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Dynamic response analysis for submerged floating tunnel with anchor-cables subjected to sudden cable breakage

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ABSTRACT

Anchor-cables are critical bearing components of the submerged floating tunnel (SFT). As the accidental cable-breakage incident will seriously threaten the public safety, this paper investigates the global dynamic response of a SFT subjected to an abrupt anchor-cable failure by focusing on the post-breakage behavior. Firstly, an approximate theoretical approach is proposed, in which the analysis model of SFT is simplified and the alternate load path method (AP method) is adopted to simulate the cable-breakage process. Then, the differential equations of the SFT tube are established based on the Hamilton principle, and solved through the fourth order Runge-Kutta method. A finite element analysis in ABAQUS is also performed as a verification of the theoretical results, in which the VUSDFLD subroutine and ABAQUS/Aqua is employed to simulate the stiffness loss of the cable and apply the fluid loads respectively. A good agreement exists between the simplified theoretical model and FE simulation. Finally, the effects of some key parameters are discussed, such as the gravity-buoyance ratio and the damping ratio of the SFT, the breakage time and position of the broken cable, etc. The results show that the structural vibration is intensive after the sudden cable breakage. Also, the remaining anchor-cables close to the cable-loss position are most affected by the cable rupture. The change of gravity-buoyance ratio and damping ratio have notable effects on structural deformation. The SFT is most unfavorable when the cable breakage happens at the mid-span or near the two ends of the tunnel. The vibration amplitude attenuates significantly with the increase of the failure time of anchor-cable.

1. Introduction

Submerged Floating Tunnel (SFT), is a new transport facility for crossing waterways. A typical SFT is composed of three major parts: (1) the hollow tunnel tube suspended in the water; (2) the supporting devices like anchor-cables or pontoons to balance the redundant buoyancy of the SFT tube; (3) the offshore connections between the tunnel and mainland on the ends. Compared with other traditional ways crossing straits, such as long-span bridges or subsea tunnels, the SFT with anchor-cables is regarded as with the greatest potential in the 21st century. It has such advantages as: (1) strong adaptability of underwater foundation; (2) lower construction cost rise with the increase of span length; (3) negligible effects on the normal navigation and other water production activities even under severe climatic conditions [1] [2]. Schematics of a typical SFT and a traditional cable-stayed bridge, as well as their main bearing load styles are shown in Fig. 1.

Since the late 1980s, the researches on SFT have been thriving around the world. In the past 10 years, scholars had begun to pay more attention to the dynamic problems of SFT during accidental situations, such as earthquakes, harsh wave conditions, impacts,

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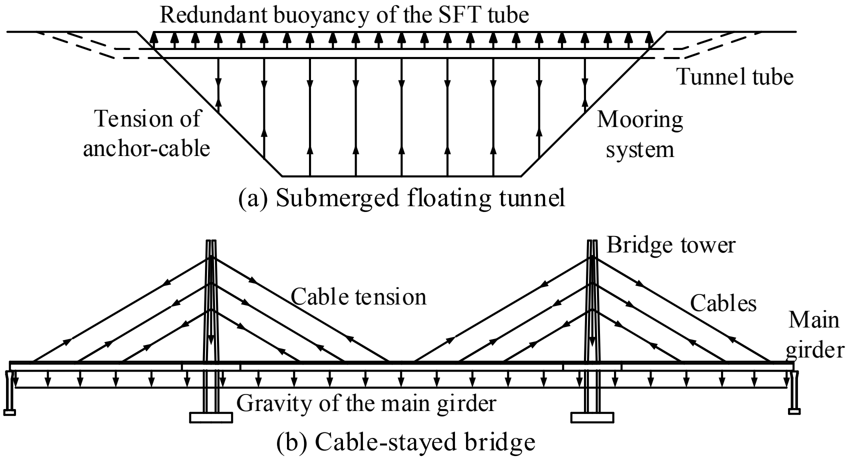

Fig. 1. Schematics of a typical SFT and a cable-stayed bridge.

and other extreme loads. Di Pilato et al. [3] studied the nonlinear dynamic performance of the Messina strait SFT under multiple-support seismic excitation and hydrodynamic load. Sun [4] carried out model experiments of the SFT under seismic excitations on the underwater shaking table. Martinelli et al. [5] analyzed the non-linear dynamic response of SFT based on the EN 1998 pseudo-acceleration elastic response spectrum. Besides, Martinelli et al. [6] reviewed the latest research developments on seismic response of SFT, with a case study in ANSYS to verify the effectiveness of two kinds of passive control devices against seismic excitations. Moreover, Lu et al. [7] studied the potential slack phenomena in anchor-cables of a rigid SFT segment caused by harsh wave loads. Seo et al. [8] calculated the deformations and internal forces of the SFT tube subjected to an underwater explosion based on the energy conservation law and compared the obtained results with FEM. Xiang et al. [9] investigated the spatial dynamic characteristics of the SFT under external impact loads. The above studies promoted the understandings of the mechanical characteristics for SFTs and established scientific basis for the later design and construction.

Since 09/11/2001 event, the structural safety and the robustness against progressive collapse has been more and more emphasized. More research achievements started to focus on the impact on the long-span cable-supported bridges from the abrupt cable failure [10–16]. In the design guideline for the cable-stayed bridges, Post-Tensioning Institute [10] stated that the sudden failure of any single cable should not lead to the zipper-type collapse, and two load application methods were given for dynamic calculations. Mozos et al. [11] studied the effects of the failure duration of the broken cable on the structural dynamic response. Cai et al. [12] compared four approaches for the cable-loss simulations considering the initial state of a cable-supported bridge. Zhou et al. [13] [14] established a time-progressive dynamic analysis framework for a cable-stayed bridge suffering the cable-breakage incident. However, up to now, the explorations of the SFT with the similar bearing load form as these long-span bridges have not involved yet.

In a marine environment, the anchor-cables and the joints between the tunnel tube and cables are regarded as the weakest components of the SFT. Once the breakage of anchor-cable suddenly occurs, it can cause strong vibration and large deformation, which will certainly endanger the social security. Therefore, during the early research phase, the dynamic response analysis of the SFT suffering from this accidental disaster, as well as the corresponding prevention and countermeasures should be given more attention.

The objective of this paper is to understand the global response in post cable-breakage stage of a seabed anchored SFT. On the one hand, a theoretical model is presented, where the SFT is treated as a beam on discrete elastic supports, meanwhile, the process of abrupt cable failure is simplified according to the AP method. Then, the governing differential equations of the SFT tube are established through the Hamilton principle, and solved by the corresponding numerical method. On the other hand, FE analysis inside ABAQUS is conducted to verify the theoretical results. Finally, some key parameters affect the structural dynamic response are discussed, which can be useful for determining the basic parameters of the actual structure.

2. Theoretical model

2.1. Basic assumptions and simplified model

The simplified SFT model is shown in Fig. 2. Referring to the reference [17], the following basic assumptions of the SFT are made.

(1) Total $(H+1)$ pairs of anchor-cables are installed along the longitudinal direction (X-axis). Because the overall vibration of structure is the main target and the vibration of cable itself is quite complex, the local vibrations of anchor-cables are neglected in this study. Consequently, the SFT can be treated as an Euler-Bernoulli beam on discrete elastic supports [17].
(2) Owing to the lack of engineering experience, it is difficult to accurately express the various reasons leading to the cable failure until now. So we consider the reduction in bearing stiffness caused by cable loss, and ignore the effects of the trigger for cable