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Submerged Floating Tunnel Bridge (SFTB): A Status Report and Evaluation of Technology Readiness Level (TRL)

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Abstract
One of the problems in archipelagic countries is the land transportation system that has not been integrated between islands. In a relatively wide strait and with a high level of depth, it is impossible to build a bridge. In this case, a submerged floating tunnel bridge/SFTB would be an effective choice. SFTB is an underwater tunnel transport route submerged between the seabed and the surface. Known as the "Archimedes Bridge", the basic principle is balancing buoyancy and tension in the mooring cables. Previous studies on SFTB are still in the form of theoretical concepts and ideas. Further research is needed in all relevant sub-topics to actualize the SFTB. This article reviews previous studies, which are grouped into three sub-topics : (1) materials and construction, (2) dynamic analysis, and (3) feasibility/sustainability studies. At the end of this article, a list of research topics that need further study is presented.

Keywords:
Dynamic analysis;
Materials and construction;
SFTB;
Status report;
Technology Readiness Level;

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INTRODUCTION

Strait crossing is one of the important issues in land route integration, especially in archipelagic countries. The common way of crossing is using the ferry ship, besides suspension bridges and underground tunnels. In addition to that, suspension bridges and underground tunnels have been built in some straits. However, a more effective alternative concept is needed for a relatively wide and deep strait.

A new concept of strait crossing is the submerged floating tunnel bridge (SFTB). Besides being suitable for wide straits, SFTB is also relatively safe and has a low risk of volcanic earthquakes. SFTB is a floating tube structure that is placed below the water surface at a depth level and supported by mooring cables or pontoons. Compared to suspension bridges and underground tunnels, SFTB has many advantages, including relatively low construction costs, fast construction time, environmentally friendly, movable, and reusable. In addition, SFTB has a relatively small risk compared to underground tunnels against volcanic earthquakes [1]. Figure 1 shows the concept design of SFT.

The SFTB concept was first proposed by Sir James Reed in England in 1886 and continued by Trygve Olsen Dale in Norway in 1924 [2]. Until now, SFTB research has been developed in several countries, such as Norway [3][4], China [5][6], and Japan [7].

Until now, the construction of SFTB is still constrained and has not been realized. Many studies have been carried out in the last few decades to realize the SFTB concept. However, the lack of available empirical data causes a low confidence level in this technology.

Figure 1. The concept design of SFT [8]

For this reason, in this paper, a mapping of previous research is carried out, and the results obtained will be presented briefly. Furthermore, at the end of this paper, further research is proposed that must be developed for the future.

METHOD

The existing research articles are grouped and discussed based on a topic. Each topic is evaluated based on assessing the Technology Readiness Level (TRL). TRL is set to have five levels. At each level, there are indicators, as shown in Table 1. This indicator refers to the Research and Community Service Manual Edition XIII [9]. In this case, simplifications and adjustments are made as necessary.

Table 1. The Technology Readiness Level (TRL) and its indicators [9]

TRL 1 The basic principles have been researched and reported, with the following indicators:
(a) Assumptions and basic laws have been determined; (b) Literature on theoretical and empirical is available; (c) The research hypothesis that will be developed to the next level already exists.
TRL 2 Concept formulation and application are available, with the following indicators:
(a) Equipment and systems to be used have been identified; (b) Theoretically and empirically, this technology is applicable (c) Theoretical and empirical designs have been identified (d) technology components have been characterized and mastered (e) Preliminary analysis shows that the main functions are working as expected
TRL 3 Experimental proof of concept:
(a) The concept has been proven by laboratory experiments (b) Technological elements have been modelled and the simulation works as expected (c) The fabrication process is guaranteed to be carried out (d) The prototype simulation can operate well in the real environment
TRL 4 The system is complete and satisfactorily demonstrated in the real environment:
(a) A pilot project has been created (b) All materials and manufacturing methods are available (c) The system is ready for production at a real scale
TRL 5 Technology is ready to be applied in the real field:
(a) Technology at full scale has been proven in the actual field (b) No significant design changes (c) An investment estimate has been made (d) All the documentation is complete

A STATUS REPORT OF SFTB RESEARCH

Materials and Construction

The SFTB, known as the Archimedes Bridge, is a tube structure placed below the water surface as a way to cross a strait, river, or lake. The cross-sectional shape of the SFTB is generally a circle but can also be in the form of an ellipse, polygon, and rectangle, as shown in Figure 2. The placement of the SFTB below the surface of the water does not prevent ships from passing above it.

