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FEASIBILITY STUDY ON THE SUBMERGED FLOATING TUNNEL IN QIONGZHOU STRAIT, CHINA

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ABSTRACT

Abstract: Currently, one of the challenging tasks for Chinese engineering community is to construct a water-way crossing of Qiongzhou Strait in the south of China. This project has also gained significant attention from researchers in academia. The study presented herein is centered on providing a feasible solution for ac-complishing the above mentioned task. Initially, different alternatives as the best location, judged on the basis of the environmental constraints, are studied. Then the comparison between various structural solutions such as suspension bridge, submarine tunnel and SFT is presented. Among these solutions, SFT appears to be a very suitable alternative for Qiongzhou Strait waterway crossing due to distinctive advantages, like shorter distance, lower cost, less impact on environment and navigation, etc. Based on the appropriate conception for cross sections, support systems, materials, joints and connection schemes, a numerical model is developed by means of the FEM software ANSYS/Fluent. It is then analyzed under the influence of different environmental loading conditions, varying the wave heights and lengths, current velocities and water depths, which are typical in Qiongzhou Strait. The numerical results reveal that the proposed SFT solution performs safely even under extreme weather conditions.

Keywords: Submerged Floating Tunnel, Qiongzhou Strait, waterway crossing, design features, numerical analysis

INTRODUCTION

In the last two decades, several proposals for waterway crossing have been carried out in China due to the demand of traffic and development of civil engineering technology. For example, crossings of Bohai Strait, Taiwan Strait, and Qiongzhou Strait are frequently discussed at present. On the other hand, the successful experiences of such waterway projects as Hangzhou Bay Bridge, Qingdao Jiaozhou Bay Submarine Tunnel, Xiamen Xiang'an Submarine Tunnel, and Hong Kong-Zhuhai-Macau Bridge have greatly increased the enthusiasm and confidence to make true the dreams.

Qiongzhou Strait is located in the south of China, between Leizhou Peninsula and Hainan Island. Since 1980s, the local government started to investigate the feasibility for a Qiongzhou Strait waterway crossing, and relevant research about this topic still keeps going even up to now. Tan et al. (2001) investigated the feasibility to construct an undersea tunnel by means of the shield method for Qiongzhou Strait waterway crossing. Mai et al. (2003) analyzed the feasibility SFT in the Qiongzhou Strait in view of the environmental conditions, design schemes, construction, and cost. Li et al. (2009) studied the feasibility to design a cable-stayed submerged floating tunnel in the Qiongzhou Strait. Yan et al. (2015) provided several proposals for SFT schemes in Qiongzhou Strait. Wu et al. (2016) studied on the significant aspects for type selection of SFT in the Qiongzhou Strait.

In this article, the environmental conditions of Qiongzhou Strait are introduced firstly, including the alternatives of locations and solutions for crossing. Analyzed next are the characteristics of bridge, submarine tunnel, and submerged floating tunnel (SFT) solutions. According to the comparisons, the central line and SFT are selected for location and solution of the Qiongzhou Strait waterway crossing respectively. Furthermore, several proposals for SFT basic aspects are made, and numerical analyses based on Qiongzhou Strait conditions are investigated, so as to verify the feasibility and stability of the proposed SFT.

GENERAL CONDITIONS OF QIONGZHOU STRAIT

GEOLOGICAL AND WEATHER CONDITION

The Qiongzhou Strait is one of the largest three straits in China. Its geological and weather conditions can be summarized briefly as following.

The length is about 80 kilometers from east to west, and the width ranges from 18 to 35.5 kilometers (29.5 km on average) from north to south. Its seabed is generally wide and deep, with the water depth ranging from 80 meters to 120 meters along the central axis. In addition, scraps with a maximum height of 70 meters and a maximum slope angle of 22°–24° are located on the south and north shores.

Fractures are the major geological structure. The submarine strata are mainly sedimentary shaped in the Tertiary and Quaternary Periods. The upper layer is filled with sludge, sandy clay or silt, and thick-bedded clay and silty sand are distributed on bottom layer with thickness of hundreds meters.

