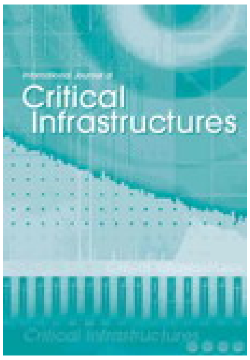

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A review of research developments on submerged floating tunnel

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Abstract: Submerged floating tunnel as a high investment project has been conceptualised multiple times by different countries, but has not been implemented yet. Being a critical infrastructure, the complexities and challenges involved in the construction of this underwater tunnel is a natural progression of the multiple factors that need consideration in its engineering analysis and design. The improvement in computational resources and techniques of the 21st century has enabled a closer to accurate engineering analysis of this structure under the influence of dynamic effects of water including design consideration for blast loading and tsunami. The techniques proposed to keep the tunnel afloat, along with the variations in the nature of its support with the seabed, have seen the coalition of multiple disciplines of engineering. The paper presents a comprehensive review of various engineering analysis that has been performed on submerged floating tunnel in addition to a review of the different policy-based conclusions on this new technology. The current trends and challenges ahead are also discussed based on projections into the future as a natural extrapolation of the current state of progress.

Keywords: submerged floating tunnel; computational fluid dynamics, stress analysis; structural design; transportation; underwater tunnel; critical infrastructure.

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1 Introduction

Through the advancement of transportation, people are able to travel long distances in a shorter time. Land travel is restricted by geography in many cases and various types of infrastructures, such as bridges and tunnels are designed and constructed to facilitate transportation lines. When these lines are interrupted by the rivers and seas, bridges, undersea tunnel and immersed tunnel can serve as a solution. The modern approaches are not efficient and economical as well as if the ocean disturbs these transportation lines. In these cases, a more useful and economical approach is a submerged floating tunnel (SFT) which also relieves the burden on land to provide for increasing transportation demand. Thus, a fully functional SFT can be deemed as critical infrastructure on account of its sheer size and extend of services it can offer. SFT is also known as the Archimedes Bridge or suspended tunnel or submerged floating tube bridge (SFTB) as shown in Figure 1 and Figure 2. It generally consists of tubes, anchoring devices, underwater foundations, and revetment structures (Mazzolani et al., 2010). The SFT has many advantages over conventional bridges and tunnels such as higher efficiency, better environmental adaptability, all-weather operation, and a comparatively lower construction cost (Zhang et al., 2010) and is a promising sustainable infrastructural concept after consideration of water bound factors such as sailing depth (Gudmestad, 2015).

Figure 1 Inside view of SFT (see online version for colours)

Source: 'Norwegian Public Roads Administration' (2012)

Figure 2 Illustration of SFT (see online version for colours)

Source: 'Norwegian Public Roads Administration' (2012)

A SFT is a tunnel that floats in water and is supported by its buoyancy (Lu et al., 2011). It maintains balance and stability by the combined effect of deadweight, buoyancy and anchoring system. SFT is an underwater channel by which vehicles and trains can move (Østlid, 2010). Historical records indicate that Sir James Reed, UK, in 1886 and later Trygve Olsen Dale, Norway in 1924 are the pioneers of this technology who are accredited with the development of the conceptual idea. During the latter part of 1960's, a revival of interest in SFT was marked by the beginning of some research ventures, which gathered momentum in Italy, Japan and Norway during the years that followed. The Høgsfjord project (Skorpa, 2010) in Norway was probably the biggest such projects, with fundamental research into four alternatives using pre-qualified contractors to carry out detailed design and complete the tenders. The Norwegian Public Roads Administration in 1999 was ready for contracts to build an SFT crossing the west coast of Høgsfjord County. The project was discontinued because of political decisions (Østlid, 2010).

In 2004, a protocol of scientific and technological cooperation was signed for the Chinese-Italian joint laboratory of Archimedes Bridge between the People's Republic of China and the Republic of Italy. The Chinese academy of Sciences-Institute was its collaborator. SIJLAB's (Sino-Italian Joint Laboratory of Archimedes Bridge) goal was to construct the world's first Archimedes Bridge (Mazzolani et al., 2010). The SFT prototype has a total length of 100m. The structure consists of five modules with a length of 20m each, which are pre-manufactured in the yard and then assembled in-situ. The prototype material is made of steel (S235 grade), concrete (C20/25 grade), and alloy alumina alloy (6061-T6 grade). The net width of the motorway is 2.5m and the internal diameter is 3.55m (Mazzolani et al., 2010). The new structure resulted in renewed international interest in this concept and much of the research work happened in China with similar progress in certain European counties like Italy and Norway.

The glamourous concept of SFT first conceptualised as early as the 19th century has lagged significantly in its implementation and widespread acceptance by developed countries owing to the many factors underlying this brazen infrastructure. On one hand, persistent ambiguity exists in the SFT life cycle, due to the large demand of investment and the long construction duration as well as the innumerable unforeseen factors underlying it (Xiang et al., 2010). The unknown hazards concealed during project planning, design, construction and working worried engineers and planners. Apart from that, many technical issues, for instance, the reliability of the connection of segments, wave load mechanism, and seismic effects on SFT have still not been addressed. There are still no universally accepted guidelines and requirements for SFT design and construction (Xiang et al., 2010).

