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Risk analysis and management of submerged floating tunnel and its application

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Abstract

Combining with the characteristics of submerged floating tunnel (SFT) and surrounding environment, it is of great theoretical and practical significance to develop research in the areas of potential risk and impact factors, risk index system, risk level of SFT. This paper summarized the main content of risk analysis of SFT, and classified the risk management into six stages: planning, feasibility study, design, tendering, construction and operation. Risk management workflow of SFT was given. Then, we focused on discussing the potential risks of SFT in investment, design, and environmental condition during planning and feasibility study stage. After identifying the risk factors of SFT, the risk assessment method of SFT was described by the presented fuzzy AHP method (FAHP). Finally, taking environment risks assessment of SFT prototype in Qiandao Lake as an example, environment risk assessment of SFT was completed by the programmed integration evaluation system of SFT based on Matlab7.5. Some measures and suggestions in risk control strategy were given.

Keywords: submerged floating tunnel; risk analysis; risk management; risk index system; fuzzy analytic hierarchy process

1. Introduction

With the requirement of rational utilizing resource and environmental protection, the engineering construction sustainability becomes a necessary in civil engineering. It is of great significance how to reduce the impact on environment caused by infrastructure project and to minimize energy consumption. The submerged floating tunnel is new type sustainable and friendly environmental solution for one waterway crossings accord with requirement of modern construction.

Submerged floating tunnel (SFT), also called Archimedes Bridge, consists of the metal tubular segment or RC tubular segment (inner space is big enough for traffic flow), the subaqueous foundation, the support system and the connecting structure which link the tube with land [1]. The idea of SFT was first proposed in England in the 1880s and further by Norwegian scholars in 1920s. From 1980s, officials and researchers from Europe, America, and

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Japan began to pay close attention to SFT structures and construction feasibility study as well as tentative design on SFT project in Messina Strait channel [2].

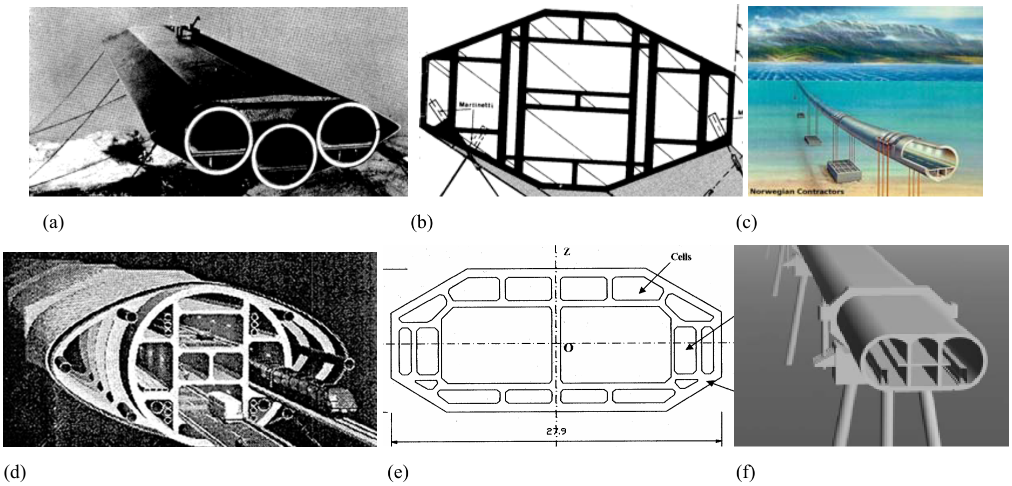

Fig. 1. (a) A. Grant (1969); (b) Archimedes Inc. (1984); (c) Norway Høgsfjord (1987); (d) North Japan exchange axis (1996); (e) Jintang Channel program (2001); (f) Lake Washington (2001)

