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Risk analysis and assessment of public safety of Submerged Floating Tunnel

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Abstract

Based on the structural characteristics and preliminary design of submerged floating tunnel (SFT) prototype in Qiandao Lake, this paper gives the risk index system of public safety of SFT and risk assessment methods by analyzing different impact factors of SFT public safety. Moreover, the public safety risk is evaluated during construction and operation of SFT prototype in Qiandao Lake by the presented analytic hierarchy process method. The results show that in spite of facing many technical problems and potential risks, these potential risks of SFT can be controlled or reduced to a minimum level with the help of reasonable design and certain measures.

Keywords: submerged floating tunnel; public safety; risk analysis; risk assessment; analytic hierarchy process method

1. Introduction

The submerged floating tunnel (SFT), also called Archimedes's bridge in Italy, is a type of tubular structure that can float under water at certain depth and keep balance. The whole structure consists of the metal tubular segment or RC tubular segment (the internal space of tube is big enough to meet the requirement of traffic flow), the subaqueous foundation, the support system (the main function is to avoid large displacement of the tube), and the connecting structure which link the tube with land [1] . Because built and operated in the water, SFT has some advantages when compared with other types of bridges, for instance, the tiny influence on the environment, no obstruction for water traffic and all-weather operation. So SFT is suitable for connecting long strait and waterway which is longer than 1000m and deeper than 50m.

But the security of SFT is hugely affected by its surroundings and natural forces such as hurricane, earthquake, deluge (in lakes) ,as well as some common period forces such as ship drag force, wave force and tidal force during construction and operation. Therefore it is of great theoretical and engineering practical significance how to understand and identify the public safety risks in SFT and take measures to reduce these risks.

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Recently, some successful models for risk assessment have been presented, such as the HAZUS-MH system [2] in USA and TELES system [3] in Taiwan. In general, the theories and methods for risk analysis can be classified into two categories [4]: qualitative analysis and quantitative analysis. The main methods of qualitative analysis are as following: brainstorming, Delphi, fault tree analysis, FTA, influence diagram and so on. And the main methods of quantitative analysis are as following: Monte Carlo simulation method which was presented by S. M. Ulam and J. V. Neumann (1940), analytic hierarchy process (AHP) [5] proposed by T. L. Saaty (1975), then, W. S. McCulloch, W. Pitts together advanced the mathematical model of neural networks which later became artificial neuron network. One of the most popular methods in risk analysis is fuzzy comprehensive assessment [12] which first appeared in <Fuzzy Set> authored by U.S. control theory scholars-- LA Zadeh in 1965.

Based on existing researches and the structure characters of SFT, this paper adapts fuzzy AHP method which combines fuzzy comprehensive assessment with analytic hierarchy process (AHP) to identify the risk factors of SFT and build risk index system of SFT. So we could assess such risks and put forward measures to reduce public safety risks and provide a scientific basis for design and construction as well as risk management of SFT.

2. SFT in Qiandao Lake

2.1. Background of SFT in Qiandao Lake

The cooperation project between China and Italy, called "The preliminary study of SFT prototype in Qiandao Lake", began in 2005. Compared with some strait area, Qiandao Lake is a relatively calm lake. Qiandao Lake is located in Chun'an county of Zhejiang in China, which is in the area of Xin-an River reservoir. The maximum depth of the lake is 100m and the average depth is 34m. The maximum wave height is 1.0m, and the three wave periods are 1.3s, 1.8s, 2.3s with maximum flow velocity of water 0.1m/s, maximum flow acceleration is 0.1g. The common wind direction in Qiandao Lake is northwest, with frequency 12%, and maximum wind speed is 28.0m/s from southeast, According to local annual statistics, the average number of typhoon windy per year is 6.3, and the average number of typhoon days every year is 40, especially the typhoon days are up to 63 days in 1963 and the least is about 20 days in 1978. The typhoon often occurs in July. According to the seismic ground motion parameter zone dividing map of China, the basic design earthquake acceleration value is 0.05g in the area of Qiandao Lake, with relative seismic fortification intensity being 6 degrees. It belongs to grade 1 in design earthquake group, and the characteristic period of the seismic response spectrum is 0.35s.

