Submerged Floating Tunnels: State-of-the-art on Design and Challenges

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Abstract. Submerged Floating Tunnel (SFT) is an alternative and new way of crossing seas and oceans at relatively deeper waters so that storms or tsunamis do not affect the transportation. SFT has distinct and significant advantages over conventional structures like concrete or suspension bridges and immersed tunnels in trans-oceanic transportation. The present paper reviews the reported studies on SFTs and discusses its design and structural features. Though reported studies on SFTs are limited in number, an attempt has been made to review the research status and summarize the findings on analysis and design methodologies of its structural components, namely, the tubes, foundation systems, anchoring tethers, and shore connection. Since there is still no functional SFT structure anywhere in the world, the present paper also discusses the challenges in design and construction of this kind of tunnel, namely, hydrodynamic response of the tube and the foundation system, and tunnel safety analysis.

Keywords: Submerged Floating Tunnels, Underwater Tunnel, Design Challenges, Review, Hydrodynamic Forces.

1 Introduction

Submerged floating tunnels, also known as submerged floating tube bridges, are waterway connecting structures that are located at around 30 meters or more below the water level. These structures use the law of buoyancy to support their weight at a suitable depth, while using anchorage cables (tethers) to stabilize their position underwater [1]. Because of their location, the transportation via these floating structures remain unaffected from natural disasters such as tsunamis and storms. This tunneling-transportation solution will compete with other traditional methods in the upcoming time due to its environmental and economic advantages [2]. Compared to the ferry system, SFTs generate significantly less air pollution; compared to the cost of a suspension bridge per km, the SFTs are more economical for both two-lane and four-lanes. Though the immersed tube tunnel is another popular way of water way connection, at considerable depths or varying water levels, installation of the immersed tube becomes impossible due to high hydraulic pressure, and hence, SFTs pose an advantage under these conditions [1]. The current paper reviews the published studies on SFTs and discusses their design and structural characteristics. Though there have been few reported studies on

SFTs, an attempt has been made to review the research status and summarise the findings on analysis and design methodologies of its structural components, namely tubes, foundation systems, anchoring tethers, and shore connection. Because there is currently no functional SFT structure anywhere in the world, the current paper also discusses the challenges in the design and construction of this type of tunnel, specifically the hydrodynamic response of the tube and the foundation system, as well as tunnel safety analysis.

2 Methodology

The present study focusses on assessing the research status and understanding the design methodologies of SFTs and their components, namely, tube, anchoring, and shore connections. Thus, the methodology adopted comprises of review of the reported literature and identify the critical factors influencing the design of this tunnel structure and its components.

3 Submerged Floating Tunnel

3.1 Components

Any SFTs consist of three essential components, namely, Tube, Anchoring, and Shore Connections. These components resist the hydrodynamic forces and seismic and dynamic conditions [1]. The details of each of these components are given in subsequent paragraphs.

The tube is an important component of SFT that provides the necessary space for traffic flow. These structures must have adequate buoyancy and curvature to carry the different types of loads and respond to hydrodynamic forces [1]. The tube is constructed using either concrete or the composite of steel and concrete [3]. The concrete tubes are cast in a dry dock, which are then transported to the locations for installation. For steel-concrete tubes, the concrete subsections are balanced cast and protected with assembled and welded steel sections to build a steel-concrete tube. Table 1 shows the comparative assessment of the features of these two different kinds of tubes [3]. The SFT tubes are designed for the permanent load (includes structure weight, concrete shrinkage, hydrostatic, and buoyancy), variable loads (includes temperature, water, vehicle, and construction loads), and the accidental loads (includes leakage, blast load, and seismic). The designs are performed under the ultimate limit state [3].

