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Risk Assessment of Immersed Tube Tunnel Construction

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Abstract: Due to the complexity of risk factors in constructing immersed tube tunnels, it is impossible to accurately identify risks. To solve this problem, and the uncertainty and fuzziness of risk factors, a risk assessment method for immersed tube tunnel construction was proposed based on WBS-RBS (Work Breakdown Structure-Risk Breakdown Structure), improved AHP (analytic hierarchy process), and cloud model theory. WBS-RBS was used to analyze the risk factors of immersed tube tunnel construction from the aspects of the construction process and 4M1E, and built a more comprehensive and accurate construction risk index system. The weight of each index was calculated by the improved AHP of a genetic algorithm. The cloud model theory was used to build the cloud map of risk assessment for immersed tunnel construction and evaluate construction risk. Taking the Dalian Bay subsea tunnel project as an example, the risk assessment method of immersed tunnel construction was verified. The results showed that this method not only solved the problem of failing the consistency check in the higher-order judgment matrix but also improved the consistency pass rate by 33.3% and accurately reflected the risk assessment results. The assessment results show that the construction risk level of the Dalian Bay submarine-immersed tunnel is medium. The risk level of indicators "slope instability" and "water-stop damage" are high risk, while "pipe section cracking", "low underwater alignment accuracy", "uneven crimping of a water-stop", and "uneven substrate treatment" are medium risk. This provides a reference for the risk assessment study of immersed tunnel construction.

Keywords: tunnel construction by immersed tube method; analytic hierarchy process; genetic algorithm; cloud model theory; risk assessment; risk control

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1. Introduction

In recent years, with the gradual rise of subsea tunnel construction, subsea tunnel construction projects are increasing. The number of subsea tunnel projects built by immersed tube method has increased significantly. Compared with other construction methods, the immersed tube method has greater difficulties in construction technology, higher requirements for construction technology, and accurate requirements for the construction monitoring system. These difficulties will cause more potential risks during the construction period and have a huge impact on the safe construction of the tunnel project [1–3]. Therefore, it is significant to carry out a risk assessment of immersed tube tunnel construction and control the risk factors.

For the research on risk assessment of immersed tube tunnel construction, most scholars have studied some procedures and conducted special risk assessments of the risk factors. Bauduin et al. evaluated the risks of partition construction and dredging in the newly built immersed tube tunnel and proposed new methods in the construction monitoring system [4]. Based on the characteristics of different pore pressures, Wu, K et al. adopted the two-dimensional finite element method to evaluate the collapse risk of the immersed pipe foundation trench slope under different pore pressures and found that the load on the top of the pipe section is the main risk [5]. Wu, M. used the finite element software ANSYS to treat the structure as an elastic–plastic model to evaluate the structural stability risk during construction and concluded that water level and wave are risk factors [6].

Some scholars have conducted risk assessments on the prefabrication and sinking stages of pipe sections in the construction project of immersed pipe and conducted an in-depth analysis of risk factors [7–9]. However, most special risk assessments only analyze the risks in a certain process, taking each process as independent without considering the links between processes, resulting in the cross or omission of risk identification results and lack of accuracy of risk assessment.

The construction of a subsea immersed tube tunnel is affected by a wide range of factors involving the entire construction cycle. It is necessary to comprehensively consider the construction risks to ensure the safety of the construction [10–12]. Wei, G. et al. conducted risk research on the main construction process of the immersed pipe method, analyzed the risks in each stage, and summarized the possible problems in the floating and sinking stages of the pipe section [13]. Huang, Z. et al. used the analytic hierarchy process and fault tree analysis to evaluate the risk of immersed tube tunnel construction. The results showed that the risk of immersed tube prefabrication, pipe section sinking and connection, pipe joint floating, and the final joint stage was high [14]. Some progress has been made in research of the comprehensive assessment of the construction risk of the subsea immersed tunnel. Still, most scholars use the expert survey method, fuzzy comprehensive analysis method, risk matrix method, and other relatively simple methods for assessment. These methods lack the consideration of the fuzziness and uncertainty of the tunnel construction risk, resulting in a limitation of the construction risk assessment results.

Based on the present situation of the research on the construction risk of immersed tube tunnels, the existing problems in the current research are analyzed. Because the cloud model is used to assess the risk of immersed tube tunnel construction, the subjective scoring situation can be converted into the cloud model parameters to avoid the deviation caused by subjectivity. Moreover, the cloud can represent the corresponding assessment set and value and accurately express the advantage of the ambiguity and uncertainty of the risk. Based on constructing a complete risk assessment system for immersed tube tunnel construction, the cloud model method and AHP-GA were used to assess the risk of immersed tube tunnel construction, and the method was studied. It was expected to put forward a new method for the risk assessment of immersed tunnel construction. This method can simplify and decompose the project and accurately quantify and scientifically analyze the indicators.

