ANALYSIS TO DETERMINE THE FEASIBILITY OF AN SUBMERGED FLOATING TUNNEL WITH SUSPENSION CABLES

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ABSTRACT

Submerged floating tunnel is an revolutionary innovation which introduces a new beginning of trend in transportation engineering. It provides a fast and easy access of transportation where the conventional methods are not applicable. SFT is implemented when the water level is too deep, rocky and highly undulated submerged ground where submerged tunnels and bridges are not sustainable or economical. SFT is based on principle of buoyancy and they are acted upon by different varying loads. Hence SFT is to be designed for desired strength, stiffness and durability. Since SFT is not constructed till now, the design analysis is complex, difficult and needs various parameters to understand and its consequential impacts of the stability of SFT.

Various researches were performed to analyze SFT under different environmental, accidental and varying loads. Continuous evaluation and inspection and improvements in the structure is required to eliminate the chances of damages.

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, 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 loads 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 project works undertakes the studies of various researchers and case studies were analyzed to determine the feasibility of an SFT with suspension cables.

Keyword: - *Submerged floating tunnel (SFT), Immersed Tunnel (IT), Cable Supported Immersed Inversed Bridge (CSIIB), Conceptual Design (CD), Buoyancy to Weight Ratio (BWR) etc.,*

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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.

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 offer significant recommendations for the design of submerged floating tunnel.

2. LITERATURE REVIEW

Submerged floating tunnels (SFTs) float underwater and have an innovative water-crossing typology, supported by Archimedes' principle. While SFTs are placed underwater, they different from the conventional immersed tunnels, which are placed directly on the seabed and are composed of segments.

However, they have several structural or infrastructural issues. Several proposals for SFTs have been designed by different countries, after the concept was proposed by Sir Edward James Reed of the United Kingdom in 1886, and are continuously being studied in the United States, France, Norway, Japan, Italy, Canada, Switzerland, Korea, China, and so forth.

An SFT has its own weight and buoyancy, according to its immersion depth volume. Generally, the tunnel cross section is designed so that the buoyancy covers the structural weight, and the tunnel is then subjected to an upward force, which is exerted by a fluid.

(a) (b)

Figure 1. Basic concept of submerged floating tunnels (SFTs): (a) tether-stabilized submerged floating tunnel concept; (b) pontoon-stabilized submerged floating tunnel concept.

Based on the vertical support, the current design alternatives for SFTs can be divided into two categories, as shown in Figure 1: a tether stabilized concept (Figure 1a) and a pontoon-stabilized concept (Figure 1b).

Italy has been continuing its research on SFTs, as an alternative to crossing the straits, since the 1960s. Norway have advanced SFT technologies. The SIJLAB (Sino-Italian Joint Laboratory of Archimedes' Bridge), as a Sino-Italian joint venture, was founded in 1998 and was co-financed by the Institute of Mechanics, Chinese Academy of Sciences, China and the "Ponte diArchimede International" company. The consortium has carried out the executive design of a prototype tunnel, with a length of 100 m, in Qiandao Lake in the eastern province of Zhejiang, China.

In addition, Norway is working on the world's first SFT project to cross the fjords. It is a long journey between Kristiansand and Trondheim, which is part of the E39 route, crossing the southwestern coast. The Norwegian Public Roads Administration (NPRA) aims to complete the construction by 2050 and plans to cut travel time by half.

However, this project focuses mainly on core technology research concerning a preliminary design and lacks experience in the practical application of an SFT, which involves, for instance, design standards and economic evaluation, and the tunnel has never been built (as of 2018). Lin et al.[1] (2019) investigated on the vehicle–tunnel coupled vibration of SFT using tether vibration, and the Hamilton principle and D'Alembert's principle were used to define a theoretical model. Xiaing and Yang[2] (2017) researched the global dynamic performance of a submerged floating tunnel (SFT) under an impact load.

Seo etal.[3] (2015) presented a theoretical method, and tests using experimental models involving a wave were proposed for verification. Xiang et al. [4] (2018) studied the global dynamic response of an SFT under anchor-cable failure, considering the post-breakage performance.