The engineers and researchers of China and Italy are going to design and construct the first SFT prototype in Qiandao Lake in order to provide experience for analysis, design and construction of SFT in the future.

2.2. Preliminary design of SFT in Qiandao Lake

According to the design proposal of SFT prototype in Qiandao Lake [6, 7] given by Italy, the whole tubular segment consists of five standard modules, each 20m long, with total length 100m. The anchorage system adopts three couples of anchor cables, in which the two side anchor cables are vertical and the middle ones (No.3) are inclined along lateral direction. The cross-section of tube is a sandwich form: 10cm thick outer layer of aluminum alloy, 30cm thick middle layer of concrete, and 2cm thick inner layer of steel. The schematic diagram and cross-section diagram are respectively shown in Fig. 1 and Fig. 2.

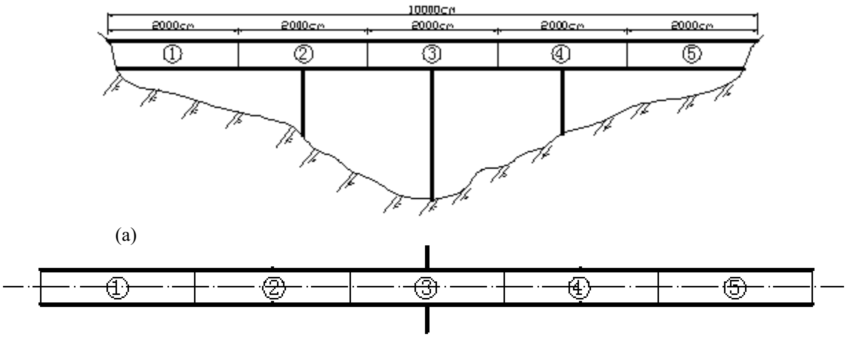

Fig. 1. (a) Elevation drawing of SFT prototype in Qiandao Lake; (b) Plain-view drawing of SFT prototype in Qiandao Lake

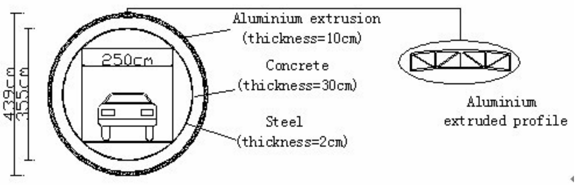

Fig. 2. Cross-section profile of SFT prototype in Qiandao Lake

3. Risk analysis of the public safety of SFT

3.1. The risk source analysis

Because submerged in the water, SFT as a new type of structure, is confronting with different public safety risks during its construction and operation compared with common bridges. SFT is also facing many challenges because there is still no mature specification or criterion for the relevant design and construction technology of SFT. Therefore, systematical risk analysis and assessment are needed according to local environment and structural characters. The risk sources of SFT prototype in Qiandao Lake and potential factors that may endanger public safety are shown in Fig. 3.

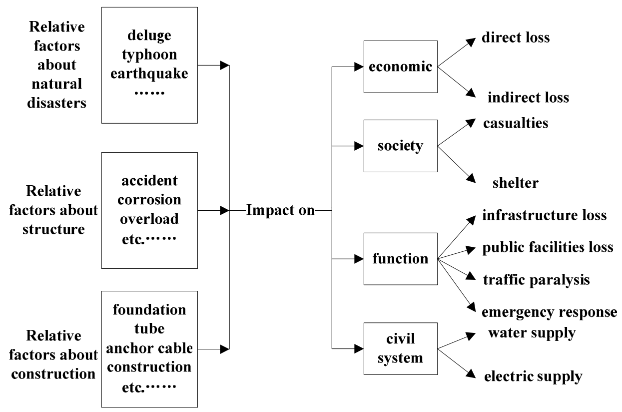

Fig. 3. Risk sources and potential factors of public safety

The natural hazard risks of SFT are as follows:

