The risk assessment of tunnel surrounding rock deformation based on entropy weight method and extension matter element method

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Abstract. The deformation of surrounding rock is an expected geological hazard when the tunnel passes through the area with unfavorable geological conditions. If the surrounding rock deformation is too large, it will lead to serious safety hazards. In this paper, the entropy weight method is adopted to calculate the weight of each index. Based on the extension theory, the risk evaluation model of tunnel surrounding rock deformation is established. Five evaluation indexes, such as surrounding rock grade, tunnel depth, groundwater status, the uniaxial compressive strength of rock, and rock integrity, were selected to evaluate the deformation risk of surrounding rock in 10 sections of Sheta Village tunnel of Zhangjihuai high-speed railway. The results show that the surrounding rock deformation is high in 2 of the 10 cavities to be evaluated, and the workers must take reinforcement measures to strengthen the surrounding rock, which is of considerable significance to guide the scientific and reasonable construction of the tunnel.

1. Introduction
With the rapid development of national traffic construction, tunnel traffic has also made rapid progress. The tunnel is developed for the long span and deeply buried condition. It will inevitably pass through the area with poor geological conditions and geological disasters will occur [1-3]. For example, Huangjiazhai tunnel [4], Jizhuqing tunnel [5], and Zhegu Mountain tunnel [6] all suffered from deformation of surrounding rock, cracking of primary or secondary lining and other disasters. Once the surrounding rock deformation occurs, it will not only affect the further construction of the tunnel but also affect the safety of equipment and workers. Therefore, it is of considerable significance for tunnel construction to evaluate the deformation risk of rocks around the tunnel.

In recent years, many scholars at home and abroad have studied the deformation mechanism, influencing factors, and failure characteristics of tunnel surrounding rock. Based on the tunnel test model design of DSCM, Li et al. [7] studied the deformation mechanism and failure law of surrounding rock deformation. They obtained the failure law of surrounding rock deformation under different confining pressures. The deformation rate and amount of surrounding rock increase with the increase of confining pressures. Also, the deformation law of surrounding rock is predicted by revealing the spatial and temporal evolution law of the development of the surrounding rock loose zone. Xue [8] used the correlation coefficient method to evaluate many influencing factors of surrounding rock deformation and obtained the correlation degree between influencing factors of surrounding rock deformation and...
tunnel deformation. Besides, the RBF neural network was used to construct the tunnel deformation prediction model, and the trial algorithm and particle swarm optimization algorithm were used to optimize the model parameters. The relative error of the final prediction results was less than 2%. Aydan et al. [9] analyzed the relationship between mechanical and physical properties of rocks and tunnel deformation by collecting damage and observation data of tunnels in Japan and based on this, proposed a general prediction method to predict the compression potential and degree of rocks around tunnels. Furthermore, the applicability and validity of the proposed method are tested by comparing the predicted value with the actual value. And the prediction method conforms to the actual deformation of the surrounding rock over the 300m long tunnel section.

In addition, the prediction of tunnel surrounding rock deformation has been widely studied. Guan et al. [10] proposed a geological prediction method based on Markov random process and Bayesian updating process to predict the ground conditions in front of the working face of the tunnel and applied the method to the Chuangshi tunnel. Jiang [11] proposed a particle swarm optimization (PSO) based support vector machine (SVM) method to predict the deformation of rock tunnel with rock mass, and used the rolling monitoring data to predict the deformation of surrounding rock. Fraldi de and Guarracino [12] based on the Hoek-Brown failure criterion and using the classical tool of the variational method, derived the exact solution of tunnel surrounding rock failure through numerical analysis to predict the stability of rock tunnel.