Lu et al.[5] (2011) studied the dynamics of an SFT, when its behavior was affected by tether slack and snap force under wave conditions. Jin and Kim studied time-domain hydro-elastic analysis of SFT using a finite element model under extreme wave and seismic excitations. Chen et al.[6] researched coupled vibration performance of SFT in wave and current.

Won and Kim [7] (2018) proposed a concept design for an SFT with an inclined cable, as an application form. It is shown in Figure 1. The hydrodynamic characteristics of the SFT were studied, and a case study on the diameters, drafts, and BWR (buoyancy and weight ratio), as variables, was conducted. In this study, a feasibility study on the applicability of an SFT with suspension cables (Figure 3) was performed at an arbitrary site.

Figure 4. illustrates two solutions concerning the components of SFTs with suspension cables, which consist of towers, main cables, hangers and anchorages. The tube, the main body an SFT, is suspended on a hanger rope and transmits a dead load and a live load, which are arranged at regular intervals, to a hanger. Moreover, they hang from the main cable, so that they can transfer the load of the SFT to the main cable.

Unlike conventional suspension bridges, since the main cable of SFTs holds loads by buoyant forces uniformly, it can be the main generator of tension and control the behavior of the SFT.

The tower is a supporting component like the tube and main cables. The SFT with a tower differs from the SFT with inclined cables, shown in Figure 4. in that the hanger supports this system vertically, so that the compressive force does not act on the tube body.

Figure 2. Concept design of a submerged floating tunnel with inclined cables

Figure 3. Concept design of a submerged floating tunnel with suspension cables

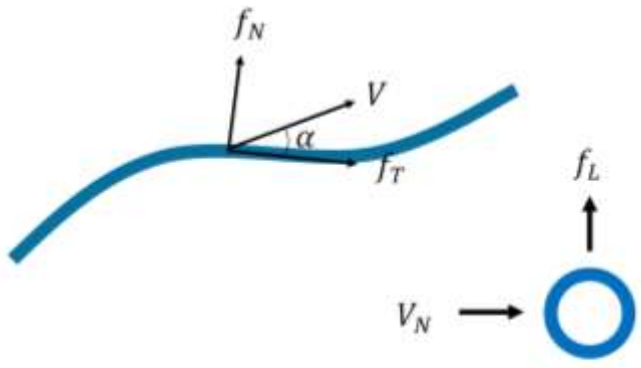


Figure 4. Hydrodynamic force on a pipe or tendon.

In this paper, case studies were analyzed to determine the feasibility of an SFT with suspension cables. In order to apply the SFT in a field site, the deformation of the system should be controlled, even under extreme wave conditions if vehicles or trains operate inside the SFT.

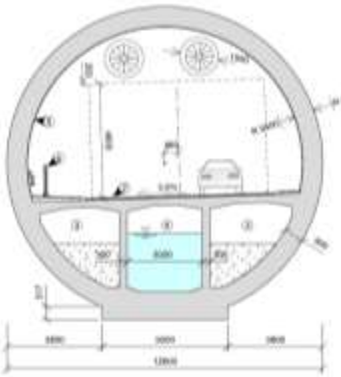
The main variables were to be the diameter of the tube, layout methods and layout angles of the main cable, BWR (buoyancy and weight ratio), installation depths, and wave heights.

The optimal conditions for the variables were derived by analyzing the behavior of the SFT with suspension cables under irregular waves.

Here, the installation depth required to minimize the effect of breaking waves and maritime activity is named the top clearance or the draft in offshore engineering.

3. ANALYTICAL METHOD-DESIGN OF SFT

A simplified version of floating tunnel one proposed by Reinertsen Olav Olsen Group [8] (2012) is used as a basis for design and analysis as shown in the figure 5. In this simplified structure configuration, pontoons and horizontal bracings are omitted, and the tubes, the traffic and the mooring lines is thought able to keep stabilization in the vertical direction due to the self-balance of its gravity and buoyancy. In summary, the structure only contains two separate tubes. In a future work, the whole tunnels should be considered as a structural system and all environmental loads should be quantitatively evaluated.