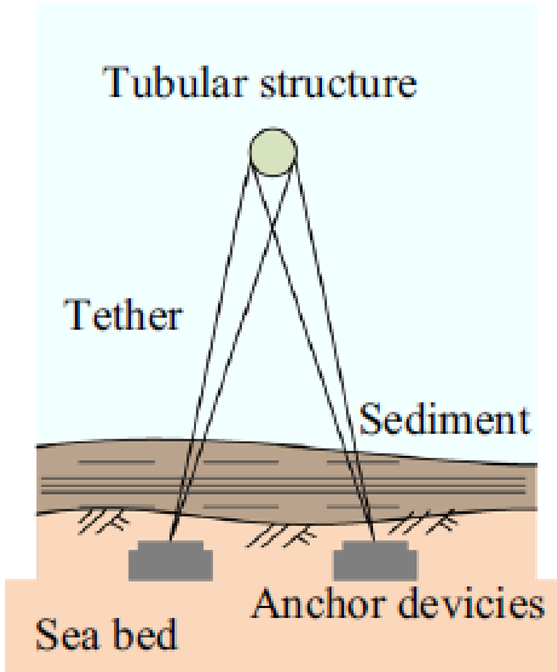
The technological advancements and growth in computational techniques in the last few decades have provided us with a better understanding of the behaviour of an SFT that is subjected to the simultaneous action of vehicular traffic (Yuan et al., 2016), wave forces (static and dynamic) (Mandara et al., 2016), underwater seismicity and accidental blast loading (Kristoffersen et al., 2019). Modelling of simultaneous effects of all the forces is possible by the concurrent use of Computational Fluid Dynamics (CFD) and Finite Element Method (FEM) (Mandara et al., 2016). The paper presents an executive summary into the history of SFT with elaborate details of the strides made in the analysis and design and conclusions drawn thereof providing a better understanding of its implementation. A summary of the anticipated future of this technology is also provided based on the extrapolation of current research trends and political developments.

2 Research progress on SFT

The turn of the 21st century witnessed the development of greater computational capabilities well supported with the development of techniques such as CFD and FEM that helped engineers and researchers to obtain a better understanding of the behaviour of SFT. With the help of FEM and CFD techniques, many studies have been conducted on SFT like dynamic and static analysis. One of the earliest research works dealing with engineering analysis of SFT was published in 1994 (Kunisu et al., 1994). In this study, SFT was modelled as a 2D structure. SFT was analysed (Paik et al., 2004) more accurately as a 3D structure by modelling it using 3Dimensional beam element by applying the Linear Potential theory. The fluid was assumed to be incompressible. This study shows that the effect of depth on the coefficient of radiation damping is much more significant than the coefficient of added-mass. It is also observed that the coefficient of radiation damping is 1/10th the coefficient of added-mass for the same depth. The effect of depth on radiation damping is more significant than that on added-mass and the maximum wave force decreases rapidly as SFT depth increases (Paik et al., 2004).

After more than a decade, the foundations were laid down by researchers that aided the development of the spatial dynamic equation for curved SFT (Dong et al., 2007). Hamilton equation was used as a reference to derive this dynamic equation. The study shows that when curved SFT is being analysed for low frequency, rotational energy may be neglected (Man-Sheng, 2007). A much-needed risk assessment of SFT as a high investment project was carried out using fuzzy analytic hierarchy process to measure the risk (Xiang et al., 2010). As per the study, SFT is still a new concept which may have lots of hidden risks that cannot be considered in the present time but that which will probably be discovered over time or with the advancement of technology.

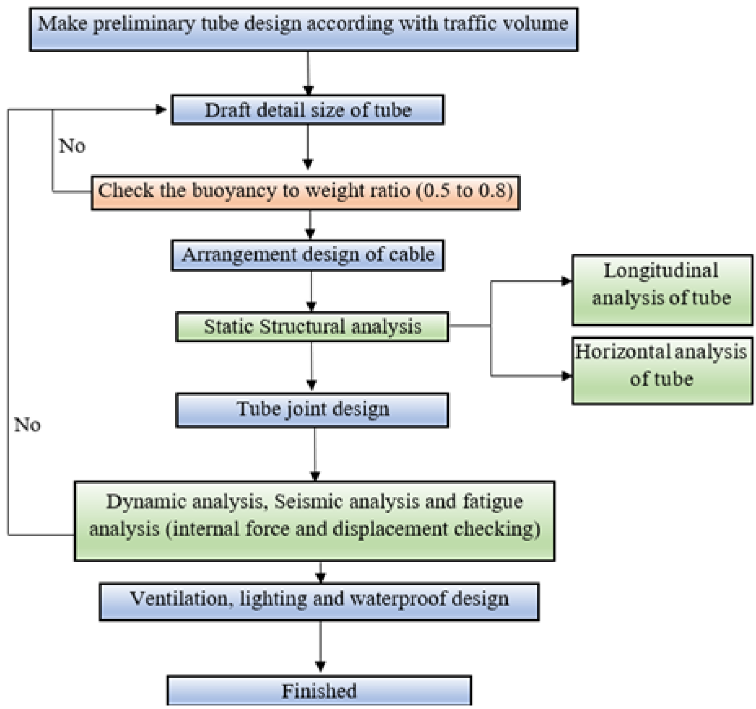
Figure 3 Different components of SFT (see online version for colours)



Source: Lin et al. (2019a)

SFT is suspended in water with the help of tethers as shown in Figure 3. Tethers are very important and an essential component of SFT. The behaviour of tethers when they are subjected to the travelling waves on vortex-induced vibrations (VIV) was studied (Wu et al., 2010). The propagation of cross-flow (CF) and inline (IL) response in tethers has been stimulated by using a modified wake oscillator. This study shows that for flexible tethers with large aspect ratio, travelling wave other than standing waves dominate the response and when travelling wave dominates the response, the maximum RMS strain response is observed in regions dominated by traveling wave response and not near the ends of the model. Fatigue damage is more expected in the region which is dominated by the travelling wave as it is more susceptible to higher harmonic forces compared to standing wave region (Wu et al., 2010). Further studies on VIV (Kang et al., 2016) were carried out and it was concluded that the maximum RMS of the displacement for a long tensioned mooring tether subjected to VIV linearly increases as the flow velocity increases only if, the low order modes are excited at the corresponding flow velocities. The conclusion was made based on the introduction of a new terminology named ‘Conditioned maximum RMS’ through a study which was the culmination of experimental set-up developed with the backing of numerical equation.

Figure 4 Procedure of SFT design (see online version for colours)



Source: Zhang et al. (2010)

In studies so far, different components and parameters of the SFT were considered individually without an integrated view of the SFT as a whole. In this context, the study considering the individual parameters intertwined in a trial-and-error loop typical of design of functional components (Zhang et al., 2010) gave a wider and clearer picture of SFT (Figure 4). The tubular segment of SFT is selected and aspects which were discussed in this study were the selection of the sectional tube form, structural analysis, design load, permeability and corrosion resistance, design and tunnel joints, ventilation, etc. The flow chart also outlines the sequence of steps prudent in understanding the procedure and approach which should be followed while designing the SFT.