2. Theoretical Model

First, establish the risk assessment index system for immersed tube tunnel construction, then use the improved AHP based on a genetic algorithm to calculate the weight, and use the cloud model to build the risk assessment model. The risk assessment process is shown in Figure 1.

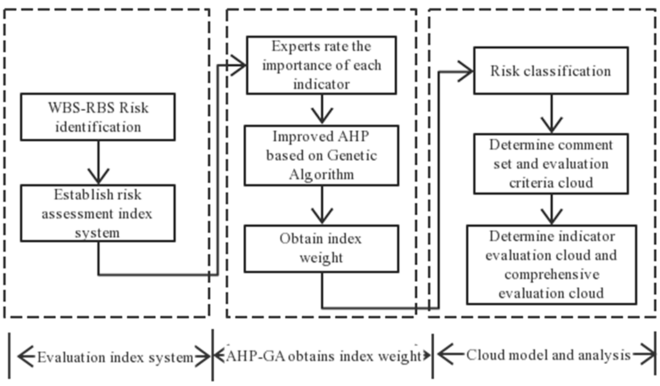


Figure 1. Flow chart of risk assessment for immersed tube tunnel construction.

(1) Establishing a risk assessment index system: To solve the problems of crossing and omission of risk factors in the process of risk factor identification of large and complex projects, and to comprehensively and accurately analyze the risk factors of immersed tube tunnel construction, WBS-RBS was proposed to identify risk factors, and the risk assessment index system was constructed according to the SMART principle. The SMART principle must be followed when constructing the risk assessment indicator system. Based on the characteristics of immersed tube tunnel construction, SMART principles are identified as simplicity, monolithically, attainable, remarkable, and tangible. When constructing the evaluation index system, according to the SMART principle, the selected indicators need to be concise and representative. The indicators can form a complete system that better reflect the actual situation of immersed tunnel construction and play an important role in risk assessment.

(2) Determining the index weight with the improved AHP: In order to obtain more accurate risk assessment results of immersed tube tunnel construction, it is necessary to improve the accuracy of the construction comprehensive risk assessment method to accurately calculate the weight of various risk factors in a comprehensive assessment. AHP can better deal with complex and fuzzy problems and reasonably combine qualitative with quantitative analysis. However, in the process of analysis with AHP, for a higher-order judgment matrix, the consistency test may fail, so relevant algorithms need to be used to correct the judgment matrix. Therefore, a genetic algorithm (GA) was proposed to improve AHP, and the improved method can get more satisfactory matrix consistency test results and more accurate index weight values. It lays a foundation for comprehensive risk assessment of immersed tube tunnel construction.

(3) Building a risk assessment model and conducting risk assessment: In the study of risk assessment of existing immersed tunnel construction, there is a problem in that the fuzziness and uncertainty characteristics of construction risk are not considered, resulting in inaccurate risk assessment results. A construction risk assessment method based on the cloud model is proposed. This is because the cloud model method can transform cloud model parameters and cloud droplets of various factors into each other through a cloud generator, realize the transformation between quantitative values and qualitative concepts, and reflect the ambiguity and uncertainty of various risk factors through entropy and super-entropy. The cloud model method is to use the cloud generator to transform the cloud model parameters of factors and cloud droplets (cloud model parameters include expected value, entropy, and hyper-entropy) to obtain a cloud image composed of numerous cloud droplets, where each cloud droplet represents a random realization of qualitative concepts, to clearly observe the fuzziness and uncertainty of factors through the cloud image. (In the cloud model, entropy represents the measurable degree of qualitative concepts.)

2.1. Construction of Evaluation Index System

The construction project of immersed tube tunnel is complicated, and there are many risk factors in the construction process. To identify construction risk factors carefully and accurately, the WBS-RBS was adopted to simplify and decompose complex projects, mainly from the six key construction processes of the immersed tube method and the five aspects of 4M1E (man, machine, material, method, and environments). At the same time, according to the “Design and Construction Manual of an immersed tube tunnel” and “Immersed tube tunnel construction and quality acceptance Code” and other relevant standards of immersed tube tunnel construction analysis, the main risk factors were screened by an expert survey [15,16]. A network questionnaire survey was used to improve the risk assessment index system, and the credibility and reliability of the index factor screening results were verified [17,18]. In this questionnaire survey, 126 questionnaires were issued, 109 were recovered, and 96 questionnaires with complete and effective information were selected after removing the incomplete information about the objects and the non-objective scoring.

The Alpha coefficient values of the questionnaire were all higher than 0.8, the KMO sample measure values were all greater than 0.7, and the significance of the Bartlett sphericity test was less than 0.001. These results indicate that in each stage of the construction of the sunk tube method, the data of the risk factor questionnaire statistical table is highly reliable and effective, and the questionnaire is reasonable.

