & 1 \\
1 & 0.7 & 0.45 & 0.2 & 0 \\
10 & 6.25 & 5.5 & 2.5 & 0 \\
0 & 6.25 & 17.5 & 100 & 300 \\
90 & 77.5 & 50 & 15 & 0
\end{bmatrix}.
\] (25)

### 4.3.2. The Determination of the Relative Membership Degree Matrix

In the first procedure, according to the monitoring value in Table 2, and in combination with the (11) and (12), it should be determined whether the assessment index in Table 2 is located on the left or right of the point $A$, the data of cross-section 1 are selected as an example, when $i = 1$, then $[a\ b]_{1j}$, $[d\ e]_{1j}$ and the point value $A$ can be expressed as follows:

\[
[a\ b]_{1j} = ([300\ 250]\ [250\ 100]\ [100\ 50]\ [50\ 25]\ [25\ 1]) \\
[d\ e]_{1j} = ([300\ 100]\ [300\ 50]\ [250\ 25]\ [100\ 1]\ [50\ 1])
\]

\[A_{1j} = [300\ 212.5\ 75\ 31.25\ 1].\] (26)

When $x_1 = 62$, $a_{11} = 300$, $b_{11} = 250$, $d_{11} = 300$, $d_{11} = 70$, and $A_{11} = 300$, $x_1$ is located in the out of intervals, so $\mu_A(u_{1j}) = 0$; when $a_{12} = 250$, $b_{12} = 100$, $d_{12} = 300$, $e_{12} = 50$, $A_{12} = 212.5$, $x_1$ is located in the out of intervals, so $\mu_A(u_{1j}) = 0.03$; when $a_{13} = 100$, $b_{13} = 50$, $d_{13} = 250$, $e_{13} = 25$, $A_{13} = 75$, $x_1$ is located in the right of $A_{13}$, it belongs to $[A_{13}\ b_{13}]$, based on (12), the relative membership degree can be obtained $\mu_A(u_{13}) = 0.74$.

Similarly, the relative membership degree matrix of cross-section 1 can be obtained as follows:

\[
\mu_A(u_{ij}) = \begin{bmatrix}
0 & 0.03 & 0.74 & 0.776 & 0 \\
0 & 0 & 0.5 & 0 & 0 \\
0.47 & 0.62 & 0.03 & 0 & 0.625 \\
0 & 0 & 0 & 0.5 & 0
\end{bmatrix}.
\] (27)

### 4.3.3. The Determination of Weight Coefficients of Different Indices

According to Table 2 and (16), the specific gravity matrix can be shown in Table 3.

According to Table 3 and (17), the entropy matrix can be shown in Table 4.

Based on (18), the weight coefficients can be calculated in Table 5.

### 4.3.4. Determining the Comprehensive Relative Membership Degree Vector

According to (19), and in combination with the matrix of $\mu_A(u_{ij})$, the comprehensive relative membership degree matrix can be obtained in Table 6.
Table 3: The synthetic parameters of surround rock quality.

| Cross-section number | $\sigma_c$ (MPa) | $K_V$ | $S_s$ | $W$ | $\theta$ |
|----------------------|-----------------|------|------|-----|--------|
| 1                    | 0.1023          | 0.0951 | 0.0231 | 0.0829 | 0.0192 |
| 2                    | 0.1188          | 0.0516 | 0.1385 | 0.1158 | 0.1673 |
| 3                    | 0.1073          | 0.087  | 0.1431 | 0.1721 | 0.0327 |
| 4                    | 0.1007          | 0.0924 | 0.0385 | 0.0814 | 0.0885 |
| 5                    | 0.1205          | 0.2092 | 0.14   | 0.1221 | 0.1212 |
| 6                    | 0.0611          | 0.1141 | 0.1031 | 0.1174 | 0.1481 |
| 7                    | 0.0957          | 0.0761 | 0.0892 | 0.0313 | 0.0808 |
| 8                    | 0.1007          | 0.0951 | 0.1385 | 0.1111 | 0.0481 |
| 9                    | 0.1073          | 0.0924 | 0.0385 | 0.072  | 0.1288 |
| 10                   | 0.0858          | 0.087  | 0.1477 | 0.0939 | 0.1654 |

Table 4: The entropy weight matrix.

| Index | $\sigma_c$ (MPa) | $K_V$ | $S_s$ | $W$ | $\theta$ |
|-------|-----------------|------|------|-----|--------|
| Index entropy | 0.9939 | 0.9713 | 0.9428 | 0.9708 | 0.9341 |

