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SUBMERGED FLOATING TUNNEL: A DETAILED STUDY ON DESIGN AND CHALLENGES

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Abstract: Submerged floating tunnel is an innovation which introduces a new trend in transportation engineering. It provides a fast and easy access of transportation where the conventional methods are not applicable. SFT is adopted when the water bed is too deep, rocky and highly undulated where submerged tunnels and bridges are not economical. SFT is based on principle of buoyancy and they are acted upon by different loads. Hence SFT is to be designed for desired strength, stiffness and durability. Since SFT is not constructed till now, the design analysis is difficult. Various researches were conducted to analyze SFT under different environmental, accidental and varying loads. Continuous evaluation and inspection of the structure is required to eliminate the chances of damages. Proper repairing and replacements are to be done without affecting the working of the structure to increase the life span of SFT.

***Index Terms* – Submerged floating tunnel, Principle of Buoyancy, Transportation.**

I. INTRODUCTION

Bridges and submerged tunnels are widely used for the purpose of crossing water bodies. Submerged floating tunnel (SFT) is an innovation for the development of society and environmental protection .SFT is also named as submerged floating bridge, suspended tunnel or Archimedes Bridge. The depth of water bed varies with a maximum of 8 km and an average of 3.3 km. When bridge is constructed for the purpose of crossing water bodies, the columns for support is not practicable for a depth of 8 km. Similarly if submerged tunnel is adopted, the pressure at 8 km depth will be very high where survival is not possible. Hence SFT is a solution for the problems faced by bridges and submerged tunnels. SFT is provided at a depth of 20-50 km below the water level, where the problem of high pressure is not relevant. Even big ships can pass over the SFT since the tube is submerged at specific depth. The stability of SFT is based on Archimedes principle. SFT can be maintained floated by positive or negative buoyancy. In case of positive buoyancy anchors to sea bed or pontoons are used for supporting, if SFT is 30 m and below water surface. Columns or pier is used as foundation when balanced by negative buoyancy, where depth of water is around 100 m.

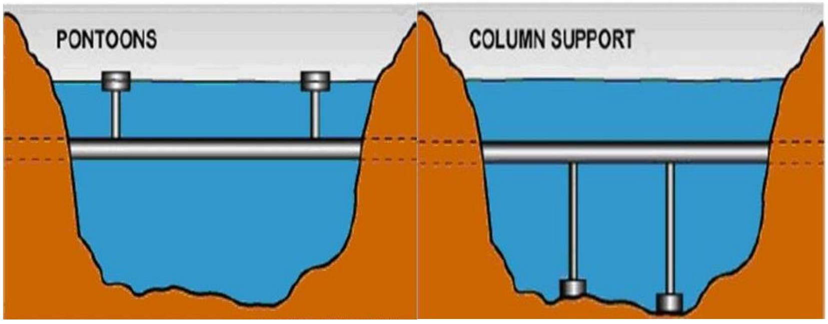
II. STRUCTURAL COMPONENTS OF SFT

SFT consists of different components for supporting and handling forces acting on the structure. These are essential for providing required strength and stiffness to SFT .The basic components are SFT tube, anchorage system, shore connections.

The tube is meant to carry the traffic and equipment loads. It can be constructed with circular, elliptical and polygonal cross sections and the length of tube varies from 100m-500m.Different tube sections are connected to form the whole SFT structure. The tube is made of steel, concrete or the combination of both. The optimum shape of SFT tube is having a vertical curvature concentrated at the middle of the tube. This curvature makes shortening of tube easier during installation. Small bending is caused to the tunnel due the variation in buoyancy at the middle of tube. Similarly little bending and axial force is created due to the amount of water present in the middle of tube during installation.

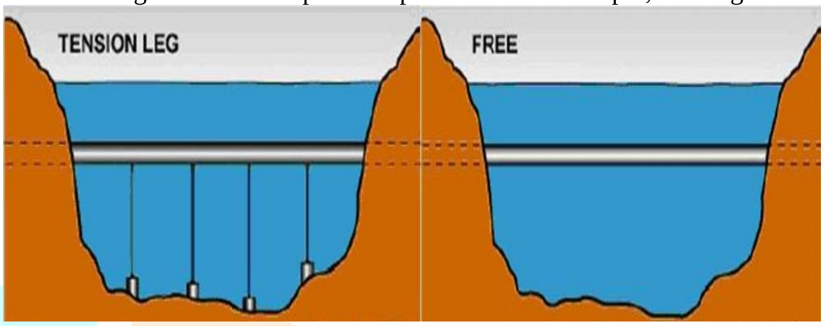
Optimal shape of SFT

The anchorage system can be provided as pontoons, column, tether to the water bed and unanchored system. SFT anchored by pontoons are affected by wind, current, wave etc. Pontoons can be provided when the water depth is too large where column anchorage will be too difficult and expensive. Column anchorage is adopted when the depth of water is not too large.



