Smart Risk Assessment Model of Water Inrush in Submarine Tunnel through AHP-TOPSIS and Intelligent Computing

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Abstract. In tunnel construction, water and mud inrush disasters are prone to occur when the tunnel traverses water-rich faults, which leads to structural damage and tunnel instability, which is one of the most severe hazards in tunnel excavation and construction. This paper proposes a method of combining AHP and TOPSIS. The weights are determined through the analytic hierarchy process utilizing expert scoring. The determined weights are evaluated and predicted by TOPSIS for water inrush risk. The Jiaozhou Bay Subsea Tunnel is used as a case to carry out the tunnel crossing the fault zone. Water inrush risk prediction provides a new idea for water inrush risk prediction.

Keywords: water inrush, TOPSIS, AHP, risk assessment

1. Introduction

With the continuous development of tunnel engineering in my country, more and more tunnel projects are facing unique and complex engineering-geological conditions [1]. Water inrush disaster is the most severe challenge in constructing submarine tunnels, causing severe economic losses [2] [3]. Therefore, risk assessment is critical that can identify and eliminate risk sources, provide guidance for risk managers [4], and play a valuable role in tunnel safety decision-making [5] [6].

To evaluate the water inrush of the tunnel, some experts and scholars have conducted a lot of research: Wei discussed the primary conditions and the possibility of water inrush of various water inrush modes in the tunnel crossing multiple faults comprehensively predicted its high-pressure water inrush hazard [7]. According to the main factors that affect the tunnel water inflow, Tian uses groundwater dynamics and fuzzy mathematics to predict the tunnel water inflow [8]. Luo predicted the tunnel water inrush risk through the analytic hierarchy process and fuzzy comprehensive evaluation, compared with theoretical calculations, and achieved good results [9].

This paper takes Qingdao Jiaozhou Bay Tunnel as an example to conduct research. It combines the analytic hierarchy process and ideal point method to evaluate the risk of water inrush in the tunnel. The weight of each influencing factor is determined through the scores of three experts, and then it is brought into the ideal point method. Conduct a comprehensive risk assessment.
2. AHP-TOPSIS comprehensive evaluation method

The analytic hierarchy process decomposes the elements related to decision-making into the target layer, the criterion layer, the scheme layer and other levels. On this basis, the elements were analyzed qualitatively and quantitatively. It is systematic, flexible and concise [10] [11]. By establishing a hierarchical structure model and constructing a judgment matrix, the overall ranking of the hierarchy is obtained after the consistency test is satisfied. With its convenient advantages, TOPSIS has become a commonly used decision-making method in analysis and decision-making. By calculating the degree of closeness of each evaluation plan to the positive and negative ideal points, it can rank the advantages and disadvantages [12] [13].

This article uses three experts to score the water inrush factors, reducing the subjectivity of each expert. By constructing a judgment matrix and consistency test, the weight vector of each expert is solved separately and then averaged. Carry out risk assessment after bringing in the ideal point method.

![Figure 1. The flow chart of AHP-TOPSIS evaluation method](image)

3. Calculate impact factor weight

Establish a hierarchical structure model, the target layer C is the tunnel water inrush risk assessment, the factors that cause the tunnel water inrush disaster are regarded as the middle layer B, and the influencing factors of the middle layer B are B1 rock integrity coefficient, B2 fault zone permeability coefficient, B3 Fault dip, B4 fault zone width, B5 apparent resistivity value, B6 overburden thickness, B7 vault to sea level distance. Three experts determine the evaluation criteria of influencing factors according to the proportional scale table and construct a judgment matrix:

| Scale | Meaning                                                   |
|-------|-----------------------------------------------------------|
| 1     | Compared with the two factors, they have the same importance |
| 3     | Compared with the two factors, one factor is slightly more important than the other |
| 5     | Compared with two factors, one factor is stronger than the other |
| 7     | Compared with two factors, one factor is more important than the other |
| 9     | Compared with the two factors, one factor is more important than the other |
| 2,4,6,8 | The intermediate value of the above two adjacent judgments needs to be a compromise between the above two standards |
| Countdown | If the factor i is compared with the judgement value $B_{ij}$ of j, then the judgement value $B_{ji}=1/B_{ij}$ is obtained by comparing the factor j and i |

