Study on fire risk assessment for underwater soft rock tunnels based on AHP

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Abstract. Based on AHP, fire risk of underwater soft rock tunnel was assessed. This study is aimed to quantify risk factors associated with fire of underwater soft rock tunnel, and calculate various risk factors. Assessment target weight through the consistency check of underwater soft rock tunnel was then obtained, and underwater soft rock tunnel fire risk will be comprehensively evaluated by comparing the weight and combining the scores of each risk factor. Suggestions for its weak parts are proposed.

1. Introduction

Tunnel accident risk assessment has been one of the most important issues in tunnel safety management, especially for underwater soft rock tunnels. In consideration of geological factors, harsh environmental conditions and confined long space for such tunnels, once fire occurred in tunnel, it can cause great economic and human loss. The risk research methods for road tunnel accidents mainly includes scenario simulation [1], risk analysis model [2-5] and preventive measures [6,7]. Combined with the environmental characteristics of underwater soft rock tunnels, Xu Zhenhao [8] evaluate and categorize these risks, such as adverse geology, formation lithology and groundwater level. Sun Ronggui [9] emphatically considered the factors of inspection and control, fire protection, ventilation, lighting, power supply and distribution equipment, and adopted the method of analytic hierarchy process (AHP) to estimate safety of underwater tunnel. In addition to geological factors, Jiang Shiyu et al. [10] also considered water pressure, water abundance of the overlying aquifer, the depth of the tunnel and the radius of the tunnel, and adopted matter element analysis, analytic hierarchy process and BP network to assess the risks for tunnel. Zhang Dingli [11] carried out detailed assessment on technical risk, economic risk, safety risk and environmental impact risk. Xu Jiancong et al. [12] studied the factors related to the height and quantity of fracture zones, and adopted AHP to evaluate the risks. Aiming at the risk management of the strong weathered layer construction of Xiang'an Tunnel, Li Feng [13] adopted the fuzzy comprehensive evaluation method to analyze the adverse geology under the consideration of design, support, management, disaster and other factors. Liu Changxiang [14] comprehensively used the methods of fuzzy evaluation, finite element simulation and fuzzy early warning to evaluate the factors affecting the stability of surrounding rock in large-span tunnel, and analyze in detail the influence of tunnel factors, equipment factors and environmental factors on tunnel stability.

The previous researches were focused on fire risks of tunnel structure and fire risks arising from the construction process. However, there were few researches on fire accidents under underwater soft rock tunnel. Many factors for the physical environment of underwater soft rock tunnel need to be considered,
including structural factors, traffic factors, equipment factors, driver factors, environmental factors, hazard factors, management factors, etc. In this paper, fire risk assessment model for underwater soft rock tunnel was established based on AHP, and the weight value of each grade index was obtained. Moreover, the feasibility and rationality of the evaluation model were further verified combining with an example.

2. Analytic Hierarchy Process
The Analytic Hierarchy Process (AHP) was developed in the 1970s. The methods for AHP could be divided to qualitative analysis method, semi quantitative analysis method and quantitative analysis method. The basic idea of this method is to decompose the complex risk problem into its constituent factors and group these factors into orderly hierarchical structure according to the dominating relationship, and make a simple comparison between the factors at the same level to obtain the risk index of each factor, thus providing a basis for the selection of the final solution.

2.1. Establish hierarchical structure model
Firstly, the basic risks are classified, then the hierarchical structure of the system is established, building the judgment matrix of risk factors, which could be used to calculate the relative weight of each risk factor, and verify sequential consistency. If the matrix has passed the consistency test, then calculate the comprehensive weight. Otherwise, the judgment matrix of risk factors should be rebuilt until the consistency test of relative weights of each risk factor is passed.

2.2. Build judgment matrix
By comparing the factors in one layer, we can eliminate much of the hardship of comparing factors with different properties, so as to improve the accuracy. Assume that one layer has n factors, $A_1, A_2, ..., A_n$, and $a_{ij}$ represents the importance of the relative comparison between $A_i$ and $A_j$ by using a scale of numbers 1 to 9, as shown in Table 1. Thus, an $n \times n$ judgment matrix is obtained, as shown in Table 2.