- **Deluge**: The water level in Qiandao Lake is usually between 95~103m (Yellow Sea datum level), and the highest level in history is 107.76m, while the lowest level in history is 82m. The water flow velocity is slow and the water level changes a little every year. When it comes to heavy rainfall, Qiandao Lake reservoir becomes very vulnerable to floods. The heaviest rainfall in recorded history at Qiandao Lake occurred in June 29~July 2, 1996, with the total rainfall of 417mm. The maximum flood peak flow volume recored in the last 28 years was 21332m^3/s [8]. The lateral stiffness of SFT is relatively small compared with its length, the accelerating flow makes SFT larger swing in side direction in the case of flood discharge and forces SFT to produce greater displacement. It threats the safety of the structure.
- **Typhoon**: According to meteorological data in Qiandao Lake, typhoon often landed at Qiandao Lake in July and August every year and leaded to produce relative disasters. The water waves caused by the typhoon make just tiny effects on SFT because SFT is usually placed at 10m or more than 10m under water surface, and the wave force is decreasing exponentially with depth. Although typhoon action on SFT structure is tiny, we should also consider secondary disasters caused by typhoon, such as landslide and slope failure.
- **Earthquake** [10] : There are no active fracture zones and phenomenon of other unfavorable geological configuration in the region of the location of SFT prototype in Qiandao Lake. The corresponding seismic fortification intensity is only six degrees. So, it doesn't need seismic resistance design. In general, the probabilistic risk of earthquake is relatively low. The site soil in the reservoir area belongs to hard clay and the construction site is classified in category II and resistant seismic design in class I, which means it is in region of unfavorable resistant seism. The main effect of earthquake to SFT includes forced vibrations caused by subsoil's vertical and horizontal shake. These may lead to local damages in SFT such as foundation damage and anchor cable failure, which can threaten the whole SFT structure in its underwater environment. So earthquake will bring about big losses once it happens.
- **Landslide**: The construction area of SFT in Qiandao Lake is hilly area where the vegetation is full and the slope is moderate. The direction of alongshore rock is basically coincident with the direction of slope, not forming out-sloping bed-parallel. The natural bank slope is fairly stable. But landslide would have great impact on the connection between tube and land.

The operation risks for SFT in Qiandao Lake are following:

- **Fire**: Just like tunnels, SFT also has many similar problems such as long distance, humidity, poor ventilation and so on. The air pollution caused by vehicles is very serious in SFT. When fire happens in the SFT, the heavy smoke and heat caused by burning are hard to discharge and finally threat trapped persons' life. Meanwhile, it also increases the safety risk if there are no special escape ways in the structure.
- **Traffic accident**: SFT is an enclosure space under water, it would be very difficult to take rescue work when traffic accident occurs. It may cause great casualties and economic losses. What's more, traffic accident would also trigger other problems, such as fire and dangerous goods leakage.
- **Water leak**: Waterproofing is also the key point for safety of SFT, because water leak could lead to the public a tremendous psychological fear. Once the leakage occurs, the great pressure water would make leakage further increase. The reliability of waterproof is very important. Connection of tube and construction detail of waterproof should be carefully treated.
- **Overload**: The risk of overload is relatively small, but overloading can lead to structural damage.
- **Environmental impact**: The average visibility of water in Qiandao Lake reaches to 5m, according with the first national water quality standard, so the environmental erosion is very small.

The construction risks of SFT can be separated into foundation construction, tube construction, anchor cable construction and ancillary facility construction [10] . When constructing SFT structure, first, the tube section should be prefabricated at the boatyards near the construction site, and then sealed at both ends by bulkhead. Next; the section can be towed to assigned position by tugboat. The anchor cable installation and deep water pile foundation construction should have in advance been carried out. Once the segment is at assigned position, the floating crane fixed by four wire ropes which are anchored at the lakebed controls the segment of SFT and lets it down to the preset position by special buoyancy balance system. After the sinking, this segment can be connected to previous one. Finally, the bulkhead is removed and waterproof at the connection should be done, and the other ancillary facilities are installed.

