The role of cable stiffness in the dynamic behaviours of submerged floating tunnel

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Abstract. Submerged floating tunnel (SFT) is a new solution for the transportation infrastructure through sea straits, fjords, and inland waters and can be a good alternative to long span suspension bridges and immersed tunnels. The mooring cables/anchors are main structural components to provide restoring capacity to the SFT. The time domain dynamic problem of SFT moored by vertical and inclined mooring cables/anchors is formulated. The dynamic analysis of SFT subjected to hydrodynamic and seismic excitations is performed. As the cable stiffness determines the deformation ability of SFT, therefore it becomes crucial to evaluate the effect of mooring cable stiffness on the response of SFT. The displacements and internal forces of SFT clearly specify that the vertical/tension leg mooring cables provide very small stiffness as compared to inclined mooring cables. In order to keep the SFT displacements within an acceptable limit, the effect of cable stiffness should be properly evaluated for practical design of SFT.

1 Introduction

Submerged floating tunnel (SFT) is a novel structural solution for waterway crossings. It floats at a specified depth and is anchored by mooring cables. SFT is subjected to sea waves, currents, tsunamis and earthquakes. The SFT is supposed to be a good alternative for waterway crossing as compared to long span suspension bridges and immersed tunnels especially for deep and wide crossings because the cost of SFT per unit length remains almost constant by increasing length [1]. SFT is supported by the mooring cables, the balance between the net positive buoyancy (Residual buoyancy) and the pre-tension in the mooring cables maintains the structural stability of SFT.

The research efforts for development of the SFT solution began in 1923 from Norway. Since then, many case studies and proposals have been made for different proposed projects, such as Hogsfjord in Norway [2], Funka Bay in Japan [3], Messina Strait in Italy [4], Qindao Lack in China [5], and Mokpo-Jejo SFT in South Korea [6].

Most of the SFT numerical models developed so for, consider the dynamic response of SFT subjected hydrodynamic waves and seismic loadings [5-7]; however, the role of

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mooring cable stiffness in the dynamic response of an SFT is not investigated or evaluated in more detail. The mooring cables are main structural components to provide restoring capacity to SFT. The mooring cable stiffness plays an important role in determination the deformation ability of SFT and therefore needs proper evaluation for practical design considerations.

This study presents the effect of cable stiffness on the dynamic response of submerged floating tunnel for hydrodynamic and seismic loadings. The dynamic problem of the SFT is solved considering the modeling of cables, tunnel, hydrodynamic waves and currents and seismic loadings. The displacements and internal forces of SFT are presented and the effect of cable stiffness on the dynamic behaviors of the SFT have been discussed.

2 Hydrodynamics

The ocean waves and currents are modeled by well-known Airy wave theory, and the wave forces are calculated from the modified Morison's equation, which is given as [9]:

$$\left\{f(q,t)\right\}=\frac{1}{2}C_D\rho_w D\left\{\left|\dot{w}_\perp \pm U-\dot{q}_\perp\right|\left(\dot{w}_\perp \pm U-\dot{q}_\perp\right)\right\}+C_M\rho_w\frac{\pi D^2}{4}\left\{\ddot{w}_\perp\right\}-C_A\rho_w\frac{\pi D^2}{4}\left\{\ddot{q}_\perp\right\} \quad (1)$$

where subscript $\perp$ denotes the perpendicular components with respect to element axis. ρ_w is the density of water, D is the external diameter of SFT, C_D is the drag coefficient, C_M is the inertia coefficient, $C_A = C_M - 1$ is the added mass coefficient, $\dot{w}$ and $\ddot{w}$ are water particle velocity and acceleration, while $\dot{q}$ and $\ddot{q}$ are structural velocity and acceleration respectively. U is the velocity of water currents acting at the centerline of SFT.

