Research on tubular segment design of submerged floating tunnel

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Abstract

Based on the design technology of immersed tunnel, bridge and tunnel engineering, combining the current relevant design codes or specification of civil and offshore engineering in China, the conceptual design method of submerged floating tunnel tubular segment is presented according to safety, applicability, economy, fine appearance and environmental protection. The selection of tube cross section type, structural analysis, design load, waterproofing and resistant corrosion, tube joint design and tunnel ventilation of submerged floating tunnel etc are described and explored by comprehensively considering the design load, buoyancy to weight ratio, flow resistance performance, durability and other factors of submerged floating tunnel. This paper provides some meaningful suggestions for the design of submerged floating tunnel.

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1. Introduction

Submerged floating tunnel, SFT for short, is an innovative structure crossing long waterway using buoyancy to bear load. Compared with traditional bridge and tunnel, SFT has following advantages:

- SFT exerts little influence on the surrounding environment of SFT structure, and rarely impedes navigation or local beauty as immersed in deep water.
- Cost of unit length structure does not significantly increase with increasing of total length of waterway.
- SFT can operate in any weather, no limitation of hurricane or heavy fog above great river or strait waterway.
- It is free to choose alignment of SFT, the length and slop of SFT can be effectively reduced.

SFT is a high-tech engineering, the design and construction of SFT involve many subject knowledge, such as concrete waterproof technique of civil engineering, drag and operate technique of ships and pipe section, pipe hydrodynamic technique of hydraulics, action analysis of wave and tide of ocean engineering, ventilation technique and pressure wave analysis of aerodynamics and so on. Some issues were deeply studied and discussed in immersed tunnel engineering. Hence, the researches and engineering experience could be used for reference in design idea and construction technology of SFT.

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Currently, some significant crossing projects of straits worldwide chose SFT scheme as alternative scheme, such as Gibraltar channel between Spain and Morocco, Qiongzhou strait channel between Hainan island and Leizhou peninsula, Taiwan strait passage project and transnational tunnel between China and Korea, etc, which are providing opportunity and challenge for SFT and greatly affecting worldwide waterway crossing. As maritime structure, SFT design should consider such issues as the effects of wave, flow, tide and typhoon, structure waterproof, structure durability and tube hydrodynamic technique of hydraulics according to characteristics of maritime structures. As a type of traffic structure, SFT design should also consider such issues as structure mechanical behavior under traffic loads, ventilation, drainage and lighting of tunnel, explosion proof and disaster prevention.

Tube is an important component of SFT, so tube design is critical. So far, there are not many papers about analysis and design of SFT tube, and the no design code in this field have been established. However, in China, there is code for design, construction and maintenance of road tunnel in terms of ventilation, drainage, waterproof and lighting of tunnel [1-3]. There are general code for design of highway bridges and culverts, code for design of highway masonry bridges and culverts, code of design of highway reinforced concrete and prestressed concrete bridges and culverts [4-6] with respect to traffic loads design, design of reinforced concrete and prestressed concrete structure. There is the guideline for seismic design of highway bridges in the earthquake proof design of highway bridge [7]. There are codes for design of river port engineering [8], design code for hydraulic concrete structures [9] with respect to hydraulic concrete structure design. There are code for durability design of concrete structure [10] and standard for durability assessment of concrete structures [11] with respect to durability of concrete structure. There are codes for design of concrete structures in port engineering [12] and code for design of steel structures in port engineering [13], etc with respect to marine loads design. Moreover, the research and project experience on immersed tunnel would be used for reference in SFT field [14].

Combining current relevant design code of civil engineering, this paper discusses some problem of tube segment design for submerged floating tunnel with reference to design technology and engineering experience of immersed tunnel, ocean drilling platform, bridge and common tunnel. It would provide some meaningful suggestions for the design of submerged floating tunnel.

2. Design principle and process of SFT tube

SFT tube provides space for traffic and buoyancy for carrying different dead and live loads. The design of SFT tube relates to oneself safety and applicability. The design load, buoyancy to weight ratio, flow resistance performance, durable performance and other factors are considered comprehensively during the tube design process. By alternatives comparison from technique, economy and environmental protection, the optimal plan should extremely utilize the space to satisfy the traffic headroom and meet the demand of ventilation and escape according to the requirements of safety applicability, reliable quality, economical rationality and advanced technology.

The principles of tube design are as follows:

- The buoyancy to weight ratio is less than 1.0, related researches show that the ratio should be between 0.5 and 0.8.
- Tube should meet the demand of strength, stiffness and stability during construction and operation stages.
- The variation of surface curvature should be gentle to resist the hydrodynamic.
- Meet the standard for classification of seismic protection of buildings.