Support Structure

SFTB has four types of support structures: (a) tension leg, (b) column support, (c) pontoons, and (d) free, as shown in Figure 3. SFTB tension leg (Figure 3a) can be configured vertically, at an angle, or a combination of both. This type is used if the buoyancy to weight ratio (BWR) > 1, thus the mooring cables receive initial tension in each condition. The stiffness of the SFTB structure depends on the bending stiffness of the tube and the mooring cables. This type has the advantage that it can be applied to deep-sea conditions with a depth of > 600 m and a span length of > 4000 m [3].

The SFTB column support (Figure 3b) is similar to an underwater bridge. This type of SFTB is used if BWR≤1, thus the supporting column receives compressive stress. This type of SFTB gains additional rigidity from the supporting column. The application is suitable in the shallow sea but difficult to build in the deep sea.

The pontoon type (Figure 3c) is chosen if the BWR ratio is < 1, meaning that the weight of the SFTB is greater than the buoyancy force, so it requires a pontoon as a counterweight. The advantages of this type are not affected by water depth but are sensitive to wind, waves, currents, and potentially ship collisions.

Free type SFTB (Figure 3d) is the simplest form. There is no additional support in the structure. It is selected for BWR = 1, making it neutral and balanced between buoyancy and structure weight. Only rely on tube bending stiffness so that its application is limited to low spans, below 300 m [3]. Therefore, its application is limited to pedestrians or low-intensity traffic. For long spans, the total construction cost for SFTB is relatively lower compared to suspension bridges, as depicted in Figure 4.

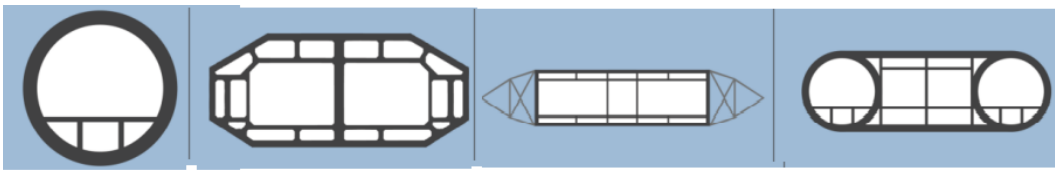

Figure 2. Various forms of SFT cross-section [10]

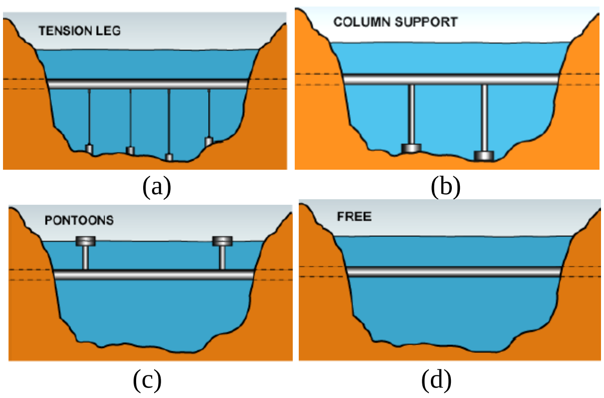

Figure 3. Support structure type, (a) Tension Leg, (b) Column support, (c) Pontons, and (d) Free [3]

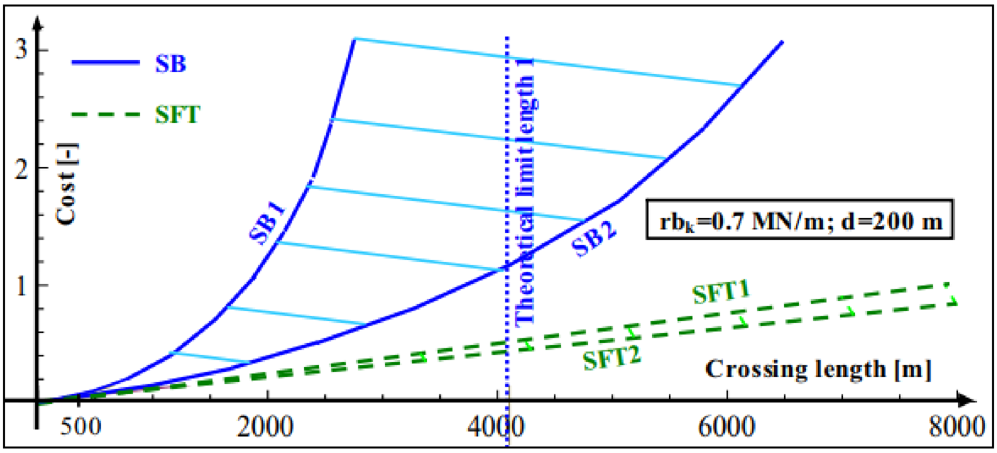

Figure 4. Cost comparison between SFT and suspension bridge [1]