Studying the risk of only one construction process will cause the risk of each process to be crossed and omitted. To solve this problem, according to the main procedures in the construction of immersed pipe method, the construction work of dry dock construction, pipe section prefabrication, foundation trench excavation, pipe section floating, pipe section sinking and docking, foundation treatment and backfilling, as well as the internal and external environmental construction risks are comprehensively analyzed. A total of 26 risk factors were identified in constructing an immersed tunnel. According to the five SMART principles [19–21], a risk assessment system for immersed tube tunnel construction was established, which consists of 3 levels, 6 aspects, and 26 indicators, as shown in Table 1.

Table 1. Risk assessment system of immersed tube tunnel construction.

Construction risk of immersed tube tunnel *U*	Dry dock construction *U*1	Poor concrete pouring quality *U*11
		Failure of water-stop and drainage system *U*12
		Insufficient dock bottom reinforcement *U*13
	Prefabrication of pipe section *U*2	Deviation in geometric dimensions of pipe section *U*21
		Cracking of pipe section *U*22
		Poor construction quality of end sealing wall *U*23
		Failure of ballast water tank *U*24
	Foundation trench excavation *U*3	Low positioning accuracy of foundation trench *U*31
		Improper selection of excavation equipment *U*32
		Backsilting of foundation trench *U*33
		Slope instability *U*34
		Uneven substrate treatment *U*35
	Floating transportation of pipe section *U*4	Collision occurs when the pipe section is undocked *U*41
		Improper operation of floating equipment *U*42
		Navigation blocked during floating *U*43
		Sudden disastrous weather during floating transportation *U*44
		Mooring position deviation *U*45
	Pipe section sinking and butt joint *U*5	Inaccurate positioning of pipe section sinking *U*51
		Unbalanced pipe section *U*52
		Low underwater alignment accuracy *U*53
		Damaged water-stop *U*54
		Insufficient anti floating of pipe section *U*55
		Uneven crimping of water-stop *U*56
	Foundation treatment and backfilling *U*6	Insufficient dredging of foundation trench *U*61
		Uneven substrate treatment *U*62
		Inadequate backfilling *U*63

2.2. Determination of Index Weight Based on AHP-GA

AHP is a multi-criteria analysis method. This method can scientifically analyze complex fuzzy problems. When analyzing problems, it can reasonably combine qualitative analysis with quantitative analysis, quantize problems that are difficult to quantify, and reduce the impact of subjective judgment to a certain extent. AHP was used to calculate the index weight of risk factors for immersed tunnel construction.

Ten experts were invited to fill in the questionnaire on the risk of immersed tunnel construction, sort out the scoring results of experts on the importance of risk factors, and construct a judgment matrix:

$$U = \begin{bmatrix} 1 & 1/3 & 1/4 & 4 & 1/5 & 3 \\ 3 & 1 & 1/3 & 5 & 1/4 & 4 \\ 4 & 3 & 1 & 6 & 1/3 & 5 \\ 1/4 & 1/5 & 1/6 & 1 & 1/7 & 1/3 \\ 5 & 4 & 3 & 7 & 1 & 6 \\ 1/3 & 1/4 & 1/5 & 3 & 1/6 & 1 \end{bmatrix}$$

$$U_1 = \begin{bmatrix} 1 & 1/3 & 2 \\ 3 & 1 & 3 \\ 1/2 & 1/3 & 1 \end{bmatrix} \quad U_2 = \begin{bmatrix} 1 & 1/2 & 3 & 3 \\ 2 & 1 & 4 & 5 \\ 1/3 & 1/4 & 1 & 2 \\ 1/3 & 1/5 & 1/2 & 1 \end{bmatrix}$$

$$U_3 = \begin{bmatrix} 1 & 1/4 & 1/6 & 1/7 & 1/3 \\ 4 & 1 & 1/4 & 1/5 & 1/2 \\ 6 & 4 & 1 & 1/2 & 3 \\ 7 & 5 & 2 & 1 & 4 \\ 3 & 2 & 1/3 & 1/4 & 1 \end{bmatrix} U_4 = \begin{bmatrix} 1 & 1/3 & 5 & 2 & 5 \\ 3 & 1 & 7 & 4 & 6 \\ 1/5 & 1/7 & 1 & 1/3 & 1/3 \\ 1/2 & 1/4 & 3 & 1 & 1/3 \\ 1/5 & 1/6 & 3 & 3 & 1 \end{bmatrix}$$

$$U_5 = \begin{bmatrix} 1 & 1/3 & 1/5 & 1/7 & 1/3 & 1/4 \\ 3 & 1 & 1/5 & 1/5 & 4 & 1/4 \\ 5 & 5 & 1 & 1/3 & 5 & 3 \\ 7 & 5 & 3 & 1 & 6 & 5 \\ 3 & 1/4 & 1/5 & 1/6 & 1 & 1/4 \\ 4 & 4 & 1/3 & 1/5 & 4 & 1 \end{bmatrix} \quad U_6 = \begin{bmatrix} 1 & 1/3 & 3 \\ 3 & 1 & 4 \\ 1/3 & 1/4 & 1 \end{bmatrix}$$

The consistency of the judgment matrix was checked, and the results are shown in Table 2.