The procedure of SFT tube design is illustrated in Fig. 1.

3. Key technology of SFT tube design

The key technology of SFT tube design mainly includes section design, structural analysis, waterproof and corrosion protection, joint design, ventilation design and so on. Ripe experience of immersed tunnel and highway tunnel can be used to guide SFT tube design.
3.1. Selection of tube type

Both concrete tube and steel-concrete tube can be adopted in SFT. The prefabricating technique, construction technique, waterproofing work of two material tubes is different, and each has advantages and disadvantages. The concrete tubes are usually prefabricated on quayside dry-dock or moving dry-dock. Then, the tube segment is floatingly transported to the design position for installation. For the steel-concrete tubes, firstly, steel tube junctions are welded and assembled on quayside shipyard near the design site. Secondly, the steel junctions are transported to design position and subsections are balance cast to form steel-concrete junctions. Finally, the junctions are floated to design position and installed. The section shape of steel-concrete tube mainly adopts round section or double round section, which are beneficial to resist hydrostatic pressure and arrange ventilation channel and other service line. The section shape of concrete tube mainly adopts rectangular section for template pouring. The section should be broadened to accommodate ventilation channel and other service line. Comparison of concrete tube and steel-concrete tube is listed in table 1.

Table 1. Comparison of concrete tube and steel-concrete tube

| Items            | Concrete tube                                      | Steel-concrete tube                                      |
|------------------|----------------------------------------------------|----------------------------------------------------------|
| Cost             | Low cost                                           | High cost                                                |
| Section type     | Rectangular section is majority                    | Round section or double round section                     |
| Construction     | Cast in dry-dock, template needing, long construction cycle | Steel shell acting as template, pouring concrete in floating state, quick construction |
| Waterproofing    | Control structural cracks and shrinkage cracks and set waterproof layer on inner and outer layer of tube to waterproof. Difficulty of waterproofing is relatively great. | The outer steel shell is used to waterproof, welding quality assurance system is key point. Difficulty of waterproofing is relatively small. |

The buoyancy to weight ratio and hydrodynamic resistance performance need to be considered in the process of the outer contour design of SFT tube. The inner contour design of SFT tube should correspond with structural approach limit of tunnel, meanwhile, allowable spaces are all taken into account for ventilation, lighting, fire protection, escape system, operation and maintenance system etc. guaranteeing conformity with the principle of safety, economy and application.
3.2. Structural design of SFT tube

SFT tube keeps balance under the action of buoyancy and cable tension bears vehicle load, wave-current load, temperature load and so on. In the system transformation during prefabrication, floating, installation and operation, the stress of tube is complex, so the tube design should carry on longitudinal and transverse analysis under these working conditions.

- SFT tube load is divided into permanent load, variable load and accidental load.
- The permanent includes structure weight, buoyancy, hydrostatic pressure, concrete shrinkage etc.
- The variable load includes vehicle load, water head load, wave-current load, temperate load, construction load etc.
- The accidental load includes seismic, sunken ship load, blast load, leakage etc.
- SFT tube is designed under ultimate limit state and serviceability limit state just as traditional hydraulic structure design [1], moreover, the stress and displacement should be analyzed and checked under progressive damage limit state and fatigue limit state based on structural reliability theory.

3.3. Waterproofing and corrosion protection design of SFT tube

The waterproofing of tube is critical for the reason that the destruction of waterproofing would bring ruinous disaster, so it is significant to do research on tube waterproofing which would promote the development of SFT.

As for steel-concrete tube, the steel shell is taken as waterproof layer for tube section was closed with steel shell, so the waterproofing quality lies on the welding quality and tightness of juncture. For concrete tube, self-waterproof roofing is pivotal issue, which means concrete should be low hydration heat and high seepage resistance grade and the structural crack and shrinkage crack should be controlled within permissible range. Besides self-waterproof roofing, it is indispensable to daub waterproof materials on the surface of concrete tube. Expansion seam measure and hydrophobic coating measure usually used in immersed tunnel also can be applied in crack control of SFT tube. The expansion seam measure is that the waterproofing completely relies on the un-cracked concrete, and expansion seam is set to avoid crack caused by longitudinal tensile stress. The hydrophobic coating measure is that the waterproofing completely relies on hydrophobic coating daubed on the surface of tube along tunnel.