While selecting the tube for SFT, buoyancy to weight ratio is a significant parameter and it should be less than 1 (more specifically between 0.5 to 0.8). Structural designing should be done in a manner that SFT tube maintains balance under the action of flooding, cable tension, supports vehicle load, wave-current load, temperature load, etc. SFT tube load was divided into permanent load, variable load and accidental load. The design of SFT should be in accordance to ultimate limit state and serviceability limit state design philosophies as applicable to traditional hydraulic structures. Stress and displacement should be evaluated and tested based on structural durability theory in compliance with progressive damage limit and fatigue limit conditions. Waterproofing and corrosion protection of SFT tube is amongst the greatest challenges. A good density of concrete and sufficient cover is necessary to ensure its durability (Zhang et al., 2010).

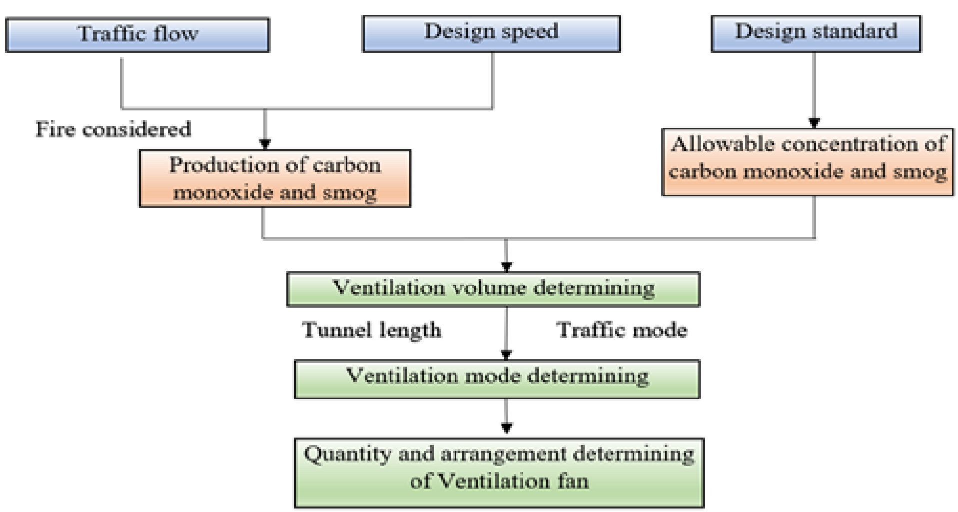
SFT is made by joining different tube segments together and hence the joint must be designed carefully to avoid any damage to the structure. The following principles needs to be followed while designing the joints:

- No seepage in the construction and operation phase, reliable water tightness, and durability.
- Construction load transfer effectively at the construction stage and convenient construction.
- Effectively transferring stress and deformation, satisfactory seismic performance, in the construction stage.

Due to the movement of vehicles, there will be the emission of many harmful gases such as carbon monoxide that led to suffocation, unhealthy environment and lead to less visibility for the driver that leads to accidents. Hence proper, the ventilation facility should be there to provide passage to these gases. Ventilation design procedure is shown in Figure 5. Ventilation facility should meet the following requirements:

- One-way road traffic tunnel wind speeds are not greater than 10m/s and two-way tunnel design wind speeds are not greater than 8 m/s.
- Ventilation fan noise and exhaust emissions comply with environmental protection guidelines.
- In the event of an emergency or fire, the method of ventilation is safe.

Figure 5 Flow chart of ventilation design (see online version for colours)



Source: Zhang et al. (2010)

SFT hence it is understood that it floats in water so as to keep the tunnel in the upright position. It should be tied to the tethers which are in turn anchored to the bottom of the seabed. It is expected that tethers will lose their tightness after some time by the continuous action of wave currents by the phenomenon called slacking of tethers. This is an important parameter as it is directly related to the safety of the SFT and may result in major disasters leading to the loss of lives and investment. This phenomenon was considered and studied (Lu et al., 2011). To investigate the slacking phenomenon, the Lagrange energy method is used to construct the governing SFT motion equations, and a bilinear oscillator is introduced to simulate the mooring tether operating in the alternating slack state. This study concludes that the response of SFT tether tension is much more sensitive towards wave height as compared to the wave period. Moreover, it indicates that the Buoyancy weight ratio (BWR) dominates the range of influence of the inclined mooring angle (IMA). The phenomenon of tether slackening is governed by the slack region and the occurrence of tether slacking is rare for SFT with an IMA of 00 and 450, but not for 150 (Lu et al., 2011).

Past studies suggest that consideration of tethers in SFT analysis is important in understanding its behaviour more accurately. Tethers parametric response is studied under random excitation (Sheng-nan and Zhi-bin, 2011) using Monte Carlo method for modelling of displacement and RMS velocity. Study shows that when Gaussian white noise random excitation occurs in the SFT tube, displacement and velocity of the random RMS responses of the tether reach their peaks when the circular frequency doubles. The displacement and velocity of the RMS responses of tethers increases with the increase in RMS of random excitation. The RMS response of the tether decreases rapidly compared to the tether in the air because of the damping effect of water.

In the conceptual designs developed up to this point, their main focus was the safety of the SFT from exterior forces or influences such as wave loads, seismic loads, tethers and their interactions with the marine environment. No literatures have been seen focused on the internal safety aspects of SFT similar to situations that can happen in the case of fire accidents. One of the earliest studies considering the safety of SFT proposes an escape device (Man-Sheng, 2012) that can be a safety vouch in the event of emergencies. These devices can be fastened with SFT and they behave like a single unit. The working principle is that whenever some accident happens, people will go to the nearest escape device and that device detaches from SFT and remain afloat in ocean due to buoyancy. The effect of escape device on SFT when they are subjected to hydrodynamic loads was analysed. Computational fluid dynamics (CFD) was used to investigate the effect of emergency escape devices on hydrodynamic loads acting in uniform and oscillatory streams and water waves. This study shows that for a rhombic section, SFT escape devices reduce the hydrodynamic loads in uniform flow sharply. In linear wave, both horizontal and vertical wave loads of SFT with escape devices has increased to some degree. Vertical wave loading has a much greater effect than the horizontal wave and hence needs to be considered in calculations.