China had introduced the concept of floating tunnel in 1990s and started the feasibility study of Jintang Strait Channel Archimedes bridge program at 2000. But until now, no SFT has been built in the world. The reason has two parts. For one thing, pervasive uncertainty exists in all life circle of SFT project because of the large investment demand and long construction period as well as many unexpected factors. Engineers and the public were worried about the uncertain risks hidden during project planning, design, construct and operation. For another thing, many technical problems yet have not been tackled, such as reliability of the connection between the segments, mechanism of wave load and seismic impact on SFT et al. Moreover, there are no full set of guidelines and acceptance specifications about design and construction for SFT now. Scholars throughout the world studied on SFT from different aspects, some mainly focused on static and dynamic response of SFT [2–12, 19]. In the area of risk analysis, Li Jian (2008) analyzed potential risks preliminarily from economy, financial affairs, contract, nature, environment, design, construction and operation [13]. However, detained index factors of each risk about SFT have not thoroughly been discussed. Author (2010) etc. studied the risk assessment system of Ling River Bridge [14, 15].

In order to provide the basis for making pre-construction decisions of SFT project, it is necessary to broad study on the risk factors and risk index system of SFT and present risk control strategy of reducing relevant risks and coping with possible risks to occur.

2. Risk analysis content and risk management stage dividing of SFT

2.1. Risk analysis content of SFT

Content of SFT project risk analysis mainly includes risk identification, risk estimation, risk assessment, risk control, etc. In general, the current theories and methods of risk analysis can be classified into two categories: qualitative analysis and quantitative analysis.

2.2. Risk management stages dividing of SFT

The risk management should run throughout all life cycles of SFT. According to actual status of construction management in China, the risk management for SFT can be classified into six stages: planning, feasibility study, design, construction tendering, construction and operation. The problems to be solved in every stage and departments to be involved may be different. The contents of risk management in different stages are shown in Table 1.

Table 1. Contents of risk management for SFT in different stages

Construction division	Contents of risk management
Planning stage	Risk analysis of planning scheme Risk source identification of important event
Feasibility study stage	Investment and financing risk analysis Classification standard and strategy of risk management Risk identification and assessment of feasibility study
Design stage (including detailed survey, environment investigation, preliminary design and construction documents design).	Risk identification and assessment of design project Risk identification and assessment of construction method Special risk control for important event risk source
Construction tender stage	Risk management guidelines for bid inviting document Risk management guidelines for bid submitting document Risk management guidelines for contract signing
Construction stage	Implementing regulations for construction risk management Early risk warning system and emergencies measures under construction Implementation and record for risk control under construction Dynamic tracking and monitoring of construction risk
Operation stage	Operations management rules Monitoring and control Repair and reinforcement

The risk management of SFT is a systematic program throughout all the life circle of SFT. The risk management workflow is shown in Fig. 2.

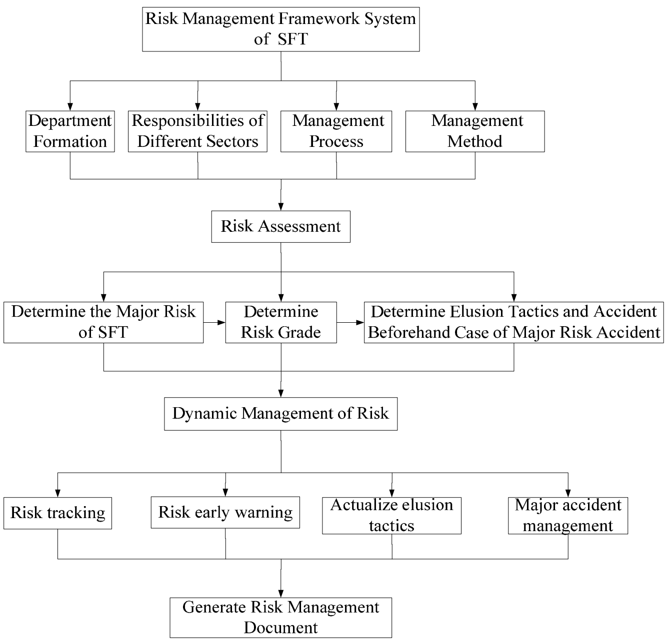

Fig. 2. Risk management workflow of SFT

2.3. Risk classification standard and acceptance criterion

The risk classification standard includes the risk probability classification standard and the risk loss classification standard. According to the function of use and environment of SFT, the risk classification standard and acceptance criterion are listed in Table 2~4.