Table 2. Consistency calculation results of the judgment matrix.

Judgment Matrix	U_1	U_2	U_3	U_4	U_5	U_6
CR	0.052	0.021	0.043	0.115	0.113	0.071
Whether the consistency inspection is passed	Yes	Yes	Yes	No	No	Yes

According to Table 1, the judgment matrices U_4 and U_5 fail the consistency test because CR is greater than 0.1. In calculating the weight of traditional AHP, there may be a problem in that the consistency of the higher-order judgment matrix is not satisfied. It is necessary to solve the problem and obtain a more accurate and reasonable weight value.

According to the definition of a judgment matrix, analyze the conditions when the judgment matrix meets the consistency. Theoretically, it is as follows:

$$\omega_k > 0, \sum_{k=1}^{n} \omega_k = 1, b_{ij} = \frac{\omega_i}{\omega_j} \quad k, i, j = 1, 2, \cdots, n \tag{1}$$

At this time, according to the unity of the judgment matrix, $b_{ii} = \frac{\omega_i}{\omega_j} = 1$, therein $i, j = 1, 2, \cdots, n$; according to the reciprocal of the judgment matrix, $b_{ij} = \frac{1}{b_{ji}}$, therein $i, j = 1, 2, \cdots, n$; according to the consistency conditions of the judgment matrix, $b_{ij} d_{ji} = \frac{\omega_i}{\omega_j} \frac{\omega_j}{\omega_i} \omega_{ik}$.

If any judgment matrix satisfies Formula (1), the judgment matrix is consistent, and the following results are obtained, $\sum_{k=1}^{n}(b_{ik}\omega_k) = \sum_{k=1}^{n}\left(\frac{\omega_i}{\omega_k}\omega_k\right) = n\omega_i \sum_{i=1}^{n}\left|\sum_{i=1}^{n}(b_{ij}\omega_k) - n\omega_i\right| = 0$, therein $i = 1 \sim n$.

Convert the problem of judgment matrix consistency into the problem of nonlinear function optimization:

$$\min CIF(n) = \frac{\sum_{i=1}^{n}\left|\sum_{i=1}^{n}(b_{ik}\omega_k) - n\omega_i\right|}{n} \tag{2}$$

$$s.t.\omega_k > 0, \sum_{k=1}^{n}\omega_k = 1, k = 1 \sim n \tag{3}$$

where $CIF(n)$ is the consistency function of the judgment matrix, and ω_k is the ranking weight of elements. As $CIF(n)$ in function Formula (3) is difficult to calculate by conventional methods, and considering that the genetic algorithm is a classical function optimization method, the genetic algorithm (GA) is selected to solve the function. The flow chart of AHP-GA is summarized, as shown in Figure 2 [22].

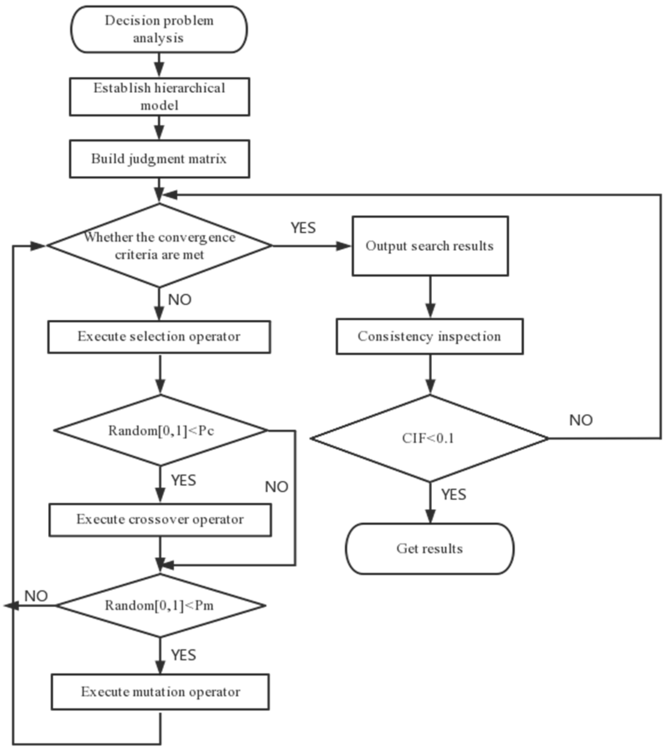


Figure 2. AHP-GA Flow Chart.

