Sādhanā (2020)45:215
https://doi.org/10.1007/s12046-020-01370-w

A static risk assessment model for underwater shield tunnel construction

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MS received 9 November 2019; revised 10 February 2020; accepted 16 February 2020

Abstract. The shield method is widely used in underwater tunnel construction. However, the shield construction process faces many uncertain risk factors that increase the level of safety risk during shield tunnel construction. Therefore, risk assessment has become a necessary task in the early stages of tunnel construction. In this study, a new risk assessment model for underwater shield tunnel construction is proposed that combines a normal cloud model with an entropy weight method. The model contains 20 assessment indexes and gives the range of each index corresponding to different risk levels, which comprehensively reflects the influencing factors of risk. By using a normal cloud model, the fuzziness and randomness of risk assessment data are taken into account effectively, and the reliability of assessment results is increased. Based on an entropy weight method, the rules and characteristics of the evaluation data in the model are considered, and the weight coefficient of the evaluation index is determined to avoid the subjectivity of the expert weight method. The risk assessment model is applied using the Xiangjiang shield tunnel as an example. The results show that the overall construction risk level of the Xiangjiang tunnel is level II, which is consistent with the site risk situation and shows that the model can objectively and accurately evaluate the construction risk level of an underwater shield tunnel.

Keywords. Underwater shield tunnel; risk assessment; cloud model; entropy weight method; determination degree.

1. Introduction

With the ongoing construction and development of urban metro tunnels, river-crossing and sea-crossing traffic tunnels, water conservancy and hydropower tunnels and municipal utilities tunnels, many tunnels need to cross rivers to meet the needs of regional economic development. Many underwater tunnel projects have been successively built in this century. According to statistics, more than 20 underwater tunnels, including those used for subways and highways, have been planned in the Yangtze River basin in China. With the improvement of shield technology, shields have occupied a major position in world tunnel construction, especially in underwater tunnels [1]. While facing underwater tunnel engineering, the shield tunnelling method has become the preferred construction method for tunnel construction because of its advantages of high mechanization, fast tunnelling speed, low environmental impact and safe construction.

However, many uncertainties remain in the underwater tunnel construction process, even when adopting the highly mechanized shield tunnelling method. For example, an underwater tunnel project must address issues of abundant groundwater, complex underwater geological conditions and inadequate geological surveys, which make it difficult to grasp the conditions of the underwater soil layer. The depth of the tunnel will change constantly due to the impact of rivers, which will make it more difficult to set the face pressure of the shield tunnel. When the underwater construction equipment and shield machinery confront serious problems, the treatment process of underwater tunnelling will become more difficult than in general strata. These uncertain risk factors can become potential risk sources during the tunnel construction process and pose a threat to safety. Therefore, it is necessary to consider the uncertainty of risk and adopt a reasonable and reliable risk assessment method to determine the risk level of tunnel construction in the early stages of underwater shield tunnel construction.

Einstein *et al* [2] and Einstein [3] proposed risk analysis for tunnel engineering; accordingly, the risk assessment of underground engineering began to develop rapidly. In the early stage, Sturk *et al* [4], Bielecki [5], Stille *et al* [6], Isaksson *et al* [7], Reilly [8], and Choi *et al* [9] conducted a large number of studies on risk assessment for road tunnels, undersea tunnels, and subway tunnels and proposed methods for tunnelling

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Published online: 29 August 2020

risk assessment. These studies laid a theoretical foundation for tunnel construction risk assessment. By 2014, the International Tunneling Association promulgated "Guidelines for Tunneling Risk Management", which provides useful methods and suggestions for tunnel risk management. In addition, fuzzy mathematical methods (Alireza *et al* [10]; Li *et al* [11]; Hyun *et al* [12]), probability models (Olga *et al* [13]; Yu *et al* [14]), rough set theory (Zhang *et al* [15]), Bayesian networks (Wang *et al* [16]; Liu *et al* [17]; Sousa and Einstein, [18]), Monte Carlo simulations (Chung *et al* [19]; Rupura and Arratiam [20]; Min *et al* [21]) and artificial neural networks (Benardos and Kaliampakos [22]; Deng *et al* [23]) have been widely used in tunnel risk assessment. Although these model methods can better reflect the uncertainty of geological conditions and the high complexity of the construction process, they can also provide a quantitative analysis of construction risk. There are some defects in these methods, such as the subjectivity of determining weight and establishing a single factor judgement matrix in risk assessment by using a fuzzy analytic hierarchy process [23]. The probabilistic method has the advantage of describing the stochastic uncertainty of the risk assessment process, but it has some shortcomings in describing fuzzy uncertainty [24]. A Bayesian network requires a large amount of input information [13]. The artificial neural network method has the ability to learn from data but cannot explain the nature of the input-output mapping process [23]. It can be seen that there is still room for improvement in the risk assessment methods of tunnel construction.

Underwater shield tunnel construction is more risky than conventional stratum construction, and there are few risk assessment models of underwater shield tunnels in existing research. Therefore, this paper proposes an assessment model that can reflect the risk level of underwater shield tunnel construction by combining a normal cloud model and an entropy weight method. First, the model establishes an index system that can comprehensively reflect the risk factors of underwater shield tunnels and gives the range of each index under different risk levels. Then, the normal cloud model method is used to effectively take into account the stochastic and fuzzy uncertainties in the risk assessment process. By combining the normal cloud model with the entropy weight method and considering the regularity of the assessment data, the weight coefficient of the index is determined to avoid the subjectivity of the expert weighting method. Finally, the reliability of the model is verified by practical application analysis combined with engineering cases.

2. Risk assessment theory

2.1 *Cloud model*

A cloud model was proposed by Professor Li Yide in 1995. It is mainly used for the transformation of uncertainty between qualitative concepts and their quantitative representations. It is a mathematical tool for uncertainty analysis [25, 26].

