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On the slack phenomena and snap force in tethers of submerged floating tunnels under wave conditions

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ABSTRACT

Under severe sea wave conditions, the mooring tethers of submerged floating tunnel (SFT) might go slack. It may cause the structure failure during the service lifetime of SFT. The paper investigated SFT dynamics when going through tether slacking and the related snap force under wave conditions. Besides the nonlinearity of fluid drag and of structural geometry for a relative large structure displacement, the problem is characterized by the nonlinearity due to the discontinuity in axial stiffness of the tethers. To include these nonlinearities, the method of Lagrange energy is used to build the governing equations of SFT motion, and a bilinear oscillator is introduced to simulate the mooring tether operating in an alternating slack-taut state. The sensitivities of the occurrence of tether slacking to wave height and wave period are investigated. Results show that at a large wave height SFT tether will go slack and snap force occurs. SFT responses are categorized into three types of state according to the dynamic response characteristics of tether tension. Effects of two fundamental structure parameters, buoyancy-weight ratio (BWR) and inclined mooring angle (IMA), on the dynamic responses of SFT are analyzed. A slack-taut map of SFT tethers is built. It intuitively describes the occurrences of slack and snap force with different combinations of the two parameters. An analytical approach for slack prediction by deriving the slack criterion is provided to reveal the mechanism of the presented slack-taut map. By present research, the authors tried to make their effort to provide an alternative philosophy for SFT structural design on concerning preventing the occurrence of tether slacking and snap force.

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1. Introduction

Submerged Floating Tunnel (SFT), also named Archimedes Bridge, is an innovative transportation concept for crossing straits, sounds, lakes or other kinds of waterways in general. As the name suggests, it is a tube-like structure floating at a certain depth in water supported by its self-buoyancy and constrained by mooring systems. An SFT mainly consists of four parts: (i) the tubes which are made up of tunnel segments and allow traffics and pedestrians to get through, (ii) the joints including those connecting the adjacent tunnel segments and the tunnel-shore connectors, (iii) the mooring systems which are anchored to the waterbed and keep the floating tunnel in position, (iv) the foundation constructed at the waterbed to install mooring systems.

Characterized as a submerged structure floating in the water, SFT has a lower impact on the local environment comparing to traditional bridges. Besides, the cost of SFT per unit length will not increase with the total span, which makes SFT an attractive option especially for deep or long waterway crossings [1–4]. SFT is exposed to many kinds of loads and potential hazards during its service life involving: (i) permanent loads encompassing structural weight and hydro-static pressure, (ii) environmental loads such as wind-induced waves, internal waves, currents, earthquakes etc., (iii) functional loads such as traffic loads and weight of ballast, (iv) accidental loads due to unexpected hazards such as internal explosion, fire, collision on the tunnel shell, loss of a mooring system, etc.

In some severe conditions such as a huge wave, earthquakes etc., SFT tethers might go slack. The occurrence of this phenomenon is due to the fact that the tether is highly resistible to tension while could hardly undertake compression. When the motion of tunnel goes large, the tension of SFT tethers might fall to a low level, and the tethers could become slack. In the cases of periodical excitation such as wind-induced wave, the tether will operate in alternating taut-slack conditions. Depending on the transition rate at which the tether becomes taut from slack state, it may cause very high tension in the tether which is referred to as “snap force” due to its impact effect [5–8].

Even though the original idea of SFT was conceived as early as 1880s [4], still there is no an SFT actually been built. Except for the social reasons, various scientific and technical difficulties are still in the way to realize it, such as fluid-structure-soil coupling, vortex induced vibration of tethers, the cable system configuration, the tunnel-shore joint design, etc. Many researches have been carried out so far.

Analytical study on dynamic response of a long SFT under wave condition was carried out in Ref. [9], and linear restoring force of mooring tethers was taken. Compressive force in the tethers was found in some cases, which meaned slack would happen in the tether. The nonlinearity due to catenary curve effect of mooring tether was considered in Ref. [10]. Comparison with linear restoring force reveals that this nonlinearity is not negligible unless for short tethers. If the ratio of leg weight to the net buoyancy of the tunnel is larger than 0.05, the linear assumption will underestimate the displacement and tether tension of SFT. Motohiro Sato et al. [11] idealized SFT as beam on elastic supports, and found that BOES (beams on equidistant elastic supports) could be modeled as BOEF (beams on elastic foundations) both for static and dynamic problems as long as the so-called relative stiffness of the supports $K_v \leq 0.05$. A finite element model accounting for geometrical nonlinearities and hydrodynamic loads was built to simulate the anchoring bars of SFT in Ref. [12]. The element was inserted in a step-by-step procedure for the numerical analysis of nonlinear response of SFT to seismic loading. In Ref. [13] this element was refined to extend its capabilities to full 3-D analysis and then implemented to the numerical procedure for full 3-D analysis of SFT under seismic and hydrodynamic excitation. Xu Long [3] took the structural design scheme of submerged floating tunnel prototype of Qiandao Lake in China as calculation model, and investigated the effects of structure parameters on dynamic responses of SFT under hydrodynamic loads. And the results indicated that the buoyancy-weight ratio (BWR) of SFT is a key structure parameter.

A series model experiments were carried out to investigate dynamic behaviors of SFT under regular waves in wave tank of the Hokkaido Development Ministry [14,15]. It is worth noting that tether slacking was observed for several mooring types of SFT; the dynamic tension of the tethers was no longer sinusoidal and snap force might occur under relatively severe wave conditions. Their results showed, for the case of tether perpendicular to sea-bed, the transverse displacement was significant but the snap force was almost negligible.