3 Equations of motion

The equation of motion for the SFT (Fig. 1) subjected to permanent, hydrodynamic, and seismic loads can be written in matrix form as follows:

$$\left[M+M_a\right]\left\{\ddot{q}\right\}+\left[C\right]\left\{\dot{q}\right\}+\left[K_e+K_m\right]\left\{q\right\}=\left\{f\right\}+\left\{f\left(q,t\right)\right\}-\left[M+M_a\right]\left\{I\right\}\left\{\ddot{q}_g\right\} \quad (2)$$

where $\left[M\right]$ is the structural mass matrix of SFT; $\left[M_a\right]$ is the added mass matrix; and $\left[C\right]$ is the system damping matrix; $\left[K_e\right]$ and $\left[K_m\right]$ are the elastic stiffness of SFT and the mooring stiffness matrices, respectively; $\ddot{q}$, $\dot{q}$, and q are the vectors representing structural acceleration, velocity, and displacement, respectively; $\left\{f(q,t)\right\}$ is the vector of time-dependent hydrodynamic forces; and $\left\{f\right\}$ is the vector of the net permanent loads acting on the SFT; $\left\{\ddot{q}_g\right\}$ is the vector of ground motions; $\left\{I\right\}$ is the influence coefficient vector. The vector $\left\{q\right\}$ for an element is given as follows:

$$\left\{q\right\}=\left[u_1 \quad v_1 \quad w_1 \quad \theta_{Y1} \quad \theta_{Z1} \quad u_2 \quad v_2 \quad w_2 \quad \theta_{Y2} \quad \theta_{Z2}\right]^T \quad (3)$$

where u , v , and w are displacements along the X, Y, and Z directions, respectively, while θ_Y and θ_Z are the rotations about the Y-axis and Z-axis, respectively. The subscripts 1 and 2 represent the first and second node of an element, respectively.

4 Numerical example

The dynamic behavior of SFT is simulated for the SFT model shown in Fig. 1 [5,7], which is supposed to be constructed in Qiandao Lake People's Republic of China; same input parameters are used for analyzing the numerical example as those used by [5]. For the dynamic response, the equation of motion (Equation 2) was solved by Newmark average acceleration method for each time step. The hydrodynamic analysis of SFT corresponds to the environmental conditions of Qindao Lake. For the seismic response of SFT, the three-dimensional ground motions of El-Centro (1940) are assumed for the SFT numerical example. The El-Centro ground motions used as input are not shown for simplicity; the ground motion components and peak ground acceleration are shown in Table 1. The ground motion component S90W was applied in longitudinal (X-direction), component S00E is applied in the transverse (Y-direction) and vertical component was applied in the vertical (Z-direction) of SFT, respectively. All three components of ground motion were applied simultaneously. For the dynamic response calculations, 5% damping was assumed for calculating structural-damping matrix using Rayleigh damping model. The simulations were performed for a total time of 300 seconds, for the hydrodynamic case and 50 seconds for the seismic case. The dynamic displacements and internal forces of the SFT numerical model were obtained.

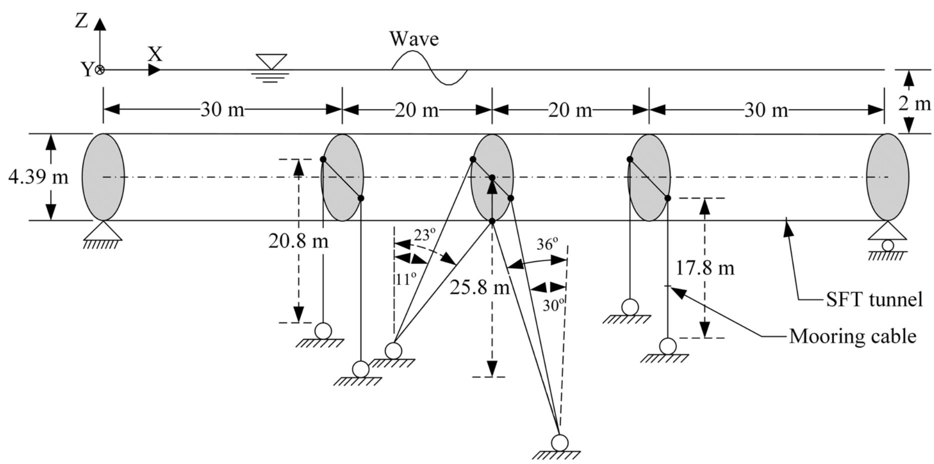


Fig. 1. Structural model of SFT used for numerical simulations

Table 1. Ground motion input (El-Centro 1940).