Table 2. Risk probability classification standard of SFT

Probability description	Interval probability	grade	score	definition
V—very low	*P<10-6*	1st	0.2~0.0	Unlikely happen
IV—low	*10-3>P>10-6*	2nd	0.4~0.2	Slightly possible happen
III—medium	*10-2>P>10-3*	3rd	0.6~0.4	Happen many times
II—high	*10-1>P>10-2*	4th	0.8~0.6	Frequently happen
I—very high	*P>10-1*	5th	1.0~0.8	Repeatedly happen

P: the probability of risk incident

Table 3. Risk loss classification standard of SFT

Probability description	grade	score	Definition			
			Economic loss	Construction damage	Construction delay	Environment damage
V—very low	1st	0.2~0.0	<30,000	None	<3d	none
IV—low	2nd	0.4~0.2	30,000~0.3M	Slight damage	3d~15d	Temporary serious damage
III—medium	3rd	0.6~0.4	0.3M~3M	Slight damage in main structure	15d~6mon	Long-term damage
II—high	4th	0.8~0.6	3M~30M	Medium damage in main structure	6 ~24 mon	Serious damage
I—very high	5th	1.0~0.8	>30M	High damage in main structure	>24 mon	Permanent serious damage

Table 4. Risk acceptance criterion of SFT

Risk level	Criterion	Definition
EH—Very high	Rejected	Give up the project
H—high	Unacceptable	Conditional accept and implement preventive actions
M— medium	Acceptable	Conditional accept and preventive measures should be planned or taken
L—low	Allowable	Conditional accept, and take preventive measures with less urgency
UL—Very low	Neglectable	Accept without appraisal

2.4. Risk management content of SFT in planning stage and feasibility study stage

In planning stage, the main task of risk management is to analyze the influence of whole road alignment scheme, site selection of construction, investment, environment impact of SFT, identify potential major risks and try to control them by scheme change and revised scheme. The risk management in planning stage mainly includes: (1) Risk analysis of compatibility between project planning and traffic network planning. (2) Risk analysis of forecasting traffic and passenger volume. (3) Risk analysis of road alignment selection. (4) Risk analysis of geological and environmental survey. (5) Risk analysis of major hazard. (6) Feasibility risk analysis of investment and financing. (7) Synthetical evaluation of different project planning.

Major risk source analysis, focusing on the key technologies and the special geological conditions which seriously influence engineering, including: (1) Key technologies for needing special design or using new craft, new equipment or new materials in engineering. (2) The highest tide water level ,typhoon season and its occurence time in the project area. (3) Special geological condition handling in the project area etc.

In feasibility study stage, the risk management mainly includes: (1) Hazard risk analysis. (2) Risk analysis of hydrogeology and engineering geology. (3) Surrounding environment impact analysis. (4) Risk analysis of construction method and period. (5) Risk analysis of project preparation and investment return. (6) Risk analysis of construction period delay and investment caused by demolishing dwelling in construction site. (7) Operation risk analysis.

The following analysis will focus on investment risk, design risk, construction risk and operation risk in planning and feasibility study stages.

3. Risk analysis of SFT–taking the risk analysis of planning and feasibility study stage as an example

3.1. Base flow of risk analysis

SFT project risk analysis involves in the risk identification, risk estimation, risk assessment, risk decision and control. The basic flow chart of risk analysis of SFT is shown in Fig. 3.