According to statistics, about ten ruinous earthquakes have occurred in this area, nine of which are over 6.0 in magnitude. The most serious earthquake occurred in the year of 1605 with a magnitude of 7.5. All of them are shallow earthquakes with the majority depth of focus ranging from 5 to 20 kilometers. Besides, there is no records about volcano in this area.

The average annual temperature is 24°C. From May to October is the rainy season, and the average annual precipitation is more than 1500 ml. From May to November is the typhoon season of the Qiongzhou Strait, especially in September.

ALTERNATIVES OF LOCATION AND SOLUTION

Alternatives of location

According to careful investigations and evaluations, several proposals of locations for waterway crossing in Qiongzhou Strait are put forward by some researchers. In general, they can fall into three lines: the east line, the central line, and the west line, as shown in Figure 1.

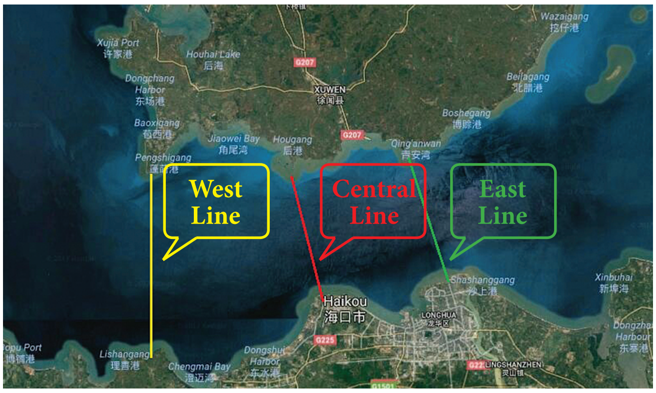

Fig. 1. Proposed lines for Qiongzhou Strait crossing

The East Line. The location is characterized by the complex topography, large water depth, and high risk of earthquakes. Because the connection point of this line on Hainan Island is far away from Haikou, the capital city of Hainan Province, it is inconsistent with the development plans of this city. It would bring more disadvantages than advantages to the city and even the province if constructed as proposed.

The Central Line. Straight line with a short waterway crossing distance, connected conveniently with the existing highways and railways at both shores. The main advantages of this line include low investment for both the main and lead projects, shorter travel time, and low operation cost. Therefore, it can well meet the requirements of the city planning. One fact should not be denied, however, which is the maximum water depth of 88 meters in this location.

The West Line. Compared with the other lines, its seabed is more flat, as the maximum water depth is only 55 meters, but the distance of waterway crossing is larger. It is farther away from the existing highways and railways at both shores, so the investment for the main project and lead projects will increase. In addition, this line has to avoid crossing the nature reserve in this area, which may cause more obstacles in construction.

Among the three lines, the central line is the most appropriate location for the waterway crossing due to its shorter distance and better geological conditions compared with the others. Therefore the central line is selected in this article, and the studies hereafter are based on this location.

Alternatives of solution

On the central line location, some solutions for crossing are proposed. In general, they can be summarized as in Figure 2.

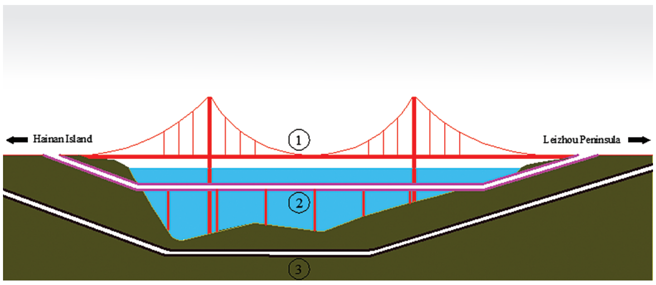

Fig. 2. Alternatives of solution: 1) Suspension bridge; 2) Submerged Floating Tunnel; 3) Submarine tunnel

Of all types of bridges, suspension bridge is the longest in span. Thus a suspension bridge is a good solution of all bridge alternatives, especially in dealing with long-distance waterways. A Submerged Floating Tunnel (SFT) is an innovative underwater structure, applied for waterway crossing in particular case of long distances. Submarine tunnels include immersed tunnels and subsea tunnels, both of which have been applied for many waterway projects. For all the advanced technical and sufficient experiences, a submarine tunnel is not suitable for seabed of bad geological conditions.

