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Structural Risk Evaluation Model of Water-Conveyance Tunnel Based on Fuzzy Hierarchical Synthesis Method

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Abstract: For underwater water-conveyance tunnels during the operation period, the tunnel may be subject to structural risks due to geological conditions, water level changes and other uncertainties. The research was carried out to evaluate the structural risk level of water-conveyance tunnel and reduce the possibility of accidents. The influencing factors and evaluation indexes of were determined through literature research. Based on the expert's scoring, the analytic hierarchy process (AHP) method is applied to obtain the index weight, and then the basic probability level of structural risk of the underwater water-conveyance tunnels is determined by the fuzzy comprehensive evaluation method. The established risk level evaluation method is applied to Pearl River Delta Underwater Tunnel. The evaluation result is accordance with the practical conditions, which verifies the reliable and practical of the method.The study provides a reference method for the structural risk evaluation of underwater water-conveyance tunnel.

Keywords: Risk evaluation, Water-conveyance tunnel, AHP, Fuzzy comprehensive evaluation

1 Introduction

In recent years, with the development of national water transmission projects, water-conveyance tunnel often needs to cross rivers and lakes to meet the requirement of remote water transfer(Nabipour et al.,2020). Since the 21st century, underwater tunnels have become an important form of water conservancy projects. However, there are many uncertain factors for water-conveyance tunnel's operation such as geological conditions, water level changes and so on. Thus, it is difficult to control structural safe of the tunnel, which makes the operation of underwater water-conveyance tunnels with extremely high risks.

Conventional risk analysis methods include the fuzzy evaluation method (Zhang et al.,2016), the analytic hierarchy process (Moradi et al.,2014), the extension theory method (Kong et al.,2011), Bayesian network (Xie et al.,2015), the fault tree method (Ding et al.,2017), the cloud model (Wang et al.,2020) and so on. The analytic hierarchy process can easily and effectively determine the weight of risk factors, and the fuzzy comprehensive evaluation method can deal with the fuzzy evaluation objects through Precise mathematical approaches. Therefore, the combination of the two methodologies can make a more scientific, reasonable, and realistic quantitative evaluation of the indicators with ambiguity (Saaty.,1982). This paper adopts the Fuzzy Analytic Hierarchy Process combining the two methods to evaluate the structural risk of the underwater water-conveyance tunnels.

Most of the current research on tunnel structural risk involves: 1) establishing individual influencing factors related to tunnel structural risk; 2) establishing tunnel structural characteristics and risk assessment models by identifying influencing factors; 3) determining the mechanism of tunnel structure based on theoretical analysis techniques. Eskesen et al. (2004) and Guglielmetti et al. (2008) well document general procedures for risk analysis in tunnelling. Hyun et al. (2015) discussed the potential risks in the shield excavation process using fault tree analysis and hierarchical analysis. Jk et al. (2021) proposed a probabilistic tunnel collapse risk evaluation model for road tunnels using AHP and Delphi survey technique. However, the study on the structural risk assessment of underwater water-conveyance tunnelsis still in the qualitative stage. Therefore, this paper uses quantitative methods (AHP, fuzzy evaluation and expert scoring methods) to assess risk the tunnels.

The present study chooses factors that may affect the structural risk of the tunnel through interviewing experts and on-site research. For each influencing factor of risk, the weight is determined depending on the analytic hierarchy process (AHP) based on expert scoring method.Then, the probability level of the risk control of the tunnel is determined by the fuzzy comprehensive assessment method. Finally, the established risk level evaluation system is applied to Pearl River Delta Underwater Tunnel to demonstrate the practicality and reliability of the system.

2 Fuzzy Hierarchical Comprehensive Evaluation Model

2.1 Analysis of Influencing Factors

Based on consulting the existing engineering data, combined with the survey results of experts, the main influencing factors involves the natural environment, the tunnel performance, and water transportation factors. The natural environmental factors include stratigraphic in homogeneity, water level changes and river erosion and deposition phenomenon; The tunnel performance includes concrete material grades, rubber gasket performance, as well as segment and bolt performance; Water transportation factors involving chlorine ion content inside the tunnel, Water delivery velocity and Internal water pressure also affect structural safety of operational underwater water-conveyance tunnel.