Pontoon and column anchorage systems

SFT tethers are provided under tension for all future situations and no slack is expected to affect the tether in any load cases. The tether can be provided as vertical or inclined connecting to the bottom of water. In case of unanchored SFT, no support is provided except at landfalls. Even though it can be adopted independent of water depth, the length of SFT will be limited.



Tether and unanchored system of anchorage

Coupling of the SFT tube with the much rigid tunnel on the ground is done using strong connections. These connections should not develop any kind of stress and must be capable of restricting the movement of tube. The joints must be water tight to prevent the entry of water to the tube. Appropriate protections are also provided in areas where chances of earthquakes and landslides are high.

III. DESIGN PRINCIPLES OF SFT

SFT is designed to carry traffic, various live loads and dead loads. Hence it is designed for maximum safety, durability and applicability. The design of SFT depends on design load, buoyancy to weight ratio, resistance to flow and durable performances. Optimum plan of the design also depends on economic and environmental factors. For proper design of SFT buoyancy to weight ratio should be less than 1.According to studies the value should vary between 0.5-0.8.During the construction and operation stages, the SFT should satisfy strength, stiffness and stability. Similar to the standards of seismic protection of building, to resist the hydrodynamics of SFT the variation of surface curvature should be gentle.

IV. CONSTRUCTION OF SFT

The SFT is constructed similar to immersed tunnel even though the concept is based on the floating bridge and offshore structures. The construction process is divided into 3 stages which are prefabrication of SFT tube, transportation and installation of tube and support systems.

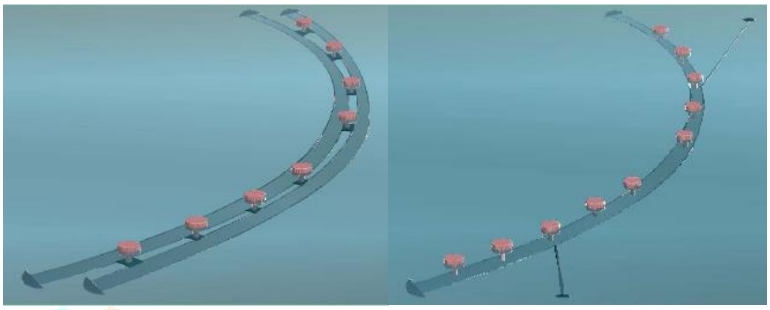
The tube sections are prefabricated in dry docks where the length of section is determined by spacing of anchorage system and transportation conditions. The cross sectional dimension should be such that it is designed to have space for carrying traffic, escape way, ventilation and air channels. An air tight condition inside the tube is ensured by adopting double walled sections. The tube must be water tight and it is provided by the structure itself and material. Penetration cracks must be completely eliminated and the surface cracks can be avoided by using high performance fiber reinforced concrete.

The prefabricated tubes can be installed to the desired location by 2 methods; floating and sinking method, incremental launching method. Installation of tube in floating and sinking method is similar to immersed tunnel. In this method permanent anchor cables are installed directly and the temporary anchors or buoys are used for maintaining stability. In incremental launching method, the tube is carried to the inclined slide way on the shore and it is pushed to the water using hydraulic jack. The connections in between tube are done by pre-stressed tension before pushing. In this method sections are first temporarily anchored and permanently anchored after finishing installation.

V.STRUCTURAL DESIGN

Various stages involved in the construction of SFT include prefabrication, floating, installation and operation. Since the transformation during these stages is complex the tube is to be designed after longitudinal and transverse analysis. The tube undergoes different types of loads including permanent loads(self-weight of tube, buoyancy, hydrostatic pressure) ,variable loads (vehicle load, water head load, temperature load and hydrodynamic loads)and accidental loads (due to seismic action, blast leakage and sinking ship).The hydrodynamic loads include wave, current loads which are caused due to water-tube interaction. The anchorage system transmits loads of vehicles, wave, current, temperature etc. The structural design of SFT is based on ultimate limit state and serviceability limit state method. It is designed similar to traditional hydraulic structures. Fatigue limit state theory based on structural reliability theory is used to analyze the stress and displacement under progressive damage conditions.