Component	PGA
S00E	0.35g
S90W	0.21g
Vertical component	0.13g

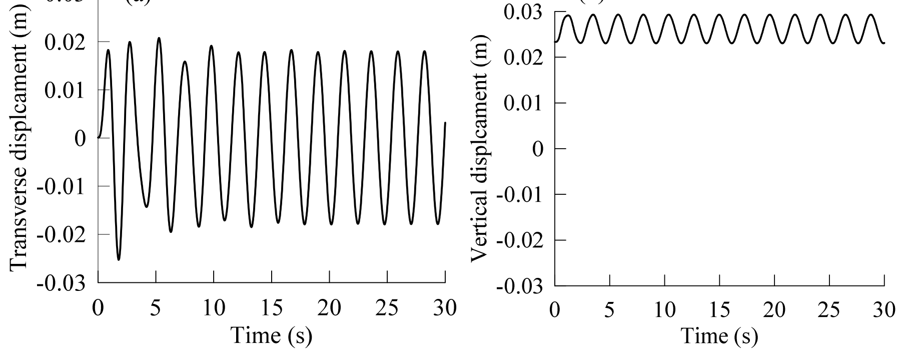
5 Results and discussions

The displacements and bending moments of SFT at the center of the tunnel for hydrodynamic analysis are shown in Fig. 2. Both transverse and vertical displacements and bending moments show a periodic pattern resembling the wave force model. The transverse bending moment of SFT is very large as compared to the vertical bending moment. The shape of the response curves for hydrodynamic analysis (Fig. 2) shows that the transient motions of SFT are small as compared to the steady state motions. As the SFT is intended to be used for railway transportation, so the maximum deflection criteria ($\Delta_{\max} = L/700$ =0.143 m) according to Korean railway bridge design specification can be assumed as a benchmark for SFT dynamic deflection. The absolute displacement ($\sqrt{u^2+v^2}$ = 0.0387 m) at the center of the tunnel is within the acceptable limit. The absolute bending moment ($\sqrt{M_Y{}^2+M_Z{}^2}$ = 9991.88 kN-m) at the center of the tunnel is within the range of design moment (M_D=70000 kN-m) referred by [5] according to EURO structural codes. The use of w-shape or double mooring is useful in restraining the horizontal displacement of SFT. However, as the wave height in the present case study is one meter and the displacement limit may be reached easily for extreme environmental conditions, as those highlighted by [8].

In order to check the effect of cable stiffness on the dynamic response of SFT, the cable stiffness (i.e. $\beta = E_c A_c = 3.486\times10^8\,\mathrm{N}$) is varied; where E_c and A_c are the elastic modulus and cross-section area of cable. The effect of cable stiffness on the dynamic response of SFT for hydrodynamic analysis is shown in Fig. 3. As the cable stiffness is increased, the displacements of SFT are reduced. For the present numerical model, both transverse and vertical displacements of SFT can be limited under 0.01 m when the cable stiffness is 4β. When the cable stiffness is less than 4β, SFT behaves as simply supported beam. To keep the SFT displacements within a small range and to avoid the slackness of the mooring cables, an optimized cable stiffness need to be used for the practical design of SFT.