| Table 1. Project risk assessment score |
|--------------------------------------|
| Importance level | Assignment for $a_{ij}$ |
|------------------|--------------------------|
| Element $i$ and element $j$ are equally important | 1 |
| Element $i$ is slightly more important than element $j$ | 3 |
| Element $i$ is obviously more important than element $j$ | 5 |
| Element $i$ is intensively more important than element $j$ | 7 |
| Element $i$ is Extremely more important than element $j$ | 9 |

| Table 2. Judgment matrix |
|---------------------------|
| $A_1$ | $A_2$ | ... | $A_n$ |
| $A_1$ | $a_{11}$ | $a_{12}$ | ... | $a_{1n}$ |
| $A_2$ | $a_{21}$ | $a_{22}$ | ... | $a_{2n}$ |
| ... | ... | ... | ... | ... |
| $A_n$ | $a_{n1}$ | $a_{n2}$ | ... | $a_{nn}$ |

2.3. Eigenvector $w$ and maximum eigenvalue $\lambda_{max}$
Using summation method to calculate eigenvector and maximum eigenvalue of judgment matrix.

$$A = (a_{ij})_{n \times n}$$ (1)

It is solved by formula (2):
The specific solution is as follows: sum the elements in each row of judgment matrix A according to formula (3).

\[ W_i = \sum_{j=1}^{n} a_{ij} \]  

(3)

Then normalize according to formula (4) to get the weight coefficient:

\[ W_i = \frac{\sum_{j=1}^{n} a_{ij}}{\sum_{k=1}^{n} \sum_{j=1}^{n} a_{kj}} \]  

(4)

Then, \( \lambda_{\text{max}} \) is obtained by solving equation (5):

\[ \lambda_{\text{max}} = \sum_{i=1}^{n} \frac{(AW)_i}{nW_i} \]  

(5)

Where \((AW)_i\) represents the ith component of AW.

For judgment matrix, the consistency test should be carried out according to formula (6), where Consistency Index expressed as:

\[ \text{CI} = \frac{\lambda_{\text{max}} - n}{n - 1} \]  

(6)

Then, find the corresponding average random consistency index RI from the Table 3 and random consistency ratio could be calculated by formula (7).

\[ \text{CR} = \frac{\text{CI}}{\text{RI}} \]  

(7)

When \( \text{CR} < 0.10 \), the consistency of judgment matrix is good, otherwise, the elements in judgment should be adjusted to meet the consistency. The greater the value of CI, the greater the deviation of judgment matrix from complete consistency. The larger the order \( n \) of general judgment matrix is, the greater the value of deviation from complete consistency index CI is.

Calculate the combined weight of the elements of each layer on the system elements and rank them. If criterion layer A contains \( m \) elements, \( A_1, A_2, ..., A_m \), their hierarchical total ranking weights are \( a_1, a_2, ..., a_m \). Scheme layer P contains \( n \) elements, \( P_1, P_2, ..., P_n \), their ranking consistency metric for the \( A_j \) are \( b_{1j}, b_{2j}, ..., b_{nj} \), as shown in Table 4.

**Table 3. Random consistency index of matrix**

| Order | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|-------|-----|-----|-----|-----|-----|-----|-----|
| RI    | 0.58| 0.90| 1.12| 1.24| 1.32| 1.41| 1.45|
Table 4. Calculation of combined weights

| $A$ | $A_1$ | $A_2$ | ... | $A_m$ | Sub-aggregate for layer B |
|-----|-------|-------|-----|-------|--------------------------|
| $P$ | $a_1$ | $a_2$ | ... | $a_m$ | $\sum_{i=1}^{m} a_i b_{ij}$ |

3. Engineering applications and analysis

3.1. Project Overview

The total length of the tunnel is 8.695 km, spanning a sea area about 4.2 km wide, of which the submarine part is 6.05 km long. Three-hole tunnel scheme is adopted in the design. The clear width and height of the main tunnel are 13.5m and 5m respectively. Due to the complex geology of the tunnel, three worldwide problems have been encountered in the construction of the tunnel, i.e. fully weathered stratum, water rich sand layer and weathered deep trench.

3.2. Determination of risk weight by analytic hierarchy process

(1) Establish the multi-level hierarchical structure of risk

According to the characteristics of underwater soft rock tunnel fire accident, and referring to the fire risk analysis and design data of the tunnel engineering in the lower soft rock, we have comprehensively used engineering geological survey and other methods to identify 8 key first-class risks that may have serious consequences in the underwater tunnel, and then established a multistage ladder structure for the fire accident risk of the underwater tunnel, as summarized in Table 5.