2.2 Analytic Hierarchy Model

Analytic Hierarchy Process (AHP), proposed by American mathematician Thomas L. Saaty, which is a multi-criteria theory for evaluating the relative priority scale of absolute numbers from individual judgments in complex decisions (Saaty.,1982). After analysing the typical tunnel structural risk cases of collapse accidents for underwater water-conveyance tunnel and combined with the survey results of experts, a risk assessment index framework is established, as shown in Table1.

Table 1. Risk assessment index system of operational underwater water-conveyance tunnel

Target hierarchy	Main hierarchy	Subordinate hierarchy
The structural risk index of underwater water-conveyance tunnel A	The natural Environmental factor B_1	Stratigraphic inhomogeneity C_1
		River erosion and deposition C_2
		Water level change C_3
	Tunnel performance B_2	Rubber gasket performance C_4
		Segment and Bolt Performance C_5
		Concrete material grade C_6
	Water transportation factors B_3	Chlorine ion content C_7
		Water delivery velocity C_7
		Internal water pressure C_8

2.3Determine the weights

The analytic hierarchy process is used based on the expert scoring method that solicits the opinions of multiple experts by making and returning questionnaires. According to the principle of AHP, using the 1~9 scale method that indicated 'equally important' to 'absolutely very important', respectively (Cao et al.,2021). Experts compare the importance of each influencing factor based on their engineering experience and professional knowledge. The weights and priority of each index is determine depending on the survey results. The judgment matrix Bcan be obtained:

$$B = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nn} \end{bmatrix}$$

The matrix B needs to meet the following conditions:

$$\begin{cases} b_{ij} > 0 \\ b_{ii} = 1 \\ b_{ij} = \dfrac{1}{b_{ji}} \end{cases}, i,j \in (1,n)$$

For the relative weight of each influencing factor, the geometric averaging method and the arithmetic averaging method are generally used. In this paper, the geometric averaging method is used for calculation. The solution process is as follows:

1) Solve the 1/nth root of the cumulative multiplication result of each row in the judgment matrix *B*.

$$W_i' = (\prod_{j=1}^{n} b_{ij})^{\frac{1}{n}} \tag{1}$$

2) Normalization

$$W_i = \frac{W_i'}{\sum_{j=1}^{n} W_j'} \tag{2}$$

3) Calculate the maximum eigen value of the judgment matrix

$$\lambda_{max} = \sum_{i=1}^{n} \frac{(B_W)_i}{n \cdot W_i} \tag{3}$$

4) Consistency check

Consistency index:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{4}$$

In the formula: n is the order of the judgment matrix, here, $n = 3$

The average random consistency index RI can be known from Table 2.

Table 2. *RI* value

	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49

Then, calculate consistency index *CR*:

$$CR = \frac{CI}{RI} \tag{5}$$

Generally, when the consistency index *CR* < 0.1, it is considered that the degree of inconsistency of judgment matrix *B* is within the allowable range. If the consistency index *CR* > 0.1, the matrix *B* needs to be adjusted until it reaches a satisfactory value. After passing the consistency test, its normalized eigenvector can be used as a weight vector.

If the authority of each expert is not considered, the comprehensive weight can be obtained by averaging the weights of each expert calculated. As shown in Table 3.

Table 3. The weight of each impact factor

Main hierarchy	Main hierarchy weight W	Subordinate hierarchy	Subordinate hierarchy weight V	Compound weighting
The natural Environmental factor B_1	0.4098	Stratigraphic inhomogeneity C_1	0.3416	0.1400
		River erosion and deposition C_2	0.2411	0.0988
		Water level change C_3	0.4173	0.1710
Tunnel performance B_2	0.3061	Rubber gasket performance C_4	0.3061	0.0936
		Segment and Bolt Performance C_5	0.3069	0.0939
		Concrete material grade C_6	0.3870	0.1184
Water transportation factors B_3	0.2841	Chlorine ion content C_7	0.2363	0.0671
		Water delivery rate C_8	0.3330	0.0946
		Internal water pressure C_9	0.4307	0.1224

3 Risk evaluation standard

This paper uses the four-level index method to evaluate risk levels. Experts will score the factors that influence the structural risk of underwater water-conveyance tunnels. Each single score is divided into four grades, with a total score of 20 points. Possibility evaluation standard is shown in Table4, scoring standard is shown inTable 5.