2.1a *Cloud model conception*: The definition of the cloud model is as follows: Let U be a quantitative domain with precise numerical representation, and $X \subseteq U$, T are qualitative concepts in U space. If the affiliation degree of element x $(x \in X)$ to T is a random number with stable tendency, then the distribution of mapping of qualitative concept T from universe U to interval [0,1] in a number space is called a cloud:

$$C_T(x): U \to [0,\ 1] \quad \forall x \in X (X \subseteq U), \quad x \to C_T(x) \quad (1)$$

The cloud model represents a qualitative concept by expecting Expectation (*Ex*), Entropy (*En*) and Hyperentropy (*He*) and reflects the overall characteristics of qualitative concepts. There are many types of cloud models, including normal clouds, floating clouds, triangular clouds and trapezoidal clouds. The normal cloud model is a new model based on normal probability distribution and the Gaussian membership function, which has strong universality [26]. Figure 1 shows an example of a normal cloud model that uses expectations *Ex*, *En* and *He* to describe the overall characteristics of the concept "about 1 m". *Ex* represents the expectation of the spatial distribution of cloud droplets in the domain and represents the point of qualitative concept or the most typical sample of quantification of this concept. *En* can measure the ambiguity range and probability density of the qualitative concept comprehensively, reflecting the uncertainty of the qualitative concept. *He* is used to measure the uncertainty of entropy, reflecting the degree of dispersion of cloud droplets in the number domain.

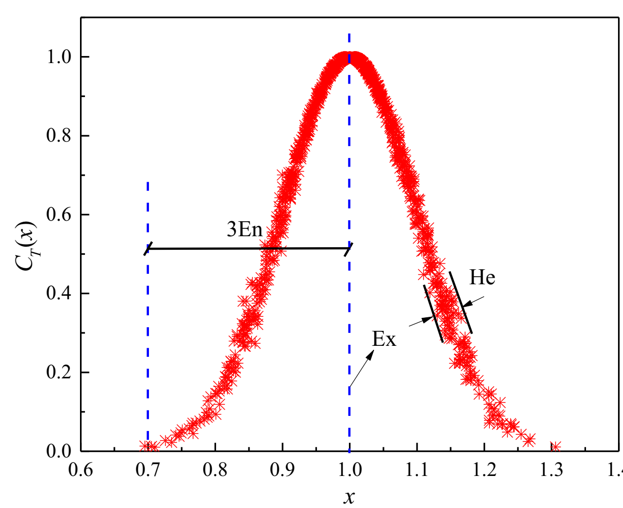

Figure 1. Cloud model of "about 1 m".

2.1b *Cloud generator*: The cloud generator is a specific algorithm for computing the cloud model, and it can be implemented by solidified integrated circuits. There are many kinds of cloud generators for normal cloud models. In this paper, forward cloud generators and reverse cloud generators are mainly used. Their algorithms are as follows.

Algorithm 1: Forward Cloud Generator (*Ex*, *En*, *He*, *N*)
A forward cloud generator is a mapping from qualitative concepts to quantitative values. It inputs three digital features of clouds (*Ex*, *En*, *He*) and the number of cloud droplets it wants to produce *N* and outputs the value of *N* cloud droplets and the cloud image composed of these cloud droplets. Figure 2 shows a diagram of a forward cloud generator.

The specific algorithms are as follows:

Input: Digital features (*Ex, En, He*), the number of cloud droplets generated *N*.

Output: *N* cloud droplets *x* and its certainty $C_T(x)$, so-called Drop (x_i, $C_T(x)$, i = 1, 2, …., *N*).

Step 1: Generate a normal random number E_n' (E_n is the expected value, and H_e is the standard deviation);

Step 2: Generate a normal random number *x* (E_x is the expected value, E_n' is the standard deviation, and *x* is a cloud droplet in the domain);

Step 3: Calculate $C_T(x) = e^{\frac{-(x-E_x)^2}{2(E_n')^2}}$ (*y* is the degree of certainty, when *x* belongs to the qualitative concept *C*);

Step 4: The above steps are repeated until *N* cloud droplets are generated.

Algorithm 2: X - Conditional Cloud Generator (*Ex, En, He,* x_0, *N*)

In the number field space of a given domain, if the three digital eigenvalues of the cloud (*Ex, En, He*) are known, the cloud generator implemented under the condition of $x = x_0$ is called the X-conditional cloud generator if the condition $x = x_0$ is set in the domain. All cloud droplets generated by the X-conditional cloud generator are distributed on the vertical line of $x = x_0$. Figure 3 shows a schematic diagram of the X-conditional cloud generator.

The specific algorithm steps are as follows:

Input: Digital eigenvalues (*Ex, En, He*), the number of cloud droplets *N* to be generated, and the specific value x_0.

Output: *N* cloud droplets corresponding to a specific value x_0 and their determinacy.

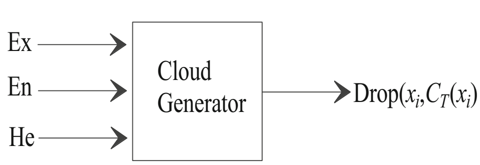

Figure 2. Forward Cloud Generator.

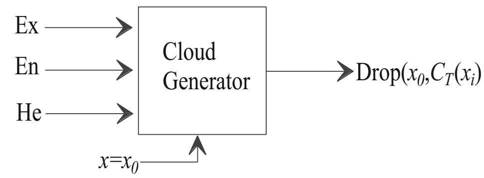

Figure 3. X-conditional cloud generator.

Step 1: Generate a normal random number $En' = NORM$ $(En,\ He^2)$ with *En* as the expected value and He^2 as the variance.

Step 2: Compute $C_T(x) = e^{\frac{-(x_0-E_x)^2}{2(E_n')^2}}$;

Step 3: Generate cloud droplets corresponding to *N* specific values x_0, namely, Drop (x_0,$C_T(x)$)

2.2 *Entropy weight method*

Entropy was initially a thermodynamic concept in physics. Then, information theory was introduced by Shannon, which was called "information entropy" [27]. Information entropy is a measure of system uncertainty, which reflects the amount of useful information provided by each index to the assessment results. The larger the entropy value is, the higher the uncertainty of the information and the smaller the utility value of the information; conversely, the smaller the entropy value is, the greater the utility value of the information.

The entropy weight method is an objective weighting method. The basic idea of the entropy weight method is to determine the weight of each index according to the degree of variation of each variable and then obtain the relative objective weight through revision. The entropy weight method enjoys the characteristics of wide applicability, high accuracy and strong objectivity, so it is widely used in engineering and economic fields. The algorithm of determining the weight by the method of entropy weight is as follows.