COMPARISONS AMONG SOLUTIONS

BRIDGE

Advantages

Advanced technology of design and construction

The hydrological, meteorological, geological and navigational conditions of the Qiongzhou Strait are complicated, and therefore it is difficult to construct a bridge in the large-depth zone. At present, the longest span of suspension bridges is found in the Akashi Bridge, whose main span reaches 1,991 meters. China has rich experience in construction of long-span bridges, such as the Zhoushan Xihoumen Bridge (1,650 meters, 2009), the Runyang Yangtze River Bridge (1,490 meters, 2005), and the Jiangyin Yangtze River Bridge (1,385 meters, 1999). In the central line location aforementioned, it is feasible to construct a multiple spans bridge with a single span of over 1,000 meters. Although the construction of piles is very difficult, the problems can be solved by means of updated construction technology.

Better traffic conditions

Compared with tunnels, it is undoubtedly much better in lighting, ventilation, vision, comfort and so on when the vehicles are running on the bridge.

Easier and more economical maintenance

After operation for public transportation, the bridge requires less expense on lighting and ventilation compared with tunnels. In addition, the bridge is easier for maintenance service.

Disadvantages

Higher expense of construction

The central line is around 20 km in length. If the bridge is designed with single spans for about 1,000 meters, it will need about 20 piles and foundations. The average water depth is over 50 meters, so it is more difficult to construct the piers and foundations in these areas, and the cost is high. On the other hand, the height of the main tower of the bridge will increase as the length of single span extends.

The critical length of spans can be estimated under different materials of cables. If only the self-weight of cables is taken into account, the relationship between the critical length of span (Lc) and the height of the main tower (h) is obtained as in Figure 3.

HSS: High strength steel (Density: 7850 kg/m³; Elastic modules: 1000 MPa)

LSS: Low strength steel (Density: 7850 kg/m³; Elastic modules: 300 MPa)

FRP: Fiber reinforced polymer (Density: 1800 kg/m³; Elastic modules: 290 MPa)

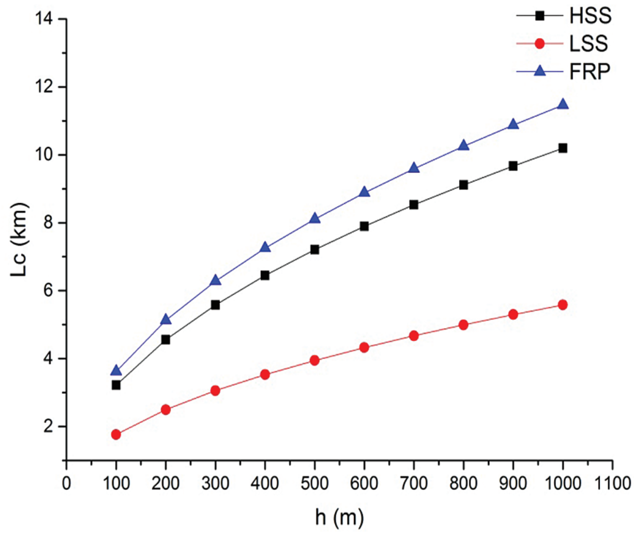

Fig. 3. Relationship between height of tower and critical length

Figure 3 shows that if HSS is selected for the cable material, when the single span reaches 5,000 meters, the height of the main tower will exceed 1,000 meters. In this case, the tower will become the tallest of its type in the world. For this reason, the design and construction of the foundation would be very complicated, but the current technology and economy can hardly support such a height.