Materials

In materials selection, considered factors are resistance ability to environmental conditions, fabrication, construction methods, maintenance, supply time, and cost [11]. In offshore structures, concrete and steel are generally used because there are a lot of experimental data available. In addition, composite materials and aluminum alloy are being investigated for use in SFTB [12].

Each material has some advantages and disadvantages. Optimization of structural performance can be achieved by combining different materials into one composite material. Each material is intended to fulfill its respective function so that overall, the benefits are obtained while covering the weaknesses. For example, the use of steel-reinforced concrete is a complementary combination for the strength and rigidity of the structure. The combination known as steel-concrete composite has been widely used and successful in the construction of immersed tunnels [13].

An aluminum alloy can be used on the outside of the SFT to prevent steel corrosion [12]. The idea of combining steel-concrete-aluminum materials has been proposed in the design of the SFT prototype in Qiandao Lake, China, as shown in Figure 5 [7]. As an alternative, rubber foam can also be used as a corrosion-resistant coating. Rubber foam has a hollow structure so it can also function as an impact damper. This material has been considered for use in immersed tunnels [14].

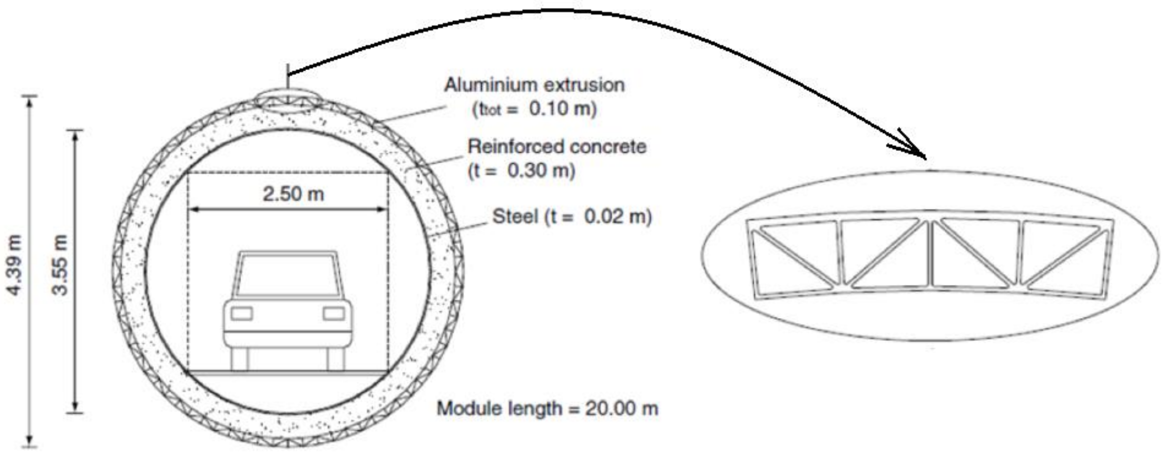

Figure 5. SFTB prototype in Qiandao Lake, China [7]

DYNAMIC ANALYSIS OF SFTB

Permanent and Functional Load

The permanent load on the SFTB is the structure's load without external loading. The permanent load consists of self-weight (G_s), buoyancy (F_b) and hydrostatic pressure (P_b), each of these can be calculated by (1), (2), and (3) [15].

$$G_s = \rho_{structure}\, g\, \pi \frac{D_{in}^2 - D_{ex}^2}{4} L_s \quad (1)$$

$$F_b = \rho_{structure}\, g\, \pi \frac{D_{ex}^2}{4} L_s \quad (2)$$

$$P_b = \rho_{structure}\, g\, z \quad (3)$$

The functional load is the load caused by the operation of the SFT. Functional load is caused by interactions with vehicles, including cars, trains, bicycles, and pedestrians.