Assume there are *m* objects to be evaluated and *N* corresponding assessment indexes. The attribute value of each assessment index is r_{ij}, which represents the attribute value of the *j* index of the first assessment object. Thus, the judgement matrix $\boldsymbol{R} = (r_{ij})_{m\times n}$ can be established.

Step 1: Process the dimensionless data in the matrix $\boldsymbol{R} = (r_{ij})_{m\times n}$ to obtain the dimensionless matrix.

Step 2: Calculate the information entropy value of each index: the information entropy value of the index data in group *j* is S_j. $S_j = -(\ln m)^{-1}\sum_{i=1}^{m} k_{ij}\ln k_{ij}$, i = 1, 2, …, m; j = 1, 2, …, n, $k_{ij} = r_{ij}/\sum\limits_{i=1}^{m} r_{ij}$.

When $k_{ij} \le 0$, the result of the ln k_{ij} calculation is meaningless, and then $k_{ij} = \left(1 + r_{ij}\right)/\ \sum_{i=1}^{m}\left(1 + r_{ij}\right)$.

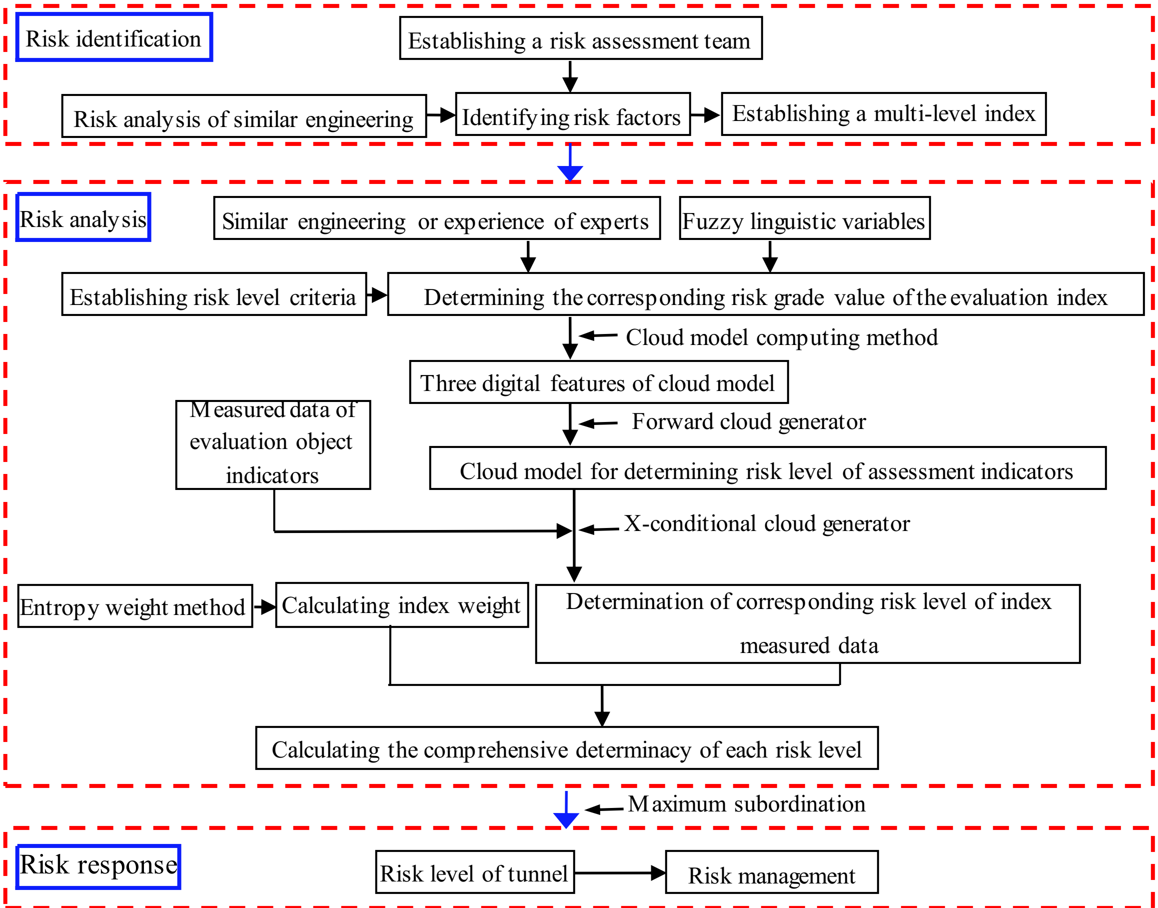

Figure 4. Risk assessment model.

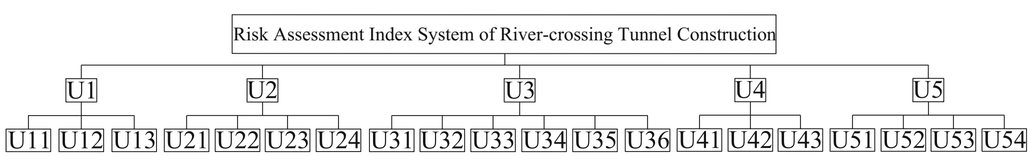

Figure 5. Risk assessment index system.

Table 1. Risk acceptance criteria.

Risk level	Description	Acceptance criteria	Risk response
Level I	Extremely high	Unacceptable	We must attach great importance to taking practical evasive measures and strengthening risk monitoring.
Level II	High	Not expected	Risk management measures must be taken to reduce risks and strengthen risk monitoring
Level III	Medium	Acceptable	Generally, risk management measures are not needed, but risk monitoring is needed.
Level IV	Low	Negligible	Risk management measures and risk monitoring are not required

Step 3: Calculating the index weight vector: $w = \{w_1, w_2, \ldots, w_n\}$, $w_j = \left(1 - S_j\right) \Big/ \sum_{j=1}^{n} (1-S_j)$, $0 \leq w_j \leq 1$, $\sum_{j=1}^{n} w_j = 1$.

3. Risk assessment model for shield tunnel construction across the river

3.1 *Assessment model*

The process of safety risk assessment in underwater shield tunnel construction is a relatively complex system that involves the construction of an assessment index system, the establishment of risk grade criteria, the determination of index weight and an uncertainty reasoning system. Based on the above risk assessment theory, this paper constructs a new comprehensive risk assessment model for the construction of an underwater shield tunnel project, as shown in figure 4.