The AHP-GA method uses MATLAB software to edit the program and calculate the result. The improved analytic hierarchy process was verified, and the risk index of immersed tunnel construction was calculated by AHP-GA. It can be concluded that all judgment matrices have passed the consistency test, as shown in Table 3.

Table 3. Consistency calculation results of the judgment matrix.

Judgment Matrix	U_1	U_2	U_3	U_4	U_5	U_6
CIF	0.035	0.009	0.017	0.041	0.032	0.029
Whether the consistency inspection is passed	Yes	Yes	Yes	Yes	Yes	Yes

2.3. Build a Risk Assessment cloud Model

Determining the evaluation criteria cloud. According to the Code for Risk Management of Underground Engineering Construction of Urban Rail Transit (GB-50652-2011), the risk matrix method was used to grade the probability of risk occurrence and the severity of potential consequences that may be caused by the risk to grade the risk of immersed tube tunnel construction. The risk level standard has four levels: low, lower, medium, and high. The evaluation grade and corresponding score range are low-risk [0, 2.5], lower-risk (2.5, 5), medium-risk (5, 7.5), and high-risk (7.5, 10]. The score is positively related to the risk level. The standard cloud model parameters are calculated according to Formulas (4)–(6), and the results are shown in Table 2.

$$Ex_i = \frac{x_i^{min} + x_i^{max}}{2} \tag{4}$$

$$En_i = \frac{x_i^{max} - x_i^{min}}{6} \tag{5}$$

$$He_i = 0.1 \tag{6}$$

where x_i^{min} is the minimum value of the risk grade score, and x_i^{max} is the maximum value of risk grade score, Ex_i is the standard cloud expectation, En_i is the standard cloud entropy, and He_i is the standard cloud super-entropy.

Draw a standard cloud diagram according to Table 4, as shown in Figure 3.

Table 4. Standard Grade and Cloud Model Parameters.

Risk Level	Score Range	Cloud Model Parameters
Low risk	[0, 2.5]	(1.25, 0.42, 0.1)
Lower risk	(2.5, 5]	(3.75, 0.42, 0.1)
Medium risk	(5, 7.5]	(6.25, 0.42, 0.1)
High risk	(7.5, 10]	(8.75, 0.42, 0.1)

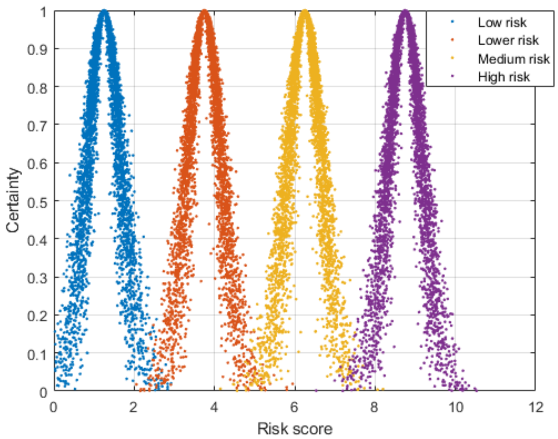


Figure 3. Standard Cloud Chart.

Determine the evaluation indicator cloud. According to the experts' scores based on the degree of risk rating, the secondary indicator cloud model parameters are calculated, and the secondary indicator cloud map is drawn. The secondary indicator cloud model parameters are calculated according to Formulas (7)–(9).

$$Ex = \bar{x} = \frac{1}{n}\sum_{i=1}^{N} x_i \tag{7}$$

$$Ex = \bar{x} = \frac{1}{n}\sum_{i=1}^{N} x_i \tag{8}$$

$$He = \sqrt{\left(S^2 - En^2\right)} \quad (9)$$

According to the cloud model parameters of the secondary indicators obtained and combined with the weight value of the secondary indicators, the cloud model parameters of the primary indicators and the cloud model parameters of the construction project are calculated using Formulas (10)–(12).

$$Ex = \sum_{i=1}^{n} (Ex_i w_i) \quad (10)$$

$$En = \sqrt{\sum_{i=1}^{n} (Ex_i w_i)^2} \quad (11)$$

$$He = \sqrt{\sum_{i=1}^{n} (He_i w_i)^2} \quad (12)$$

After obtaining the cloud model parameters of evaluation indicators at all levels, the cloud map was drawn through MATLAB. After that, the assessment cloud map and the standard cloud map obtained were compared and analyzed. According to the principle of maximum membership, determine the standard cloud closest to the assessment result cloud map, and this standard cloud level is the assessment cloud level. The final evaluation results are obtained this way [23–26].