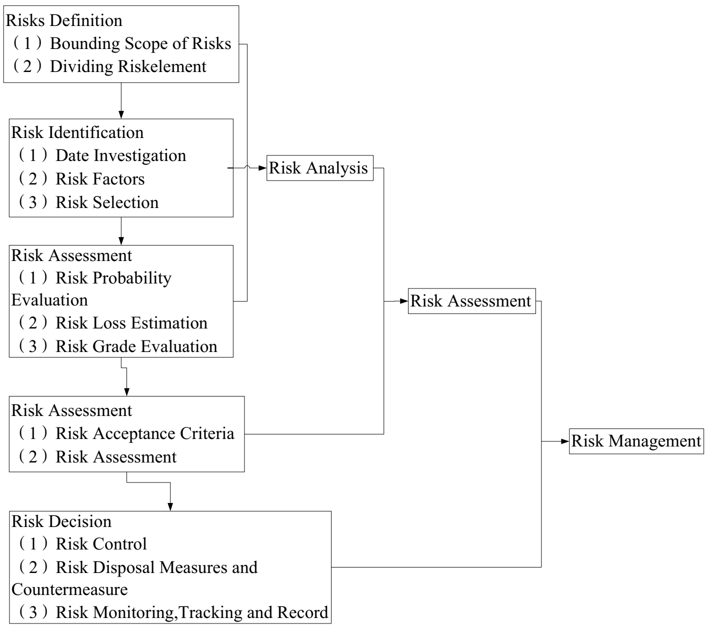

Fig. 3. Basic flow chart of risk analysis for SFT

3.2. Risk source analysis and risk index system of SFT in planning stage and feasibility study stage

According to risk sources survey and related research results [17, 18], we can establish the risk index system of SFT from structure function, construction method and operation condition by expert investigation based on AHP method. The risk sources in planning and feasibility study stage can be divided into three parts: investment risk, design risk and environment risk. The relevant risk index systems are shown in Fig. 4. Each system has top index, medium index and bottom index.