Table 5: The weight coefficient matrix.

| Index | $\sigma_c$ (MPa) | $K_V$ | $S_s$ | $W$ | $\theta$ |
|-------|-----------------|------|------|-----|--------|
| Weight coefficients | 0.0328 | 0.1536 | 0.3056 | 0.1558 | 0.3522 |

Table 6: The comprehensive relative membership vector.

| $f \& p$ | $v_k(\alpha_k)$ |
|----------|-----------------|
| $f = 1, p = 1$ | 0.0732 | 0.0976 | 0.1057 | 0.2784 | 0.3671 |
| $f = 1, p = 2$ | 0.128 | 0.1631 | 0.1398 | 0.3301 | 0.4599 |
| $f = 2, p = 1$ | 0.0662 | 0.0116 | 0.0138 | 0.1295 | 0.2517 |
| $f = 2, p = 2$ | 0.0211 | 0.0366 | 0.0258 | 0.1954 | 0.4203 |

According to (20) and (21), the normalized comprehensive relative membership degree vector can be obtained in Table 7.

4.3.5. Determining the Level of the Surrounding Rock Quality.

According to (22), and in combination with Table 7, the ranking feature value of cross-section 1 can be shown in Table 8.

Similarly, the feature value of cross-section 2–10 can be shown in Table 9, respectively.

To test the assessment results of surrounding rock quality, the results in the paper are compared with the other methods, they are shown in Table 10.

The variable fuzzy set assessment model is applied to assess the surrounding rock quality; the complete results are shown in Tables 9 and 10. It can be found in Table 10 that the quality levels of surrounding rock from cross-sections 1 to 10 are different. The surrounding rock quality level at cross-section 1, 2, and 4 are IV; one at the cross-section 5 is II; and one at rest is III. It means that the quality level of surrounding rocks at the cross-sections 1, 2, and 4 is bad. The necessary consolidation measurement should be performed about the surrounding rocks at these cross-sections; one of surrounding rock quality at the cross-section 5 is good, so no measurement needs to be done. Ones at the rest cross-sections are common, so the qualified rate of surrounding rock quality in all cross-sections arrives at 70%.

Based on the comparative results of the assessment model in Table 10, it can be found the results assessed by using the variable fuzzy sets method are consistent with the current specification for ten different cross-sections, except the cross-sections 2 and 9. Its accurate rate arrives at 80% in the text method, which is higher than the results (70%) from the rough set theory [32]. Moreover, in comparison with the rough set methods, the proposed model can accurately convey the risk degree of surrounding rocks. So, the conclusions are drawn that it is feasible to estimate the quality level of surrounding rock by using the entropy weight-variable fuzzy sets model. The method provides accurate results and brings more details about the surrounding rock quality levels. For example, the uniaxial compressive strength of cross-section 6 is 37, which should belong to level IV, according to Table 1. In addition, the degree of membership of the other indices obtained by the variable fuzzy sets model belongs to level III, so the quality level probability of cross-section six at the level III is more extensive than that of grades I, IV, II, and V. Hence, the surrounding rock quality of cross-section six only belongs to level III and almost impossibly belongs to groups I, IV, II, and V. Furthermore, the level of cross-section 6 is more likely to be level III than that of cross-section 7, 8, and 10 because the mean ranking feature value (3.2718) of cross-section 6 for level III is higher than that of cross-section 7 (2.9787), 8 (2.8092), and 10 (2.5486). In total, the results obtained by using the entropy weight-variable fuzzy sets model demonstrate the quality level not only accurately but also further determine the ranking of surrounding rock quality for different cross-sections at the same level.

5. Discussion and Comparative Analysis

5.1. Comparison with Existing Studies

(1) The rough set theory is suggested to evaluate the quality level of surrounding rocks, and good results are obtained. However, relative to the model of rough sets, the proposed model can accurately convey the risk degree of surrounding rocks by adopting the eigenvalue of level H [33]. So, the proposed method is much stricter in the superior grade, and the integrity is improved to assess the quality level of surrounding rocks.

(2) In comparison with the other traditional models, the fuzziness and randomness of evaluating index are considered, and interval-oriented evaluation criteria
are adopted. So, the proposed method improves the reliability of the assessment process and effectively detects surrounding rock quality status.