3.2 *Assessment index system*

The primary task of risk assessment is to establish a risk assessment index system. The principles should follow the principles of scientificity, independence, completeness and hierarchy. Among them, the scientificity is mainly embodied in the rationality of index establishment and whether it can truly reflect the engineering situation. The independence is mainly manifested in the independence of each index. The completeness is mainly embodied in the index system, which can reflect the risk factors existing in each stage of the assessment object. The hierarchy mainly refers to the hierarchical relationship between the indicators.

An underwater shield tunnel project is a systematic and complex construction process, and there are many factors affecting its safe construction. According to statistics on the causes of safety accidents in the construction of underwater shield tunnels and the environment faced by actual engineering, these factors can be summarized as hydrogeological factors, river factors, tunnel design factors, external environmental factors and construction management factors. According to the establishment principle of the index, these influencing factors are initially taken as the first level index, and then, the factors closely related to the first level are listed in the second level. For example, the tunnel design factors can be further decomposed into the tunnel diameter, average buried depth, minimum buried depth and maximum longitudinal slope. Figure 5 shows a system chart of the safety risk assessment index for the construction of an underwater shield tunnel. There are 20 indexes in the second layer.

Table 2. Scope of each index of river factors.

Risk level	U11/m	U12/%	U13/m
Level I	30～50	10～20	1000～2000
Level II	20～30	6～10	500～1000
Level III	10～20	1～6	100～500
Level IV	0～10	0～1	0～100

U1: River factors
U11: River water level depth
U12: Average river slope
U13: River width
U2: Tunnel design factors
U21: Diameter size
U22: Average burial depth
U23: Minimum burial depth
U24: Maximum longitudinal slope
U3: Hydrogeological factors
U31: Thickness of soft soil
U32: Void development
U33: Spacing between voids and tunnel floor
U34: Degree of fracture water development
U35: Stratigraphic complexity
U36: Stratigraphic stability
U4: External environmental factors
U41: Continuous rainfall days
U42: Crossing underground pipelines
U43: Crossing structures
U5: Construction management factors
U51: Construction experience of construction units (quantity of similar engineering)
U52: Rationality of construction scheme
U53: Personnel safety education level
U54: Safety management level.

3.3 *Risk acceptance criteria*

There are many methods used to classify the risk level of tunnel construction, such as three-level classification, four-level classification and five-level classification, among which five-level classification is developed on the basis of four-level classification. On the basis of these existing risk classification methods, considering the wide application of the four-level classification method, the construction risk level of the underwater shield tunnel is divided into four levels, i.e., level I, II, III and IV, in which level I represents extremely high risk, level II represents high risk, level III represents medium risk, and level IV represents low risk. The meaning of risk acceptance criteria at all levels is shown in table 1.

Table 3. Quantitative range of indicators of tunnel design factors.

Risk level	U21/m	U22/m	U23/m	U24/%
Level I	15∼20	5∼15	2∼10	4∼5
Level II	10∼15	15∼25	10∼15	3∼4
Level III	6∼10	25∼35	15∼30	2∼3
Level IV	3∼6	35-50	30∼50	0∼2

3.4 *Assessment indicators corresponding to risk level quantity value*

The assessment indicators correspond to the assessment criteria of different risk levels. Some can be quantified by precise numerical values, and some can be described by fuzzy linguistic variables. Among them, the exact values are obtained by similar engineering project investigations or consultations with construction and design experts, while the fuzzy language variables are mainly used to express indicators that cannot be quantified by numerical values. Tables 2 to 6 give the quantities or vague linguistic descriptions of each index at different risk levels.

The units of various indicators in tables 2 to 7 are not uniform, so it is necessary to address them in a dimensionless manner. In this paper, the min-max standardization method is used to address index units in a dimensionless way. Its definition is as follows.

The larger the mathematical value is, the more advantageous the index is, and the expression is

$$x' = \frac{x_{ij} - x_{i\,\min}}{x_{i\,\max} - x_{i\,\min}} \tag{2}$$

The smaller the mathematical value is, the more advantageous the index is, and the expression is

$$x' = \frac{x_{i\,\max} - x_{ij}}{x_{i\,\max} - x_{i\,\min}} \tag{3}$$

x' denotes standardized data, X_{ij} denotes raw data, and x_{imax} and x_{imin} denote the maximum and minimum values of line i data, respectively.

For the discrete index described by fuzzy linguistic variables in tables 2 to 6, according to the degree of its impact on construction safety, the fuzzy interval number method is used to assign the corresponding values. Interval number can retain the fuzziness of data, which is one of the best methods to quantify fuzzy language variable. Tables 7 to 11 show the results of dimensionless treatment of each index.

3.5 *Cloud model for determining the risk level of assessment indicators*

To analyse the risk uncertainty, we need to transform the dimensionless processing results of different risk levels into the three digital features of the corresponding cloud model

Table 4. Scope of each index of hydrogeological factors.

Risk level	U31/m	U32	U33/m	U34	U35	U36
Level I	16∼30	The cavities are well developed, located under or on the side of the tunnel, and the diameter of the cavities is larger than the diameter of the tunnel	Inside tunnel	Extremely high	There are large-scale upper soft and lower hard, strong permeability and high viscous strata.	Extremely bad
Level II	8∼16	The cavities are well developed and located below the tunnel, and the diameter of the cavities is larger than that of the tunnel	0∼5	High	There are upper soft and lower hard and strong permeable strata in some places	Bad
Level III	4∼8	The cavities is generally developed, located under the tunnel, and its diameter is smaller than the tunnel diameter.	5∼10	General	Moderate stratum homogeneity	Good
Level IV	0∼4	Cavities are undeveloped and smaller in diameter.	>10	Non development	Excellent conditions of each stratum	Excellent

Table 5. Measurement range of indicators of external environmental factors.