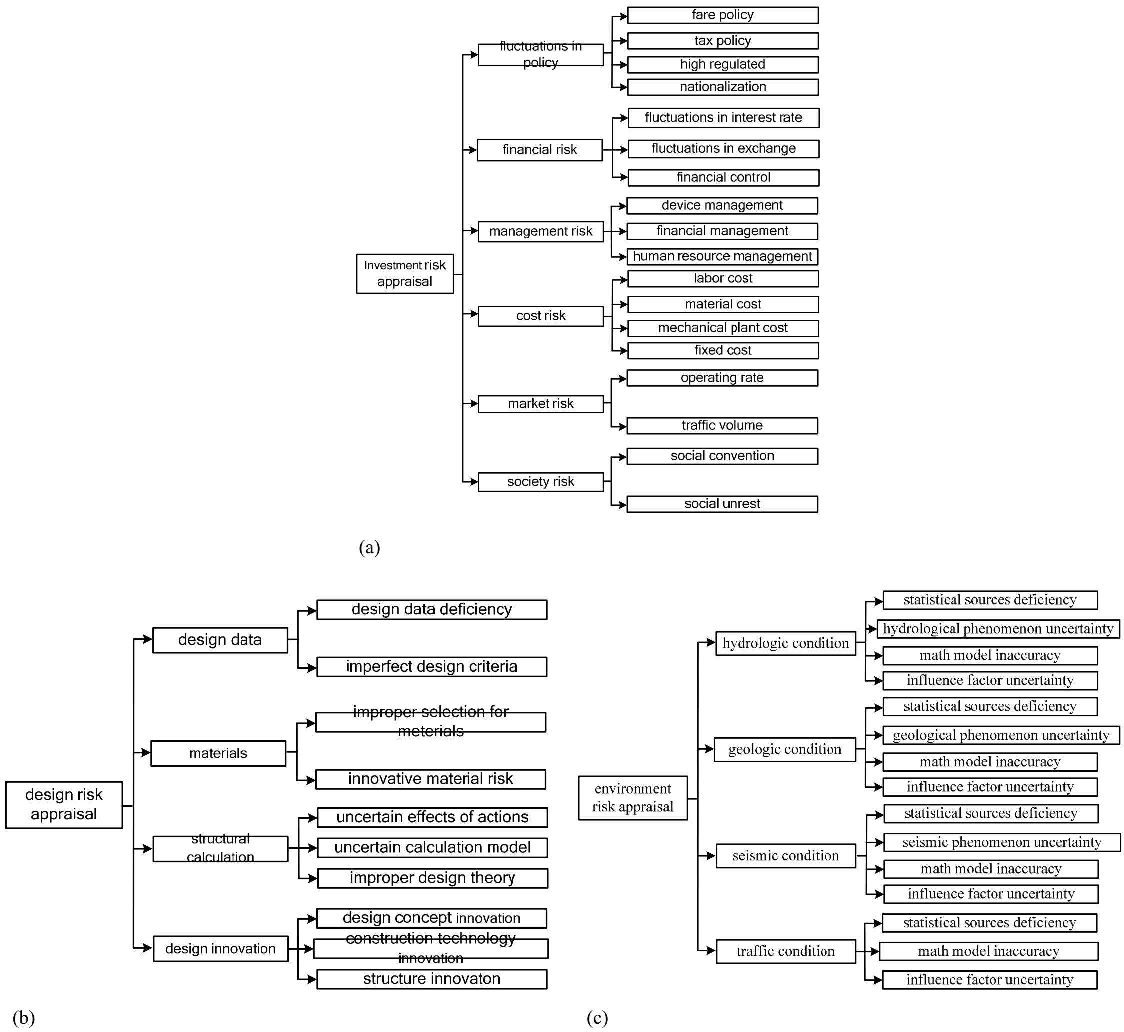

Fig. 4. (a) Investment risk index system of SFT; (b) Design risk index system of SFT; (c) environmental condition risk index system of SFT

3.3. Risk assessment method

The fuzzy AHP method (FAHP) [20] is presented, which combines AHP method with fuzzy comprehensive assessment, to identify the risk factors of SFT. This method has not only some advantages of quantification and objectivity which are inherited from AHP method, but also of comprehensiveness which is inherited from fuzzy comprehensive assessment. Through FAHP method, we can consider risk factors more comprehensively and objectively. FAHP method is regarded as a decision method with high applicability. Based on analysis steps of FAHP method, it is adopted to carry out the risk assessment of SFT:

Assume the bottom index as $U_k = \{u_1, u_2, \ldots, u_n\}$, and the middle index as $U_{ki} = \{u_{k1}, u_{k2}, \ldots, u_{kn}\}$.

- By using AHP method to calculate the index weight vectors in each layers.

$$w = [w_1 \ w_2 \ \cdots \ w_n] \tag{1}$$

- Use Fuzzy evaluation to get fuzzy matrix from assessment scores which is obtained from expert investigation which considers both the risk probability and risk loss.
  Define set of risk probability reviews: V= {neglectable, low, medium, severe, extremely severe}
  Establish fuzzy relational matrix:

$$R=\begin{bmatrix} R_1 \\ R_2 \\ \cdots \\ R_n \end{bmatrix}=\begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nn} \end{bmatrix} \tag{2}$$

where r_{ij} means the degree of membership which the i^{th} bottom index corresponding to the j^{th} risk probability. In this paper, we use semi-trapezoid distribution as the membership function which is shown in Fig. 5.