3. Case Analysis

3.1. Basic Situation of Submarine Immersed Tube Tunnel in DALIAN Bay

The Dalian Bay subsea tunnel is the first subsea tunnel built in northern China. The climate in the north is cold, and cold weather needs to be overcome during construction. The hydro-meteorological environment in the Dalian Bay area is complex, with more rain in summer, accounting for about 65% of the annual precipitation. The annual average fog in the sea area is about 40 days, mostly in March and August; the area has strong wind in winter and light wind in summer. It is minimally affected by storms and typhoons, with an annual average of 1 to 2 times. The sea area is densely navigable and is the intersection of multiple channels. The complex environment requires accurate construction monitoring equipment, as well as high-standard construction technology and construction technology during the construction process. All of these are great challenges to tunnel construction.

3.2. Determine Indicator Weight

Firstly, an expert was invited to fill in the questionnaire concerning the risks of immersed tube tunnel construction, and the questionnaire data were sorted out to construct a judgment matrix:

Then AHP-GA was used to calculate the weight of each index in the index system of immersed tube tunnel construction, and a consistency test was carried out. The results are shown in Table 5.

Table 5. Calculation Results of Weights of Various Factors.

	Weight of Each Factor						
Judgement Matrix	ω_1	ω_2	ω_3	ω_4	ω_5	ω_6	*CIF*
U_1	0.2005	0.5999	0.1996				0.035
U_2	0.3585	0.4345	0.1196	0.0874			0.009
U_3	0.0514	0.0843	0.2855	0.4662	0.1126		0.017
U_4	0.2690	0.4769	0.0527	0.1284	0.0730		0.041
U_5	0.0654	0.1118	0.2555	0.3643	0.0860	0.1169	0.032
U_6	0.2152	0.6280	0.1568				0.024
U	0.0785	0.1875	0.2997	0.0452	0.3331	0.0560	0.082

According to the consistency test results calculated by AHP-GA, *CR* values were less than 0.1, the higher-order judgment matrices had satisfactory consistency, and the index weights with high accuracy were obtained. It provides a basis for comprehensive risk assessment of immersed tube tunnel construction.

3.3. Analysis of Evaluation Results

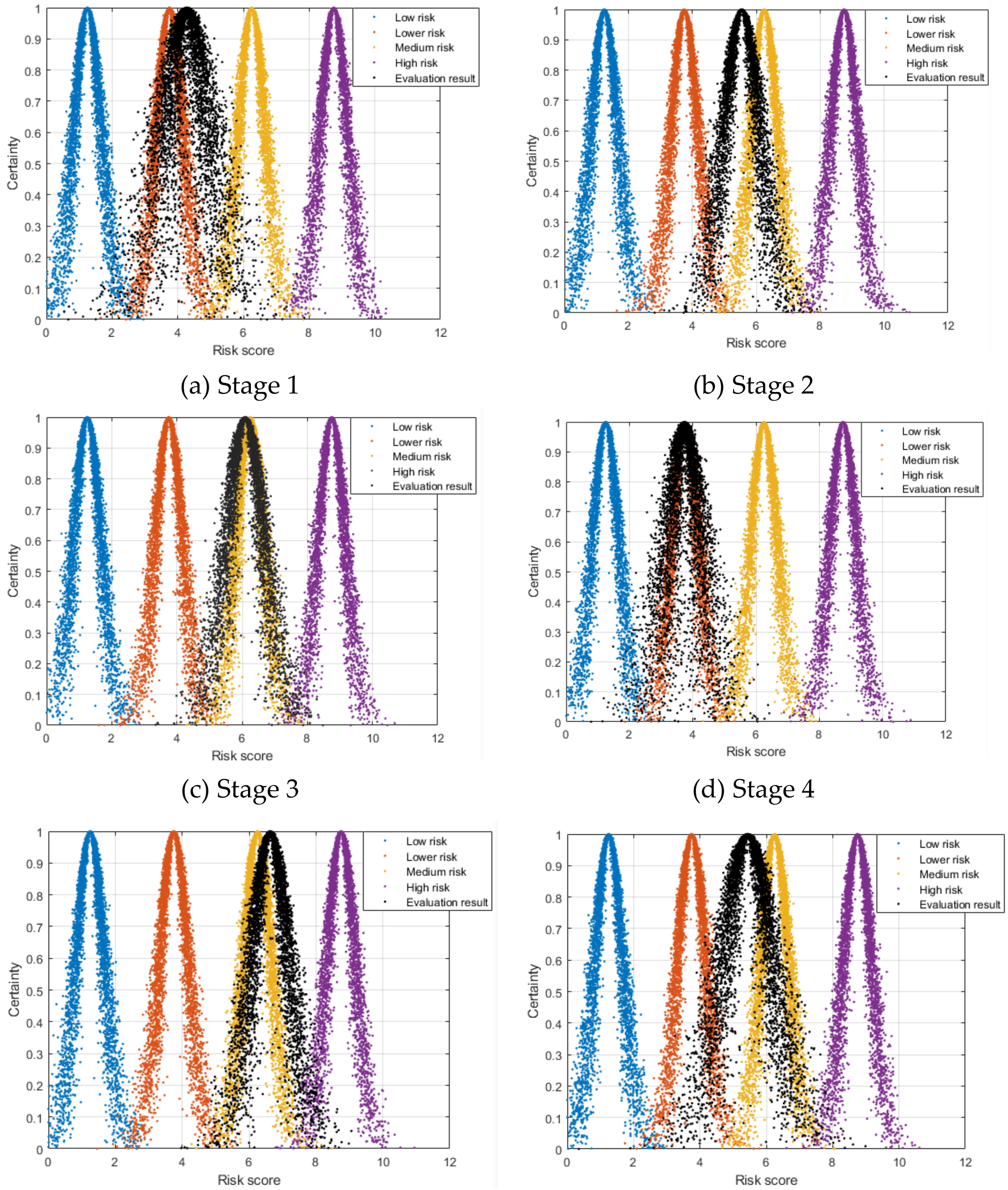
According to the questionnaire, the construction risk of the Dalian Bay subsea immersed tube tunnel was scored. According to the expert scoring results, calculated the average value, entropy value, and super-entropy of the scores according to Formulas (7)–(9) and obtained the parameters of each indicator cloud model, as shown in Table 6.

