DYNAMIC BEHAVIOR OF SUBMERGED FLOATING BRIDGE DUE TO MOVING HIGH SPEED TRAIN

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ABSTRACT: This study intends to develop an algorithm for the dynamic interaction analysis of submerged floating tunnel and vehicles. The dynamic behavior of a submerged floating tunnel differs from that of general structures because the floating tunnel is submerged in water and subjected to permanent buoyance. Therefore the analyses in various aspects should be carried out to secure the structural stability and practicality of the structure. A tension leg submerged floating tunnel is selected and modeled by the commercial FEM program ABAQUS to investigate its modal characteristics and conduct the dynamic interaction analysis. The added mass concept is applied to represent the inertial force by a fluid, and then dynamic interaction analyses are conducted with superposition method when the KTX is moving along the submerged floating tunnel. The time histories are presented for vertical and lateral displacements at the center of the tunnel.

Keywords: Submerged floating tunnel, mode superposition, added mass, tension leg, dynamic interaction.

INTRODUCTION

The structures for inter-island or inter-continental links are generally bridges constructed above the surface of water. However, interest grew recently on submerged bridges leading to numerous studies dedicated to diversified erection techniques for the promotion of their application. These studies resulted in diverse types of submerged structures like the floating tunnel floating in water by buoyance, the immersed tunnel of which segments are fabricated onshore and sunk in water, and the underwater tunnel constructed under water.

The dynamic behavior of the submerged floating tunnel (SFT) differs from that of general structures in that it is submerged in water and subjected to permanent buoyance. This means that, to secure its applicability and structural safety, analysis should be conducted in various aspects like the analysis of the soil and foundations supporting the tension legs, the seismic analysis, the interaction analysis considering the waves and tides, the analysis of the failure behavior by impact, the analysis of the connections and anchors, the analysis of the waterproofing and drainage (Park et al. 2012).

Overseas research on the SFT is very active. The first patents were granted in Norway in 1923 and 1947 and set the bases for research on the SFT project at Høgsfjord in the western coast of Norway linking Lauvvik and Oanes through a length of 1,400 m and maximum water depth of 155 m. Research was also conducted to evaluate the feasibility of a SFT linking the mainland of Italy to Sicily through the Messina Straits, where the famous Messina Bridge is planned for construction. Even if the feasibility analysis decided to erect a bridge, advanced studies have been performed on the SFT as an alternative to ordinary bridges. Japan also carried out studies for the construction of 3 SFTs of which the Northern Japan Exchange Axis linking Sapporo and the northern part of Honshu.

As part of the “Development of design examples for the core technologies of SFT” supported by the Korea Institute of Construction & Transportation technology Evaluation, the present research focuses particularly on the development of an algorithm enabling relatively simple analysis of the dynamic behavior of SFT considering the structure-vehicle-fluid interaction. The type and dimensions of the SFT at hand are presented and the concept of added mass is introduced to simulate the structure-fluid interaction (FEHRL 1996). The dynamic vehicle-structure interaction using modal superposition is presented briefly. The SFT structure is modeled by the commercial software ABAQUS. Eigenvalue analysis is then conducted to obtain the natural frequencies and mode shapes, which are in turn used to evaluate the dynamic behavior of the SFT in the vertical and lateral directions by means of dynamic interaction analysis of the SFT crossed by the KTX, the Korean high-speed train.

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TYPES OF SUBMERGED TUNNELS AND SELECTED SUBMERGED FLOATING TUNNEL

Four types of SFT can be distinguished according to the relation between the buoyance and weight. The first picture in Fig. 1 depicts the structure with tension legs adopted when the buoyance is larger than the weight (B>W). The pontoons and column supports types are adopted when the buoyance is smaller than the weight (B<W). The free type SFT without supporting cable or column is chosen when the buoyance and weight are identical. The tension leg SFT is the most commonly used type during the design of submerged SFT (Østlid 2010). The tension leg SFT develops its advantages by offering economic efficiency compared to the other types when the obstacle to be crossed is deep and long and by enabling traffic to be practically free from meteorological conditions since it is erected under water.

The structure selected for the analysis is the tension leg SFT running along 7 km between the second and third aeration towers of the structure linking the Bay of Funka in Japan. The SFT is located at a depth of 30 m and its cross section is illustrated in Fig. 2. The selected structure is of tension leg type when the buoyance is larger than the weight (B>W) and is supported by cables disposed at intervals of 100 m as shown in Fig. 3.