Risk level	U41/d	U42	U43
Level I	24 ~ 32	Mass crossing	Mass crossing
Level II	16 ~ 24	General crossing	General crossing
Level III	8 ~ 16	Small crossing	Small crossing
Level IV	0 ~ 8	No crossing	No crossing

(*Ex, En, He*) according to the assessment indicators. The calculation methods of cloud digital eigenvalues are as follows:

$$E_x^p = \frac{M_p + N_p}{2}, \quad (p = 1, 2, \ldots, n) \tag{4}$$

$$E_n^p = \begin{cases} \dfrac{E_x^2 - E_x^1}{3} & p = 1 \\ \dfrac{E_x^p - E_x^{p-1}}{3} & p \geq 2 \end{cases}, \quad (p = 1, 2, \ldots, n) \tag{5}$$

$$H_e = \beta \tag{6}$$

E_x^p *and* E_n^p are the expectation and entropy of the cloud corresponding to the *P-Level* risk, respectively; *He* is the superentropy of the cloud; *P* is the risk level classified in the risk acceptance criterion; M_p and N_p are the boundary values of the assessment index corresponding to the *P-Level* risk; *c* is a constant; and hyper-entropy *He* can reflect the thickness of the cloud droplets. To consider the "atomization" degree and stability of the cloud model, the mathematical value of β is 0.005, and the value of *He* in this paper must be consistent [24, 28].

For single boundary variables, such as $(-\infty, C_{max}]$ or $[C_{min}, +\infty)$, the default boundary parameters or expected values can be determined according to the upper or lower limit of the assessment data, and then the cloud characteristic parameters can be calculated according to Eqs. (4) to (6).

Taking the shield diameter index U21 as an example, this paper calculates the digital characteristics of the U21 cloud model in different grades using Eqs. (4) to (6). The results are as follows: level I (0.145, 0.098, 0.005), level II (0.440, 0.098, 0.005), level III (0.705, 0.088, 0.005), and level IV (0.91, 0.068, 0.005). Based on the cloud model parameters, the forward cloud generator algorithm is used to generate the corresponding cloud model, as shown in figure 6.

3.6 *Weight determination of assessment index*

Determining the weight of each assessment index is the core issue in the risk assessment process and the key to the accuracy of the assessment model. The traditional expert experience method has strong subjectivity in determining the weight of indicators. In many cases, different experts obtain different weight results, which will lead to a large deviation in assessment results. The importance of the law of data itself is superior to the experience of experts. Therefore, the determination of weights should take into account the law and characteristics of data itself on the basis of on-site investigation and empower each index scientifically. The entropy weight method is an objective weighting method that can consider the law of data itself. This method has strong objectivity, wide application and high accuracy. Therefore, this method is used to calculate the weights of assessment indicators. The specific algorithm is shown in section 2.2 of this paper.

3.7 *Membership degree of the corresponding risk level of actual indicator data*

Through actual measurement, construction data statistics and expert assessment and consultation, the actual data of each assessment index needed to evaluate the tunnel are obtained. Then, according to the cloud model of the corresponding risk level of the assessment index determined in section 3.5 of this paper, using the X-conditional cloud generator algorithm (section 2.1b of this paper), the determination degree $\mu_{p,ij}$ of the measured data of each index corresponding to each risk level is obtained.

3.8 *Calculating the comprehensive determinability of risk levels*

Comprehensive determinacy is a parameter associated with measurement results, which is used to characterize the degree of membership of measured data. In this paper, according to the measured data of each index, this model corresponds to the certainty of each risk level $\mu_{p,ij}$ and the calculation result of the weight coefficient of the assessment index. Then, using the weighted summation method to calculate the comprehensive certainty of each risk level, the formula for calculating the comprehensive degree of certainty $U_{p,i}$ is as follows:

$$U_{p,i} = \sum_{j=1}^{m} \mu_{p,ij} \lambda_j, \; (p = 1, 2, \ldots, 4; j = 1, 2, \ldots, 4) \tag{7}$$

$U_{p,i}$ are the synthetical determinant values of *i*-sample corresponding to the *p*-level risk; $\mu_{p,ij}$ is the certainty of the *p*-level risk corresponding to the assessment index *j* of *i*-sample; and λ_j is the synthetical weight coefficient of the assessment index.

According to the calculation results of the comprehensive certainty of each risk level and the principle of maximum membership, the risk level corresponding to the maximum value of the comprehensive certainty is determined as the safety risk level of tunnel construction. The formula is as follows:

Table 6. Scope of indicators of construction management factors.

Risk level	U51/term	U52	U53	U54
Level I	0～1	Extremely unreasonable	Extremely bad	Extremely bad
Level II	1～3	Unreasonable	Bad	Bad
Level III	3～6	Generally reasonable	General	General
Level IV	6～10	Reasonable	Good	Good

Table 7. The range of dimensionless measurement values of each index of river factors.

Risk level	U11	U12	U13
Level I	0～0.4	0～0.5	0～0.5
Level II	0.4～0.6	0.5～0.7	0.5～0.75
Level III	0.6～0.8	0.7～0.95	0.75～0.95
Level IV	0.8～1	0.95～1	0.95～1

Table 8. The range of dimensionless measurement values of each index of tunnel design factors.

Risk level	U21	U22	U23	U24
Level I	0～0.29	0～0.22	0～0.17	0～0.2
Level II	0.29～0.59	0.22～0.44	0.17～0.27	0.2～0.4
Level III	0.59～0.82	0.44～0.67	0.27～0.58	0.4～0.6
Level IV	0.82～1	0.67-1	0.58～1	0.6～1

Table 9. The range of dimensionless measurement values of each index of hydrogeological factors.

Risk level	U31	U32	U33	U34	U35	U36
Level I	0～0.47	0～0.3	0～0.25	0～0.3	0～0.3	0～0.3
Level II	0.47～0.73	0.3～0.6	0.25～0.5	0.3～0.6	0.3～0.6	0.3～0.6
Level III	0.73～0.87	0.6～0.8	0.5～0.75	0.6～0.8	0.6～0.8	0.6～0.8
Level IV	0.87～1	0.8～1.0	0.75～1	0.8～1.0	0.8～1.0	0.8～1.0

$$p = \max\{U_{1,i}, U_{2,i}, \ldots, U_{p,i}\} \tag{8}$$

4. Engineering cases

Using the Hejiangtao Xiangjiang Tunnel as an example, the application of the risk assessment model proposed in this paper in the construction safety assessment of underwater shield tunnels is verified.

Table 10. The range of dimensionless measurement values of each index of external environmental factors.