3.2. Risk index system of SFT

It is the key to risk assessment for public security of SFT that establishing the risk index system which not only should include operational public security risk, but also comprise other risks in SFT's whole life cycles, such as constructional public security risk and hazard public security risk. According to above risk source analysis, the risk index system of SFT has three layers: top index, medium index and bottom index, as shown in Fig. 4.

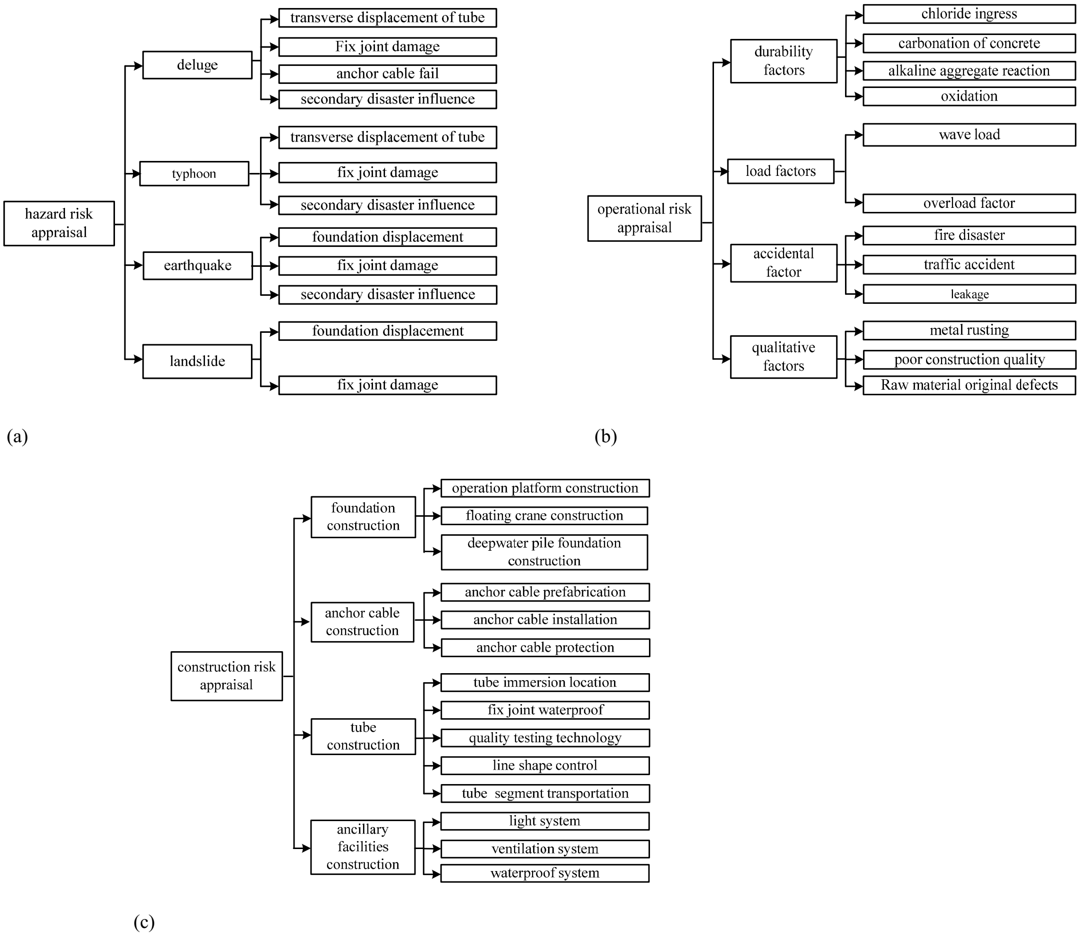

Fig. 4. (a) Risk index system of SFT hazard; (b) Risk index system of SFT Operation; (c) Risk index system of SFT construction

3.3. Risk assessment method

Using Fuzzy AHP Method (FAHP) [11] to identify the risk factors of SFT, when confirm index set of risk factors, we can get the degree of membership between each two bottom index belonged to one medium index by expert investigation and establish fuzzy consistent matrix. Then, we can confirm each bottom and medium index factor's weight by AHP method. The bottom index weight vectors are as follows:

$$w_k = \left[w_{l1} \; w_{l2} \;\; \cdots \;\; w_{ln} \right] \tag{1}$$

where w_{li} is the weight of i^{th} bottom index calculated by AHP method. Accordingly, we can also obtain the middle index weight vectors:

$$w_m = \left[w_{m1}\ w_{m2}\ \cdots\ w_{mt} \right] \tag{2}$$

where w_{li} is the weight of i^{th} medium index calculated by AHP method.