Table 4. Possibility evaluation standard for underwater shield tunnel (Wang et al.,2019)

Scores	Accident probability description	Rating
1~5	Improbable	Ⅰ
6~10	Haphazard	Ⅱ
11~15	Possible	Ⅲ
16~20	Highly possible	Ⅳ

Table 5. Scoring standard

Rating value	Ⅰ(1~5)	Ⅱ(5~10)	Ⅲ(10~15)	Ⅳ(15~20)
Stratigraphic inhomogeneity C_1	Not catastrophic	Weak catastrophic	Medium catastrophic	Catastrophic
River erosion and deposition C_2	<0.5m/y	0.5~3m/y	3~5m/y	>5m/y
Water level change C_3	Very small	Small	Huge	Very huge
Rubber gasket performance C_4	Very good	Good	Bad	Very bad
Segment and Bolt Performance C_5	Very good	Good	Bad	Very bad
Concrete material grade C_6	eC50	C40~C50	C30~C20	dC20
Chlorine ion content C_7	<0.02	0.02~0.03	0.03~0.05	>0.05
Water delivery velocity C_8	<5m/s	5~10m/s	10~20m/s	>20m/s
Internal water pressure C_9	<60m	60~106m	106m~130m	>130m

Notes: The value of the internal water pressure is specifically the height of the water head.

4 Engineeringcase

It is proposed to use the risk assessment system to evaluate structural risk based on section B3 of Pearl River Delta Water Allocation Project.Section B3 is 11.36km long and has 4 shield sections. The underwater shield section is 4.2km long and crosses the Lianhua Mountain River and the Shishiyang River. The diameter of the tunnel is 8.65m and the depth is about 46m. There are complex geological conditions in this project, including 9 major faults, unidentified uneven weathering strata and mud-bearing strata. The underwater section was excavated by mud and water shield method. Segment damage and non-uniform settlement are typical structural risks of this project. The roadmap of B3 section and geological section map for shield tunnel section 2 is shown in Figure1 and Figure2.

Figure 1. Tunnel roadmap of B3 section.

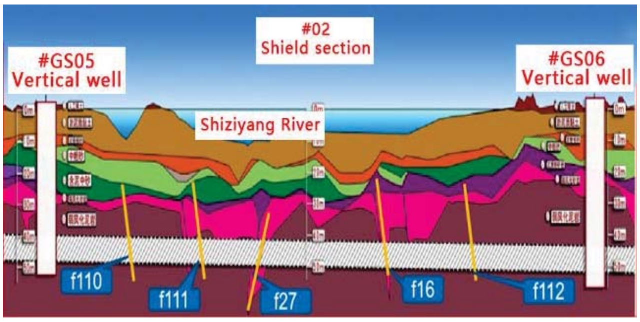

Figure 2. Geological section map of shield section 2.

Table 6. Expert scoring results

Subordinate hierarchy	Expert 1	Expert 2	Expert 3	Expert 4
Stratigraphic inhomogeneity C_1	10	10	12	15
River erosion and deposition C_2	5	4	5	2
Water level change C_3	7	9	8	5
Rubber gasket performance C_4	1	5	6	2
Segment and Bolt Performance C_5	3	4	1	1
Concrete material grade C_6	2	3	3	4
Chlorine ion content C_7	2	3	3	1
Water delivery rate C_8	3	5	3	4
Internal water pressure C_9	4	1	3	6