Table 5. Multistage ladder structure of underwater soft rock tunnel fire risk

| One-level | Two-level | Three-level | Evaluation factors and scores |
|-----------|-----------|-------------|------------------------------|
| Tunnel structural factors $a$ | Section $a_1$ | Average speed (km/h) $b_{11}$ | $>$100 m² | 100-100 m² | $\leq$50 m² |
| | Span $a_2$ | Proportion of large cars (%) $b_{12}$ | 10 - 20 | 20 - 40 | 40 - 60 | 60 - 80 | 80 - 100 |
| | Length $a_3$ | Time headway (s) $b_{13}$ | 13 - 20 | 10 - 13 | 8 - 10 | 5 - 8 | 0 - 5 |
| Traffic factors $b$ | Traffic characteristics $b_1$ | Pavement condition $b_{21}$ | 85 - 100 | 70 - 85 | 55 - 70 | 40 - 55 | 20 - 40 |
| | Traffic environment $b_2$ | Rationality of guidance signs $b_{22}$ | Reasonable | Basically reasonable | Slightly unreasonable | Obviously unreasonable | Seriously unreasonable |
| | Equipment factors $c$ | Lighting $c_1$ | Intact rate | 70 - 80% | 80 - 90% | 90 - 95% | >95% |
| | | Ventilation system | Intact rate | 70 - 80% | 80 - 90% | 90 - 95% | >95% |
| Driver factors | Visual recognition | Good recognition | Certain influence | Basic recognition | Incomplete recognition | Difficult recognition |
|----------------|--------------------|-----------------|------------------|------------------|----------------------|----------------------|
| d1             | 10                 | 8               | 6                | 4                | 2                    |                      |
| Fire safety awareness and ability | Good | Medium | Poor |
| d2             | 10                 | 6               | 2                |                  |                      |                      |

| Environ-mental factors | Tunnel internal environment | Fire safety awareness and ability |
|------------------------|-----------------------------|---------------------------------|
| e1                     | e11                          | Noise: NS-I or NS-II, NS-III, NS-IV |
|                        | e12                          | Air quality: Low-risk, Medium-risk, High-risk |
|                        | e13                          | Smoke concentration: SS-I, SS-II, SS-III, SS-IV |
|                        | e14                          | Import and export brightness: I, II, III, IV |
|                        | e15                          | Groundwater level: 0<H<30, 30<H<50, H>50 |
|                        | e16                          | Geological features: Soft rock III, Soft rock II, Soft rock I |
|                        | e17                          | Strength characteristics: Rc≤5, 5<Rc≤15, 15< Rc≤30 |

| Hazard factors | Osmotic water | Seepage grade | Deformation grade of rock |
|----------------|--------------|---------------|---------------------------|
| f1             | f11          | f12           | f13                        |
|                | Infiltration water flow: Q<1, 1<Q<5, Q>5 |
|                | Scope of leakage point: (1/L)<10%, 10%<(1/L)<20%, (1/L)>20% |
|                | Drainage effect of blind ditch: Good, Medium, Poor |
|                | Seepage grade: Disastrous, Very serious, Serious, Consider, None |
|                | Deformation grade of rock: None, Conventional, I level, II level, III level |

| Manage-ment factors | Fire prevention | Fire-fighting capacity | Fire education |
|---------------------|-----------------|------------------------|---------------|
| g1                  | g12             | g13                    | g14           |
| Fire prevention: Complete, Medium, Infallible |
| Fire-fighting capacity: Good, Medium, Poor |
| Fire education: Complete, Medium, Infallible |

| Other | h1 | 2 | 6 |
|-------|----|---|---|
| Terrorist attack or arson: Especially serious, Generally serious, Not serious |
(2) Determination of evaluation index weight

Based on the above index system, the relative importance of each criterion layer is judged and the judgment matrix is constructed. It can be seen from table 5 that the one-level includes tunnel structural factors, traffic factors, equipment factors, driver factors, environmental factors, hazard factors and management factors etc. The judgment matrix is shown in formula (8).

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

According to the calculation steps of AHP, the weight vector of each index is calculated as follows: \(w_I = (0.208, 0.097, 0.118, 0.095, 0.132, 0.118, 0.145, 0.088)\).

Similarly, the weight of the second level criterion layer evaluation index judgment matrix, \(A_2, A_3, A_4, A_5, A_6, A_7, A_8\) are as follows: \(w_2 = (0.326, 0.443, 0.231); w_3 = (0.333, 0.667); w_4 = (0.127, 0.093, 0.151, 0.116, 0.203, 0.192, 0.118); w_5 = (0.667, 0.333); w_6 = (0.833, 0.167); w_7 = (0.190, 0.476, 0.333); w_8 = (0.750, 0.250)\).

The weight of the third criterion layer evaluation index judgment matrix, \(A_9, A_{10}, A_{11}, A_{12}, A_{13}\) are as follows: \(w_9 = (0.558, 0.153, 0.289); w_{10} = (0.333, 0.167); w_{11} = (0.087, 0.093, 0.346, 0.474); w_{12} = (0.414, 0.336, 0.250); w_{13} = (0.570, 0.321, 0.109)\).