Then, the probability of bottom index risk factor T may be determined by statistics and experts integrated method. The specific values are as follows:

$$T = \left[\text{very low-}V\ \ \text{low-}IV\ \ \text{medium-}III\ \ \text{high-}II\ \ \text{very high-}I \right] \tag{3}$$

Table 1. Standard of probability evaluation of risk factors

Probability description	V—very low	IV—low	III—medium	II—high	I—very high
Probability interval	P<10-6	10-3>P>10-6	10-2>P>10-3	10-1>P>10-2	P>10-1
grade	first-class	second-class	third-class	forth-class	fifth-class

Then, the suitable index membership R should be selected correctly as we use semi-trapezoid distribution in this paper:

$$r_{ij} = \begin{cases} 1 & x_{ij} \le a \\ \dfrac{b - x_{ij}}{b - a} & a < x_{ij} < b \\ 0 & x_{ij} \ge b \end{cases} \tag{4}$$

where r_{ij} means the degree of membership which the i^{th} bottom index corresponding to the j^{th} risk probability. The x_{ij} is the absolute quantity of i^{th} risk probability in [0, 1] distribution. The constant a and b represents the maximum and minimum value of probability interval which i^{th} bottom index is belonged to.

After determining every r_{ij} of one medium index K, we can establish the membership relational matrix R_k:

$$R_k = \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} & r_{15} \\ r_{21} & r_{22} & r_{23} & r_{24} & r_{25} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ r_{n1} & r_{n2} & r_{n3} & r_{n4} & r_{n5} \end{bmatrix} \tag{5}$$

Then, using the aforesaid weight of medium index factor w_k and membership relational matrix R_k, the fuzzy evaluation set of medium index can be calculated by fuzzy mapping:

$$B_k = w_k \circ R_k = \left[w_{l1}\ w_{l2}\ \cdots\ w_{ln} \right] \circ \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} & r_{15} \\ r_{21} & r_{22} & r_{23} & r_{24} & r_{25} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ r_{n1} & r_{n2} & r_{n3} & r_{n4} & r_{n5} \end{bmatrix} = \left[b_{k1}\ b_{k2}\ b_{k3}\ b_{k4}\ b_{k5} \right] \tag{6}$$

where "$\circ$" is a fuzzy composition symbol and b_{ki} can be solved by the specific operation: $b_{ki} = \max\left[\min_{j=1}^{n}\left(w_j, r_{ji} \right) \right]$. The physical interpretation of b_{ki} is the weight that medium index K having i^{th} risk probability.

Further, the fuzzy evaluation set of top index can also be obtained by using matrix multiplication:

$$B = \begin{bmatrix} w_{m1} & w_{m2} & \cdots & w_{mt} \end{bmatrix} \cdot \begin{Bmatrix} B_1 \\ B_2 \\ \vdots \\ B_k \\ \vdots \\ B_t \end{Bmatrix} = \begin{bmatrix} b_1 & b_2 & b_3 & b_4 & b_5 \end{bmatrix} \tag{7}$$

where b_i is the weight that top index have i^{th} risk probability. We can comprehensively evaluate the risk probability by the Eq. (7).

We can also define set of risk probability reviews as V= {neglected, low, medium, severe, extremely severe}; and set of risk probability scores $G = \{0.15, 0.35, 0.55, 0.75, 0.95\}$. Let $P=V*B$, in which we define P as the overall score value of top index. P can be classified as follows:

Table 2. Risk classification

Risk level	Extremely high	High	Medium	Low	Extremely low
Score interval	1.0~0.8	0.8~0.6	0.6~0.4	0.4~0.2	0.2~0.0

The specific process of SFT risk assessment can follow standard assessment procedures.