By this time significant studies have been carried out on tethers with the inputs obtained from earlier studies that served as variables for parametric studies to determine their effect on specific components of SFT. The seismic response of tethers was studied using numerical analysis using 3 waves (Livermore wave, EL- Centro wave and Treasure Island wave) and the variations in the mid-span displacements (Zhi-bin and Sheng-nan, 2013) were obtained. For analysis, they used the multi-step Galerkin method and the fourth-order Runge-Kutta integration method. This study concludes that the vibration response of the tethers under the seismic wave, suited to the soft soil foundation, is the largest. Due to the dispersion of the seismic wave, the response of the tether under different seismic waves varies greatly. Resonance of tethers occurs when the parametric excitation frequency is 2 times the natural frequency. When the resonance of tethers does not occur, then the mid-span displacement under parametric excitation and the seismic wave is a little higher than the corresponding displacement under the seismic wave acting alone.

More parametric studies on tethers continued to be taken up by researchers. The effects of various factors like length, density, and pre-tensioned forces were studied on the VIV fatigue damage in the cable (tethers) of SFT (Luo et al., 2015). The different values of densities chosen were 1960kg/m3, 3925kg/m3 and 7850kg/m3 and their effects were studied on fatigue damage of the tethers. The study concluded that with an increase in density of anchor cable, the longitudinal RMS stress and fatigue damage reduces. A second parametric study was carried out by varying the length of cables (100m, 200m and 300m). It was observed that with an increase in the length of the cable, the VIV fatigue damage also increases. This result shows that the length of cable is directly proportional to the VIV fatigue damage. The third parameter considered was the pre-tensioned force (800 kN, 1,600 kN and 2,400 kN). The variation of Pre-tension force was seen to have limited effects on the VIV fatigue damage of cables. The study also affirmed that with an increase in pre-tension force, stress and damage will also increase correspondingly.

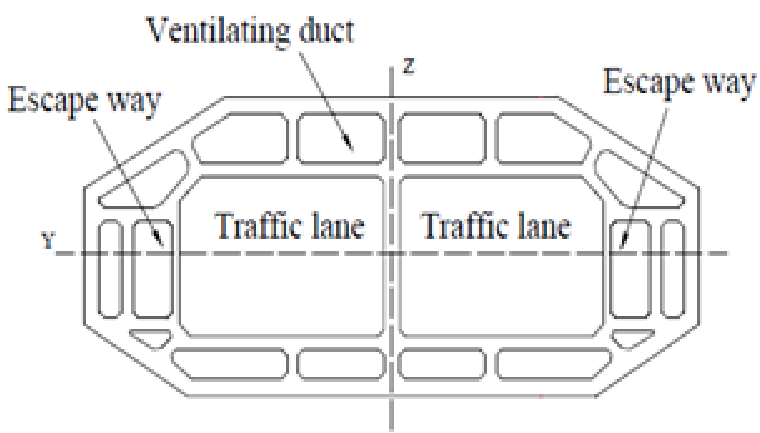
An experimental and numerical study has been carried out on an SFT to compare the efficiency of single and double mooring system (Seo et al., 2015a) when it is subjected to wave loads. The Morison's equation was used to estimate the wave load composed of drag force and inertia force. The physical model of SFT was placed in wave flume to estimate the wave loads experimentally. Further both the results were compared to determine which system is better (single mooring or double mooring). The study shows that a double mooring system is better than the single mooring system. The effect of drag force was insignificant as compared to the inertial force. The experimentally calculated wave loads agree with the values obtained by Morison's equation. A related study was conducted (Wu et al., 2016) using wave forces whereby a computational method was developed to study the behaviour of the non-linear waves by varying its type (regular wave and multi-directional irregular wave with variation in wave height from 0.02 m–0.3 m in the towing tank experimental setup). In this method, three-dimensional diffraction potential and radiation potential associated with the floating body is utilised and the three-dimensional green function is applied to solve the radiation-diffraction problem. The proposed method was observed to be in good agreement with the existing method and experimental data.

Independent studies have shown that the IMA of 450 for mooring lines is the most efficient. As per the study (Lu et al., 2011) carried out with a focus on the slacking phenomenon of tethers on a 100m deep tunnel, it was concluded that 450 is the ideal orientation among the range of angles considered (00 to 450). As per a different study conducted on a 150 m long SFT (Marina et al., 2015) for IMA of 300, 450, and 650, minimum slacking and maximum tension was observed with 450 orientation of mooring lines. Thus 450 has emerged as a good starting point for IMA as per multiple researches works.

Safety has always been one of the greatest concerns of SFT. The full functionality and the intended purpose of an SFT can be realised only if the multitude of factors that govern its safety is considered. A study was carried out to investigate the behaviour of an SFT subjected to underwater explosion (Seo et al., 2015a). SFT is modelled as a simply supported uniform beam 200m long and supported by continuous elastic springs. Shock wave and impulse pressure were generated by an explosion away from the SFT modelled mathematically. FEM analysis of beam model under the impulse load was carried out and its response was found to match closely with theoretical analysis based on classical beam theory. This study shows that when the length of the body is extended and natural frequency of the body itself is much smaller than that of mooring system, response of the body could be obtained using one dimensional model considering the mooring system only.

A state-of-art paper on SFT (Xiang and Yang, 2016) discusses the challenges ahead for it in becoming a sustainable project that can overcome the challenges of the wave, corrosive environment, safety, challenges in foundations, and risk during construction & operation. This study provides a broader and clearer picture of SFT considering the realities in the field not often taken up in optimistic research work. The study emphasises the need for materials that meet several requirements like high strength, anti-impact toughness, crack and fatigue resistance, waterproofness, and corrosion resistance. The paper points out the lack of Chinese standards that can provide guidelines to follow in the implementation of SFT. The multi-disciplinary aspect of SFT requiring the collaboration of different sciences has been echoed by other researchers as well (Zhang et al., 2010). The paper provides comprehensive guidelines into generic aspects of analysis, design, and construction of SFT including details of a more practical cross section with due consideration of ventilation and emergency exit (Figure 6).