For the above judgment matrix, the calculated Cr is less than 0.1 in the consistency test, therefore, it is not necessary to modify the parameters of the judgment matrix.

3.2.1. Composite weight coefficient of bottom factor. The weight of the first level criterion layer, the second level criterion layer and the three-layer criterion layer are respectively \(c_i, c_j, c_k\). The composite weight C of bottom layer factor could be calculated by formula (9).

\[
c_{ik} = c_i c_j c_k
\]

Based on this formula, we can get the composite weight of each factor in the bottom layer to the overall system target. According to the actual situation of underwater tunnel with weak surrounding rock to be evaluated, score the bottom factor, then multiply by the composite weight coefficient of the underlying factor. Finally, the fire risk value R of underwater tunnel in soft rock is calculated by summing each term. Among them, \(R < 3\) represents very low risk, \(3 \leq R < 5\) represents low risk, \(5 \leq R < 7\) represents medium risk, \(7 \leq R < 9\) represents high risk, and \(R \geq 9\) represents extremely high risk.

4. Fire risk assessment of underwater soft rock tunnel

In order to simplify the matrix operation and make the operation convenient, the fire risk assessment program of underwater soft rock tunnel is compiled with MATLAB software. Firstly, check the consistency of judgment matrix until the condition is satisfied. After the judgment matrix has passed the consistency test, if fire risk factors for a particular underwater soft rock tunnel are to be evaluated, the elements of the standard layer can be assigned as appropriate, finally, a safety risk assessment value is obtained.

The actual condition of the tunnel was researched and counted according to the needs of the assessment model, and expert scoring methods were used, with the scoring values shown in Table 6.
Table 6. Evaluation value of operation safety impact parameters of subsea tunnel

| Serial number | Parameter                     | Score | Serial number | Parameter                      | Score |
|---------------|-------------------------------|-------|---------------|--------------------------------|-------|
| a1            | Tunnel section                | 2     | e11           | Noise                          | 4     |
| a2            | Tunnel span                   | 4     | e12           | Air quality                    | 6     |
| a3            | Tunnel length                 | 6     | e13           | Smoke concentration            | 4     |
| b11           | Average speed                 | 6     | e14           | Import and export brightness   | 4     |
| b12           | Proportion of large cars      | 6     | e21           | Groundwater level              | 2     |
| b13           | Time headway                  | 4     | e22           | Geological features            | 4     |
| b21           | Pavement condition index      | 2     | e23           | Strength characteristics       | 4     |
| b22           | Rationality of guidance sign  | 2     | f11           | Infiltration water flow        | 4     |
| c1            | Lighting                      | 2     | f12           | Scope of leakage point         | 2     |
| c2            | Ventilation system            | 2     | f13           | Drainage effect of blind ditch | 4     |
| c3            | Video surveillance            | 2     | f2            | Seepage grade                  | 4     |
| c4            | Power supply                  | 4     | f3            | Deformation grade of rock      | 4     |
| c5            | Fire detection and alarm      | 4     | g1            | Fire prevention                | 4     |
| c6            | Automatic sprinkler           | 2     | g2            | Fire-fighting capacity         | 2     |
| c7            | Smoke control                 | 4     | g3            | Fire education                 | 2     |
| d1            | Visual recognition            | 2     | h1            | Terrorist attack or arson      | 2     |
| d2            | Fire safety awareness         | 6     |                |                                |       |

The evaluation model is used to analyze and evaluate the underwater soft rock tunnel. It is indicated that the risk value of fire accident \( r \) of the tunnel is about 3.45, which is a low risk. In combination with the results of the tunnel fire risk assessment mentioned above, the tunnel itself, the driver and the equipment (power supply and distribution system, alarm system) need to be further improved in order to achieve the goal of ensuring operational safety and to reduce the occurrence of tunnel fire accidents to a greater extent.

5. Conclusion

In this paper, hierarchical analysis was used to study the factors influencing the risk of fire accidents in underwater soft rock tunnels, and the values and weight sizes of typical risk parameters were obtained to establish a fire risk assessment model for underwater soft rock tunnels. And MATLAB software was used to prepare the underwater soft rock tunnel fire risk assessment program, simplifying the process of a large number of matrix calculations and making the operation more convenient. Based on the established operational safety risk assessment model for underwater soft-rock tunnels, a typical underwater soft-rock tunnel was selected to realize the effective application of the analytical assessment method on the underwater soft-rock tunnel.

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