Affected by weather

The Qiongzhou Strait is located in a tropical area which is subject to the tropical monsoon climate. Every year, the period from May to November is typhoon season. Every year, in particular, there are more than 5 days in September when the wind force is stronger than Level 8. Besides, there are more than 24 days with dense fog on average every year. Because the bridge is directly exposed to the natural environment, the traffic condition is affected largely by weather conditions. In case of strong wind, heavy fog, or other inclement weather conditions, the safety of vehicles would be reduced inevitably, or what's worse, the traffic will be interrupted due to serious weather conditions.

Impact on surroundings and navigation

The Qiongzhou Strait is a busy sea crossing. If the bridge proposal is accepted, the piers of the bridge will have impact on the navigation of ships. In addition, the height from the deck to the water surface will limit big ships from crossing the strait. Moreover, the tall main tower resulting from the long-span bridge will affect flights.

Security during war time

The bridge project will be the most effective and convenient in connecting China Mainland and the Hainan Island when open to the public. Hence the security of this kind of huge projects should be considered at the beginning phase of design. If war should happen one day, this bridge would be destroyed soon by the enemy. Moreover, it is also an easy target of terrorist attacks even during peace time.

SUBMARINE TUNNEL

Advantages

Advanced technology of design and construction

Over the past years, the world has seen great improvements in the technology of submarine tunnel design and construction. Several submarine tunnels have been completed in the past decades, such as the Seikan Tunnel (Japan, 1988) and the Channel Tunnel (Great Britain–France, 1994). In China, researchers have also obtained experiences from some subsea tunnel projects, such as the Xiamen Xiang'an Subsea Tunnel (2010) and the Qingdao Jiaozhou Bay Tunnel (2011). At present, the Hong Kong-Zhuhai-Macao Bridge is under construction in China, it will be completed in December, 2017. More construction experiences could be gained. Therefore, it is feasible in view of design and construction, according to the experiences from home and abroad.

Guarantee of crossing

The submarine tunnel can provide all-weather services, as the weather has slight influence on vehicles crossing.

Less impact on the environment

Compared with a bridge, a submarine tunnel has far less impact on the environment due to its location.

Disadvantages

Large buried depth and long distance

On the middle line, the maximum water depth is around 85 meters. According to the construction experiences of existing submarine tunnels, the buried depth of such a submarine tunnel in this location will be over 100 meters. In order to meet the slope requirement, the submarine tunnel should be extended to land with a long distance. It is estimated that the minimum distance of the submarine tunnel will reach 30 kilometers, and for certain the cost of construction will increase.

High requirements for geological conditions

A submarine tunnel needs to meet higher requirements for geological conditions. Due to some uncertain factors that could exist in the formation, it will result in large investment, high risks and a long construction period. In Japan, the Seikan Tunnel costs 24 years to complete the construction, during which there were 4 big accidents of landslides and water gushing. The most serious water gushing accident occurred in the Hokkaido side parallel heading in May 6, 1976, when the water inflow hit 70 m^2/min. It consumed 5 months to bypass the water gushing area.

The Qiongzhou Strait consists of several groups of fractures: the East-West fracture, the North-East fracture, and the North-West fracture. Due to the net-structural frameworks fractures, landslide and water gushing accidents will almost inevitably occur during the construction and operation.

Higher expense of maintenance

During operation, the cost on lighting, ventilation and other maintenance aspects will be higher than those of a bridge.

Larger losses under disasters

As previously mentioned, the Qiongzhou Strait is located in a seismic region, so the subsea tunnel would suffer catastrophic damages in case of an earthquake. Once a disaster happens, the water will flow into the subsea tunnel from some partial failures due to high water pressure. As a consequence, the tunnel could never be repaired. According to records, this region had thirty-one earthquakes of above magnitude 4.75 from year of 1400 to 1995, including nine earthquakes of above magnitude 6.0. In 1605, an earthquake of the highest magnitude (7.5) occurred in Qiongshan. Two magnitude-6.1 earthquakes occurred in the Northern Gulf in December 1994 and January 1995, respectively. All these indicate that the southeast coastal area tends to enter a period of active earthquakes.