Figure 6 Ideal cross- section of SFT



Source: Xiang and Yang (2016)

Up to this point, the idea of SFT was not in the limelight and the research area was small and limited and the studies were confined to analytical modelling and experiments. However, following the release of the conceptual and realistic images of SFT by the Norwegian Public Road Administration in 2012, they announced that Norway will be the first country in the world (Dhar, 2018) that will construct the tunnel and make it fully operational and functional by 2050. This news sparked global attention leading to massive pumping of money in projects and research programs. After this researcher's approach changed and it became an infrastructure that is more realistic and practical. Instead of an analytical approach, research works focus shifted to CFD and FEM analysis for a more realistic modelling. Studies were carried out on circular and elliptical cross-sections (with same transport capacity) of SFT for combined railway and motorway service (Mandara et al., 2016). The behaviour of SFT was investigated by varying the water current velocity from 1m/s to 4m/s and carrying out static and dynamic analysis, based on both Implicit Large Eddy Simulation and the RANS-based Spalart-Allmaras model, followed by a co-simulation procedure in which the fluid dynamics and the structural analysis were carried out separately and interfaced with each other. The work provided confidence to researchers to investigate the combined effects of static and dynamic response of SFT along with the fluid interaction. The study concludes that turbulent water flow does not have any major effects on tubular section of SFT.

With multiple studies carried out on full structure modelling, the research works have become more realistic and functional. Studies have been carried out in which the effect of SFT was analysed under the moving load (Yuan et al., 2016). In this study, SFT tube was simplified as an elastically supported beam with two springs and dampers at both ends. Kinematic equations were applied for the moving load acting inside the SFT tube and solved by Galerkin method at its mid-span section and corresponding displacement were obtained. Study shows that the anchor stiffness plays a significant role in the displacement of SFT. It has been found that the vertical stiffness of tension legs helps to suppress the SFT displacement. From this, it is inferred that with an increase in vertical stiffness, the mid-span displacement reduces. From this study, it is evident that the magnitude of the moving load has a great influence on the displacement and the extend of this influence changes with the rate of change of displacement.

The onset of full structure modelling of SFT instilled confidence in the researchers which pushed them to carry out studies on more practical scenarios such as impact loads that can happen once in a while. Few researchers carried out studies in which they investigated the effect of impact loads generated from the outside of an SFT. A rectangular cross-section of SFT was considered and its 2D seismic behaviour was investigated when subjected to an impact load in the form of hydrodynamic pressures (Lee et al.,2016). Hydrodynamic pressure was calculated from the wave equation for fluid with rigorous consideration of the compressibility of seawater. The hydrodynamic pressure was applied to SFT and it was studied for its fluid-structure interaction. SFT was subjected to vertical and horizontal ground motion and the effects of the water depth and the compressibility of seawater, location of SFT in seawater, energy absorbed by flexible seabed were studied. Study shows that vertical ground motion has a much more significant impact than horizontal ground motion. On the other hand, the low-frequency sway and roll motion of the tunnel has a dominant effect on the seismic response as the force in mooring cable can be greatly influenced by the low-frequency content of ground motion.

Under the influence of impact load, spatial dynamic response analysis was carried out (Xiang and Yang, 2017) for an SFT. In this study, the SFT tube is treated as a beam on the elastic foundation (BOEF) with 3 degrees of freedom (horizontal displacement, vertical displacement, and torsion angle). The modal superposition and Runge-Kutta method were used to calculate the spatial displacement response of SFT. The effect of parameters such as BWR, IMA, anchorage stiffness, and hydraulic resistance were studied. Analysis shows that an increase in BWR ratio resulted in an increase in the maximum displacement and natural frequency and it recommends an IMA range between 450 to 600. Earlier studies (Lu et al., 2011; Marina et al., 2015)) have shown that 450 is the most suitable angle for tethers. Hydraulic resistance also has a significant effect on

SFT and hence should be considered in design. The anchor stiffness is found to have an inverse relationship with the maximum displacement of SFT and hydraulic resistance.

A detailed impact loading study was carried out on SFT including the "Fluid vehicle-tunnel interaction" effects (Lin et al., 2018). The study investigates the dynamic response of SFT when subjected to moving vehicular traffic. A theoretical model was proposed in which SFT was assumed as a beam and the moving vehicle is modelled as a spring-mass lump. The governing equation was solved with the modal superposition method and obtained results were verified by those obtained from finite element analysis. The vertical displacement and bending moment of SFT were amplified under the fluid-vehicle interaction. The BWR taken in the study was around 1.5 but some earlier studies concluded that it should be less than 1 (Zhang et al., 2010). The range of IMA was considered from 300 to 750. The study shows that the angle of inclination affects the dynamic response of SFT by changing the stiffness of the support. Larger the inclination angle, greater its vertical stiffness.

Consideration of impact loading on SFT continued to be researched upon wherein the impact of blast loading generated inside the tube was studied (Kristoffersen et al., 2019). Two cross sectional shapes were considered (rectangular and circular) to investigate the blast performance with a shock tube used to generate the blast loading against concrete slabs with and without reinforcement and the test was filmed with a high-speed camera and later used to measure the out-of-plane deformation. A finite element model of SFT was developed using ABAQUS and simulation was done. When results of both shock tube experiment and finite element analysis were compared, SFT with the circular cross-section was found to perform better than the rectangular cross section. The work suggests that where extra reinforcements are required, fibre reinforcement can be used as a good alternative.

Studies were carried out on the marine sediment effect of P-wave on SFT (Lin et al., 2019). The study assumes seawater as an ideal compressible fluid and the sediment is modelled as a linear porous medium using Biot theory. The angle of incidence of P-wave was varied from 00 to 900. The study brings out some significant findings such as if we go deep in ocean, the resonance peak of dynamic pressure decreases suggesting that SFT should be placed deeper in the ocean. Tether stiffness was found to have an inverse relation with dynamic pressure. Partially saturated sediment with high permeability may accelerate the release of dynamic pressure and lead to less pressure for SFT, and hence reduce the impact load.