In this paper, the entropy weight method and extension theory are used to evaluate the deformation risk of surrounding rock of the tunnel. The entropy weight method is adopted to calculate the weight coefficient of each evaluation index, which can avoid subjectivity and human interference in determining the weight coefficient. Five indexes, such as surrounding rock grade, tunnel depth, groundwater state, the uniaxial compressive strength of rock, and rock integrity, were selected. The weight coefficient of each evaluation index was determined by the entropy weight method, and the extension evaluation method was used for extension rating, to establish the deformation risk evaluation model of surrounding rock of tunnel. The model is applied to the risk assessment of 10 tunnel sections in Sheta Village Tunnel of the Zhangjihuai high-speed railway.

2. Methods
This section mainly uses the sampling anomaly characteristics of the secondary equipment of the Smart Substation to analyze the sampling value anomaly of the relay protection device, the synchronization anomaly between multiple MUs and the SV data anomaly of the merging unit, and gives a description of the evaluation method.

2.1. The entropy weight method
The entropy weight method is an objective weighting method, which is not affected by subjective factors. Based on the degree of uncertainty, the entropy weight of each index is calculated. The degree of change of the index determines the entropy of information, indicating the amount of information contained in the index, to determine the weight of the index.

The entropy weight method is adopted to calculate the weight of the index, which can be divided into the following steps:

1. Assume that the deformation risk of surrounding rock evaluated is divided into M grades, and each grade has N evaluation indexes, and the original data evaluation matrix is constructed $A = (a_{ij})_{m \times n}$:

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mn} \end{bmatrix}_{m \times n} \quad (1)$$

Where, $a_{ij}$ is the $j$-th evaluation index value of the $i$-th surrounding rock deformation risk level; ($i=1,2,\cdots,m; j=1,2,\cdots,n$)
(2) The original data evaluation matrix is standardized to obtain a standard matrix $B = (b_{ij})_{m \times n}$, which is unified into a standard index that can be directly calculated $b_{ij}$:

$$b_{ij} = \frac{a_{ij} - \min(a_{ij})}{\max(a_{ij}) - \min(a_{ij})}$$

(2)

Where $\max(a_{ij})$, $\min(a_{ij})$ is the maximum and minimum index values of all deformation grades under index; Value range of is: $0 \leq b_{ij} \leq 1$.

(3) Calculate the entropy value of the risk evaluation index $e_j$:

$$e_j = -(\ln m)^{-1} \sum_{i=1}^{m} p_{ij} \ln p_{ij}$$

(3)

Where $p_{ij} = b_{ij} / \sum_{i=1}^{m} b_{ij}$.

(4) Calculate the variation degree coefficient of each indicator $d_j$:

$$d_j = 1 - e_j$$

(4)

Where, $e_j$ is the entropy value of the $j$-th evaluation index.

(5) Calculate the weighting coefficient of each evaluation index $w_j$:

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j}$$

(5)

As an objective evaluation method, the entropy weight method has the advantage that it is weighted based on objective data and is not affected by subjective factors.

2.2. Extension element method

Cai et al. [13] first put forward the theory of "Extensions" in 1983, which is based on matter-element theory and extension mathematics. The concept of matter element $R$ is introduced, and the characteristics and quantity of the evaluation object are combined to solve the incompatible problem in reality from the perspective of qualitative and quantitative analysis.

Extension theory takes "matter-element" as the basic element and as the basic matter-element. $R=\{N,C,V\}$ The three elements of matter element are $N$, $C$, and $V$, respectively, which represent the object, feature, and quantity value. The model establishment process is shown in Figure 1.
Figure 1. Modeling process.

To establish an extension matter element model, it can be divided into the following steps:

1. Determining the classical domain

   The classical domain in the matter-element model can be represented by the following matrix:

   \[
   R_{0i} = (N_i, C_i, V_i) = \begin{bmatrix}
   N_i & C_i & V_{i1} \\
   \vdots & \vdots & \vdots \\
   \vdots & C_i & V_{in}
   \end{bmatrix} = \begin{bmatrix}
   N_i & C_i & (a_{i1}, b_{i1}) \\
   \vdots & \vdots & \vdots \\
   \vdots & C_i & (a_{in}, b_{in})
   \end{bmatrix}
   \]

   Where, \( R_{0i} \) denotes one of the many matter-elements in the matter-element model, \( N_i \) denotes the \( i \)-th evaluation level in the model, \( C_i \) denotes the \( i \)-th evaluation index, and \( V_i \) denotes the interval value of the \( i \)-th evaluation level.