SUBMERGED FLOATING TUNNEL (SFT)

Advantages

Shorter distance

From the above figures, it is clear that the distance of the submerged floating tunnel is the shortest, for it does not need to consider the slope.

Less influence on surroundings and navigation

The underwater SFT has less influence on the surroundings. Besides, the gap between the SFT and the water surface can guarantee the security of navigation.

Lower cost

The unit cost of the SFT is constant, whereas the cost of the suspension bridge and the submarine tunnel will increase rapidly as the span increases.

Stronger resistance and easier escape

Compared with a bridge or a submarine tunnel, SFT has better performance in resisting earthquakes. Because the foundations of a bridge or a submarine tunnel are under the seabed, they will suffer big influence when an earthquake occurs undersea. In contrast, an escape route could be designed as an extra structure of the SFT, from where passengers can escape in a short time when an accident happens.

Disadvantages

Construction of foundation

The cables will need a foundation, and the requirement of such a foundation is strict and important.

Less experience on construction

So far, no SFT project has been constructed due to many reasons. In this case, the lack of relevant construction experience is a big challenge.

PROPOSALS FOR SFT IN QIONGZHOU STRAIT

GENERAL ASPECTS

Compared with a bridge or a submarine tunnel, SFT is the most suitable solution for the Qiongzhou Strait waterway crossing due to its distinctive advantages, such as shorter distance, lower cost, less impact on environment and navigation, etc.

The Qiongzhou Strait is a busy shipping way. In order to satisfy the requirement of navigation space for big vessels and reduce the impact from the water surface wave, the clearance depth between the water surface and the submerged floating tunnel is proposed to be 30m. (Xiang et al. 2017).

Based on the geological condition of the central line and the requirements mentioned above, the longitudinal profile for the proposed SFT is shown in Figure 4.

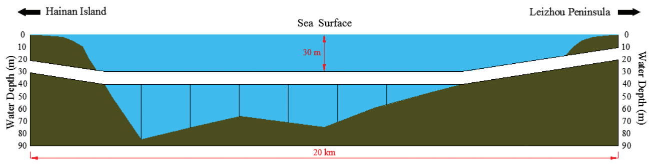

Fig. 4. Longitudinal profile of proposed SFT on central line

CROSS-SECTION

First of all, the cross-section of the proposed SFT should be confirmed. In this paper, only the type of motorway traffic is considered. Compared with other cross-sections, circular or elliptical cross-section has a better performance in the aspects of hydrodynamic behavior, space utility, fabricate convenience, etc. In addition, considering the workability and durability of fabrication and erection, the circular cross-section is confirmed eventually.

According to the clearance space requirements for traffic lanes in the Code for Design of Road Tunnel (JTG D70-2004, in Chinese), we combine the above-mentioned considerations and propose the following circular cross-section with dimension (external diameter: 14.0 m, internal diameter: 12.0 m) as illustrated in Figure 5.

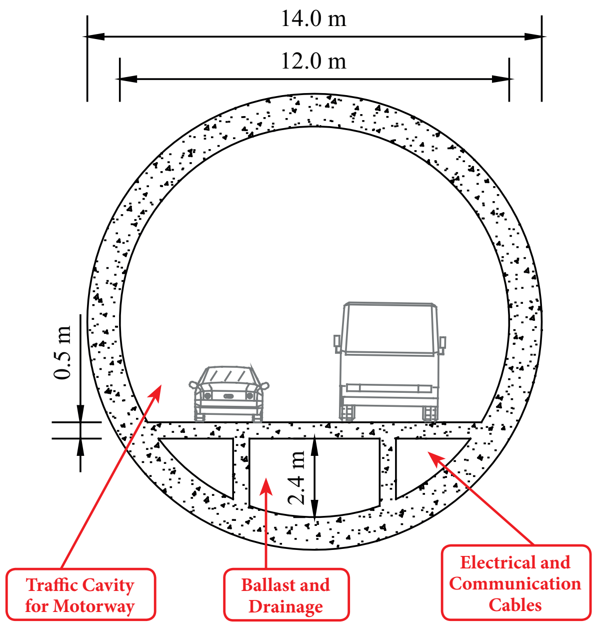

Fig. 5. Schedule of circular cross-section (Unit:m)