SFT can be constructed in circular, rectangular or polygonal shape where circular shape is favorable for handling hydrodynamic forces. The vertical position of the tube is balanced by tethers or pontoons. Pontoons and vertical tethers contribute vertical stiffness to the system but horizontal stiffness is not satisfied. The long, slender SFT tubes require sufficient horizontal stiffness for their stability. Horizontal stiffness to tube can be achieved by adopting horizontal arched tube or by providing inclined tethers. Inclined tethers are expensive in case of deep or wide crossings. This can be solved by adopting 2 horizontal arches which are installed more or less parallel. These arches are connected at regular intervals by rigid connections and they provide space for one directional transportation and escape possibility in case of fire. Horizontal stiffening tendon system can be used as an alternative method for double tube system. In this system pre-tensioned tendons are used which are properly anchored to shore to strong rocks.



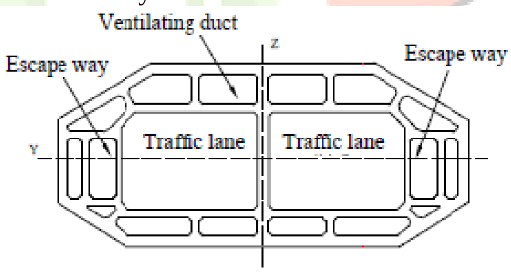
SFT as double tube system, SFT with horizontal stiffening tendon system

5.1 Design of Tube Joint

The joints in SFT should satisfy non seepage and water tight condition under construction and operation stages. The joints must be able to transfer the load during the whole stages of SFT functioning. It should transfer stress and deformation in construction stage and for fine seismic performance. The joints can be provided as both rigid and flexible joints based on the stiffness and deformation requirements.

5.2 Ventilation

The ventilation system in the tube should be properly designed since the quality of ventilation system affects the engineering cost and environment inside the tube. Effective ventilation acts as major disaster relieving system. SFT ventilation provides a healthy environment inside the tube by reducing the concentration of harmful gases like carbon monoxide. It also helps to improve the visibility inside the tube and to clear the heat and smoke when fire occurs. According to the studies conducted, for a one-way traffic tunnel, the design wind speed should not be more than 10 m/s and for two way traffic it should not exceed 8 m/s. The noise generated within the tube due to ventilation fan and exhaust emission should follows environment protection guidance. The ventilation system should remain stable even under any traffic conditions and fire accidents.



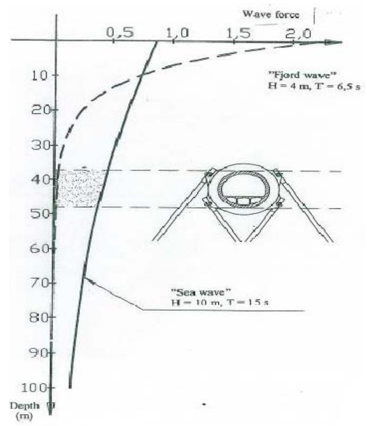
SFT tube section

VI.CHALLENGES IN DESIGN AND CONSTRUCTION OF SFT

Stability of the SFT mainly depends on the balance between dead load, moving load, buoyancy and anchorage force. In addition to these loads environmental forces like wind force, current force etc. also contributes to the stability of SFT. Wave and current acting on the SFT cause fluid –solid coupling vibration on the structure and its components, which makes difficulty in the analysis of structure. Due to the continuous exposure to saline environment, the SFT tube and the components may face the problems of corrosion which leads to the failure of structure. Chances of collision accidents is also a challenge faced by the SFT ,hence proper safety measures have to be adopted to reduce or avoid the risk of accidents. Construction of foundation to a greater depth under complex marine geological condition is another challenge, which can be solved by providing alternate methods.

6.1Wave Force

The fluid force acting on SFT can be calculated by Morison equation. The variation of horizontal and vertical wave force with depth is calculated using layered integration method. According to the studies conducted in fjord basin, different wave heights and their periods are compared. The result shows a great difference in wave period compared to their corresponding wave heights. Hence intensity of wave force depends on wave period i.e. higher wave force is created by waves with higher period.



