Numerical study on hydroelastic dynamics of a submerged floating tunnel in tsunami waves

Sung-Jae Kim and MooHyun Kim
Department of Ocean Engineering, Texas A&M University
College Station, TX, USA

ABSTRACT

This paper aims to investigate the dynamics of a submerged floating tunnel (SFT) with inclined taut mooring lines under tsunami-like freak waves. The SFT is modeled using the lumped-mass line model and the dummy-connection-mass method to examine the hydro-elastic behavior and the interaction between the long tunnel and multiple mooring lines. The study applies both a single solitary wave and the combined solitary waves based on measured data to the numerical model. The results provide insights into the elastic behavior of the long tunnel and the tension in the mooring lines under extremely long waves with various wave height conditions.

KEYWORDS: Submerged floating tunnel, Hydroelasticity, Tsunami waves, Mooring tension, Snap loading

INTRODUCTION

A submerged floating tunnel (SFT), which was proposed in the 1970s (Remseth et al., 1999), is an innovative solution to overcome the challenges of traditional underwater tunnel construction. The concept involves a fully submerged floating tunnel anchored to the seabed. However, the unique design of SFTs introduces complex hydroelastic behavior, which has significant impacts on the structural performance, stability, and safety of the system. Hydroelastic behavior refers to the dynamic interaction between the tunnel structure and the surrounding water, which leads to deformation, vibration, and wave excitation of the system.

In order to further understand the hydroelastic behavior of SFTs, several studies have been conducted by various research groups under severe environmental conditions, providing valuable insights and references. For example, Di Pilato et al. (2008) developed a three-dimensional model of a flexible SFT under hydrodynamic and seismic excitation to design an anchor system. Jin and Kim (2018) evaluated the elastic responses of a 700m-long SFT to extreme waves and earthquake-like seismic excitation using the rod-theory-based finite element method. Besides, Jin and Kim (2021) analyzed the impact of design parameters, such as Buoyancy-Weight-Ratio (BWR) and submergence depth, on the performance of a moored SFT during severe weather conditions. Jin et al. (2023) also analyzed a flexible SFT with mooring lines under water wave excitation, considering second-order sum and difference wave loads using the discrete module beam method. From these studies, it is evident that the primary focus of SFT analysis is the response to wind-driven waves and seismic excitation. Even if Zou et al. (2020) considered tsunami waves as an environmental condition, they were focused on the evaluation of tsunami wave loads, not investigating the elastic behavior of the tunnel.

This study explores the elastic behavior and safety of a moored Submerged Floating Tunnel (SFT) under tsunami-like waves. Despite the significant impact that tsunamis, with their long wavelengths, can have on deeply submerged structures, current research focuses on the evaluation of sectional hydrodynamic forces. To address this gap, the study employs a finite element model of a flexible SFT with multiple mooring lines and models tsunamis as solitary waves with long wavelengths and high wave amplitudes (Synolakis, 1987). The responses of the moored SFT are first analyzed under a single solitary wave with different ratios of wave height and water depth. Subsequently, regenerated tsunami waves based on the Tohoku tsunami measurement are applied to the moored SFT model, and the corresponding responses are presented.

NUMERICAL MODEL

Time domain analysis for a moored SFT

The established time-domain model takes into account the effects of fluid-structure interaction, simulating the hydrodynamic and structural behavior of the SFT by OrcaFlex (Orcina, 2014). This study utilizes a 700m-long tunnel and plenty of mooring lines as Fig. 1, while they are expressed by applying lumped mass finite element method with linear springs (Fig. 2). The equation of motion for a tunnel can be described as:

\[ M\ddot{x} + C\dot{x} + Kx = F_s + \ddot{w} + F_c \]  

(1)