SUPPORT SYSTEM

Among all the support systems of the SFT, obviously free and pontoons support is not suitable for the long distance and busy navigation in the Qiongzhou Strait. In addition, with the various fractures distributed on the seabed, column support is also not appropriate solution yet. Based on the geological condition of the Qiongzhou Strait, cables support is a more reasonable alternative for the proposed SFT, which is more popular in design of most SFT prototypes nowadays.

In order to control the displacement induced by the environmental loads, either in the horizontal or vertical direction, the inclined configuration of four cables into a group is proposed as in Figure 6.

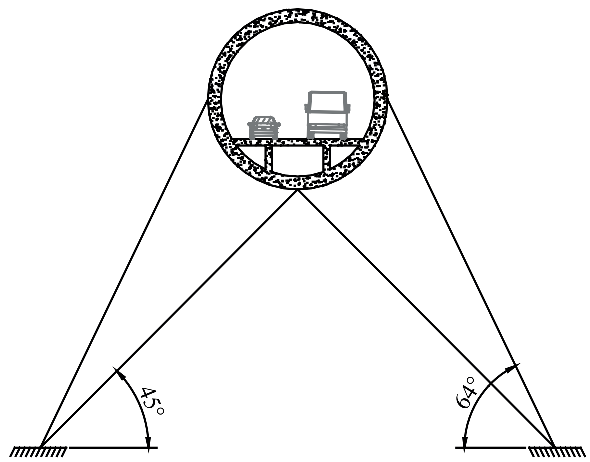

Fig. 6. Proposed inclined configuration of cables

MATERIALS

The appropriate selection of materials is one important decision for any projects, the design and execution of the SFT in particular. On the other hand, the marine structures have distinctive requirements for the materials.

Reinforced concrete is used widely in maritime structures and particularly recommended when a large structural weight is required to stabilize the structure. It can be used to contribute to the structural strength and stiffness, as well as to provide the weight needed to counteract the tunnel buoyancy. Bring references from Immersed Tunnel, reinforced concrete can be proposed for tube material of SFT, but the SFT structure must be guaranteed to have the excellent capacity of water-proof via concrete itself and coating material.

Besides, steel strands are proposed for the material of cables. The cables will be subjected to tremendous and reduplicated tension forces, and steel strands can provide high strength and high resistance to corrosion and fatigue.

JOINTS AND CONNECTIONS

Like an immersed tunnel, the SFT construction process includes the fabrication and installation of modules. In this process, the inter-module joints and the shore connections will play a significant role in the whole SFT structure.

In general, the inter-module joints either of a flexible or rigid type, must satisfy the requirements of tightness, durability and workability. The shore connections should allow different types of displacements, such as longitudinal, vertical, horizontal, or tensional displacements, which depends on design (Panduro, 2013).

The SFT is to be suspended in the water and can be subjected to significant displacements and rotations in the longitudinal bending planes. In this case, rigid inter-module joints are more suitable than flexible ones. In addition, the axial displacements are allowable at the terminal joints due to thermal variations and triaxial rotations (Martire, 2010). Therefore, rigid joints are proposed for the inter-module joints of the Qiongzhou Strait SFT.

The connection between the SFT and the shore requires appropriate interface elements to couple the flexible water tunnel with the much more rigid tunnel bored underground. This connection should be able to restrain tube movements, without any unsustainable increase in stresses. Furthermore, the joints must be watertight. In particular, the Qiongzhou Strait is located on the seismic area, so the risk of submarine landslides needs additional attention.