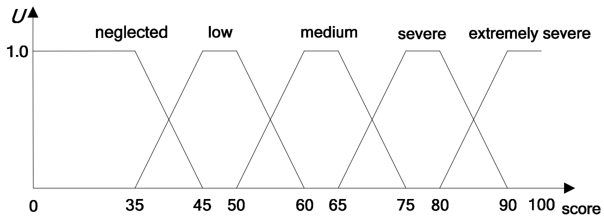

Fig. 5. Index membership functions

- Use fuzzy mapping to get synthetical evaluation set of medium index:

$$B_k = w \circ R = \begin{bmatrix} w_1 & w_2 & \cdots & w_n \end{bmatrix} \circ \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} & r_{15} \\ r_{21} & r_{22} & r_{23} & r_{24} & r_{25} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ r_{n1} & r_{n2} & r_{n3} & r_{n4} & r_{n5} \end{bmatrix} = \begin{bmatrix} b_1 & b_2 & b_3 & b_4 & b_5 \end{bmatrix} \tag{3}$$

where "$\circ$" is a fuzzy composition symbol and b_{ki} can be solved by the specific operation: $b_{ki} = \max\left[\min_{j=1}^{n}\left(w_j, r_{ji}\right)\right]$.

Then normalize B_k to get synthetical evaluation set of medium index.

- Use matrix multiplication to get synthetical evaluation set of top index *B*.
- Define the set of risk probability scores: *G*= {0.15, 0.35, 0.55, 0.75, 0.95} corresponding to the set of risk probability reviews: *V*= {neglectable, low, medium, severe, extremely severe}. Let *P=G*B*, where we define P as the overall score value of top index. And *P* can be valued by table 2~4.

4. Implementation and application of SFT risk Assessment

According to the design project of SFT prototype in Qiandao Lake [2, 19], we comprehensively analyze the risk of SFT prototype in Qiandao Lake in planning and feasibility study stage. As space is limited, only environment risks assessment are taken as an example of application.

Use object-oriented programming tools Matlab7.5 to program the overall process and establish the integration evaluation system of SFT in terms of above mensioned theory and method. This system applies multi-index evaluation and FAHP method. It contains three modules as follow:

- **Input module**: Input expert data through dialog box in the interface of program.

- **Data checking and calculating module**: Check the validity of input data and display the input data on screen. Run calculating module to get the evaluation result, risk level and relevant measures proposal.
- **Output module**: Output the result in the form of text files.

The integrating evaluation system of SFT, taking environment risks assessment as an example of application, is shown in Fig. 6. In fact, the risk analysis evaluation of investment, design and construction of SFT is similar to environment risk analysis evaluation.

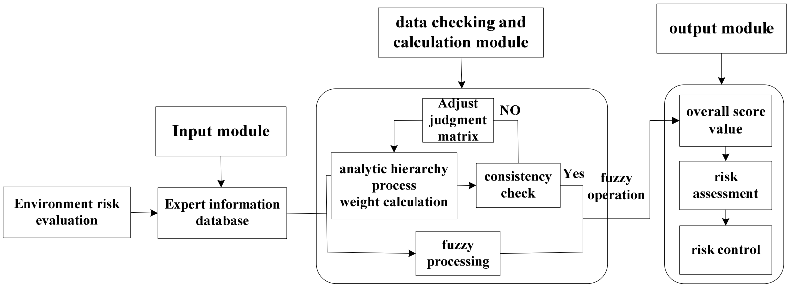

Fig. 6. Integration evaluation system of SFT- taking environment risks assessment as an example

According to risk index system shown in Fig. 3, we assume the top index of environmental condition risk as U, and every medium index as: hydrologic condition U1, geological condition U2, seismic condition U3, and traffic condition U4. The corresponding index weight vectors are calculated as follows:

$$\begin{aligned} w &= \{0.5650 \quad 0.1175 \quad 0.2622 \quad 0.0553\} \\ w_1 &= \{0.1685 \quad 0.3761 \quad 0.4020 \quad 0.0533\} \\ w_2 &= \{0.0457 \quad 0.6574 \quad 0.2027 \quad 0.0942\} \\ w_3 &= \{0.0473 \quad 0.3950 \quad 0.3950 \quad 0.1626\} \\ w_4 &= \{0.2789 \quad 0.6491 \quad 0.0719\} \end{aligned} \tag{4}$$

Then, use expert investigation to get scores of every risk factor which we can use to get fuzzy evaluation. The results are listed in Table 5.