Studies have been carried out in which the behaviour of SFT has been investigated in the unlikely event of sudden breakage of cables (tethers) ((Xiang et al., 2018; Xiang et al., 2020). A theoretical approach is proposed (Xiang et al., 2018), in which the analysis of SFT was simplified and the Alternate load Path method (AP method) is adopted to simulate the cable-breakage process. The theoretical model developed was found to be in good agreement with the FEM model. The behaviour of SFT under the sudden failure of cable was studied (Xiang et al., 2020) by installing a set of sensors on the SFT. The model was analysed using ABAQUS and the results were found to be in good agreement with the experimental model. Both studies conclude that the anchor-cables neighbouring the cable with rupture are the most affected ones. AP method was found to be a suitable method for modelling of SFT vibration effects initiated by cable-loss. Based on the common conclusion that the cables neighbouring the location of cable rupture are the most severely affected, cable failure events can be avoided by providing multiple pairs of anchor-cables.

The importance of resonance is amplified for a structure like SFT which is subjected to a multitude of forces such as wave load, hydrostatic pressure, impact load, etc. due to which vibration is induced in the SFT. Resonance can amplify the displacement of SFT and lead to failure of the structure. Some studies considering resonance were carried out (Lin et al., 2019a; Sun et al., 2020). In these parametric studies, behaviour of tethers was observed when resonance occurs. To analyse the vehicle-tunnel coupled vibration of SFT due to the parametric excitation (Lin et al., 2019b), the theoretical model was conceptualised by the Hamilton principle and D'Alembert's principle. The model was solved by the fourth-order Runge-Kutta method. The beam on the elastic foundation (BOEF) model was proposed to verify the results obtained from the theoretical model. Study shows that if the vehicle-tunnel vibration is confined to a smaller region, then its effect can be reduced. The vehicle having less velocity is most affected by the tethers vibration when travelling through the tunnel. Study also suggests the ideal range of gravity-buoyancy ratio (GBR) considering slack risk to lie between 0.75–0.85.

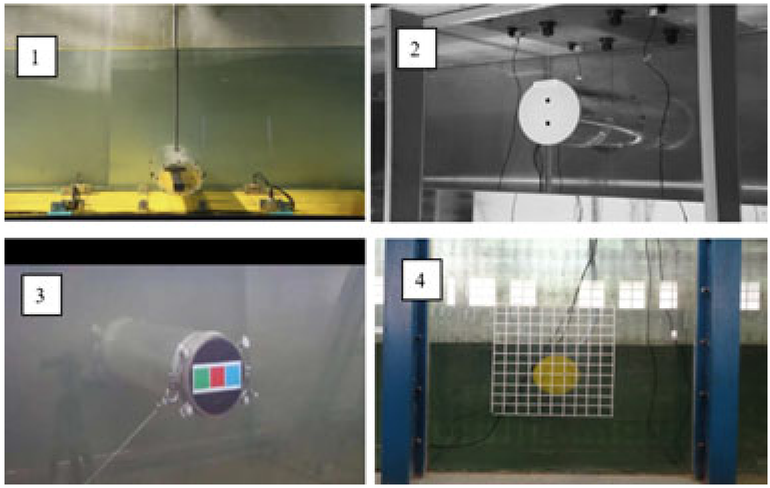
Another parametric study of tethers was carried out (Sun et al., 2020) in which the resonance effect was considered. In this analysis, it was assumed that tethers are a nonlinear beam model hinged at both ends and nonlinear vibration equations are derived. The multi-order modal vibration response of tethers (of the SFT) was analysed under axial and transverse excitation. The study (Sun et al., 2020) concludes that the axial and transverse resonance should not be allowed to happen or should be avoided as this will alter the linear relationship between vibrational amplitude and excitation amplitude. If there is no axial resonance, then there will be very less mid-span displacement. But when axial resonance occurs due to excitation amplitude, then the mid-span displacement increases sharply.

3 Wave flume test models of SFT

Much of the research works on SFT were analytical or numerical. Few researchers have carried out experiment on scaled model of SFT in a wave flume to replicate the actual environment at sea (Figure7). All these experiments were confined to 2D testing. The parametric studies covered through these experiments include, variation of wave height and BWR (Oh et al., 2013), comparison of single and double mooring system (Seo et al., 2015b) and comparison of different cross-sectional shapes of SFT (Li et al., 2018).

Use of image processing techniques in the experiments have improved the accuracy of results. Multiple studies (Oh et al., 2013; Yang et al., 2020) have concluded that effect of heave motion is negligible. The experimental studies also agree with the results obtained from analytical studies that BWR should be less than 1 for optimal performance. A comparison of the experimental works is given in Table 1.

Figure 7 Wave flume experiments on SFT (see online version for colours)



Source: 1: Seo et al. (2015a), 2: Oh et al. (2013), 3: Yang et al. (2020) and 4: Li et al. (2018)

Table 1 Comparison of modelling aspects

	Scale	*Shape*	*Size of wave flume*	*Diameter of SFT (prototype)*	*Material*
Oh et al. (2013)	1/100	Circular	53 × 1 × 1.25 m	23m	Not mentioned
Seo et al. (2015a)	1/148	Circular	0.6m (width)	15m	Acrylic plastic
Li et al. (2018)	1/60	Circular, Elliptical, Polygon	60 × 2 × 1.9 m	41.5 m 45 × 19 m 41.2 × 13.6 m	Plexiglass
Yang et al. (2020)	1/80	Circular	90 × 3 × 1.8 m	12.8 m	PVC and steel

SFT was studied (Oh et al., 2013) in wave flume by normal waves of differing heights and periods under various BWR (1.1, 1.3 and 1.5) and water depth. The SFT model has a length of 98cm (2cm less than the wave flume width). The depth of water used were 65, 80 and 95cm. Study shows that the magnitudes of SFT movements and forces is increased by increasing the height and duration of the wave. Unless the magnitudes of surge and pitch motions were comparable to the design wave, heave action was negligible. The behaviour of a SFT in waves was estimated and later verified with wave flume experiments (Seo et al., 2015). In this study, it was the assumed that SFT was 40m below the free surface in the 60m deep seabed. The lateral displacement of SFT is analysed with single and double mooring system of SFT under the effect of wave forces. Wave loads are calculated with the help of Morison's equation. Study concludes that the response of SFT with single mooring system is similar to the pendulum model, disregarding the damping effect and the nonlinear term. Study shows that the drag force was insignificant in this study compared with inertia force and the lateral displacement in double mooring system were considerably lower when compared to single mooring.