Risk level	U41	U42	U43
Level I	0～0.25	0～0.3	0～0.3
Level II	0.25～0.5	0.3～0.6	0.3～0.6
Level III	0.5～0.75	0.6～0.8	0.6～0.8
Level IV	0.75～1	0.8～1.0	0.8～1.0

Table 11. The range of dimensionless measurement values of each index of construction management factors.

Risk level	U51	U52	U53	U54
Level I	0～0.1	0～0.3	0～0.3	0～0.3
Level II	0.1～0.3	0.3～0.6	0.3～0.6	0.3～0.6
Level III	0.3～0.6	0.6～0.8	0.6～0.8	0.6～0.8
Level IV	0.6～1	0.8～1.0	0.8～1.0	0.8～1.0

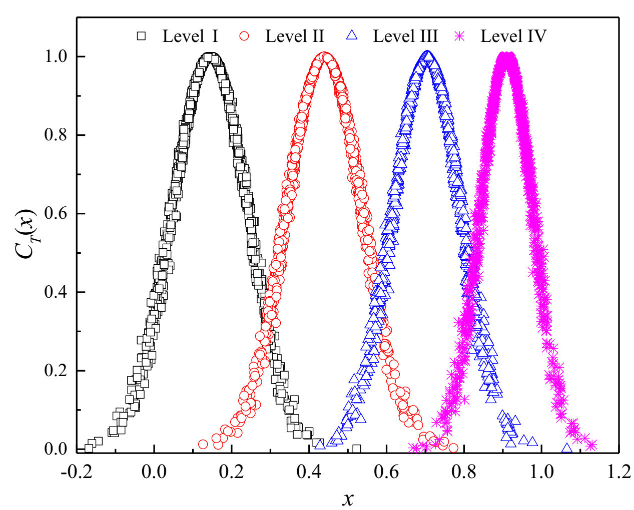

Figure 6. Cloud models of different levels for U21.

4.1 *Project overview*

The Hejiangtao Xiangjiang Tunnel, located north of Hengyang City and the three water inlets of Xiangshui, Leishui and Zhengshui, is one of the most important underwater channels in Hengyang. The shield tunnelling method is used in the cross-river section of the Hejiangtao Xiangjiang Tunnel. The shield tunnelling diameter is 11.81 m. The

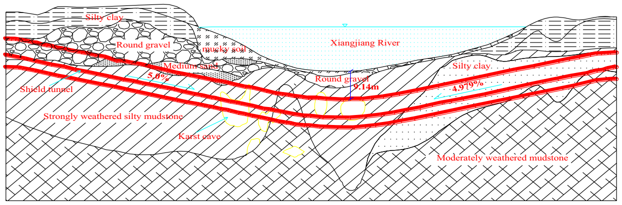

Figure 7. Geological section of the Hejiangtao Tunnel.

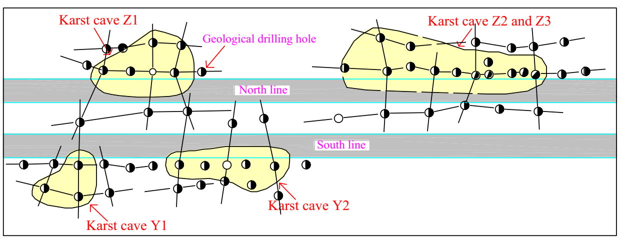

Figure 8. Distribution of local karst cavities in the Hejiangtao tunnel.

shield tunnel is divided into North and South lines crossing the Xiangjiang River. The North line is 935 m long, the South line is 932 m long, the width of the riverbed is 610 m, the average water level is 14.0 m, and the average slope of the river is 0.28‰. The average depth of the tunnel is 13.8 m, the thickness of the covering soil at the lowest point of the tunnel is 9.14 m, and the maximum longitudinal slope of the tunnel is 5%. Figure 7 shows the geological profile of the North line of the Hejiangtao Xiangjiang Tunnel.

According to the geological survey report, the whole rock stratum of the tunnel is stable, but there is silty soft soil in some areas with an average thickness of 2.76 m. The tunnel part is located in the conglomerate stratum, and the permeability of this kind of stratum is strong. The weathering fissures of rocks are well developed, and the development degree of fissure in rocks is high. There are karst cavities around the shield tunnel, the size of the cavities is different, and the development is irregular. The results of the geological survey show that the height of the cavities ranges from 0.6 to 11.6 m; 15 cavities are located inside the tunnel, with 11 cavities between 0 and 5 m and 5 cavities between 5 and 10 m. These cavities have a great influence on the stability of the tunnel. The development position of karst cavities around the tunnel is shown in figure 8.

Experts were organized to review the construction experience, construction scheme, safety management measures and personnel safety education level of the construction firm used in the project. The results show that the construction firm was founded in 1953 and is ranked among world's top 500. It has extensive experience, a reasonable construction scheme and a good safety management level. It employs different construction operators, technicians and safety managers. The three-level safety education adopted has a good level of education.

4.2 *Statistical results of the data of risk assessment indicators*

By reviewing the design scheme, construction scheme, geological exploration data and hydrological historical data of the Xiangjiang shield tunnel, the actual data of the risk assessment indicators of the tunnel, the measured data results of the indicators and dimensionless processing (calculated according to Eqs. (2) and (3)), and the dimensionless results of the discrete indicators are calculated according to the median value of the fuzzy interval number. The statistical results of the risk data are shown in table 12.

4.3 *Calculation results of weights of assessment indicators*

According to the actual data of risk assessment indicators in table 12 and the results of dimensionless processing, the weight coefficients of each assessment index are determined by using the weighting method in section 2.2 of this paper. The weights of each index are calculated in the last column of table 12.

4.4 *Determination degree of the corresponding risk grade for measured data of indicators*

The dimensionless results of the measured data of each assessment index of tunnel construction safety risk are combined in table 12. Then, according to the corresponding risk level cloud model of the assessment index determined in section 3.5 of this paper, using the X-conditional cloud generator algorithm (section 2.1b of this paper), the determination degree $\mu_{p,ij}$ of each index corresponding to each risk level is obtained. Taking the size of the tunnel diameter U21 index as an example, the digital characteristics of the U21 cloud model are combined at different levels, i.e., level I (0.145, 0.098, 0.005), level II (0.440, 0.098, 0.005), level III (0.705, 0.088, 0.005), and level IV (0.91, 0.068, 0.005), using the X-conditional cloud generator algorithm to generate the corresponding conditional cloud model, as shown in figure 9. The U21 corresponding to the degree of determination of each risk grade $\mu_{p,ij}$ is level I (0.0303), level II (0.9534), level III (0.0028), and level IV (0). The calculated results of the determination degree of each risk level corresponding to the measured data of each index are shown in table 13.