Table 6. Cloud model parameters of each indicator.

Primary Indicators	(*Ex*,*En*,*He*)	Secondary Indicators	(*Ex*,*En*,*He*)
Dry dock construction	(4.281, 0.643, 0.334)	Poor concrete pouring quality	(3.9, 0.652, 0.353)
		Failure of water-stop and drainage system	(5.1, 0.652, 0.353)
		Insufficient dock bottom reinforcement	(2.2, 0.551, 0.146)
Prefabrication of pipe section	(5.549, 0.561, 0.150)	Deviation in geometric dimensions of pipe section	(4.8, 0.551, 0.146)
		Cracking of pipe section	(6.8, 0.551, 0.146)
		Poor construction quality of the end sealing wall	(4.6, 0.652, 0.185)
		Failure of ballast water tank	(3.7, 0.802, 0.238)
Foundation trench excavation	(6.097, 0.573, 0.161)	Low positioning accuracy of foundation trench	(4.1, 0.451, 0.311)
		Improper selection of excavation equipment	(4.5, 0.251, 0.249)
		Back-silting of foundation trench	(4.9, 0.652, 0.185)
		Slope instability	(7.7, 0.551, 0.146)
		Uneven substrate treatment	(4.6, 0.652, 0.185)
Floating transportation of pipe section	(3.744, 0.491, 0.266)	Collision occurs when the pipe section is undocked	(3.8, 0.551, 0.146)
		Improper operation of floating equipment	(4.1, 0.451, 0.311)
		Navigation blocked during floating	(2.2, 0.551, 0.146)
		Sudden disastrous weather during floating transportation	(3.7, 0.802, 0.238)
		Mooring position deviation	(2.4, 0.401, 0.119)
Pipe section sinking and butt joint	(6.631, 0.542, 0.160)	Inaccurate positioning of pipe section sinking	(4.5, 0.251, 0.249)
		Unbalanced pipe section	(5, 0.752, 0.244)
		Low underwater alignment accuracy	(7.2, 0.551, 0.146)
		Damaged water-stop	(7.8, 0.551, 0.146)
		Insufficient anti-floating of pipe section	(4.6, 0.652, 0.185)
		Uneven crimping of water-stop	(6, 0.251, 0.249)
Foundation treatment and backfilling	(5.440, 0.741, 0.239)	Insufficient dredging of foundation trench	(5, 0.752, 0.244)
		Uneven substrate treatment	(6, 0.752, 0.244)
		Inadequate backfilling	(3.8, 0.551, 0.146)

From Table 6, the expected values of the two indicators of slope instability ($U34$) and water-stop damage ($U54$) are greater than 5, indicating that the two indicators of construction are of high risk, and it is necessary to propose targeted control measures to reduce risks and formulate emergency plans; The expected values of pipe section cracking (*U*22), low underwater alignment accuracy (*U*53), uneven crimping of water-stop (*U*56), and uneven substrate treatment (*U*62) are within the range of 5–7.5, indicating that the two indicators of construction have relatively high risk. Corresponding control measures need to be put forward to reduce risks and prevent risks.

The normal cloud forward generator was used to process the cloud model evaluation results and generate the cloud map of the primary indicators, as shown in Figure 4.



(a) Stage 1 (b) Stage 2

(c) Stage 3 (d) Stage 4

(e) Stage 5 (f) Stage 6

Figure 4. Cloud Chart of Primary Indicator Evaluation (**a**–**f**).