Experimental works on SFT to analyse the pressure characteristics of different section types under waves (Li et al., 2018) were carried out. The flume was split into two 1m thick flumes with a width of 2m. The test area was located in the lower half and the reflected waves were diffused in the upper half. As the wave propagates to the test area, once the structure is encountered, a portion of the wave may be reflected back. In the parallel flume in the upper half, a portion of the reflected wave is diffused and the energy of the reflected wave is eventually dissipated by the gravel. The other component is reflected back into the wave-maker ‘s vicinity. The reflected wave’s height is determined by the wave height instrument. Study shows that in the three categories of SFT sections, the maximum and minimum pressure are consistent. In the polygon section, the increase in vertical wave force compared to horizontal wave force is greater than that in the elliptical section, and the difference is the smallest in the circular section. Among the sections considered, the circular section emerged as the most efficient section as the distribution of forces is uniform.

In yet another study on SFT using wave flume, its motion when subjected to the wave loads was captured using image processing technique (Yang et al., 2020). The analysed images were captured using a 60 Hz frequency digital camera, such that the time interval between two frames was 0.0167 s. The spatial resolution of the image is 1,920 × 1,024 pixels and the precision of the motion measurement is 0.1mm. The study concludes that SFT is most unstable when BWR is close to 1 and with increase in wave height, the motion amplitude also increases because of the great energy associated with large waves.

4 Current trends and projected future of the technology

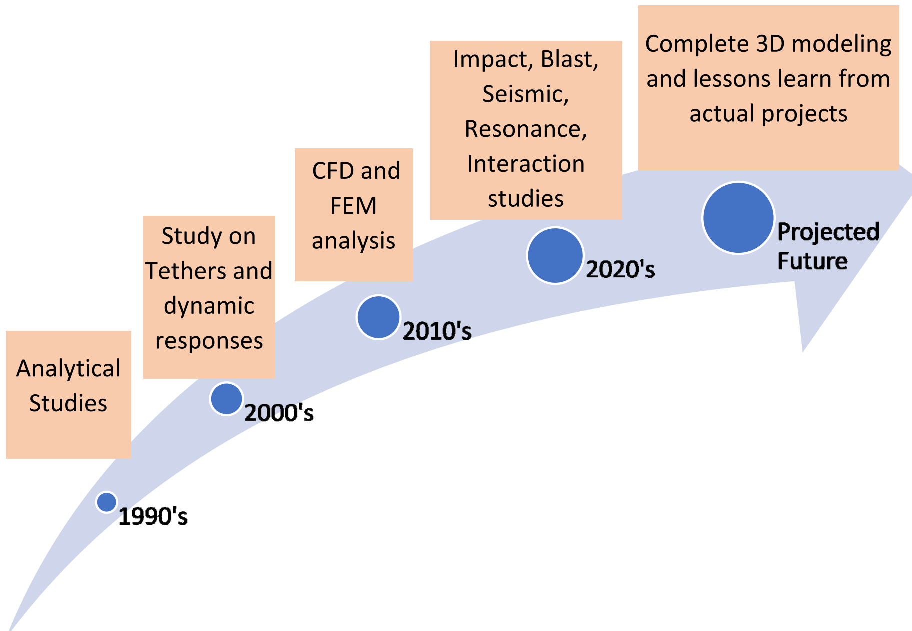
Based on the review of literature, the research trends of SFT have been summarised in Figure 8 which also includes a proposed future based on the current trends seen amongst the research community.

SFT is a special infrastructure which is proposed through oceans and hence may cross borders of countries and pass-through continents. Hence an SFT cannot be studied in isolation without a discussion on the political and socio-economic environment of different countries that it may be ultimately connected with. A discussion on the different projects that have been proposed or is in the pipeline within and outside of international borders are detailed as follows:

4.1 Norway SFT

In 1999, the Norwegian Public Road Administration (NPRA) was planning to enter into contracts with Norway Høgsfjord County to construct an SFT crossing the west coast. But due to political decisions, the project was cancelled. Later in 2012, the Norwegian Public Road Administration released the conceptual and more realistic images of SFT and announced that Norway will become the first country in the world to build a full-scale SFT. Initially, it was assumed that this project will end in 2025, but till now only 10 percent work is completed and hence the revised date of completion is 2050 (Lo, 2019). Technical difficulties in this project include the risk of explosions, fire and overloading. It is very difficult to rescue people if some kind of explosions take place due to Collison of vehicles or train. There will be no proper exit passage for smoke produced during such collisions. This has prompted NPRA to initiate studies on the effect of blast loading on tubular concrete structures.

Figure 8 Research trends as per literature review (see online version for colours)



4.2 UAE-India rail link

A futuristic project to construct a subsea rail link with India has been proposed by the National Advisor Bureau of UAE. The tunnel concept is based on well-known technology applied to floating bridges, offshore structures and submerged tunnels according to the Bureau. The underwater tunnel would consist of two curved concrete tubes submerged beneath the surface of the Arabian Sea. The submerged tubes would be stabilised by being attached to the pontoons on the surface of the sea or by vertical ties to the seafloor. This project will connect the Fujairah city of UAE to the Mumbai city of India. The Fujairah-Mumbai Subsea Tunnel Project will include a subsea high-speed railway, aimed at boosting bilateral trade between the two nations. Till now only rail link is proposed but in future plans may also include provision for a road to be built inside the SFT for car and truck transportation as well as a floating hotel. The trains envisaged would operate with a speed of 600–1,000 km/h. The distance of 1,826km between Mumbai and Fujairah could be covered in less than four hours, while the distance from Gwadar port to Fujairah could be covered in less than an hour.