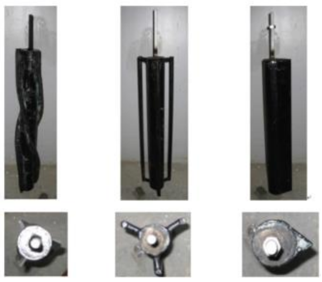
Variation of effect of wave force with depth of SFT for different wave periods

The interpretation of figure shows that the effect of fjord wave force can be reduced by placing the SFT at large depth and for sea waves SFT should be placed at further larger depth. Moderate wave force is developed due to swell force which is having only decimeters amplitude. SFT may develop high dynamic eigen periods due to its flexible nature. Hence detrimental resonance for long periodic resonance has to be avoided. Internal waves are another source which produces long periodic resonance, which is produced due to the variation of density of water due to salinity variation. Different layers are formed with light denser layer at top of a denser layer. The layering generates wave force on the object at the vicinity of boundary of different layers. But the internal waves are not proven to exist in reality.

6.2 Current Force

The current speed across the fjord surface varies with large difference which give rise to both symmetrical and antimetrical current profiles. The current when comes in contact with SFT tube give rise to constant in line force having intensity proportional to square of current velocity and this symmetrical current force is balanced by the axial force formed by the arched SFT tube. The bucking capacity of tube determines its strength of resistance. The antimetric current force does not create axial force in the arched tube; hence it is to be resisted by the bending capacity of the tube or by introducing support tendons.

When the current force comes in contact with an obstacle it produces vortex shredding. The frequency of vortex shredding is directly proportion to the current velocity when current passes the cylindrical tube. The frequency of vortex when approaches the natural frequency of tube results in vortex induced vibration (VIV),as a result in line and cross flow vibrations are formed. In tubes cross flow vibrations should be eliminated. This can be achieved by providing tube outer diameter as 16 m tube and current velocity of 1.5 m/s is limited as maximum. Similarly the fundamental period of 30 sec or less is provided for the vertical vibration modes. Inline vibration causes only fatigue issues due to its low intensity. The vibration in SFT tube affects the instantaneous amplitude on tendons. For supporting systems like tendon and tethers cross flow vibrations are unavoidable. It can be limited by adopting the tendon diameter as 1 m and the fundamental period should be less than 3-4 seconds. The current velocity is reduced to 1 m/s at the relevant depth. The inclination of the tendons or cables should be between 45˚-60˚.VIV on tendons can be eliminated by adopting different methods such as choosing appropriate structural parameters, introducing damping devices or by using disturbing flow device. Different flow disturbing devices such as spiral fringe, control rod and fairing are experimented and the spiral fringe gives the most effect on all working conditions while control rod and fairing works on current direction. At a higher current velocity than velocity required to induce VIV, a phenomenon called galloping occurs. But this phenomenon does not occur in tubes with circular cross section.



Three disturbing flow devices of anchor cables: Spiral fringe, Control rod and Fairing

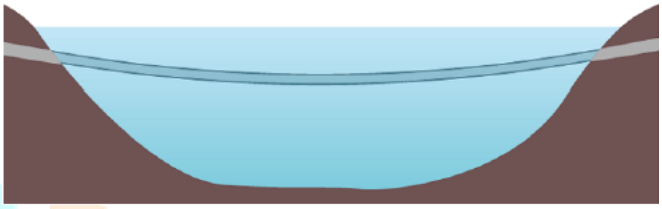
6.3 Artificial Damping

The SFT is experiencing many low intensity environmental forces which may not produce any damage to the system unless acted by a major vibrating force. One of the methods to minimize the challenge due to this vibration is by keeping the fundamental eigen period lower than the period of force. But by adopting this method, the number of anchors required will be more with less spacing which results in increased cost of SFT construction. As a solution for this problem artificial damper can be installed in the system, which can limit the resonance phenomenon as well as anchor points also get reduced. The damping system is provided as tuned mechanical dampers in which the eigen period of internal mechanical system is tuned to the frequency to be damped out. Space available below the road way of SFT, hanging heavy concrete blocks, chains below the tunnel are alternative options for damping system. Chains provided under the tubes can provide more hydrodynamic damping. Water basins can be provided under the roadway of SFT which is connected by tube is another alternative. The movement of water between the basins induced by the tube provides viscous damping.

6.4 Accident Analysis

Even though the chances of accident in SFT in very low the after effects will be huge if once occurred. Accidents due to earthquake, ship collision, terrorist attacks are some of the possible challenges that may occur to the SFT. Due to the collision of ship, the pontoon may get damaged; hence pontoon connections are done such that the damage of pontoon will not cause any immediate effect on the stability of the SFT. Damage to the pontoons can be also reduced by dividing the pontoons to different compartments and providing connections to the tube with weak links.