Initial Design Requirements

Factors that should be considered as necessary for the initial design of the SFTB include [16]:

1. The internal diameter is determined according to space requirements, depending on the number of transportation lines required.
2. The wall thickness of the SFTB is determined to obtain the requirements for stiffness, strength, and elasticity. To improve the structural performance, composite materials, a combination of several materials, can be used.
3. Based on previous research, the BWR affects the natural frequency. Some researchers suggest the optimal BWR around 1.5 to minimize bending moment. A BWR between 1.25 and 1.4 can improve structural performance in extreme sea conditions. BWR can be determined using (4). Where G_s, G_b, and P_l are self-weight, ballast weight, and live loads, respectively.

$$BWR = \frac{F_b}{G_s + G_b + P_l} \quad (4)$$

Wave Theory

SFTB is an offshore structure. Therefore, it receives environmental loads from waves, currents, tides, wind, and earthquakes. The dominant environmental loads are waves and currents. Wave theory is needed to understand the dynamic behavior of SFTB. Many wave theories explain particle kinematics and wave profiles, which approximate the actual wave phenomenon. The wave theory commonly used is the linear wave theory, known as Airy's theory, developed from simple assumptions. Besides Airy's theory, several other theories such as Stokes', Cnoidal and Solitary theories. The comparison of profiles based on these theories can be seen in Figure 6.

Airy's theory is classified as a first-order Stokes' theory. Airy's theory is valid for relatively small waves if higher orders are ignored. High-order Stokes' theory represents more real wave conditions. Stokes' theory was developed with the assumption that the velocity potential of the particle is a quadratic series, and a solution is obtained if the wave conditions are not extreme. Stokes' theory is relevant for the sea that is not too deep [17]. For relatively shallow sea, it is more valid to use the theory of Cnoidal Theory. The limitations of the Cnoidal theory are not suitable for very long or infinite wavelength conditions, wherein this Solitary condition theory can be used.

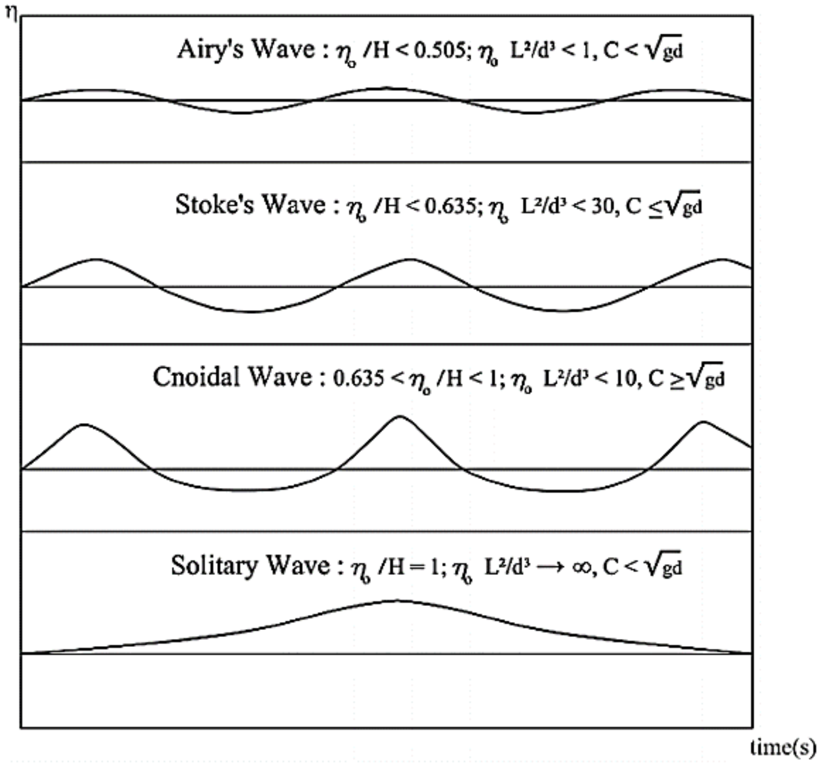

Figure 6. Wave surface profile [18]