The displacements and bending moments of SFT at the center of the tunnel for seismic analysis are shown in Fig 4. The seismic response curves of SFT show more pronounced transient behaviors. The absolute displacement ($\sqrt{u^2+v^2}$ = 0.138 m) at the center of the tunnel is within the limit of maximum deflection criteria ($\Delta_{\max} = L/700$ =0.143 m) according to Korea railway bridge design specification. The absolute bending moment ($\sqrt{M_Y{}^2+M_Z{}^2}$ = 43292.6 kN-m) at the center of the tunnel is within the range of design moment (M_D=70000 kN-m) referred by [5] according to EURO structural codes. As both deflections and bending moments are within the range from railway specifications but to avoid the slackness of mooring cables [3] a smaller range of deflections and bending moments need be investigated/fixed for SFT.

The seismic response of SFT is very large as compared to hydrodynamic response. A comparison of maximum absolute displacements and bending moments for hydrodynamic and seismic analysis are shown in Table 2. The response of SFT has an approximate relative difference of 81 % and 32% in transverse and vertical direction for hydrodynamic and seismic analysis.



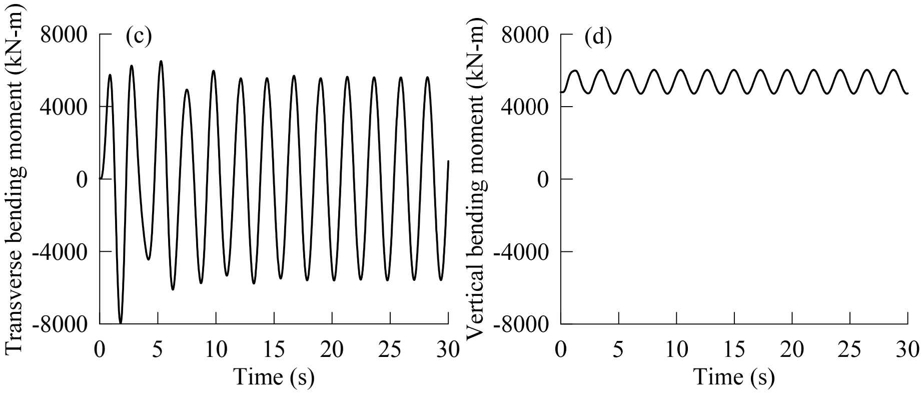


Fig. 2. The displacements and bending moments of SFT at the center of the tunnel for hydrodynamic analysis: (a) transverse displacement, (b) vertical displacement, (c) transverse bending moment, and (d) vertical bending moment.

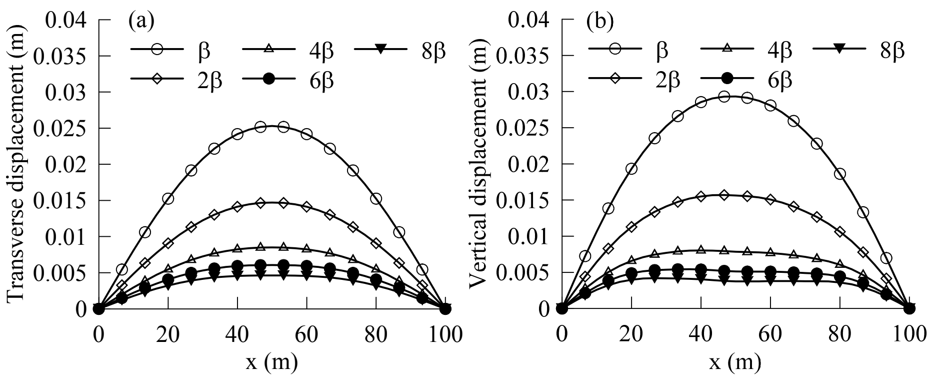
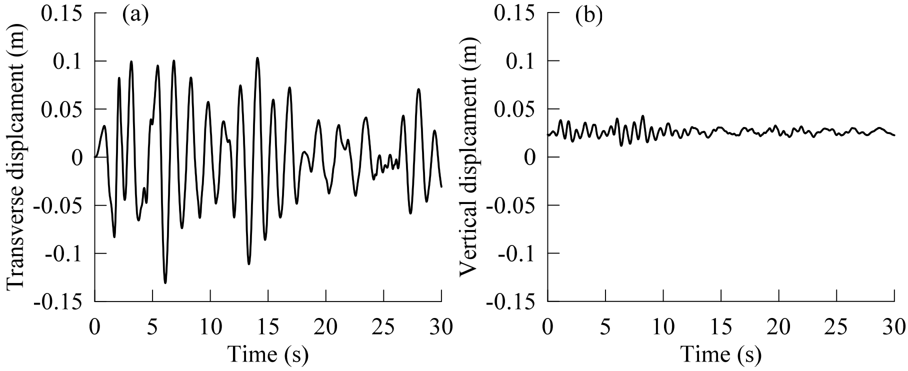