Table 12. Risk data statistics of the Xiangjiang shield tunnel.

Risk index	Measured data	Dimensionless processing results	Weight coefficient
U11	14.00/m	0.75	0.0337
U12	0.28/‰	1.00	0.0054
U13	610.00/m	0.70	0.0235
U21	11.81/m	0.41	0.0818
U22	13.80/m	0.28	0.0741
U23	9.14/m	0.18	0.0923
U24	5.00/%	0.00	0.0824
U31	2.76/m	0.91	0.0391
U32	The cavity is relatively developed and located under the tunnel	0.45	0.0954
U33	Located in the tunnel	0.13	0.0917
U34	High	0.45	0.0647
U35	Strong permeable stratum in some places	0.45	0.0354
U36	Good	0.70	0.0546
U41	18.00/d	0.44	0.0137
U42	Small crossing	0.70	0.0259
U43	No crossing	0.90	0.0234
U51	>10.00/item	1.00	0.0309
U52	Reasonable	0.90	0.0598
U53	Good	0.90	0.0364
U54	Good	0.90	0.0357

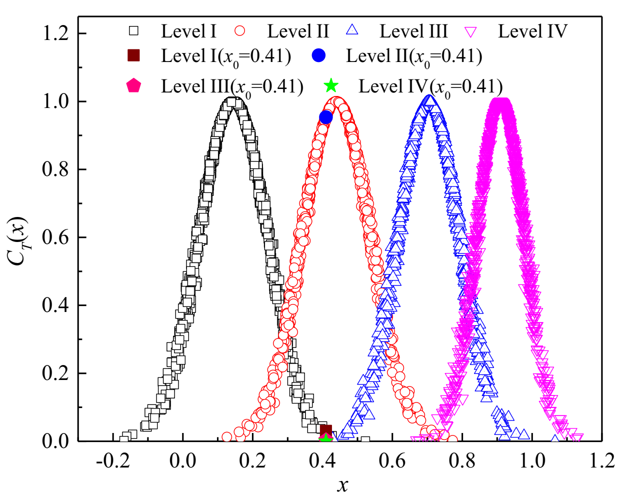

Figure 9. Conditional cloud models of different levels for U21 ($x_0 = 0.41$).

Table 13. The certainty of each risk level corresponding to the measured data of each index.

Risk index	Level I	Level II	Level III	Level IV
U11	0.1329	0.6708	0.0001	0.0000
U12/‰	0.3749	0.2864	0.0000	0.0000
U13/m	0.4340	0.2824	0.0000	0.0000
U21/m	0.0303	0.9534	0.0028	0.0000
U22/m	0.0006	0.4526	0.1682	0.0000
U23/m	0.0000	0.0000	0.9789	0.0078
U24/%	0.0000	0.3111	0.3616	0.0002
U31/m	0.3584	0.2773	0.0000	0.0000
U32	0.0202	0.9143	0.0027	0.0000
U33/m	0.0027	0.9014	0.0405	0.0000
U34	0.2260	0.9238	0.0024	0.0000
U35	0.0329	0.9036	0.0041	0.0000
U36	0.0398	0.9213	0.0011	0.0000
U41/d	0.0121	0.9156	0.0335	0.0000
U42	0.0322	0.9233	0.0022	0.0000
U43	0.0269	0.9017	0.0070	0.0000
U51/item	0.0000	0.0000	0.8964	0.0044
U52	0.0385	0.9203	0.0037	0.0000
U53	0.0339	0.9315	0.0010	0.0000
U54	0.0265	0.9166	0.0074	0.0000
U42	0.0584	0.6699	0.1661	0.0009

4.5 *Computational results of comprehensive determinacy for each risk level*

According to the actual measurement data of each indicator in table 13 corresponding to the certainty of each risk level $\mu_{p,ij}$ and the calculation results of the weight coefficient of each indicator in table 12, the comprehensive certainty of each risk level is calculated by Eq. (7). The calculation results of the certainty of each risk level are shown in the last row of table 13.

Combined with Eq. (8), the risk level corresponding to the maximum comprehensive determinacy is calculated. The calculation results show that the safety risk level of shield tunnel construction is level II, and the comprehensive determinacy is 0.6699. According to the risk acceptance criteria in table 1, the construction risk of the tunnel is undesirable. Risk management measures must be taken to reduce the risk and strengthen risk monitoring.