4.3 Irish Sea Crossing

Several proposals have been made over the years to connect Ireland with Great Britain. In 2004, the Irish Academy of Engineers proposed a 50miles tunnel this time under a much wider section of the Irish Sea, linking Rossiare in Ireland to Pembrokeshire in Wales. It is estimated that journey would take one hour and ten minutes. In 2007, a bridge from north Ireland to Galloway in Scotland was proposed by the Centre for Cross Border Studies. It will have to run for 21miles and the plan is to link with trains going to Glasgow (and then probably on to London). The project cost is estimated to be £3.5bn.

4.4 Japan-Korea Tunnel

A new tunnel project was suggested that could connect Japan and South Korea at their shortest connecting point measuring 128 km. In 2009, a feasibility study was ordered by the then-South Korean President, Lee Myung Bak, but such a connection is not expected to be cheap at more than £50bn. The technical difficulties associated with this project is two-fold: On one hand, the high seismicity of Japan unlike other countries require it to depend on rail network heavily for the realisation of this tunnel. The railway track associated with the countries involved may pose additional challenges due to compatibility of its track sizes as Japan uses 1,067mm narrower tacks and South Korea uses 1435mm gauge tracks.

4.5 Helsinki-Tallinn Tunnel (FinEst Link)

Helsinki, the Finnish capital and Tallinn, the Estonian capital, which are 80 km apart, is proposed to be connected with a tunnel under the Gulf of Finland. In 2015, a feasibility report was published that sounded optimistic, indicating that the tunnel could pay for itself in 40 years. It will also establish a land-link between Finland and the Baltics for the first time, which does not require travellers to cross Russia. The new tunnel will also include a bonus stop on the planned new Rail Baltica railway, which would build quicker rail connections between Berlin, Warsaw, and major cities in the three Baltic states when construction starts in 2020. However, there are some technical difficulties as 5% of total tunnel length on the Estonian side will penetrate in soft Ediacaran sandstone that overlies the crystalline basement (Vikman-Kanerva, 2018). This sandstone is aquifer and important groundwater reservoir for Tallinn and surrounding areas. Hence, the challenge in design involves optimisation of the effect of groundwater in this layer.

4.6 Fehmarn Belt fixed link

Construction started in 2015 for a new 18km long tunnel connecting Lolland’s Danish island and Fehmarn’s German island, which is then linked to the German mainland. The Fehmarn link will be constructed as 79 separate components using 217 m long prefabricated elements, floating out into the sea on a barge, and then submerged and put in a trench dug at the bottom of the ocean. Significant dredging is a big challenge in terms of depth of water, varying soil types and strict environmental regulations and it is estimated that 20 million m^3 (Lykke and Janssen, 2009) of soil will be dredged and as the disposal of such large quantities of soil in the marine environment may prove to be unacceptable, alternate methods of disposal needs to be sought. Other major challenge is the ventilation problem associated with the estimated annual increase in volume of traffic leading to increased emission of CO_2 and NO_2. These emissions if not released will lead to high pressure and suffocation within the SFT.

5 Conclusions

SFT is a new age technology and a high investment project which is set to revolutionise the connectivity and transportation system. This topic has a multidisciplinary domain which necessitates contribution from transportation engineers, geotechnical engineers, offshore engineers, structure engineers, mechanical engineers, etc. A culmination of these disciplines is needed in a complete study of this concept. Although the amount of research so far in this field has been limited, the number of common conclusions is further limited because each of the researcher is focused on the specific domain of SFT that is relevant to their discipline. Based on literature review, few important takeaways have been specifically identified and are listed as follows:

1 There is a lack of universally accepted standards for SFT and a potential way out of this problem will be to compile all the research findings by researchers worldwide in developing design and construction protocols and also hold regular conferences and symposiums exclusive for SFT so that knowledge is shared and ideas are brought to the table.

2 Researchers have given due attention to tethers which anchor the SFT to seabed and multiple studies have concluded that Inclined mooring angle (IMA) is a very important factor in SFT and the ideal range was observed to be within 300 to 600 with 450 as the optimum. Soil anchoring which continues to be a major area of research in geotechnical engineering should focus on advanced research of 450 angle of tethers for the loads experienced by an SFT.

3 Vortex-induced vibration (VIV) will be induced on the SFT tube and tethers due to the action of the vortex. If the frequency of vortex is closer to the natural frequency of the structure or the tethers, then due to vortex-excited resonance, the vibration amplitude will increase and structure may collapse. Fluid-structure interaction is found to be one of the leading cause of failures in SFT, the effect of which is not fully captured in many of the studies which are based on simplistic approach using Morison's equation. Hence, analysis needs to focus on including flow-solid-soil interaction to obtain accurate results and relationships between structure, loads and constraints.

4 Through the CFD and FEM analyses, the circular cross-section geometry of SFT is found to be more efficient than rectangular and other cross-sections. This is because the stress distribution in circular geometry is uniform. The merit of circular shape for SFT is evidenced through wave flume based experimental studies as well.

5 Resonance should be avoided at all cost for SFT so that a linear relationship is maintained between vibrational amplitude and excitation amplitude. To minimise the effect of resonance damage, new materials having enhanced properties (high strength, anti-impact-toughness, corrosion resistance, crack and fatigue resistance) should be used. The use of special concrete mixes like bendable concrete developed during the last decade should be examined for its suitability as the material of SFT.

6 The stiffness of anchorage plays a very significant role in the stability of SFT. Increase in stiffness help to reduce the mid-span displacements and also show inverse variation with dynamic pressure. Reduction of mid-span displacement is also

vital from the point of view comfort of vehicles using SFT even if the safety is not a concern.

SFT once build will become the largest man-made structure under-water and hence the effect of the SFT on aquatic life in general and the impact forces generated by big fishes (blue whale, shark, etc.) on accidental collision with it during its normal feeding routines is significant. This has to be considered in the planning, design and implementation of SFT at a time when much of the aquatic species are facing extinction due to human activities.

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