Table 1: Comparison of different type of tubes

Parameters	**Concrete Tube**	**Steel-Concrete Tube**
Cross-section type	Rectangular	Round or double round
Cost	Low	High
Waterproofing	High difficulty	Low difficulty
Construction time	Long construction cycle	Quick construction

Anchoring of the tubes ensure that the tubes are in-place and are able to resist the permanent and temporary loads induced on it. In unanchored SFTs, there is no anchor support, and it simply connects shore-to-shore like a supported beam [1]. This kind of SFTs are primarily applicable for small-scale connecting structures. The pontoon type of anchors is used when the gravity of the tube is more significant than the buoyancy [1]. Pontoon balances the gravity and minimizes displacement. However, it affects the maritime navigation due to its floating action and wave motion. So, it cannot be used in an adverse environment. Pressure-bearing-pier type of anchors are underground columns that support the tube as an underground bridge. Tethers connect the tubes with the foundation, and does not get affected by wave motion or floating ice. However, due to vortex-induced vibration, these are easily worn from the upper or lower joints [4]. The Shore Connections should be rigid, watertight, and adequate to restrain the movements of the tube. Its design considers the effects of earthquakes and submarine landslides [1].

3.2 Concepts and Challenges in Analysis and Design

Table 2 lists the details of the reported studies on SFTs. The presented data also aids in comparatively assessing the status of the present research on design and analysis of SFTs.

F.M. Mazzolani et al. (2010) [5] explained the prototype design, construction, and installation process of a 100 m long SFT in the Zhejiang Province of China. The prototype was constructed with a tube layer of steel, reinforced concrete, and aluminum (inner to outer) and was anchored suing W-shaped tethers and hinge-type shore connections used. The design used a buoyancy ratio of 1.3. The different aspects like a geotechnical and hydrodynamic studies were reported by F. Gao et al. [6], S. Zhang et al. [7], and S. Yuan et al. [8].

After extensive investigations in FEM-based software ABAQUS, F. Gao et al. (2010) found that the tension piles are more suitable for tethering the SFT prototype. It was also observed that the sediment characteristics and the loading angle influence the shear stress and ultimate tensile load on the pile [6]. J. Xiao et al. (2010) discussed the different types of shore connections. By using the ANSYS FEM program, it was found that the bi-linear elastic type shore connection is better than rigid, hinged, elastic connections [9]. W. Yan et al. (2010) studied the interaction of tensional pile sediment under vertical loading and found that its bearing capacity mainly depends on pile-sediment characteristics and cohesion by ABAQUS [10]. X. Jiang et al. (2016) discussed the effects of different inclinations of tethers on the ultimate bearing capacity of tension pile and found that it is maximum and minimum at 30º and 90º, respectively [11].

S. Zhang et al. (2010) discussed the wave and seismic analysis of SFT tubes and reported that the SFT tube had higher allowance strength for water waves and currents than seismic loads [12]. It was also observed that the energy absorption capacity of the aluminum panel of the tubes were 80% more significant than that of the impact energy [7]. L. Martinelli et al. (2010) discussed the seismicity prediction using Load-Unload Response Ratio (LURR) in the SFT prototype, and reported that the chance of a massive earthquake is significantly less as the LURR value is less than 1 for the considered case [8]. H. Kunisu (2010) calculated the wave, drag, and inertial forces on the SFT tube by both Morrison’s equation and BEM (Boundary Element Method). It was found that although the drag and the inertial forces act simultaneously on the SFT, the inertial force has more dominance [13]. W. Lu et al. (2010) discussed the Slack prediction using the analytical solution, which provides the design value of tethers layout using the Bi-linear stiffness model [14]. H. Lin et al. (2018) studied the dynamic response of SFT due to fluid vehicle tube interaction and found that current velocity, BWR & tethers inclination influence most of the bending moments and vertical deflections [15]. J. H. Leea et al. (2016) studied the seismic behavior of rectangular cross-section tubes and suggested that factors such as compressibility of fluid, depth of SFT, energy absorption by the seabed, and sea depth affect the seismic response of the structure [16].