Table 1. Proportional scale table
According to the above table, a judgment matrix can be established, a judgment matrix can be established, and a weight vector can be calculated:

\[
P_i = \begin{bmatrix}
1 & 1/3 & 1/2 & 1/3 & 2 & 1/4 \\
3 & 1 & 2 & 1/2 & 1/3 & 1 \\
1 & 1/2 & 1 & 1/2 & 1/2 & 1/2 \\
2 & 2 & 2 & 1 & 1/3 & 1 \\
3 & 3 & 2 & 5 & 1 & 2 \\
4 & 3 & 2 & 3 & 1 & 4 \\
\end{bmatrix}
\]

\[
P_2 = \begin{bmatrix}
1 & 2 & 1 & 1/2 & 1/2 & 1 \\
1/2 & 1 & 2 & 1 & 1/3 & 1/2 \\
1 & 1/2 & 2 & 1/2 & 1/3 & 1/2 \\
2 & 1 & 2 & 3 & 1 & 3 \\
1 & 1 & 2 & 1 & 1/2 & 1 \\
1 & 1 & 1 & 1 & 2 & 1 \\
\end{bmatrix}
\]

\[
P_3 = \begin{bmatrix}
1 & 1/2 & 2 & 1/2 & 1 \\
1 & 3 & 3 & 1 & 2 & 1 \\
1/2 & 1/2 & 1 & 1/2 & 1/2 & 1/2 \\
1 & 1/2 & 1 & 1/2 & 1 \\
1 & 1 & 1 & 1 & 2 & 1 \\
1 & 1 & 2 & 1/2 & 1 \\
\end{bmatrix}
\]

According to the formula \( B_n = \left[ b_{11} b_{22} b_{33} b_{44} b_{55} b_{66} \right] (b_{ii} — Corresponding to row \( B_i )) \), Orthogonalize to find the weight vector \( W_i \), the required weight vector is as follows:

\[
\begin{align*}
W_i &= \begin{bmatrix} 0.074 \\ 0.106 \\ 0.076 \\ 0.113 \\ 0.260 \\ 0.092 \\ 0.278 \end{bmatrix} \quad W_2 = \begin{bmatrix} 0.126 \\ 0.154 \\ 0.114 \\ 0.098 \\ 0.210 \\ 0.145 \\ 0.153 \end{bmatrix} \quad W_3 = \begin{bmatrix} 0.142 \\ 0.166 \\ 0.163 \\ 0.142 \\ 0.129 \\ 0.129 \\ 0.129 \end{bmatrix}
\end{align*}
\]

Hierarchical single sorting and its consistency check:

\[
MW_i = \begin{bmatrix}
1 & 1/3 & 1/2 & 1/3 & 2 & 1/4 \\
3 & 1 & 2 & 1/2 & 1/3 & 1 \\
1 & 1/2 & 1 & 1/2 & 1/2 & 1/2 \\
2 & 2 & 2 & 1 & 1/3 & 1 \\
3 & 3 & 2 & 5 & 1 & 2 \\
4 & 3 & 2 & 3 & 1 & 4 \\
\end{bmatrix}
\]

\[
MW_2 = \begin{bmatrix}
1 & 2 & 1 & 1/2 & 1/2 & 1 \\
1/2 & 1 & 2 & 1 & 1/3 & 1/2 \\
1 & 1/2 & 1 & 1/2 & 1/2 & 1/2 \\
2 & 1 & 2 & 3 & 1 & 3 \\
2 & 1/2 & 2 & 1/3 & 1 & 1 \\
1 & 1 & 1 & 1 & 2 & 1 \\
\end{bmatrix}
\]