2. To determine the section domain

   The expression of the node field is:

   \[
   R_p = (N_p, C_p, V_p) = \begin{bmatrix}
   N_p & C_p & V_{p1} \\
   \vdots & \vdots & \vdots \\
   \vdots & C_p & V_{pn}
   \end{bmatrix} = \begin{bmatrix}
   N_p & C_p & (a_{p1}, b_{p1}) \\
   \vdots & \vdots & \vdots \\
   \vdots & C_p & (a_{pn}, b_{pn})
   \end{bmatrix}
   \]

   Where, \( N_p \) denotes all evaluation grades and \( V_{pi} \) denotes the range of \( N_p \) values.

3. Determine the element to be evaluated

   The basic matter elements in extension theory can be expressed as:

   \[
   R_s = (T, C_s, V_s) = \begin{bmatrix}
   T & C_s & V_s \\
   \vdots & \vdots & \vdots \\
   \vdots & C_s & V_n
   \end{bmatrix}
   \]

   Where, \( R_s \) stands for the element to be evaluated, \( T \) stands for the thing to be evaluated and \( V_s \) stands for the quantitative value of the thing to be evaluated.

4. Calculate the correlation degree of evaluation index
According to the definition of the correlation function, the correlation degree of every single index concerning each evaluation level is:

$$K_j(V_i) = \left\{ \begin{array}{ll} -\rho(V_i(t), V_{ij}) & \frac{1}{V_{ij}} \\
\rho(V_i(t), V_{ij}) & \rho(V_i(t), V_{ij}) - \rho(V_i(t), V_{ij}) \end{array} \right. \quad (9)$$

Where, $K_j(V_i)$ is the correlation function of $V_i$, and $\rho(V_i(t), V_{ij})$ represents the distance between the value range $V_{ij}$ and the score $V_i$ specified by each evaluation index for the matter element to be evaluated under each evaluation index.

(5) Calculate the comprehensive correlation degree

$$K_i(T) = \sum_{i=1}^{n} w_i K_j(V_i) \quad (10)$$

Where, $K_i(T)$ denotes the comprehensive correlation degree of the $j$-th grade thing to be evaluated, and $w_i$ denotes the weight of each evaluation index. If $K_i = \max \{ K_i(T) \}$, then the category to which the thing to be evaluated belongs is level $i$.

3. Analysis of influencing factors of surrounding rock deformation and deformation risk assessment system

3.1. Influencing factors of tunnel surrounding rock deformation

According to existing literature and engineering experience, five influencing factors of surrounding rock deformation, namely surrounding rock grade (H1), tunnel depth (H2), groundwater status (H3), the uniaxial compressive strength of rock (H4) and rock integrity (H5), were selected as the deformation risk evaluation indexes of tunnel surrounding rock.

1) Surrounding rock grade (H1)

The grading of the surrounding rock is based on its hardness and integrity. Under normal circumstances, the surrounding rock in the tunnel is generally classified into five levels. The higher the level of the surrounding rock, the better the surrounding rock conditions, and the higher the deformation resistance of the surrounding rock. Therefore, the grade of surrounding rock is selected as the index for the risk assessment of tunnel surrounding rock deformation.