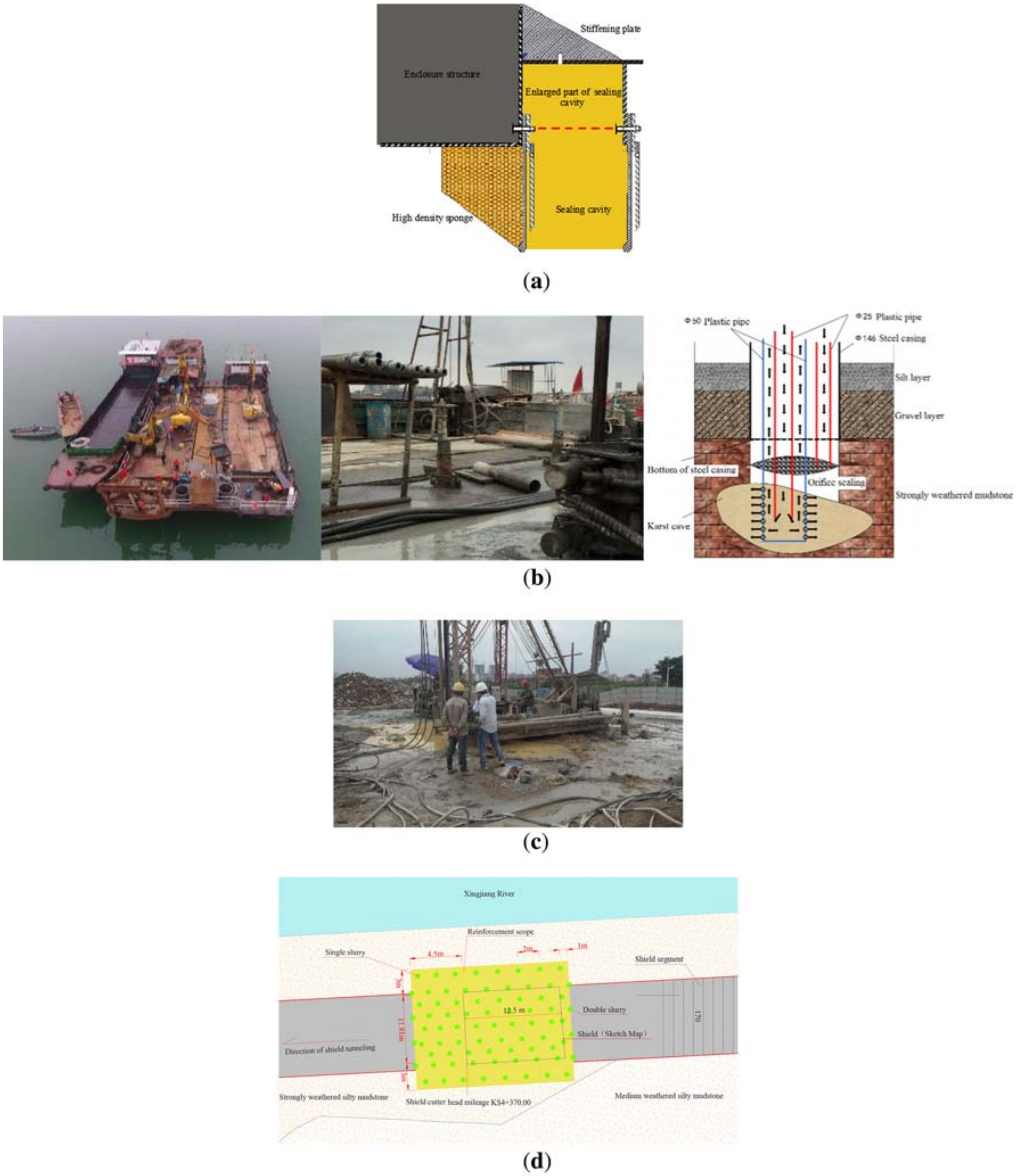

Figure 10. Construction risk control measures of Hejiangtao Xiangjiang Tunnel: (**a**) starting and sealing method of a large slope shield, (**b**) cyclic static pressure grouting reinforcement technology, (**c**) reinforcement site of river levee by jet grouting pile and (**d**) grouting reinforcement at the position of shield machine tool change.

5. Discussion

(1) The evaluation model is adopted before the construction of the Hejiangtao Xiangjiang Tunnel, and according to the corresponding risk acceptance criteria, the corresponding risk control measures are used as the key risk factors of shield tunnelling with large slope, karst cavern area, river embankment crossing, tool change with pressure in fractured stratum with strong permeability and shield disturbance. For example, in the initial excavation of large slope shield tunnelling, double-folded blade-type turning plate + double-curtain rubber plate + slurry agent + high density sponge cushion are used for sealing, as shown in figure 10(a). The karst cavern area in the tunnel is treated by cyclic static pressure grouting reinforcement technology, as shown in figure 10(b). In the process of

crossing the embankment, the waterproof curtain is first used to treat the embankment. According to geological conditions, three-pipe rotary jet grouting piles with a single row diameter of 1000 mm (the reinforcement spacing of rotary jet grouting piles is 0.75 m, occlusion is 0.25 m) are selected for anti-seepage treatment. The area of plane reinforcement is 25 m outside the tunnel structure line, and the depth of reinforcement is more than 1.5 m into a strong weathered rock layer. The scene processing photos are shown in figure 10(c). The cutter changing position of the shield machine is located in the rock breaking area with strong permeability. To ensure the safety and stability of the cutter changing operation of the shield machine, the stratum at the cutter changing position is reinforced by grouting, as shown in figure 10(d); the prediction of shield disturbance risk is verified by numerical calculation software. After the completion of the tunnel, there are no unacceptable and unexpected risk events, such as water inrush, mud inrush, face instability, shield machine collapse in the karst area, riverbank collapse or excessive stratum settlement, and only a few small risk events are evident. Therefore, the actual situation of the site coincides with the evaluation results, which also verifies the correctness of the risk assessment model for underwater shield tunnel construction proposed in this paper.

(2) The cloud model overcomes the shortcomings of "hard computing" in probability theory and mathematical statistics when studying the uncertainty of spatial data. The membership function of fuzzy sets is inherently incomplete. The cloud model absorbs the advantages of natural language. It can take randomness and fuzziness into account in spatial data mining and establish the mapping relationship between the qualitative concept expressed by the linguistic value and its quantitative expression. This makes the uncertainty of risk level assessment of underwater tunnel construction solvable.

(3) The assessment index system should be further studied, and more risk factors under specific conditions, as well as construction cost and efficiency factors, should be considered, and the quantitative scope of indicators should be studied under different risk levels to avoid more subjective factors.

6. Conclusion

(1) From the five aspects of river factors, tunnel design factors, hydrogeological factors, external environmental factors and construction management factors affecting the construction safety of underwater shield tunnels, twenty assessment indicators are proposed. The construction risk of underwater shield tunnels is evaluated comprehensively, and the quantitative range of each assessment index corresponding to different risk levels is given, which reflects the comprehensiveness of the selected indicators.

(2) Based on the cloud model and entropy weight method, a new comprehensive risk assessment model for underwater shield tunnel construction is constructed. The cloud model can unify the uncertain linguistic values and precise values and realize the natural conversion between qualitative linguistic values and quantitative values. Considering the laws and characteristics of the data, the weight coefficients of each assessment index are determined based on the entropy weighting method, which avoids the subjectivity of the expert weighting method.

(3) The results of the risk assessment model in this paper are consistent with the risk situation of site engineering, which shows that the model can objectively and accurately evaluate the risk level of underwater shield tunnel construction. The risk assessment model is suitable for the construction of shield tunnel crossing the river, and can be used as a reference for other types of underwater shield tunnel construction.

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