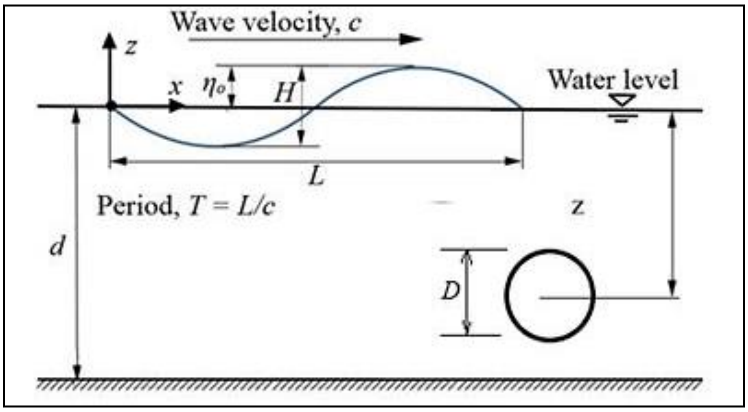

Figure 7. The ocean wave profile

The ocean wave profile is depicted in Figure 7, with parameters; wavelength (*L*), wave height (*H*), wave amplitude (η), wave period (*T*), wave speed (*c*), and sea depth (*d*). Wave speed can be calculated by (5). Here, ω is the wave frequency, and *k* is the wavenumber, each obtained from (6) and (7).

$$c = \frac{\omega}{k} \quad (5)$$

$$\omega = \frac{2\pi}{T} \quad (6)$$

$$k = \frac{2\pi}{L} \quad (7)$$

The motion of water particles depends on the velocity potential, which satisfies the Laplace equation, as seen in (8) [18]. Here, the vertical axis is denoted as z, and the horizontal axis is denoted as x. If the boundary conditions on the seabed are $\partial\phi/\partial z = 0$ at $z = -d$, then the solution of (8) can be obtained by separating variables, as shown in (9) [17][19]. The distribution relationship can be seen in (10). Thus, the wave propagation speed is the relationship between the frequency and the number of waves, as shown in (11).

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial z^2} = 0 \tag{8}$$

$$\phi = \frac{\pi H}{kT}\frac{\cosh[k(z+d)]}{\sinh(kd)}\sin(kx-\omega t) \tag{9}$$

$$c^2 = \frac{\omega^2}{k^2} = \frac{g}{k}\tanh(kd) \tag{10}$$

$$c = \frac{g}{\omega}\tanh(kd) \tag{11}$$

Kinematics of Water Particles

The hydrodynamic force due to wave motion depends on the velocity of the water particles in the horizontal and vertical directions. The velocity of water particles can be obtained from spatial derivatives of ϕ, as shown in (12) and (13) [17,18,19].

$$u_x = \frac{\partial\phi}{\partial x}\frac{\pi H}{T}\frac{\cosh[k(z+d)]}{\sinh(kd)}\cos(kx-\omega t) \tag{12}$$

$$u_z = \frac{\partial\phi}{\partial z}\frac{\pi H}{T}\frac{\sinh[k(z+d)]}{\sinh(kd)}\sin(kx-\omega t) \tag{13}$$

The hyperbolic function causes an exponential reduction in velocity from the surface (z/d = 0) to the seabed (z/d = 1). Acceleration of water particles can be determined by deriving the velocity equation to the time, in the horizontal and vertical directions, as shown in (14) and (15).

$$\dot{u}_x = \frac{2\pi^2 H}{T^2}\frac{\cosh[k(z+d)]}{\sinh(kd)}\sin(kx-\omega t) \tag{14}$$

$$\dot{u}_z = -\frac{2\pi^2 H}{T^2}\frac{\sinh[k(z+d)]}{\sinh(kd)}\cos(kx-\omega t) \tag{15}$$

Hydrodynamic Force

Calculation of the wave force on the structure is the primer task to analyze the dynamic behavior of the SFTB. When kinematic water particle (acceleration & velocity) has been determined, the wave force can be calculated using the Morison equation, as shown in (16). Where ρ is the fluid density, D is cylinder diameter, A is the cross-sectional area of a cylinder, C_D is the drag coefficient, and C_I is the inertia coefficient. This equation explains that the wave forces acting on the cylindrical structure consist of drag forces and inertial forces [20]. This equation has been widely used to calculate wave forces on underwater structures. When compared with experimental results, Morison's equation can be relied upon to calculate the wave force on a cylindrical structure [21].

$$F(t) = \frac{1}{2}\rho D C_D u|u| + \rho A C_I \dot{u} \tag{16}$$

Morison equation has a limitation that only applies to relatively small cylinders ($D/L < 0.2$) because this equation ignores the effect of diffraction. However, for large cylinders ($D/L > 0.2$), the hydrodynamic force includes diffraction effects and can be calculated by diffraction theory [22].