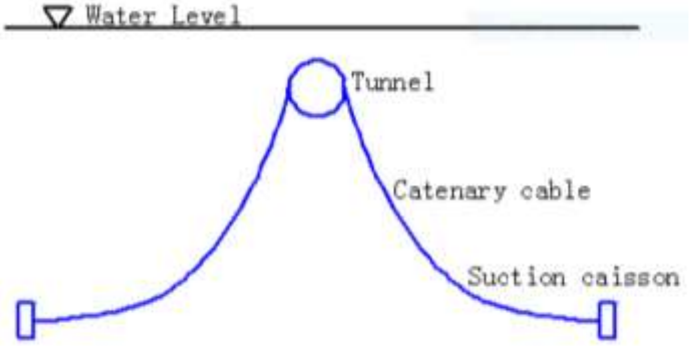


Figure 5. Floating tunnel tube cross-section, extracted from Reinertsen Olav Olsen Group (2012)

Figure 6. Sectional view of the anchor system configuration for one tunnel tube

3.1 LOAD ANALYSIS OF SFT

To simplify the analysis only one single tube of 1000meters submerged within the waterbody is considered. To make things easier the design analysis, environmental condition such as wind, current and wave, can be regarded as uniformly distributed along the fjord width, therefore the environmental loadings on the tubes correspondingly follows an even distribution over the tunnel, making it reasonable to assume that each set of mooring cables and suction anchors is subjected to the loadings on one specific tunnel section close to it.

3.1.1 SELF WEIGHT

Self-weight includes two different components, SW1-Permanent self-weight and SW2-Variable self-weight. SW1 covers the weight of concrete tube, structural elements in tunnel, ballast, equipment and pavement, while SW2 covers the weight of water absorbed by concrete and solid ballast as well as the weight of vegetation growth on structures.
Hence, **Self-Weight = SW1 + SW2………………………………………………………………………………(eq.1)**

3.1.2 TRAFFIC LOAD

The vertical distributed load due to the movement of traffic through the tunnel is calculated based on the modes of traffic and is calculated using…
Traffic Load, T = Vertical distributed load * 1000 ………………………………………………………..(eq.2)

3.1.3 BUYONCY UNDER TIDE

The tunnel is totally submerged in water, so the buoyancy can be determined using Archimedes Principle, i.e.
Buoyancy = ρgV ……………………………………………………………………………………………...(eq.3)
Where, ρ=fluid density, kg/m3; g=gravity coefficient, N/kg; V=volume of tube.

The water buoyancy also known as Archimedes buoyancy is obtained with the following equation.
$Bk = \gamma w\ Atot$ **…………………………………………………………………………………………………..(eq.4)**
Where, γw : Specific weight of water. This value is related to the salinity and temperature of the water. The salinity is generally measured as Practical Salinity Unit (PSU). Atot : Total area of the SFT cross section.

Finally, the algebraic sum of the self-weight of the structure and the water buoyancy gives the residual buoyancy of the tunnel.
$RBk = Bk - Atot$ **………………………………………………………………………………………….(eq.5)**

BWR determines the tension force in the tether section and influences the dynamic behavior of SFT structure (Hong Y. et al. 2010).
BWR = Bk/Atot………………………………………………………………………………………….(eq.6)

3.1.4 TIDAL CURRENT DRAG FORCE

The current considered here-tidal current, is strongly coupled with tide, which means that the horizontal movement of water (current) is closely related to the water vertical movement (Kartverket, Currents, 2014a) [9]. Flow velocity or current strength often follows a distribution over water depth, with higher value near the surface and lower value at depth (Chakrabarti, 2005)[10].
The drag force on the tunnels depends on fluid density, flow velocity and the projected area of the tube normal to the current flow:
$f = 0.5\rho C d A U^2$ ……………………………………………………………………………………………………….(eq.7)
Where, f=current drag load; ρ=fluid density, kg/m3; Cd=drag coefficient; A=structure projected area normal to the flow, $m2$; U=flow velocity, m/s.