Table 5. Fuzzy evaluation results

Top index	Medium index	Weight	Fuzzy evaluation set of medium index	Fuzzy evaluation set of top index
Environmental condition risk U	Hydrologic condition U1	0.5650	(0, 0. 3130, 0.3145, 0.2943, 0.0782)	(0.0306, 0.2766, 0.2980, 0.2713, 0.1236)
	Geological condition U2	0.1175	(0, 0.0860, 0.0860, 0.2281, 0.5999)	
	Seismic condition U3	0.2622	(0.1166, 0.2832, 0.2832, 0.2832, 0.0339)	
	Traffic condition U4	0.0553	(0, 0.2789, 0.6492, 0.0719, 0)	

Above all, the overall score value is $P = G \cdot B = 0.5139$.

According to the risk classification standard and acceptance criterion, P belongs to medium level, and can be conditionally accepted but some preventive measures should be planned or taken.

Likewise, we can calculate the other two overall score values of top index:

The overall score value of investment risk $P = G \cdot B = 0.4657$, which belongs to medium level.

The overall score value of design risk $P = G \cdot B = 0.5768$, which belongs to medium level, but is very close to high level.

5. Risk control strategy of SFT

The object of risk management and control is to minimize the risk loss through prior treatment and process control according to the result of risk assessment.

In planning and feasibility study stage, we can find that the design risk is most concerned problem by the experts. This is mainly because the deficiencies in drawings and criterion for SFT structure, and uncertain effects of actions. As we know, SFT structure is fully immersed in water, which is built in much more severe environment when compared with traditional bridge on land. So the concept of life cycle design should be emphasized. Meanwhile, many new types of modern technology may be applied in SFT project and should be researched comprehensively.

For investment risk which belongs to medium level, it shows that the cost risk and management risk is of greatest weight. No experience can be learned because no SFT has been built. The new type of structure may face many problems and require some unpredictable cost while constructing. It is important to develop feasibility study and risk management for SFT. It makes us foresee possible cost to save unnecessary expenses with the help of modern management consciousness. It is also benefit to owners, contractors and designers to cooperate together and exchange information in order to reduce the risk of accidents risk.

According to surrounding environment near the site of SFT prototype in Qiandao Lake, the environment risk is not very high. This is because the hydrologic condition, geological condition and seismic condition are fairly acceptable. The risk of traffic condition is also very low for the functional character of SFT prototype in Qiandao Lake. But the risk of typhoon should be concerned and discussed deeply, because the typhoon may hugely influence water flow and wave height, they probably force extra actions on SFT structure.

6. Conclusions

SFT still faces many technical difficulties as a new type of structure. The uncertain risks exist throughout whole life cycle of SFT from planning and design stage to construction and operation stage especially without any technical specification or guideline about SFT.

According to practical situations in civil engineering construction and management in China, this paper summarized the main content of risk analysis of SFT, and classified the risk management into six stages: planning, feasibility studies, design, tendering, construction and operation. Risk management workflow of SFT was given. Then, we focus on discussing the potential risks of SFT in investment, design, and environmental condition during planning and feasibility study stage. After identifying the risk factors of SFT, the risk assessment method of SFT was described by the presented fuzzy AHP method (FAHP), which combined AHP method with fuzzy comprehensive assessment. Finally, taking environment risks assessment of SFT prototype in Qiandao Lake as an example, the environment risk assessment of SFT was completed by the programmed integration evaluation system of SFT based on Matlab7.5. Some measures and suggestions in risk control strategy were given. It contributes to a better understanding the risks of SFT.