Initial Force

The inertial force consists of the Froude-Krylov force and the hydrodynamic mass force [23]. The pressure gradient causes the Froude-Krylov force in the fluid flow, which can be expressed by (17). On the other hand, the amount of hydrodynamic mass force depends on hydrodynamic mass or known as the added mass, which can be calculated by (18). The hydrodynamic mass coefficient C_M depends on the cross-sectional shape of the structure and can be seen in Table 1.

$$F_{fk} = \rho A\dot{u} \tag{17}$$

$$m_a = \rho A C_M \tag{18}$$

The hydrodynamic mass force can be calculated using (19). In the SFTB structure, there is a relative acceleration between the structure and the water; hence the hydrodynamic mass force can be expressed as (20). In a simple form, by defining the coefficient of inertia as C_I, which can be seen in (21), the total inertial force can be expressed as (22).

$$F_{mh} = \rho A C_M \dot{u} \tag{19}$$

$$F_{mh} = \rho A C_M |\dot{u}_w - \dot{u}_s| \tag{20}$$

$$C_I = C_M + 1 \tag{21}$$

$$F_I = \rho A C_I \dot{u} \tag{22}$$

Euler-Bernoulli's Theory for SFTB

The simplest model of SFTB is a straight tube free of support. The value of BWR is equal to one. Its stiffness is only obtained from flexural rigidity. Euler-Bernoulli's theory can be analysed, as illustrated in Figure 8.

The Euler-Bernoulli theory is assumed that the length of the SFTB is much larger than the cross-sectional area, the deviation is not too large, ignores rotational inertia, and ignores shear deformation [24]. The equation of motion is modeled as a partial differential equation, as shown in (23) [25]. Here, ω is the displacement, EI is the bending stiffness, ρA is the mass per unit length and f is the external force (hydrodynamic force) per unit length. The natural frequency ω_n and the vibration mode W_n can be seen in (24) and (25), respectively.

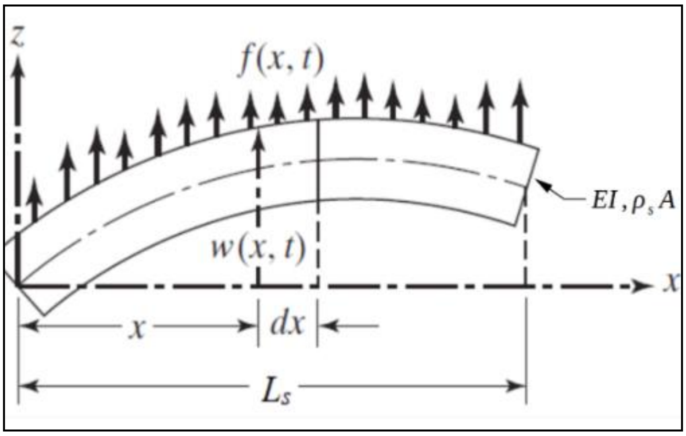

Figure 8. Continuous beam [22]

$$EI\frac{\partial^4 w}{\partial x^4}(x,t)+\rho A\frac{\partial^2 w}{\partial t^2}(x,t)=f(x,t) \quad (23)$$

$$\omega_n=\sqrt{\left(\frac{n\pi}{L_s}\right)^4\frac{EI}{\rho A}} \quad (24)$$

$$W_n=C_n\sin\left(\frac{n\pi x}{L_s}\right) \quad (25)$$

Stiffness of Tension Leg

In SFTB with tension leg support (*BWR* > 1) the tension in the rope contributes to the stiffness of the SFTB structure. Figure 9 shows the free body diagram of the SFTB. The position of the mooring line can be vertical or inclined, depending on the required rigidity. The difference between the buoyant force F_b and the gravity F_w causes the rope to receive an initial tension T_0. The horizontal (sway) stiffness and the vertical (heave) stiffness are expressed in (26) and (27), respectively [16].

$$K_h=\frac{2EA}{L_t}\sin^2\theta \quad (26)$$

$$K_v=\frac{2EA}{L_t}\cos^2\theta \quad (27)$$

The tension leg stiffness can be applied to the equation of motion if the SFTB is modeled as Beam on Elastic Support (BOES), but the natural frequency cannot be obtained analytically. Therefore, SFTB is modeled as Beam on Elastic Foundation (BOEF). The SFTB model as BOES and BOEF is shown in Figure 10.