As can be seen from Figure 4, the risk level of dry dock construction and floating transportation of pipe sections are lower risks, and the expected values are lower than 5, so the construction risks are low. The entropy and super-entropy of the foundation treatment and backfill stage are large, as is the cloud droplet dispersion degree, so it is necessary to strengthen construction control at this stage. The cloud chart of the pipe section sinking and docking stages is between medium and high risk, and the expected value is 6.631 higher than that of other stages, so construction risk is higher. The risk level of each construction stage is ranked as follows: pipe section sinking and docking stage > foundation trench excavation stage > pipe section prefabrication stage > foundation treatment and backfilling stage > dry dock construction stage > pipe section floating transport stage. It shows that in the construction of an immersed tunnel, the influence of the pipe section sinking and docking stages is the greatest, and the damage factor of the water hose at this stage is the most important.

According to the calculated primary indicators cloud model parameters and the weight of primary indicators, the comprehensive cloud model parameters (5.872, 0.561, 0.165) of the construction risk of submarine immersed tube tunnel in Dalian Bay were calculated by Formulas (10)–(12). The comprehensive evaluation cloud map of the construction risk of the submarine immersed tube tunnel in Dalian Bay was generated by the MATLAB forward cloud generator (Figure 5).

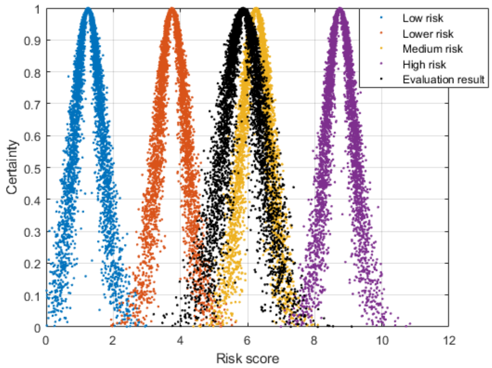


Figure 5. Cloud Chart of Comprehensive Assessment.

According to Figure 5, it can be intuitively concluded that the comprehensive risk assessment cloud map is located between low and medium risk and has a high similarity with the medium risk level cloud map. Therefore, the construction risk level of the Dalian Bay subsea immersed tunnel has been determined as medium risk. The cloud layer in the cloud map is thicker, and the cloud droplet span is smaller, showing that the comprehensive risk assessment has strong credibility and reliability and the assessment results are applicable.

4. Conclusions

Based on the complexity and fuzziness of the risk factors in the process of immersed tube tunnel construction, this paper put forward a method to identify the construction risk factors using WBS-RBS, and used cloud model theory and improved AHP to build an evaluation model for the risk assessment of immersed tube tunnel construction. In calculating the weight, a problem was that the consistency of the higher-order judgment matrix test did not pass. To solve this problem, a genetic algorithm was proposed to optimize the judgment matrix, which passed the consistency test. After inspection, the improved AHP can improve the pass rate of consistency inspection. The main conclusions are as follows:

(1) WBS-RBS was adopted to identify the risk factors in the construction period of an immersed tube tunnel. According to the six construction procedures, 26 risk factors, such as damage to the water-stop belt, were obtained. Based on the SMART principle, a three-level risk assessment index system for immersed tube tunnel construction was established;

(2) As the construction risk factors of subsea immersed tunnel are various and complex, when using the AHP method to calculate the weight, the consistency check of the higher-order judgment matrix may fail. To solve this problem, a genetic algorithm (GA) was introduced to improve AHP. When AHP-GA was used to calculate the weight of risk factors in the construction of immersed tube tunnel, the risk impact degree of each construction stage was ranked as follows: pipe section

sinking and docking stage > foundation trench excavation stage > pipe section prefabrication stage > dry dock construction stage>foundation treatment and backfilling stage > pipe section floating stage;

(3) The risk assessment system and model of immersed tube tunnel construction were verified using the actual construction situation of the submarine immersed tube tunnel in Dalian Bay. The cloud model was used to evaluate the construction risk of the underwater immersed tube tunnel in Dalian Bay. The risk levels of each factor and the construction project were obtained. Among the risk factors, the expected value of two factors is greater than 7.5, which belongs to the high-risk level; the expected value of the four factors is 5–7.5, which belongs to the medium-risk level; in the construction stage, the risk of pipe section sinking and docking stage is the highest; the expected value of the comprehensive risk of the Dalian Bay subsea immersed tunnel construction project is 5.872, a medium risk project.

The evaluation and research on the construction risk of an immersed tube tunnel provide a reference value for the future construction of immersed tube tunnels. However, the analysis of the risk factors of the immersed tube tunnel construction project is not comprehensive enough, and the established risk assessment index system is not perfect enough. It can also increase the number of respondents and refine the questionnaire to analyze further the risk factors in a scientific and in-depth way.

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