2) Tunnel depth (H2)

The depth of the tunnel refers to the distance from the top of the excavation face to the ground. The increase of tunnel depth results in a linear increase in ground stress in the rock mass. The greater the lateral pressure of rock mass, the more complex the stress state of the tunnel, and the greater the deformation hazard of surrounding rock. Therefore, the tunnel depth will affect the stability of the tunnel. Yang Xiaojie et al. [14] believe that the depth of the tunnel is the main reason for the large deformation of the rocks around the tunnel. In principle, large deformations are possible for any type of rock mass. Verman et al. [15] studied the influence of tunnel construction depth on rock mass deformation modulus and drew the conclusion that rock mass deformation modulus is proportional to tunnel depth.

3) Groundwater status (H3)

Groundwater status is the most important factor in most engineering disasters. For example, for the weaker surrounding rock, its interior usually contains an argillous structure or an argillous interlayer, and the groundwater in the stratum will accelerate the disintegration of the rock mass, which will reduce...
the bearing capacity and strength of the rock mass, thus causing deformation phenomenon. For the expansive surrounding rock, such as the expansive rock containing montmorillonite and kaolinite, the groundwater will exert expansion pressure on the rock, significantly reduce the rock strength, and increase the risk of instability of the surrounding rock.

(4) The uniaxial compressive strength of rock (H4)
There is no doubt that the uniaxial compressive strength of rock can most intuitively reflect the rock's ability to resist deformation under the action of external load, and it is also the most widely used quantitative index representing the rock strength. Therefore, UCS is selected as the quantitative index of rock strength. According to UCS, the surrounding rock deformation class standard is UCS>60MPa, 40MPa<UCS<60MPa, 20MPa<UCS<40MPa, and UCS<20MPa.

(5) Rock Integrity (H5)
There is no doubt that rock integrity affects the deformation of surrounding rocks. Rock integrity is an important feature of surrounding rock and plays a key role in the risk assessment of surrounding rock deformation. Due to the existence of the structural plane, the rock around the tunnel is cut into blocks of different sizes and shapes, which affects the strength of the surrounding rock. In this paper, rock mass coefficient RQD is selected as a quantitative indicator of rock integrity.

3.2. Rock deformation risk assessment system
Based on the above considerations, the surrounding rock deformation risk of the tunnel is divided into four levels: Level I means low risk, Level II means medium risk, Level III means high risk, and Level IV means very high risk.

By referring to previous research results and field investigations, and combining with expert experience, the range of each index value of tunnel surrounding rock deformation risk grade evaluation is given, as shown in Table 1.

| Risk grade | Tunnel buried depth H2 (m) | Groundwater state H3 | UCS H4 (MPa) | Rock mass coefficient H5 (%) |
|------------|-----------------------------|----------------------|--------------|----------------------------|
| I          | <III                        | No water             | >60          | 75~100                     |
| II         | III                         | Water seepage        | 40~60        | 50~75                      |
| III        | IV                          | Drip water           | 20~40        | 25~50                      |
| IV         | V                           | Linear drop          | <20          | 0~25                       |

Among them, the evaluation indexes of the qualitative factors "surrounding rock grade" and "groundwater state" were discretized according to the criteria of {low risk} corresponding to 0.125, {medium risk} corresponding to 0.375, {high risk} corresponding to 0.625 and {very high risk} corresponding to 0.875, as shown in Table 2.

| Risk level | Surrounding rock grade H1 | Groundwater state H3 | Interval value | Discrete values |
|------------|---------------------------|----------------------|---------------|----------------|
| I          | <III                      | No water             | 0.75~1        | 0.875          |
| II         | III                       | Water seepage        | 0.5~0.75      | 0.625          |
| III        | IV                        | Drip water           | 0.25~0.5      | 0.375          |
| IV         | V                         | Linear drop          | 0~0.25        | 0.125          |

The normalized value range of each indicator in Table 1 was obtained, as shown in Table 3.
Table 3. Range of normalized standard values of various indexes in surrounding rock deformation risk assessment

| Risk level | H1     | H2     | H3     | H4     | H5     |
|------------|--------|--------|--------|--------|--------|
| I          | 0.75~1 | 0.875~1| 0.75~1 | 0.75~1 | 0.75~1 |
| II         | 0.5~0.75| 0.75~0.875| 0.5~0.75| 0.375~0.75| 0.5~0.75|
| III        | 0.25~0.5 | 0.5~0.75 | 0.25~0.5 | 0.125~0.375 | 0.25~0.5 |
| IV         | 0~0.25 | 0~0.5 | 0~0.25 | 0~0.125 | 0~0.25 |