Analyzing the BOES model to BOEF has been verified for static and dynamic analysis of SFTB [25, 26, 27]. The natural frequencies of BOES and BOEF are the same if $K_v \leq 0.05$. It has a little bit different if $K_v \leq 0.05$ and much different if $K_v \geq 0.05$, as shown in Figure 11. Here, K_v is the relative stiffness constant. It can be calculated by (28).

$$K_v=\frac{k_s i^3}{24EI} \quad (28)$$

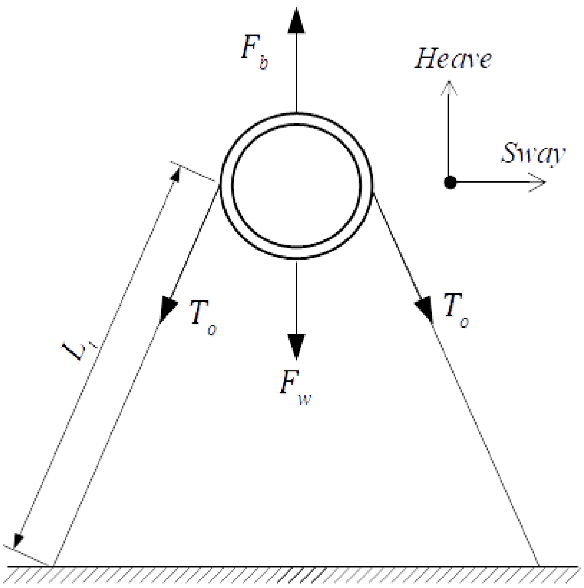

Figure 9. SFTB with Tension Leg

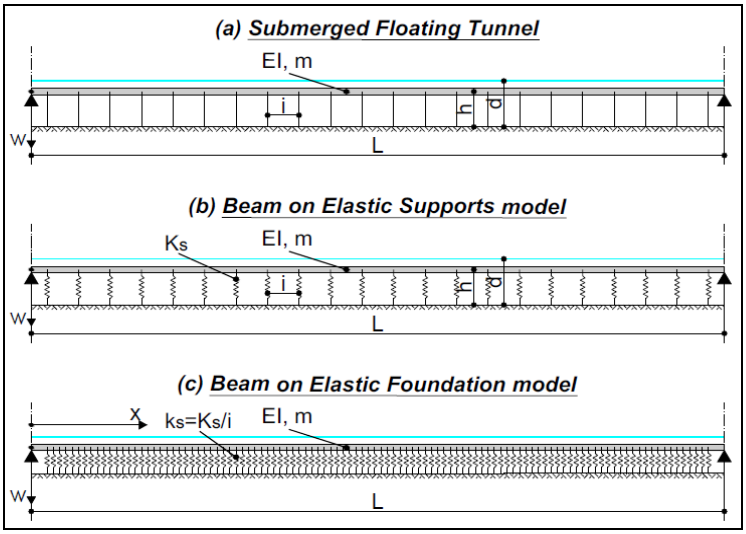

Figure 10. SFTB Modeling (a) SFTB Structure, (b) BOES Model, (c) BOEF Model [11]

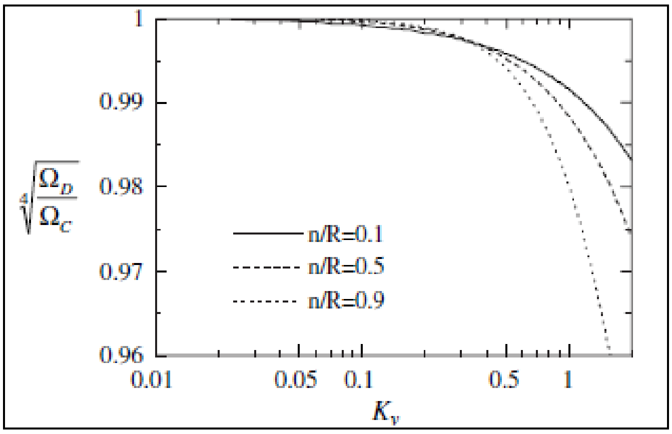

Figure 11. Comparison of natural frequencies in BOES and BOEF

Where i is the mooring rope distance and k_s is the stiffness modulus. The value of k_s can be calculated using (29), and k_s is obtained from (26-27).

$$k_s = \frac{K}{i} \tag{29}$$

When SFTB is analogous to BOEF, the equation of motion becomes a partial differential equation, as can be seen in (30). The natural frequency can be determined by (31).