SFT tubes are subjected to ship sinking, submarine collision, internal fire and explosion, water filling due to rupture damages. This damages results in spontaneous flow of water to the tube. Thus the tube has to be designed to be ductile to withstand this kind of damages. Double hull steel lining can be used for concrete tubes and the tube is shaped to have apex at its mid span so the water inside tube is expelled out through the end of tube. Anchorage systems are affected by collision of submarine, trawling of gears and anchors and sinking ships. Hence the system is made redundant in which damaged elements can be replaced or repaired without affecting the working of the whole system. The problems caused while crossing the SFT can be eliminated by providing an unanchored single SFT tube. In this system pontoons and tethers are eliminated and the weight is balanced by its net buoyancy. The tube is now having its apex at mid span and the water inside the tube flows out to each side of tube to the prepared basins. The tube is curved in the other way compared to ultimate SFT curvature.



Ultimate SFT solution

According to experiments the effect of earthquake can be analyzed using green function, response spectrum method, large mass method, pseudo-excitation method and finite element method (FEM). The dynamic response of underwater explosion can be analyzed using ANSYS/LS-DYNA software. Using simplified elastic support beam model of FEM the response analysis of SFT under impact and collision loads can be studied. From the studies conducted, the effects of submarine collision on SFT and the numerical analysis is found to be ineffective due to model size and calculation cost .Smoothed particle hydrodynamics (SPH) and FEM are used for the effective analysis of SFT under collision. The variation in physical quantities of the SFT collided by submarine is analyzed using ANSYS/LS-DYNA software. The studies based on the equations resulted in a submarine impacted SFT model which shows 40% of total energy is absorbed by the tunnel mainly as internal energy which is produced by the tunnel wall deformation. The studies also reveals the parameters such as displacement, speed and acceleration shows maximum value at impact point during the collision process and shows an inverted V shaped variation. The anchor cables were found to restrict the movement of tunnel so as to prevent disaster expansion due to collision.

6.5 Durability

The structures such as bridges, tunnels etc. are designed for a design life of 120-150 years. But for a submerged floating tunnel due to the continuous exposure to saline environment chances of corrosion is high. In a SFT of reinforced concrete once crack occurs, results in degradation of strength when subjected to corrosion and thereby reduction in life span of structure. Hence continuous inspection, repairing, replacement etc. are required when the life of any component is found to be lower the design life of the whole structure.

VII. RISK ASSESMENT AND CONTROL

The risks associated with SFT can be assessed by both qualitative and quantitative techniques. Qualitative analysis depends on knowledge, experience, and by logical judgment of an expert. Quantitative analysis evaluates the risk by test results and statistical data where mathematical model and numerical simulations helps in analyzing the risk. According to the studies, based on the BP neural network theory, all types of risk indexes in the construction stage of SFT were evaluated and a reference index value has been obtained. The overall risk of SFT is then divided into 8 classes based on fuzzy comprehensive evaluation method and a security risk value is obtained. This value is found to be moderate for SFT and hence it is acceptable by people.

Risk control is the method used to reduce the losses due to hazards by adopting precautions and control process after analyzing the risks. The resistance of SFT against natural hazards can be controlled by providing reinforcements and protection methods. Hazard warning and monitoring methods can be used to control the aftereffects to a great extent. For handling the operational risk associated with SFT, along with disaster prevention and relief system the facilities in the SFT must include proper ventilation and lighting, traffic indication signs and smooth line shape. Evacuation system under emergency and longitudinal ventilation for fire and smoke emission are also designed as control measures. Both the structural and operational safety is given much importance to control the risks. Hence the stress, strain variation are thoroughly studied under different environmental as well as structural conditions and design is prepared as per the investigations to guarantee maximum durability.

VIII. CONCLUSION

SFT opens a new opportunity for extremely deep water transportation mode in situations where the existing methods are difficult and expensive. This is an excellent alternative for linking rural network and underground infrastructures in modern cities. Unlike other underwater transportation system, SFT has very low energy consumption because of gentle gradient. SFT reduces environmental pollution and thereby the natural beauty can be conserved. One of the major advantages of SFT is construction of

SFT tube does not cause any disturbance in densely populated area since the tubes are prefabricated. Even though SFT is still an innovation, the application of SFT concept enables a fast and efficient transportation system.

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