Moreover, the longitudinal gradients of the underwater tunnel should be taken into account. Because the SFT should keep straight on the longitudinal direction, the longitudinal gradients cannot be ignored. The length of the bored tunnel is closely related to the cost of the entire project, so it should be implemented by appropriate gradients. From the regulations of longitudinal gradients specified in different codes as shown in Table 1 (Zhang et al. 2013), the longitudinal gradients of a bored tunnel are proposed to range from 0.3% to 3%. The aim of the variable gradients is to connect the two smoothly and reduce the entire length.

Tab. 1. Regulations of tunnel longitudinal gradients specified in different codes (Zhang et al. 2013)

Codes	Tunnel longitudinal gradients
P.R China (MOT. JTG D70-2004 Code for design of road tunnel)	0.3%–3%, maximum 4% depends on traffic conditions
European Union (DIRECTIVE 2004/54/EC)	Normal is less than 5%, it needs assistant measures between 3% and 5%.
United States (FHWA Road Tunnel)	Recommended less than 3%–4%
Great Britain (Design code for Road and Bridge)	Depends on traffic and ventilation requirements, should be less than 6%
Norway (NPRA Motorway Tunnel)	Maximum gradient depends on traffic, normal between 6%–8%
Sweden (VV Tunnel 2004)	Normal less than 5%, it can be increased in short distance permitted by experts
Netherlands (SATO)	Design speed 90 km/h, less than 4%; design speed 120 km/h, less than 3%.

NUMERICAL ANALYSES

On the basis of the aforementioned design aspects, the numerical model scheme is created as in Figure 7, with some basic parameters selected from Table 2.

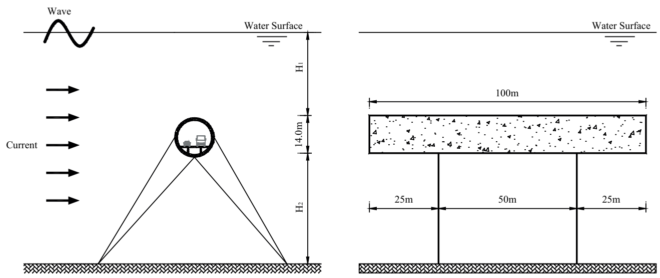

Fig. 7. Geometry of numerical model

Tab. 1. Regulations of tunnel longitudinal gradients specified in different codes (Zhang et al. 2013)

Parameters	Values	Units
Density of tunnel	2500	Kg/m³
Elastic modules of tunnel	32x10³	MPa
Density of cable	7850	Kg/m³
Elastic modules of cable	201x10³	MPa
Diameter of cable	0.3	m
Density of Fluid	1028	Kg/m³

The numerical model is implemented by means of the FEM software ANSYS/Fluent, in which process the Airy wave and RNG $k - \varepsilon$ viscous mode are applied for simulating the wave and turbulence, respectively. Only displacement and rotation along direction Z are restrained at both ends of the tube. Spherical hinges have been assumed at both ends of the cables. In order to reproduce the full turbulent phenomenon in the water volume, the distance from the inlet upstream side has been assumed equal to 3D (D width of the polygonal section = 32.3 meters). Likewise, a distance of 10D has been set so as to fully reproduce the wake turbulence that takes place downstream the tunnel. The width along direction Z is set to 100 meters, and so is the length of tube. The depth of the entire fluid volume varies depending on the location of the proposed SFT. The hexahedron elements are applied for meshing the fluid and tube.

Concerning traffic loads, only motorway traffic loads are considered in this numerical model. According to the Chinese code (MOT. JTG D70-2004 Code for design of road tunnels), the traffic loads are defined as distributed loads of 10.1 kN/m².

To investigate the variable loading conditions subjected to the SFT, different cases are adopted:

1) Different water depths. In Figure 7, H_1 is fixed as 30 meters, while H_2 is changed for 40 meters, 30 meters, and 20 meters according to different geological conditions of the seabed;
2) Different wave loads. According to the monitoring data in the Qiongzhou Strait, the extreme wave loads are selected. The extreme wave conditions include:
   Return period of 20 years: Wave height 7.0 meters, Wave length 115.11 meters.
   Return period of 25 years: Wave height 7.3 meters, Wave length 119.45 meters.
   Return period of 100 years: Wave height 8.6 meters, Wave length 137.38 meters.