$$EI\frac{\partial^4 w}{\partial x^4}(x,t) + \rho A\frac{\partial^2 w}{\partial t^2}(x,t) + k_s w(x,t) = f(x,t) \tag{30}$$

$$\omega_n = \sqrt{\left(\frac{n\pi}{L_s}\right)^4 \frac{EI}{\rho A} + \frac{k_s}{\rho A}} \tag{31}$$

Damping Estimate

Since the SFTB is an underwater structure, the presence of fluid around the SFTB needs to be considered. The fluid around the SFTB creates a viscous damping effect. Due to the limitations of measuring the viscous damping and based on existing research results, structural damping from SFTB structural materials is used. Damping can arise from friction between layers of concrete and steel or even from the concrete itself. SFTB structural materials made of concrete have a damping ratio of 0.8% [28]. Some studies assume a damping ratio of 0.25% [16][29].

Damping ratio can be applied in the form differential equation of multi-degree of freedom, so (30) needs to be converted to an ordinary differential equation with finite element method. The method used to find the damping matrix is the Rayleigh damping method. This method calculates structural damping as a mass and stiffness proportional damping combination. Rayleigh damping is expressed by (32). Where [M], [K], and [C] are mass, stiffness, and damping matrix, respectively. The coefficients α and β can be calculated using (33) and (34), respectively [30].

$$C = \alpha[M] + \beta[K] \tag{32}$$

$$\alpha = \zeta\frac{2\omega_1\omega_2}{\omega_1 + \omega_2} \tag{33}$$

$$\beta = \zeta\frac{2}{\omega_1 + \omega_2} \tag{34}$$

Based on Figure 11, Rayleigh damping is determined according to two different vibration modes. Each vibration mode has a different natural frequency (ω_1, ω_2) and damping ratio (ζ_1, ζ_2). Unfortunately, the damping ratio for each mode of the SFTB is not available. But it is known that the damping ratio for the first and second modes is almost the same. So that in this calculation, the value of damping ratio is $(\zeta_1 = \zeta_2)$.

RESULTS AND DISCUSSION

Evaluation of Existing Research

In general, research to support the SFTB design implementation is still at the analysis and simulation stages, and some of them have been studied experimentally on a laboratory scale. Research is dominated by dynamic analysis with respect to the response of SFTB to wave forces, in addition to research on construction and materials.

Table 2. Evaluation of existing research

Topic	(TRL) 1	2	3	4	5
Main Structure	√	√			
Support Structure	√	√	√		
Materials	√	√			
Permanent and Functional Load	√	√	√		
Initial Design Requirements	√	√	√		
Wave Theory	√	√	√		
Kinematics of water particles	√	√	√		
Hydrodynamic Force	√	√	√		
Inertia Force	√	√	√		
Euler-Bernoulli Theory for SFTB	√	√			
Stiffness of Tension Leg	√	√			
Fluid-Structure Interaction	√	√			

Table 3. Further research needed

Category of dynamic analysis
1. Dynamic behavior of submerged floating twin tube, 2. Effect of traffic flow on SFTB, 3. Dynamic analysis of tethering cable failure, 4. and others.
Category of construction and materials
1. Joint and gasket, 2. Tethering system, 3. Anchor system, 4. Fatigue analysis, 5. Fracture analysis, 6. Impact analysis, 7. Preliminary design in real scale and environment, 8. and others.
Categories of safety, operation and maintenance
1. Anticipation of being hit by a submarine, 2. Anticipation of potential explosions, 3. Design of control system, 4. Design of air conditioning system, 5. and others.

At this stage, in general, existing research is categorized as reaching TRL 3, as shown in Table 2. Thus, it is necessary to continue these researches to the next levels. These researches need to be developed to level 4 to be compatible with the real environment and further developed to level 5 to be implemented in real terms. Table 3 shows the topics that are open to research.

Further Research Needed

Several topics on SFTB analysis have been researched and reported, but some other topics have not been discussed at all, as shown in Table 3. These topics need to be researched for actualization of the SFTB development.

CONCLUSION

Theoretically, the SFTB concept is possible to be applied. However, this concept still requires more advanced and comprehensive studies to depict real conditions. In the dynamic analysis category, the research is still limited to analytic and simulation with TRL 1-3, so it needs to be further developed to TRL 4 and 5. Meanwhile, in the category of construction and material, security, operational system, and maintenance, relatively not much research has been done. The topics of this category are still open for research.

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