3.2 DESIGN ANALYSIS OF MOORING CABLE

Catenary lines are used to moor the tunnels to the fjord bottom, see Figure 48. Assume that the anchor cable at the lower end lies almost horizontally at depth below soil surface. According to Chakrabarti (2005) [10], the catenary cables are thought to be subjected to tension only meaning that shear forces and bending moments are simply ignored.
Besides, the horizontal component of cable tension T_h keeps constant along the cable line. From the perspective of static equilibrium of the catenary cable itself, the cable tension at the top end owns a vertical component Tv_top equaling to the self-weight of the whole cable.

Figure 7. Mooring cable layout

Besides, considering the symmetric layout of cables at the two sides of tunnel and the static equilibrium of the concrete tube, vertical component of the top cable tension Tv_top at the top end of mooring cable can be easily obtained as…
Tv_top = 0.5 ∗ (buoyancy−gravity−traffic load) ……………………………………………………………..……(eq.8)

The horizontal component of Tmean is the mean value of horizontal cable tension. Now considering current effect, dynamic horizontal force on the tunnel section will be balanced by the two cable strands beside the tunnel.
From the symmetry point of view, this current load will increase tension in one cable and decrease the same amount of tension in another cable, i.e.,
T_{dyn} = +/- 0.5 * Current Drag Force ……………………………………..…………………………………...(eq.9)

The 21st Bjerrum [11] Lecture presented in Oslo, 23 November 2007, 2009, the cable needs to have a mean tension Tmean no less than Tdyn, i.e.,
$Tmean \geq Tdyn$ ……………………………………………..……………………………………...…………(eq.10)

Horizontal component of cable tension Th consists of a mean value Tmean and a dynamic value Tdyn, which perceptively comes from static cable pre-tension as well as dynamic current loading effect, i.e.,
Th = Tmean + Tdyn …………………………………………………………………….………………………….(eq.11)
Three conditions are known or simplified:
1. The water depth in M meter.
2. The cable lies horizontally at the lower end.
3. The vertical tension component at the top end in kN.
With these conditions, assume an angle to horizontal α (Figure 7) at the cable top end when no current effect is involved, and calculate the horizontal component of pre-tension via known Tv_top and α, i.e.,
Tmean = Tv_top / tan (α) ………………………………………………………………………………….(eq.12)
Furthermore, providing the general equation of catenary line (Math24.Net, 2014), calculate the line length and choose proper cable properties.
The mooring cable in this project is taken as catenary line (see Figure 7) which is shaped by equation according to (Math24.Net, 2014) [12]:

$\boldsymbol{Y = a\cosh(X/a)}$……………………………………………………………………………………………(eq.13)

Where, Y, X – the y and x coordinates in a crossing coordinate system;
a – a parameter which satisfies $B=Th/(\rho material$ gA), where; Th – horizontal component of pre-tension in the cable line; $\rho material$ – cable material density; A –area of cable line.

degree angle to horizontal at the cable top end is illustrated (without considering dynamic current loading effect). The analysis makes full use of algebra geometry provided by Math24.Net (2014)[12]. Tan(α) refers to the derivative of line function $\boldsymbol{Y = a\cosh\ (X/a)}$ at the top point, i.e.,

$\mathbf{(dY/dX)_{top}} = \boldsymbol{T}\mathbf{an}\ (\boldsymbol{\alpha})$ ……………………………………………………………………………(eq.14)

Therefore, $\mathbf{Sinh(X_{top}} / \boldsymbol{a}\mathbf{)} = \mathbf{Tan}(\boldsymbol{\alpha})$………………………………………………………………………(eq.15)
Then it can be easily calculated that at the top end the X coordinate satisfies, $\boldsymbol{X_{top}/a}$**.** If set the X coordinate of the lower end of cable line as 0, it yields: $X_{low} = 0$; $Y_{low} = a$.