Table 2: Details of studies (Analytical or Design-based) on SFTs reported in literature

Author (Year)	**Objective of the study**	**Methodology**	**Observations/Summary**
F. Gao et al. (2010)	Selection of foundation type by geotechnical investigation.	Simulation of tension pile in ABAQUS software.	Loading angle has more influence on ultimate tension load.
F. M. Mazzolani et al (2010)	Selection of cable configuration for SFT prototype.	ABAQUS software used to examine hydrodynamic behavior on SFT.	W-shaped configuration adopted for cables.
S. Zhang et al. (2010)	Energy absorption capacity of tube due to accidental collision.	Plastic hinge hypothesis	Aluminum panel has high energy absorption capacity.
S. Yuan et al. (2010)	Prediction of seismicity of Qiandao lake.	LURR (Load-Unload Response Ratio)	Chance of earthquake is very low for LURR less than 1.
H. Kunisu (2010)	Calculation of wave force, drag force and inertial force on tube and its effect on its shape.	Morison’s equation and Boundary element method.	Round-shape tube is preferred over elliptical shape. Wave force can be determined by both Morrison’s equation and BEM. Drag force and inertial force acts simultaneously on SFT but inertial force has more dominant for KC value less than 15.
J. Xiao et al. (2010)	Selection of different types of shore connections.	Dead load deformation & dynamic analysis by Newmark method, ANSYS LS-DYNA FEM program used to model structure.	Hinge connection reduces the dynamic response w.r.t rigid and elastic, bilinear elastic and passive isolation reduces more w.r.t hinge connection with proper parameters.

W. Lu et al. (2010)	Estimation of Slack due to hydrodynamic load.	Bilinear stiffness model to observe tethers under hydrodynamic load.	Slack prediction using analytical solution, which provides the design value of tethers layout.
M. Dong et al. (2010)	Escape device influence on drag force.	Navier-Stokes equations used, GAMBIT used as preprocessor and Fluent as solver.	In uniform flow, a significant reduction in drag force and very little influence in oscillatory flow.
W. Yan et al. (2010)	Interaction of pile-sediment under vertical loading in tension pile.	2D numerical analysis of tensional pile by ABAQUS software.	Bearing capacity of tensional pile mainly depend on pile-sediment characteristics and cohesion.
X. Jiang et al. (2016)	Ultimate bearing capacity of tension pile with different inclination.	Numerical simulation with displacement curve under different inclination in FLAC3D.	At 30º, the bearing capacity of pile is maximum and minimum at 90º.
J. H. Leea et al. (2016)	Seismic behavior of rectangular cross-section tube.	2D seismic behavior of SFT is examined by FEM.	Compressibility of fluid, depth of SFT, energy absorption by seabed, sea depth affects the seismic response. So, these parameters must consider in design.
H. Lin et al. (2018)	Dynamic response of SFT due to fluid vehicle tube interaction.	Bending moment & deflection is determined by MSM and FEM.	Current velocity, BWR & tethers inclination influence most on bending moment and vertical deflection.

Although the above-mentioned discussion highlights the positive aspects of the SFTs, researchers have also identified the challenges in analyses and design of these waterway-connecting structures. The first challenge in analysis and design are the Vortex-induced vibration (VIV). These vibrations are fatal to SFT safety, and are observed to be reduced by 45º-60º inclined cables, dampers, and additional disturbing flow devices [17]. However, under the VIV, even the tethers are highly vulnerable. Another challenge in analysis and design is the accidental analysis of the tube structure. This analysis includes the influence of seabed on P wave with cables. For the analysis of the tube structure, many researchers follow Morison’s equation to calculate the wave load on the tube to estimate fluid-tube interaction. However, this equation includes many assumptions and hence, does not apply to complex environmental conditions [13].

Another identified challenge in the design of such a system is the limitation in a rescue program in the event of an accident or terrorist attack. Rescue operations under 20-30 m head of water pose a challenge to the operational safely of the SFT [17]. Risk management of SFT is also a big challenge, which involves natural disasters, construction risk, and investment risk [18].

4 Summary and Discussion

This review paper gives an overview of the advantages of SFT over alternate options, and its analyses and design under hydrodynamic conditions. Further, this paper also addresses the gaps in the reported studies and identifies the research areas which need more focus in near-future.

The review showed that since an SFT structure is yet to be built, its design is not yet established. Since the tube structure must have the properties of corrosion resistance, waterproofing, high-stiffness, and crack resistance, developing and utilizing such a robust material is vital for the functionality of this structure. A contingency plan is crucial with respect to structural safety and maintenance as accident inside the tunnel (e.g., explosion, vehicle accident, fire) or outside (wearing of tethers) can prove disastrous. Since the concept of such structures are still new, establishing codes of practice for design, safety, and maintenance is vital.

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