3) Different current velocities.
1.0 m/s, 2.0 m/s, 4.0 m/s

Displacement responses (Ux and Uy) of the SFT structure are investigated based on the aforementioned parameters and cases. The results are presented in Figures 8–10.

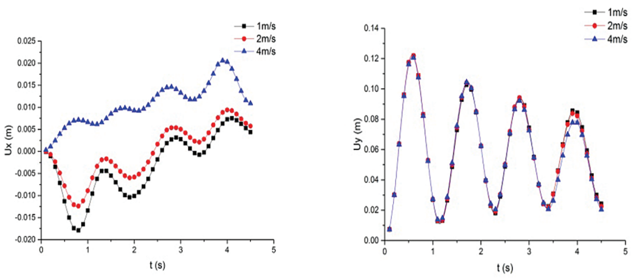

Fig. 8. Displacement response under different current velocities (H2:40 m, Wave height: 7.0 m)

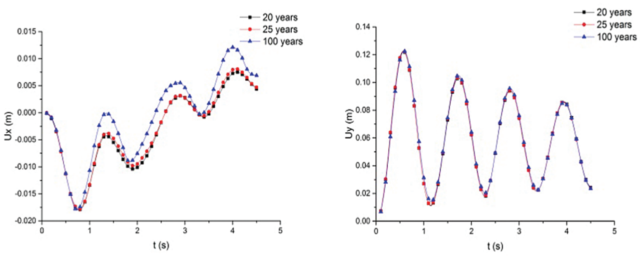

Fig. 9. Displacement responses under different waves (H2:40 m, current velocity: 1.0 m/s)

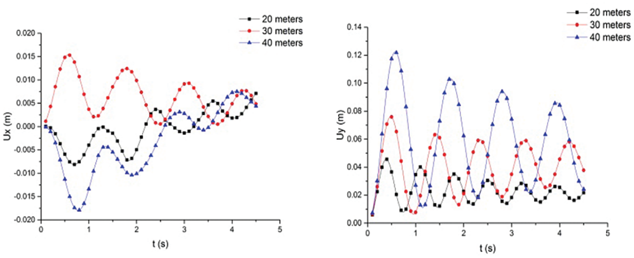

Fig. 10. Displacement responses under different water depths H2 (wave height: 7.0, current velocity: 1.0 m/s)

According to Figure 8 and 9, the maximum amplitude of displacement responses (Ux and Uy) enlarge as the current velocity and wave height increase. In Figure 10, it shows that the SFT structure is more stable while the H_2 depth decrease. However, the displacement responses are slight and acceptable relative to the size of structure. In general, the results prove the proposed SFT structure is safe even under extreme weather conditions.

CONCLUSIVE REMARKS

This article presents the preliminary feasibility studies on a Submerged Floating Tunnel (SFT) for the Qiongzhou Strait waterway crossing.

According to the comparisons with a suspension bridge and a submarine tunnel, the SFT is selected as a better solution due to its distinctive advantages, such as shorter distance, lower cost, less impact on the environment and navigation, etc. The central line in the Qiongzhou Strait is proposed as an appropriate location because of its geological and weather conditions.

Concerning the main aspects of the SFT design, the circular cross-section, the inclined cable support system, the concrete and steel strand materials, the rigid inter-module joints and special shore connections are investigated for the proposed SFT in the Qiongzhou Strait.

In addition, different simulated cases based on the Qiongzhou Strait conditions are calculated by means of the numerical software ANSYS/Fluent. The numerical results reveal that the SFT dynamic responses are still acceptable under ordinary and even extreme weather conditions.

In conclusion, the feasibility studies on the SFT aim to render the Qiongzhou Strait waterway crossing into reality. If the SFT technology is adopted in the Qiongzhou Strait, it will be a revolutionary event of civil engineering in the world, and will also be considered the realization of a common dream of all SFT researchers.

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