Reference

[1] Xiang Y. New development of submerged floating tunnels in the world. *Journal of China & Foreign Highway* 2002; (6). (in Chinese)

[2] Fiorentino A, Mazzolani FM, Perotti F, et al. (Italian Team of SIJLAB). *Design Report of Archimedes Bridge Prototype in Qiandao Lake (P. R. China)*, 2007.

[3] Li J. *Conceptual Design and Key Technology of Submerged Floating Tunnel*. Doctoral degree dissertation of Tongji University. Shanghai: 2003.

[4] Mai J, Luo Z, Guan B. The vortex-excited dynamic response for a submerged floating tunnel under the combined wave and current effect. *Journal of the China Railway*, 2005; 27(1): 102-5. (in Chinese)

[5] Chen J, Sun S, Su Z. Dynamic response of submerged floating-tunnel tethers subjected to current. *Engineering Mechanics*, 2008; 25(10): 229-34. (in Chinese)

[6] Ge F, Hui L, Hong Y. Research on dynamic response of submerged floating tunnel to regular wave forces. *Engineering Mechanics* 2008; 25(6): 188-94. (in Chinese)

[7] Brancaleoni F, Castellani A, Asdia PD. The response of submerged tunnels to their environment. *Engineering Structures* 1989; 11(1): 47-56.

[8] Venkataramana, Katta; Yoshihara, et al. Current-induced vibrations of submerged floating tunnels. *Proceedings of International Offshore and Polar Engineering Conference*, 1996; p. 111-8.

[9] Terje Hauka's; Svein Remseth. Global dynamic analysis of floating submerged tunnels preliminary study. Department of Structural Engineering. Norwegian University of Science and Technology, 1997.

[10] Xiang Y, Gan Y , Xu X. Spatial analysis of the submerged floating tunnel in the Jintang Strait. *Proceedings of the Seventh International Symposium on Structural Engineering for Young Exports*, Tianjin, P. R. China, 2002.

[11] Xiang Y, Zhang K, Chao C, et al. Health monitoring system of submerged floating tunnel prototype in Qiandao Lake. *Proceeding of the 4th International symposium on lifetime engineering of civil infrastructure*. Science Press, 2009: 25-26. Changsha: 471-47.

[12] Ge F, Hui L, Hong Y. Nonlinear response of submerged floating tunnel to wave forces. *Journal of applied mechanics* 2008; 25(2): 207-11. (in Chinese)

[13] Li J. Fuzzy Synthetic Evaluation on risk of submerged floating tunnel. *Journal of underground space and engineering* 2008; 4(2): 383-6. (in Chinese)

[14] Xiang Y, Zhang T, Sun Y. State-of-the-art report of the risk and its evaluation of bridge engineering abroad. *Journal of China & Foreign Highway* 2010; 4: 153-7. (in Chinese)

[15] Zhang T. Study on risk assessment system, method and application of Ling River Bridge. *Master's degree thesis of Zhejiang University*, 2010.

[16] Liu Y, Xie W. Summary of bridgework risk analysis method. *Urban road bridges & flood control* 2009; 4: 123-5. (in Chinese)

[17] Xiang Y, Liu C, Chao C, Liu H. Risk analysis and assessment of public safety of submerged floating tunnel. *Proceedings of First International Symposium on Archimedes Bridge*, Chun'an, China, 2010.

[18] Lin X. *Risk Analysis of SFT*. Master's degree thesis of Dalian University of technology, 2006.

[19] Hong Y, Li J, Liang N, et al. (Chinese Team of SIJLAB). *Report of Research and Design for Archimedes Bridge Prototype at Qiandao Lake, Institute of Mechanics, CAS*, 2007.

[20] Gan X, Yu W. The logistics system evaluation based on fuzzy analytic hierarchy process. *Proceedings of IEEE Computer Society*, Changsha, China, 2009.