Fig. 3. Effect of cable stiffness on the dynamic response of SFT for hydrodynamic analysis (a) Transverse displacement, and (b) vertical displacement SFT.



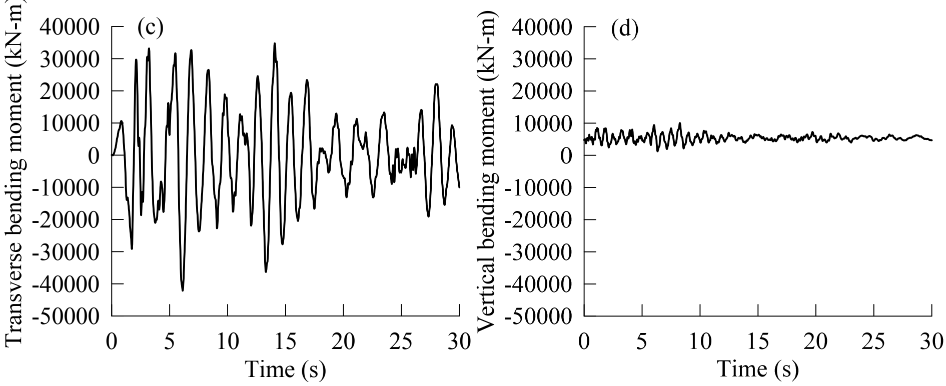


Fig. 4. The displacements and bending moments of SFT at the center of the tunnel for seismic analysis: (a) Transverse displacement, (b) vertical displacement, (c) transverse bending moment, and (d) vertical bending moment.

Table 2. SFT maximum absolute displacements and bending moments at the center of the tunnel.

	Transverse displacement (m)	**Vertical displacement (m)**	**Transverse bending moment (kN-m)**	**Vertical bending moment (kN-m)**
Hydrodynamic	0.0253	0.0293	7961.9884	6036.9302
Seismic	0.1310	0.0428	42112.2048	10040.6098

6 Conclusions

The equations of motion for submerged floating tunnel (SFT) are formulated considering the modeling of structure, cable system and ocean waves and currents. The equations of motion are then solved numerically using Newmark's average acceleration method. The dynamic simulations of SFT are performed for the hydrodynamic and seismic excitations.

Waves and currents are modeled by the Airy wave theory and wave forces are calculated using modified Morison's equation. The displacements and bending moments of SFT for hydrodynamic analysis (environmental conditions of Qindao Lake, Peoples Republic of China) and seismic analysis (El-Centro ground motions, 1940) are presented. The seismic response of SFT is very large compared to hydrodynamic response, due to two reasons (1) hydrodynamic action is small because the wave height of the site is one meter only; for practical design, the SFT need to be checked for a wide range of wave heights (2) SFT is a massive structure.

The effect of cable stiffness on the dynamic behavior of SFT is evaluated. The vertical/tension leg mooring cables are the least effective as compared to inclined mooring cables due to the smaller horizontal stiffness of vertical mooring cables. The transverse bending moments of SFT are found to be larger than vertical bending moments of SFT, and this is attributed to the smaller cable stiffness in the transverse direction. Based on the numerical results of the present study, it is concluded that to keep the SFT displacements within an acceptable range and to avoid the slackness of the mooring cables, an optimized cable stiffness need to be used for the practical design of SFT.

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