Largest characteristic root:

\[
\lambda_{1\text{max}} = \frac{1}{7} \left[ 0.582 \cdot 0.07 + 0.808 \cdot 0.11 + 0.575 \cdot 0.08 + 0.862 \cdot 0.11 + 1.982 \cdot 0.70 + 0.699 \cdot 0.09 + 2.013 \cdot 0.28 \right] = 7.769
\]

\[
CI = \frac{\lambda_{1\text{max}} - n}{n-1} = \frac{7.769 - 7}{7-1} = 0.1282 \quad CR_i = \frac{CI}{RI} = \frac{0.1282}{1.32} = 0.097 < 0.1 \quad \text{(Meet the requirements)}
\]

Largest characteristic root:

\[
\lambda_{2\text{max}} = \frac{1}{7} \left[ 0.976 \cdot 0.13 + 1.196 \cdot 0.15 + 0.843 \cdot 0.11 + 0.730 \cdot 0.10 + 1.648 \cdot 0.21 + 1.121 \cdot 0.14 + 1.210 \cdot 0.15 \right] = 7.719
\]
\[ CI = \frac{\lambda_{\text{max}} - n}{n-1} = \frac{7.719 - 7}{7 - 1} = 0.1198 \cdot CR = \frac{CI}{RI} = \frac{0.1198}{1.32} = 0.091 < 0.1 \text{(Meet the requirements)} \]

\[ MW = \begin{bmatrix}
1 & 1 & 1 & 1 & 2 & 1/2 & 1 \\
1 & 1 & 1/2 & 2 & 2 & 2 & 1 \\
1 & 2 & 1 & 1/3 & 1 & 2 & 2 \\
1 & 1/3 & 3 & 1 & 2 & 1/2 & 1/2 \\
1/2 & 1/2 & 1 & 1/2 & 1 & 2 & 2 \\
1 & 1/2 & 1 & 1/2 & 1 & 1 & 1 \\
1 & 1 & 1/2 & 2 & 1/2 & 1 & 1 \\
\end{bmatrix}
\]

\[ MW = \begin{bmatrix}
0.142 & 1.064 \\
0.166 & 1.189 \\
0.163 & 1.329 \\
0.142 & 1.280 \\
0.129 & 1.032 \\
0.129 & 0.854 \\
0.129 & 0.996 \\
\end{bmatrix}
\]

Largest characteristic root:

\[ \lambda_{\text{max}} = \frac{1}{7} \left[ 1.064 + 1.189 + 1.329 + 1.280 + 1.032 + 0.854 + 0.996 \right] = 7.746 \]

\[ CI = \frac{\lambda_{\text{max}} - n}{n-1} = \frac{7.746 - 7}{7 - 1} = 0.1243 \cdot CR = \frac{CI}{RI} = \frac{0.1243}{1.32} = 0.094 < 0.1 \text{(Meet the requirements)} \]

The matrices meet the requirements, and the final weight vector is determined after averaging:

\[ W = [0.114 \ 0.142 \ 0.118 \ 0.118 \ 0.200 \ 0.122 \ 0.187]^T \]

**Figure 2.** The weight of each influence factor

### 4. Risk assessment

In this paper, the Jiaozhou Bay Subsea Tunnel was selected as an engineering example, and seven fracture zones were selected for tunnel water inrush risk assessment. The selected parameters and various data are as follows:

**Table 2. Fault zone index value [14]**

| Fault name | Rock integrity | Permeability coefficient | Fault dip | Fault zone width | Apparent resistivity | Cover layer thickness | Distance to sea level |
|------------|----------------|--------------------------|-----------|-----------------|---------------------|----------------------|---------------------|
| F1-1       | 1.8            | 0.015                    | 88        | 2               | 390                 | 13.28                | 13.5                |
| F1-2       | 2.8            | 0.03                     | 84        | 0.7             | 289                 | 13.67                | 13.9                |
| F1-3       | 1.9            | 0.04                     | 77        | 30              | 350                 | 41.83                | 57.92               |
| F2-3       | 3.5            | 0.19                     | 24        | 30              | 107                 | 20.91                | 60.44               |
| F3-1       | 2              | 0.045                    | 51        | 25              | 298                 | 26.77                | 57.08               |
| F4-1       | 1.9            | 0.03                     | 70        | 100             | 302                 | 22.19                | 24.38               |
| F5         | 2.2            | 0.04                     | 85        | 80              | 343                 | 36.87                | 40.24               |
According to the characteristics of the project, the risk classification standard of the tunnel was determined, and the water inrush risk is dividing into four levels: Very high risk (IV), high risk (III), medium risk (II), and low risk (I). Refer to Table 3 for the grading standards of each evaluation index based on engineering experience and related data.

Table 3. Indicators corresponding to water inrush risk

| Fault name           | Rock integrity | Permeability coefficient | Fault dip | Fault zone width | Apparent resistivity | Cover layer thickness | Distance to sea level |
|----------------------|----------------|--------------------------|-----------|------------------|----------------------|-----------------------|----------------------|
| Low risk (I)         | 1.5-2.5        | 0-0.05                   | 20-37     | 0-25             | 391-320              | 42-36                 | 13-28.75             |
| Medium risk (II)     | 2.5-3.5        | 0.05-0.1                 | 37-54     | 25-50            | 320-249              | 36-30                 | 28.75-44.5           |
| High risk (III)      | 3.5-4.5        | 0.1-0.15                 | 54-71     | 50-75            | 249-178              | 30-24                 | 44.5-60.25           |
| Very high risk (IV)  | 4.5-6          | 0.15-0.2                 | 71-88     | 75-100           | 178-100              | 24-13                 | 60.25-76             |

Combine the previously calculated weights and use the following formula to calculate:

$$D_{+k}^* = \left\{ \sum_{i=1}^{n} W_i \left[ q_i - A_{+k}^* \right]^2 \right\}^{\frac{1}{2}}, \quad D_{-k}^- = \left\{ \sum_{i=1}^{n} W_i \left[ q_i - A_{-k}^- \right]^2 \right\}^{\frac{1}{2}}$$

According to the criterion of maximum closeness, each set of data’s water inrush risk level is judged. Table 4 is used to verify the index values of these seven sets of data for engineering verification and the ideal point closeness between different water inrush risk levels.

Table 4. The result of the evaluation

| Fault name | Closeness to the ideal point | TOPSIS Evaluation result |
|------------|-----------------------------|--------------------------|
|            | $T_1$ | $T_{II}$ | $T_{III}$ | $T_{IV}$ |                  |
| $F_{1-1}$  | 0.4597 | 0.4830 | 0.5817 | 0.6301 | IV                |
| $F_{1-2}$  | 0.4328 | 0.4283 | 0.6178 | 0.6104 | III               |
| $F_{1-3}$  | 0.4064 | 0.4291 | 0.4296 | 0.5489 | IV                |
| $F_{2-3}$  | 0.4165 | 0.3284 | 0.3756 | 0.4093 | I                 |
| $F_{3-1}$  | 0.3595 | 0.3317 | 0.4427 | 0.5694 | IV                |
| $F_{4-1}$  | 0.4081 | 0.3799 | 0.4724 | 0.5382 | IV                |
| $F_5$      | 0.3966 | 0.3840 | 0.4198 | 0.5137 | IV                |

5. Conclusion

The evaluation result of the TOPSIS method is biased towards danger, but during the construction process, the evaluation result biased towards safety tends to ignore the existence of risk. Therefore, the stability evaluation model of the cross-river shield tunnel excavation surface established in this paper based on the AHP-TOPSIS method is reasonable and feasible. However, for the full evaluation result, the risk of the water inrush model is somewhat high. It is speculated that the weight determination is determined by a single method. Although the process of scoring by multiple experts is used, it still has too much subjectivity. It is possible to use a combination of subjective and objective methods to determine the comprehensive weight before proceeding with the risk assessment.

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