The corrosion mechanism of reinforced concrete in marine environment is mainly caused by steel corrosion in chloride [11]. However, it is hard for the steel in the water to corrode because there is no enough oxygen in the sea. In fact, durability investigation in ocean engineering proved that reinforced concrete immersed in the sea permanently possesses reliable durability. It is noteworthy that gypsum and aluminum sulfide dissolve easily in chlorine-rich environment, so the sulfate cement is not applicable, otherwise, the concrete sensitivity of chloride ion would enhance. The best way to ensure the durability of reinforced concrete tube is to make a good density of concrete and have sufficient thickness of concrete cover. Code for durability design of concrete structures offers reference for the minimum thickness of concrete cover in chlorine-rich environment [10].

3.4. Tube joint design

Joint design of SFT tube should conform to four principles:
- Not seepage in construction and operation stage, reliable water tightness and durability.
- Concise design, stressing definite and working independently.
- Transferring construction load effectively in construction stage and convenient construction.
- Transferring stress and deformation effectively in construction stage, fine seismic performance.

There are two ways of tube joint based on stiffness and deformation: rigid joint and flexible joint. Table 2 enumerates difference of two types of joints, and figure 2 is schematic drawing of two types of joints design.
Table 2. Comparison of rigid joint and flexible joint

| Items                  | Rigid joint                                                                 | Flexible joint                                                                 |
|------------------------|------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Structural composition | End steel shell, GINA water stop, junction steel plate and reinforced concrete | End steel shell, GINA water stop, OMEGA water stop, shear key, longitudinal displacement limiting device |
| Deformability          | Poor deformability                                                           | Absorbing some temperature deformation, consuming some seismic energy for their good deformability |
| Construction           | Long period and great difficulty                                              | Convenient construction                                                       |
| Cost                   | Cheap                                                                        | Expensive                                                                    |
| Applicable position    | End joint                                                                    | Intermediate joint                                                           |

Since Gina water stop was invented in Holland in 1960s, this water stop is generally applied to joint waterproofing of immersed tunnel [20], and practice shows that this method is liable and durable. Hence, Gina water stop is considered as a reasonable choice for joint waterproofing of SFT. As for rigid joint connected by reinforced concrete, Gina water stop is installed in outer of tunnel. The conformation of flexible joint is complex relatively, Gina water stop and OMEGA water stop are combined to waterproof, and the former is the principle device while the latter is secondary. The shearing force of tube is transferred by shear key, and the axial force is transferred by longitudinal displacement limit device. As first defense line for waterproofing of tube joint, its working condition influence on structure life and safety of SFT, so the maximum and minimum compression rate, compression rate in installation and emplacement stage, residual compression rate etc. should be analyzed strictly to ensure good performance of Gina water stop.

3.5. Waterproofing and corrosion protection design of SFT tube

Tube ventilation design is an important link of SFT design, and quality of ventilation scheme and operation effect has direct relation to engineering cost, operation environment, disaster-relieving function and operation benefit. The aim of tube ventilation is to guarantee allowable concentration of harmful gas represented by carbon monoxide, provide healthy environment and suitable visibility for people and vehicle in tunnel, and control pervasion of smog and heat for evacuation and extinguishment when fire occurs.

Tube ventilation should accord with following requirements [1]:

- Design wind speed of one-way traffic tunnel is not more than 10m/s; design wind speed of two-way traffic tunnel is not more than 8m/s.
- Noise produced by ventilation fan and exhaust emission meet the environment protection guidance.
- Ventilation type is stable when the transportation condition changes or fire occurs.
- Downstream direction of operation ventilation is stable.

The procedure of ventilation design is illustrated in Fig.3.
There are two ways of tunnel ventilation: horizontal and vertical. Transverse ventilation apply two-way traffic tunnel for two air passages are set in two sides of tunnel and the ventilation effect is reliable, however, the engineering cost increases when setting of designed air passages results in augmentation of tunnel dimension; horizontal ventilation apply one-way traffic tunnel whose length is no more than 2.5km, and in this way, total section is taken for air passage and no design air passage is needed to set, moreover, it is benefit for safe escape when fire occurs.

After selection of suitable ventilation, quantity and arrangement of axial fans are determined based on the design concentration and production of carbon monoxide and smog in normal working conditions and obstruction condition; quantity and arrangement of jet fans are determined based on design diffusibility of smog in fire.

4. Conclusions

SFT, which has characteristics of tunneling engineering and ocean engineering, is a complicated structure involved in many disciplinary fields. It is significant to make prophase researches on SFT which has wide prospect for great crossing projects. This paper has done researches of tube design for submerged floating tunnel including selection of pipe, structural analysis, waterproof and corrosion protection, joint design and ventilation. There is no engineering practice while no SFT have been built in a real sense in the world, so the detailed design and construction technology remain to be further studied.

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