FLUID-STRUCTURE-VEHICLE INTERACTION ANALYSIS

Submerged Structure-Fluid Interaction

Various formulae have been proposed by Morison and other researchers to evaluate the behavior of a structure submerged in a fluid and to calculate the forces acting on the structure (Son 1995, Martinellia et al. 2010, Chakrabarti 1987). The submerged structure is subjected additionally to an added mass brought by the hydrodynamic mass. This added mass is obtained by inverse calculation using Eq. (1), which is added to the unit mass of the SFT for the analysis. Using the term related to the inertial force in the Morison formula, the calculation is performed assuming a coefficient of inertia $C_m = 2$ and an acceleration of the fluid $\partial u/\partial t = 1$.

$$C_m \rho \frac{\pi D^2}{4} \partial u/\partial t \partial \sigma = \rho_{added} A'$$

where $u$ and $\partial u/\partial t$ are the horizontal velocity and acceleration of the fluid; $C_m = 1 + C_a$ is the coefficient of inertia and $C_a$ is the coefficient of resistance; and, $\rho_{added}$ is the added unit mass due to the inertial force.

Submerged Structure-Vehicle Interaction

The deflection of the structure is expressed by applying the mode superposition through the natural frequency and vibration modes so as to derive the equations of motion of the SFT. The equations of motion of the structure considering the external loads can be expressed as follows (Kwon 1988).

$$M_b \ddot{d}_b + C_b \dot{d}_b + K_b d_b = F_0 \delta(x-x_i)$$

where $M_b$, $K_b$, and $d_b$ are respectively the $N \times N$ mass, stiffness and nodal displacement matrices and $N$ is the total number of degrees of freedom of the structure model; the upper dots stand for the derivation with respect to time; $x_i$ is the location at which the load acts. The vertical deflection $d_b(x, t)$ of the structure can be expressed as follows as the product generalized coordinate $q_i(t)$ and mode shape $\phi_i(x)$.

$$d_b(x, t) = \sum_{i=1}^{N_{nod}} \phi_i(x) q_i(t)$$
Modeling using ABAQUS

The numerical analysis software ABAQUS was used to model and obtain the mode shapes of the structure. The modeled section has a total length of 7 km and supported by cables disposed every 100 m. The effective buoyance obtained above is introduced on the whole section.

The model assumes simply supported conditions at its extremities. The natural frequencies and mode shapes obtained by eigenvalue analysis are shown in Table 1 and Fig. 4.

Table 1 Natural frequencies in lateral and vertical directions

<table>
<thead>
<tr>
<th>Mode direction</th>
<th>Natural frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st lateral mode</td>
<td>0.64892</td>
</tr>
<tr>
<td>2nd lateral mode</td>
<td>0.64915</td>
</tr>
<tr>
<td>3rd lateral mode</td>
<td>0.64953</td>
</tr>
<tr>
<td>1st vertical mode</td>
<td>1.1222</td>
</tr>
<tr>
<td>2nd vertical mode</td>
<td>1.1222</td>
</tr>
<tr>
<td>3rd vertical mode</td>
<td>1.1223</td>
</tr>
</tbody>
</table>

ANALYSIS RESULTS

The time histories of the vertical and lateral displacements at the center and at a point located 50 m away from the center of the considered 7 km-long section of the SFT crossed by the KTX (Park 1998) were obtained by mode superposition using the mode shapes provided by ABAQUS. The following conditions were assumed for the analysis: consideration of 5 mode shapes (2 modes in the horizontal direction, 3 modes in the vertical direction); traveling distance of 10 km (7 km of the selected SFT section and additional 3 km); and, train running at speed of 300 km/h.

From these results, it appeared that the maximum vertical deflection of the SFT crossed by the KTX reached 1.081 mm with a maximum horizontal displacement of 6.925x10^-6 mm. These values correspond to those at the center of the whole 7 km of the considered section of the SFT. However, this center is located in a segment supported...
by 2 cables which reduce the displacements. Therefore, it was expected that larger displacements would be obtained at the position of a segment between the cable supports and located 50 m away from the center. That is, the results were recomputed for a point located at 3.45 km, which is 50 m before the center at 3.5 km.

Fig. 6 Time histories of vertical and lateral displacements at the center of SFT

Following, the maximum displacements for this point located at 3.45 km of the SFT were found to be 1.239 mm in the vertical direction and $1.025 \times 10^{-5}$ mm. Compared to the same results at the center, these displacements are respectively 1.146 times and 1.48 times larger. Accordingly, the maximum displacements in the vertical and lateral directions appeared to be larger at the point located at 3.45 km than at the central point located at 3.5 km.

Fig. 7 Time histories of vertical and lateral displacements at point 50 m away from the center of SFT

CONCLUSIONS

A structure-vehicle-fluid interaction analysis method has been proposed for the analysis of the dynamic behavior of the SFT. The SFT was modeled using the commercial software ABAQUS and the static behavior as well as the modal characteristics of the SFT could be examined. Furthermore, the concept of added mass was introduced to simulate the structure-fluid interaction and eigenvalue analysis was conducted for the structure subjected to buoyance. The vertical and lateral displacements of the structure were investigated by mode superposition using the natural frequencies and mode shapes. The analysis results revealed that the vertical and lateral displacements were larger at a position located at 3.45 km that is 50 m away from the center of the SFT than at the center of the SFT located at 3.5 km. Consequently, attention should be paid for the position located between the supporting cables and 50 m away from the center rather than on the center.

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REFERENCES