3.4. Risk assessment of SFT prototype in Qiandao Lake

Following above mentioned risk assessment method, the analysis results of hazard risk, constructional risk and operational risk of SFT prototype in Qiandao Lake are as follows:

- Combining with particular case in Qiandao Lake, every judgment matrix of index can be determined by expert investigation and related references [12] . Then preliminary weight of each index in all levels can also be determined by AHP method.
- Next, based on further consulting experts "advice", we can obtain the modified membership relational matrix: $R_k = [r_{ij}]_{m \times n}$
- The fuzzy evaluation set of each medium index B_k can be determined through the fuzzy composition. Furthermore, the fuzzy evaluation set of top index B can also be calculated, and then let $P = V * B$. We can judge the risk level of each top index by referring to risk classification.

As space is limited, this paper only gives the fuzzy evaluation set of top index B_k and overall score value P:

The fuzzy evaluation set of hazard risk of SFT is as follows:

$$B = \begin{bmatrix} 0.3470 & 0.2203 & 0.1630 & 0.1891 & 0.0902 \end{bmatrix} \tag{8}$$

The overall score value P=0.4462, which belongs to medium level. Some relevant strategy to control the risk should be considered.

The fuzzy evaluation set of operational risk of SFT is as follows:

$$B = \begin{bmatrix} 0.1253 & 0.1601 & 0.3063 & 0.2351 & 0.1742 \end{bmatrix} \tag{9}$$

The overall score value P=0.5851, which also belongs to medium level but much higher. We should give efficient ways to control risk.

The fuzzy evaluation set of constructional risk of SFT is as follows:

$$B = \left[0.1541\ 0.1333\ 0.1764\ 0.2641\ 0.2721\right] \qquad (10)$$

The overall score value P=0.6234, which belongs to high level. We can conditionally accept some corresponding risks and give protective measures to mitigate and reduce risks.

4. Risk control of SFT in Qiandao Lake

The meaning of risk control is to minimize the risk loss through prior treatment and process control according to the result of risk assessment. Aiming at SFT in Qiandao Lake, the risk control measures can also be taken by three aspects as follows:

- Corresponding to the natural hazard risk of SFT in Qiandao Lake, we should put forward reinforcement and protection methods against hazard under the construction of SFT to improve capacity of disaster prevention. In the one hand, we should establish the system of hazard monitoring and hazard early warning as well as hazard database of SFT project site, which includes hazard's type, duration, destructive degree and repair measures. On the other hand, the mechanism research of structure damage caused by hazard, nonlinear elastic-plastic analysis by using computer simulation technology and some control technologies and methods of SFT should be carried out.
- Corresponding to the operational risk of SFT in Qiandao Lake, not only should we improve the SFT disaster prevention and relief system, but also ensure SFT facility integrity including smooth line shape, explicit traffic indicator sign and adequate ventilation as well as lighting system. Meanwhile, we may also research the influence of longitudinal ventilation on working fire and smoke emission. The comprehensive set emergency evacuation system are considered and designed, such as special evacuation channel.
- Corresponding to the constructional risk of SFT in Qiandao Lake, we should consider the combined action between structure and environment in each construction stage. The control section's structure parameters during the construction of SFT, such as strains and stresses should be monitored in time in order to guide construction and guarantee the constructional reliability of SFT structure.

5. Conclusions

SFT is a new type of innovative structure which has great application prospect. It is different from traditional bridges or tunnels. Although SFT is still facing so many technical problems and potential risks, these risks can be minimized to lowest level with the help of proper measures and suitable designs. It is possible to build a good SFT.

Combining with the characteristic of SFT structure and the preliminary design for SFT in Qiandao Lake, this paper presents the risk index system and risk assessment method for SFT. The potential natural hazard risk, constructional risk and operational risk for SFT are evaluated. Moreover, it provides several protective methods and measures to control or reduce the risk. It contributes to a better understanding public safety risk of SFT.

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