5.2. The Advantages and Limitations of the Proposed Model.

By comparing the appropriate methods, the advantages of the suggested method can be summarized as follows:

(1) The proposed method can accurately convey the risk degree of surrounding rocks, so it has higher accuracy.

(2) Compared with the traditional method, its assessment process has higher reliability and efficiency.

However, the suggested model still exist some limitations. For example, calculation is complicated, and multiple variable parameters required to calculate the degree of difference; these limited its application, but the theory has still great space for the improvement in the future.

6. Conclusions

Considering the uniaxial compressive strength of rocks $\sigma_c$, the integrity coefficients of rock mass $K_V$, the conditions of the structural plane $S$, the seepage amount of groundwater $W$, as well as the intersection angle $\theta$ between the axis line and structural plane, a new assessment method is introduced in this paper to assess the surrounding rock quality level based on the fuzzy variable sets theory. The relative membership degree matrix of the assessment sample is determined at first. Then, the weighting coefficients are calculated using the entropy weighting method. Finally, the quality level of surrounding rock is determined using the mean ranking feature value.

The proposed method is applied to assess the surrounding rock quality level. Finally, its result is compared with that of the current specifications and the rough set theory; the results obtained based on the variable fuzzy sets method are consistent with the current specification; its accuracy is 80%. The qualified rate of surrounding rock quality in all cross-sections is 70%. In other words, except the cross-sections 1, 2, and 4, for any different cross-sections, no measurement need be adopted to consolidate the surrounding rock quality. Moreover, the results obtained by using the entropy weight-variable fuzzy sets model demonstrate the quality level not only accurately but also further determine the quality ranking of surrounding rock quality for different cross-sections at the same level. The proposed method can accurately convey the risk degree of surrounding rocks; and in comparison with the traditional method, its assessment process has higher reliability and efficiency. But its calculation is complicated, and multiple variable parameters required to calculate the degree of difference, so the proposed method can still be improved in the future.

In short, the proposed model could provide an alternate way to assess the risk level in civil engineering accurately.

Data Availability

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

| Table 8: The feature value of sample 1. |
|----------------------------------------|
| Sample number | $f = 1, p = 1$ | $f = 1, p = 2$ | $f = 2, p = 1$ | $f = 2, p = 2$ | Mean value |
|--------------|----------------|----------------|----------------|----------------|------------|
| 1            | 3.8335         | 3.6804         | 4.4753         | 4.3691         | 4.0896     |

| Table 9: Values of the assessment model at 10 cross-sections. |
|---------------------------------------------------------------|
| Sample number | $f = 1, p = 1$ | $f = 1, p = 2$ | $f = 2, p = 1$ | $f = 2, p = 2$ | Mean value |
|---------------|----------------|----------------|----------------|----------------|------------|
| 1             | 3.8335         | 3.6804         | 4.4753         | 4.3691         | 4.0896     |
| 2             | 2.0646         | 2.2142         | 1.4552         | 1.5525         | 1.8217     |
| 3             | 3.0904         | 3.0334         | 3.4244         | 3.2092         | 3.1894     |
| 4             | 3.5304         | 3.5206         | 3.6001         | 3.6032         | 3.5636     |
| 5             | 2.0952         | 2.1564         | 2.0483         | 2.1328         | 2.1082     |
| 6             | 3.3334         | 3.294          | 3.2563         | 3.2035         | 3.2718     |
| 7             | 2.9503         | 2.8702         | 3.0879         | 3.0065         | 2.9787     |
| 8             | 2.7532         | 2.7751         | 2.8597         | 2.8489         | 2.8092     |
| 9             | 3.2021         | 3.1736         | 3.3937         | 3.327          | 3.2741     |
| 10            | 2.7779         | 2.8859         | 2.2319         | 2.2987         | 2.5486     |

| Table 10: The comparison of results from the different models. |
|---------------------------------------------------------------|
| Cross-section number | Method in the text | The current specification | The rough set theory |
|----------------------|--------------------|--------------------------|---------------------|
| 1                    | IV                 | IV                       | IV                  |
| 2                    | II                 | IV                       | III                 |
| 3                    | III                | III                      | III                 |
| 4                    | IV                 | IV                       | IV                  |
| 5                    | II                 | II                       | II                  |
| 6                    | III                | III                      | III                 |
| 7                    | III                | III                      | III                 |
| 8                    | III                | III                      | III                 |
| 9                    | IV                 | III                      | IV                  |
| 10                   | III                | III                      | III                 |
Conflicts of Interest

The authors declare that they have no conflicts of interest.

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