4. Engineering Verification

4.1. Research Area
The Sheta Village tunnel of Zhangjihuai High-speed Railway is located in Hunan Province. It is a single tunnel with two lines, with a design speed of 350km/h. The tunnel length is 1408m and the buried depth is 20m~155m. One-way tunneling method from the exit is adopted by the three-step method. The entrance and exit of the tunnel are undulating greatly, with a relative height difference of about 200m. This study focuses on 10 segments of the tunnel.

According to the monitoring meter, tunnel construction ledger record table and working face information record table, rock mineral identification report, rock mechanical property test report, ground stress test, and inversion, a total of 10 tunnel section data sets are obtained, as shown in Table 4.

Table 4. Measured values of all indexes of surrounding rock deformation risk assessment

| Section | H1 (m) | H2 (m) | H3              | H4 (MPa) | H5 (%) |
|---------|--------|--------|-----------------|----------|--------|
| 1       | III    | 32     | No water        | 65       | 80     |
| 2       | III    | 45     | Water seepage   | 70       | 77     |
| 3       | III    | 54     | No water        | 55       | 65     |
| 4       | IV     | 67     | No water        | 50       | 68     |
| 5       | IV     | 88     | Water seepage   | 40       | 45     |
| 6       | V      | 101    | Linear drop     | 35       | 32     |
| 7       | IV     | 95     | Drip water      | 40       | 55     |
| 8       | III    | 87     | No water        | 60       | 72     |
| 9       | III    | 82     | Water seepage   | 55       | 84     |
| 10      | III    | 76     | No water        | 70       | 79     |

To eliminate the influence of different physical meanings, dimensions, and quantity values, the data sets of 10 tunnel sections were normalized by dividing the maximum boundary value, as shown in Table 5.

Table 5. Normalized values of each evaluation index of 10 tunnel sections

| Section | H1      | H2      | H3      | H4   | H5   |
|---------|---------|---------|---------|------|------|
| 1       | 0.375   | 0.106666667 | 0.375   | 0.65 | 0.8  |
| 2       | 0.375   | 0.15    | 0.375   | 0.7  | 0.77 |
| 3       | 0.375   | 0.18    | 0.125   | 0.55 | 0.65 |
| 4       | 0.625   | 0.223333333 | 0.375   | 0.5  | 0.68 |
| 5       | 0.625   | 0.293333333 | 0.375   | 0.4  | 0.45 |
| 6       | 0.875   | 0.336666667 | 0.625   | 0.35 | 0.32 |
| 7       | 0.625   | 0.316666667 | 0.625   | 0.3  | 0.45 |
| 8       | 0.375   | 0.29    | 0.375   | 0.6  | 0.72 |
| 9       | 0.375   | 0.273333333 | 0.375   | 0.55 | 0.84 |
| 10      | 0.375   | 0.253333333 | 0.375   | 0.7  | 0.79 |
4.2. Calculation of the weight of tunnel surrounding rock deformation risk evaluation index

Equation (1)-(5) is used to calculate the weight of each influencing factor on surrounding rock deformation, as shown in Table 6, and the pie chart is shown in Figure 2.

| Table 6. Weights of the five indexes of surrounding rock deformation risk assessment |
|----------------------------------|-----|-----|-----|-----|-----|
| The weight | H1 | H2 | H3 | H4 | H5 |
| \(w_j\)    | 0.224 | 0.207 | 0.262 | 0.146 | 0.161 |

4.3. Establishment of tunnel surrounding rock deformation risk evaluation model

After the digital characteristics of the extension matter element model are determined, this information is combined with the weight calculated by the entropy weight method.