Establish the fuzzy evaluation matrix X_i of the subordinate hierarchy according to Table 6. Based on the subordinate hierarchy weight vector V_i, the evaluation vector Y_i of each index in main hierarchy is obtained:

$$Y_i = X_i \times V_i \tag{6}$$

The main hierarchy evaluation matrix Y can be obtained by combining the evaluation vectors:

$$Y = \begin{bmatrix} 7.5426 & 8.1360 & 8.6431 & 7.6928 \\ 2.0008 & 3.9190 & 3.3044 & 2.4462 \\ 3.1944 & 2.8046 & 3.0000 & 4.1524 \end{bmatrix}$$

Finally, multiply the main hierarchy weights to get the final evaluation matrix Z:

$$Z = W \times Y = [4.6108 \quad 5.3304 \quad 5.4055 \quad 5.0873]$$

According to the principle of maximum membership, the final score result for the safety of the tunnel is 5.4055, the safety degree is classified into “Level Ⅱ” based on possibility evaluation standard (Table4). Thus,the structural accident of the tunnel has low probability of occurrence. When extremely conditions are occurred, such as rapid changes in internal water pressure of the tunnel caused by floods, the assessment results may be completely different. The structural risk of the operational underwater water-conveyance tunnel needs to be reassessed to obtain more accurate results.

5 Structural risk preventive measures

To fundamentally prevent the occurrence of structural accidents, it is necessary to take safety measures based on the idea of "prevention first". In similar projects, corresponding measures can be adopted to prevent the occurrence of structural accidents.

5.1 Risk control measures for natural environment factors

There is a superimposed effect on the underwater tunnels originally from stratigraphic inhomogeneity, water level changes, as well as river erosion and deposition phenomenon. At first, water level changes and river erosion and deposition will possibly lead to the settlement or floating of tunnels. Due to the non-uniformity of the stratum, the settlement or floating conditions of each tunnel section is often non-uniform, which result in structural damage to the tunnels.

To prevent possible structural accidents, risk control methods are needed to leave the structural risk at the design and construction stage. Initially, adequate safety stocks should be reserved during the design process. In addition, monitoring and measurement should be strengthened to get real-time status of the tunnel. Once the uneven settlement is detected, measures such as bottom grouting should be used to correct the tunnel status in time.

5.2Risk control measures for tunnel performance factors

The improvement of the tunnel performance can also greatly reduce the possibility of structural accidents. During the construction phase, the segment waterproofing material needs to be properly installed. The adhesive should be applied evenly and fully, and the waterproof rubber strip and cork liner should be pasted flatly and firmly. In addition, the putty sheet should be firmly embedded with accurate position.

The cracks and leakage seriously endanger operation safety of the water-conveyance tunnel. In addition, if the tunnel is slated to enter service, it is almost impossible for staffs to enter the tunnel internal to inspect and repair.Thus, it is necessary to establish a groundwater level monitoring network system, regularly arrange real-time groundwater level observation based on hole drilling.Through comparing with groundwater level monitoring data and the data comes from internal water-pressure sensor, whether exists the leakage phenomenon in the tunnel can be clearly known.

5.3Risk control measures for water transportation factor

During the operation stage, the high-speed water flow will locally bypass and separate the unevenness of the tunnel surface, resulting in the reduction of localized pressure and causing cavitation phenomenon. Therefore, it is necessary to strictly control the degree of plainness of the tunnel surface. Besides, small conduit grouting and bolt reinforcement techniques can be applied in the construction stage to ensure a stable increase in tunnel lining stress under the condition of high-water pressure.

6 Conclusions

The main conclusions of this study are as follows:

- In this paper, a new evaluation system of the structural risk of operational underwater water-conveyance tunnels is established based on AHP and fuzzy comprehensive evaluation.
- Among the factors affecting the structural risk, the natural environmental factors hold a dominant position.Stratigraphic inhomogeneity and water level changes have the greatest impact on tunnel safety, which the weights are0.1400 and 0.1710, respectively.
- The established risk assessment system of structural risk of operational underwater water-conveyance tunnel is successfully applied to the Pearl River Delta Water Allocation Project. The consequent result is accordance with the practical condition which suggests that this approach is reliable and practical. This study provides references for other similar tunnel constructions.
- This paper uses the expert scoring method to analyse each qualitative or quantitative index, which exists a certain degree of subjectivity. Further risk research is needed to reduce subjectivity.

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