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Spatial dynamic response of submerged floating tunnel under impact load

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Abstract: In order to analyze the global spatial dynamic response of a submerged floating tunnel (SFT) under the impact load, the tube is treated as a beam on elastic foundation (BOEF) with three degrees of freedom (horizontal displacement, vertical displacement, and torsion angle). The governing differential equations of the tube are derived based on the Hamilton principle considering the non-linear hydraulic resistance. The spatial displacement responses of the SFT are presented by the modal superposition method and Runge-Kutta method. The coupling motion of the horizontal displacement and torsion angle is also investigated. A finite element model of the SFT is established in ABAQUS to verify the results of the BOEF model, and the UAMP subroutine is used to simulate the effect of hydraulic resistance. Finally, the effects of the parameters, such as the anchorage stiffness, inclined angle of the cable, buoyancy-weight ratio, and hydraulic resistance on the impact response are studied. The results show the BOEF model is validated to be a suitable simplified method for the global impact response analysis. The coupling motion between the horizontal displacement and torsion angle has a significant influence on the torsion. The change of buoyancy-weight ratio has effect on displacement results and the natural frequency of the tube. It suggests the reasonable inclined angle of cable is between 45° and 60°. The hydraulic resistance considered in this paper had an effect of more than 20% on the maximum displacement, so it should not be ignored in analyses.

1. Introduction

Submerged floating tunnel (SFT), also known as Archimedes Bridge, is an innovative alternative to cross straits, large lakes, and other long, deep water areas [1]. It generally consists of a tube, anchor devices, underwater foundations, and revetment structures [2]. The SFT has many advantages over traditional bridges and tunnels, including a greater spanning capacity, better adaptability to the environment, all-weather operation, and relatively lower construction cost [3]. Hence, the SFT is thought to have great development potential in the 21st century.

Since 1960s, scholars have carried out numerous studies on the aspects of conceptual design, dynamic behavior in relation to waves and currents, and seismic response. Fogazzi et al. [4] analyzed the seismic response of the SFT using the spatial beam element. Di Pilato et al. [5] analyzed the three-dimensional dynamic response of the SFT under seismic and hydrodynamic incentives. Martinelli et al. [6] proposed a new method to obtain the response spectrum based on the median pseudo-

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acceleration response spectrum. They also developed a cable element with three nodes that took into consideration the fluid action and analyzed the non-linear seismic response of the SFT. Remseth et al. [7] studied the random dynamic response of the SFT under the wave action by taking into consideration the fluid-structure interaction. Xiang et al. [8] paid attention to the vortex-induced vibration of the cable-tube coupling system and deduced the motion differential equations according to the Hamilton principle. Seo [9] developed a conceptual design of the SFT and proposed theoretical equations to estimate the hydrodynamic forces working on it, which were verified by experiments. Lu et al. [10] studied the non-linear dynamics of a submerged floating moored structure subjected to vertical excitation using the incremental harmonic balance method, which took into consideration the possible slackness in the mooring system. Moreover, Tariverdilo et al. [11] gave the vibration responses of the SFT under vehicle moving loads.

In addition to the action of the waves and currents, vehicle load, and seismic excitation, the SFT faces a collision risk from sunken ships, submarines, and internal vehicles during its operation. Despite the low occurrence probability of such incidental loads, they can threaten the safety of the SFT structure. The impact issues related to the SFT should be given thorough attention in the early stages of design.

There is very little research on the dynamic response of the SFT regarding the impact load. For local analysis, Hui et al. [12] developed a simplified calculation model using the equivalent mass method. The local radial displacement and the stress of the tube at the impact position were analyzed. The BOEF model is often used in analysis in terms of the global response. Seo et al. [13] [14] presented the global response of the SFT against collisions and underwater explosions. Lee et al. [15] simulated the local damage and global behavior of the SFT in a collision with a submerged moving body via the commercial software ANSYS/LS-DYNA. In these previous studies, the global impact responses of the SFT are mainly given in the two-dimensional vibration. Simplified calculation models tend to ignore the influence of the hydraulic resistance.

The present paper aims at the global spatial impact response of the SFT by taking into consideration the non-linear hydraulic resistance. To this end, the tube of the SFT is simplified as a beam on elastic foundation (BOEF). The vibration differential equations of the three degrees of freedom (vertical displacement, horizontal displacement, and torsion angle) are derived according to the Hamilton principle. The coupling motion between the horizontal displacement and torsion angle is studied. The modal superposition method and Runge-Kutta method are used to solve the equations. Finite element software (ABAQUS) is used to verify the results of the BOEF model. Finally, the factors that affect the impact response, such as anchorage stiffness, inclined angle of the cable, buoyancy-weight ratio, hydraulic resistance, are studied.

2. Simplified model and assumptions

Fig. 1 shows a typical SFT structure. In a global analysis, the anchor cables can be generally regarded as discrete elastic supports with certain stiffness. When the stiffness between the anchorage system and tube meets the condition of Eq. (1), the discrete elastic supports can be simplified as an equivalent imaginary elastic foundation [16] [17].

$$\frac{kl^3}{24EI} \leq 0.05 \tag{1}$$

where k is the anchor stiffness of a set of anchor cables; l is the cable interval; and EI is the bending stiffness of the SFT tube.

Therefore, the tube of the SFT here is considered a BOEF with both ends constrained, as shown in Fig. 2.

Some further assumptions for the structure are made as follows:

- The tube is a simply-supported Euler-Bernoulli beam with constant sections and equal stiffness. The displacements in the Y and Z directions and the torsion with respect to the X axis are considered.
- The anchor system consists of rigid cables, which can withstand both tension and compression. The anchor cables have the same length and equal intervals.
- Only the elastic vibration of the SFT tube is considered. The influence of the tube damage caused by the impact load is not taken into account.

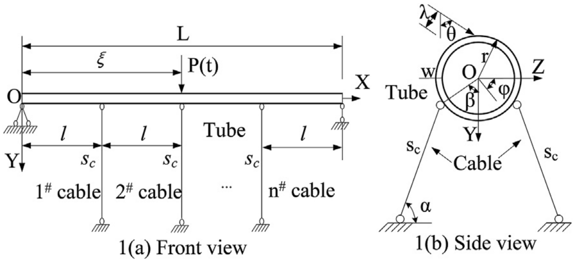

Fig. 1. Schematic diagram of a typical SFT structure.