Table 7 shows the results of the deformation risk assessment of surrounding rock using the extension element model for the data sets of ten tunnel sections.

| Table 7. Tunnel surrounding rock deformation risk assessment results |
|----------------------------------|-----|
| Section | rating |
| 1 | II |
| 2 | II |
| 3 | II |
| 4 | II |
| 5 | II |
| 6 | III |
| 7 | III |
| 8 | II |
| 9 | II |
| 10 | II |

4.4. Analysis and discussion of results

In this paper, the entropy weight method is used to calculate the weight of 5 evaluation indexes of tunnel surrounding rock deformation. According to Table 6, the weights of surrounding rock grade (H1), tunnel depth (H2), groundwater status (H3), the uniaxial compressive strength (H4), and rock integrity (H5) are 0.224, 0.207, 0.262, 0.146 and 0.161, respectively.

As is known to all, groundwater has a great impact on engineering safety. It can also be seen from different index weights that the groundwater state (H3) in the tunnel has the greatest impact on surrounding rock deformation (accounting for 26%). To reduce or eliminate the influence of
groundwater, tunnel builders can adopt the methods of drainage and water plugging. Lead holes are used for drainage and lead tubules for grouting. Shallow-buried tunnels can also use well point precipitation to control the water table.

The risk grade of tunnel surrounding rock deformation is fuzzy and affected by many factors. For this reason, a deformation risk assessment model of surrounding rock based on the extension element model is proposed, and the risk assessment of 10 tunnel sections in Sheta Village tunnel is carried out. Among them, 6th, 7th cavern deformation of surrounding risk ratings for the level III, corresponding to high risk, high deformation shows that the cavity segment on the risk, in order to prevent the cavity section of large deformation of surrounding rock, further affect tunnel construction, construction personnel can strengthen support, grouting, and bolting is to improve the integrity and strength of the surrounding rock.

The deformation of rock around the tunnel is the result of many factors. Reasonable selection of the grading standards for influencing factors of surrounding rock deformation can accurately evaluate the risk grade of surrounding rock deformation. In this paper, quantitative factors are continuously graded, and qualitative factors are discretized and graded. Different classification standards should be chosen for different research tunnels. The tunnel data studied in this paper do not record the daily groundwater flow but classify the groundwater status according to the advanced borehole in the tunnel working face. However, if it is possible to record the daily flow of groundwater, it should be used as a criterion for judging the status of groundwater. It is suggested to determine different classification standards according to different tunnel site conditions.

5. Conclusion

(1) Five factors influencing the deformation of surrounding rock are selected in this paper. These five influencing factors are taken as the indexes for the risk assessment of surrounding rock deformation, and the weights of the indexes are calculated by entropy weight method. By using this method, the influence of subjective factors in the traditional process of weight seeking is overcome, and the shortcoming of the attribute of the index itself is considered, which makes the weight more scientific. The comparison of the weights of evaluation indexes shows that the groundwater status is the most important factor, followed by the level of surrounding rocks, tunnel depth, rock integrity, and the uniaxial compressive strength of rock. Thus provides scientific guidance for the construction.

(2) According to five evaluation indexes that affect the deformation of surrounding rock, a risk evaluation model for surrounding rock deformation is established, and the risk grade is divided into four levels: low risk, medium risk, high risk, and very high risk. It provides a reference for the classification of surrounding rock deformation risk.

(3) This risk assessment model is used to evaluate the deformation risk of surrounding rock of 10 tunnel sections in Sheta Village Tunnel of the Zhangjihua high-speed railway. The results show that the 6th and 7th cavern sections are at high risk of deformation, and workers must support and grouting the surrounding rocks of the cavern section to improve the strength of surrounding rocks, prevent and reduce the deformation of the cavern section, and thus ensure the construction in the early stage and the open to traffic in the later stage.

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