Since the water depth is assumed to be M meters, it can be easily obtained that at the top end, the Y coordinate yields, $\mathbf{Y_{top}} = \mathbf{M} + \boldsymbol{a}$………………………………………………………………………………(eq.16)

$$R_u = \frac{1}{3} JkLx^3 + \left(\frac{3}{2}\, Dk + \frac{1}{2}\,\gamma D + \frac{1}{2}\, JS_{u0}\right) L^2 + 3DS_{u0}L$$ …………………………………………………(eq.17)

Insert Equation 17b into shape function 17a, $\mathbf{M}+\boldsymbol{a}=\boldsymbol{a}\times\boldsymbol{\cosh}(\boldsymbol{X_{top}/a})$**,** Solve Equation iteratively till a (m) value arrives near most, that will be the Tmean value for the considered, $\boldsymbol{\alpha}$**.**

Now choose the cable properties based on shape function. At the top end Tan(α), therefore, $Th=Tv$ / Tan(α) kN
From $\boldsymbol{B=Th/(\rho}\mathbf{material\ g}\boldsymbol{A)}$……………………………………………………………………… (eq.18)

Based on the value of ρmaterial$A$, choose `nos of sets of *Xtreme Spiral Strand* with the following properties. Cable properties for top cable angle of $\boldsymbol{\alpha}$ degree are.

- Diameter = in mm
- Minimum Breaking Load = in kN
- Submerged weight = in kg/m
- actual submerged weight of no's of set spiral strands = in kg/m
- Axial stiffness = in MN
- Cable horizontal length x= in m
- Total length s= in m
- Maximum cable force = in kN
- Strength utilization= (Maximum cable force / Minimum Breaking Load) in %

The submerged weight of the nos of sets of *Xtreme Spiral Strand* should be more than the $\boldsymbol{\rho}$**material g**$\boldsymbol{A}$ value.

3.3 DESIGN VALUE OF LINE TENSION AT PADEYE

The design cable tension at padeye depth $Td(zp)$ in this project is taken as horizontal and equaling to the design value of cable tension at dip-down point $Td(zD)$where cable enters soil, i.e., neglecting soil resistance between the embedded cable and its surrounding soil. Also, considering the dynamic characteristics of current load which changes velocity and direction periodically, design line tension at dip-down point is calculated according to DNV-RP-E303 (DNV, 2005):

$\boldsymbol{Td(zD)=Tc{-}m}\mathbf{ean}\boldsymbol{*\gamma m}\mathbf{ean}\boldsymbol{+Tc{-}d}\mathbf{yn}\boldsymbol{*\gamma d}\mathbf{yn}$…………………………………………………………………(eq.19)

Where, $Tc{-}m$ean = the characteristic mean line tension; $Tc{-}d$yn = the characteristic dynamic line tension;
γmean = the load factor on the mean tension component; γdyn = the load factor on the dynamic tension component.

4. CONCLUSIONS

- A simplified version of floating tunnel one proposed by Reinertsen Olav Olsen Group[8] (2012) is used as a basis for design and analysis.

- The submerged floating tunnel is subjected to complex environmental loadings, and this study will deal with the evaluation as well as calculation of the loadings on the floating tunnels.
- Since the two tubes are separated and considered individually, only one tube is taken for analysis in this thesis project while the other one could be easily analyzed in the same way.
- To simplify the analysis, environmental condition such as wind, current and wave, can be regarded as uniformly distributed along the fjord width, therefore the environmental loadings on the tubes correspondingly follows an even distribution over the tunnel, making it reasonable to assume that each set of mooring cables and suction anchors is subjected to the loadings on one specific tunnel section close to it.
- Simplified analytical approach has been set were SFT stability and suspension cable utilizations were derived with end anchorage and Design ultimate load for suction anchors.
- In future studies the complete set of Submerged floating tunnel end to end to be analyzed
- More precise and careful evaluation of the loadings should be achieved in a future work beyond the simplifications and assumptions made in this thesis work, to achieve more accurate design and analysis.

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