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Characterization of Single and Dual Section SFTs through 2-D Wave Flume Experiment

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ABSTRACT

In this study, structural behaviors on single/dual section submerged floating tunnels (SFTs) under various wave loads are experimentally characterized. Two acrylic SFT specimens are designed to have the same number of traffic lanes and installed in a 2-D wave flume. Sinusoidal regular waves are generated by using piston-type wavemaker to be applied on the specimen. Tensile forces on mooring lines and tunnel displacements are measured and discussed, and semi empirical Morison's equation is introduced to evaluate the wave force and to compare structural responses. As a result, possibilities and characteristics of single/dual SFTs can be systematically investigated.

1. INTRODUCTION

A cylindrical marine structure has been actively adopted for various objective such as electricity power line cables and oil transportation risers. A submerged floating tunnel (SFT), an emerging structure of cylindrical shape, is attracting a lot of attention due to its structural advantages over other type tunnels (Chen et al., 2020; Kim et al., 2021). Compared to an immersed tunnel, damage of the SFT in a case of earthquake can be dramatically reduced, if the mooring arrangement is optimally designed even with much lower constructional budget (Park et al, 2013). For the structural design of the SFT, determination of the external load is the most important process including a type, magnitude, direction of the load, and a geometry of the structure as well (Faltinsen, 1993). Wind-driven wave load which has the greatest effect on the structure, is generated at the sea level and propagates into the water, interacting with the structure.

Depending on the section specification, many characteristics of waves such as a dimension to wavelength ratio (D/L) are highly affected, resulting in the influence of the wave load on the structure becomes different (McCormick, 2009). For example, a single circular section SFT can be considered as a small body despite of its gigantic dimension,

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because a section diameter is relatively smaller than incident wavelengths, and this means that the slender rod theory would be used for evaluating the structural response of the single SFT. With this assumption, the hydrodynamic force affecting on the SFT can be expressed by using semi-empirical Morison's wave equation, which includes wave effects of inertia, added mass, and drag force with a consideration of the viscosity of fluid particles (Sarpkaya, 1986). Through the assessment of hydrodynamic forces and conjunction with theoretical backgrounds, coefficients (C_a, C_d) in Morison's equation required to evaluate the horizontal and vertical wave force on the structure can be determined.

Based on the evaluated hydrodynamic wave forces, the structural responses under wave loads can be characterized with variation of design parameters, including section shape, diameter, and wave conditions. In this study, two acrylic SFT specimens are introduced with 1:100 similarity. Dimensions of single and dual sections are determined to have the same number of traffic lanes, which means the specimens are identically designed in a functional aspect. Each specimen is installed with mooring lines at 615 mm submergence in 2-dimensional (2-D) wave flume, with 1,000 mm water depth. By using piston-type wavemaker, sinusoidal regular waves are generated and applied to the SFT specimens. Measured hydrodynamic values such as fluid velocity and acceleration are compared with analytical results and the semi-empirical Morison's equation. After that, dynamic tensile forces, tunnel displacements are measured by using load cells on mooring lines and high-speed camera, respectively. Through the study, a global structural safety of SFT system can be investigated.

2. SEMI-EMPIRICAL MORISON'S EQUATION

When a dimension to wavelength ratio D/L of the structure is less than 0.2, it can be assumed that wave diffraction is not interrupted by the obstacle and a slender rod theory is introduced (Faltinsen, 1993). The Morison's equation is a widely adopted semi-empirical method when the external wave load applies on the slender structure (Morison et al., 1950). Normally, the Morison's equation includes wave inertia force F_i, added mass effect F_a to express the increased mass effect by surrounding section fluid particles, and drag force F_d by the resistance of the structure from the external flow. The horizontal wave force F_H is expressed as:

$$F_H(\mathrm{t}) = F_{Hi}(\mathrm{t}) + F_d(\mathrm{t}) = \frac{\pi}{4} D^2 \rho C_{MH} a_H(t) + \frac{1}{2}\rho D C_d(\mathrm{u}(t) - v(t))|\mathrm{u}(t) - v(t)| \quad (1)$$

where D is the characteristic section diameter, ρ is the fluid density, C_{MH} and C_d are the horizontal inertia and the drag coefficients, and u(t), $a_H(t)$, and v(t) are the free stream horizontal velocity, acceleration of the fluid, and horizontal velocity of the moving body, respectively. The added mass effect F_a affecting on the floating specimen is neglected here but will be considered in the future work.

Meanwhile, the vertical wave force can be evaluated by using the transverse equation (Cheong et al., 1989). The equation is expressed by the linear combination of a vertical inertia force F_{Vi} and a lift force, F_L.

$$F_V(\mathrm{t}) = F_{Vi}(\mathrm{t}) + F_L(\mathrm{t}) = \frac{\pi}{4}D^2\rho C_{MV}a_V(t) + \frac{1}{2}\rho D C_L \mathrm{u}(t)^2 \tag{2}$$

where C_{MV} and C_L are the vertical inertia and the lift force coefficients, and $a_V(t)$ is the vertical acceleration of the surrounding flow. Here, F_{Vi} is induced from the time-series vertical velocity variation, while the F_L is occurred by asymmetric pressure field of the external flow at the SFT.

3. EXPERIMENTAL DESCRIPTION AND PRELIMINARY RESULTS

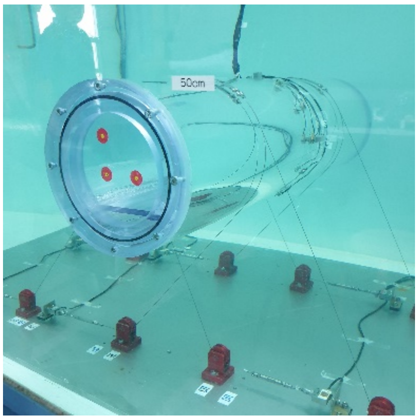

Fig. 1 Description of 2-D flume experiment (single SFT)

Fig. 1 shows a description of single SFT specimen installed in the 2-D wave flume. Two acrylic specimens, namely, single and dual are designed to serve the same number of traffic lanes in total. 1:100 similarity is used in the experiment, outer diameter of single SFT is 230 mm, while that of each section in dual type is 160 mm. Water depth is 1,000 mm and the submergence depths are 615 mm for both type of SFTs, connected by eight mooring lines fixed at the bottom. Piston-type wavemaker is used to reproduce the sinusoidal regular wave loads. The wave heights (H) are from 100 mm to 130 mm, and the wave periods (T) are from 1.00 s to 1.95 s.

Table 1. Comparison of horizontal and vertical Morison's wave force between analytical and experimental results (single SFT, H = 100 mm, T = 1.15 s)

	$F_{H\_Morison}$ [N/m]			$F_{V\_Morison}$ [N/m]		
	Drag	Inertia	Total	Lift	Inertia	Total
Analytical value-based	4.77	121.57	126.34	0.33	11.37	11.70
Experimental value-based	5.29	142.81	148.11	0.35	12.14	12.49
Difference (%)	10.92	17.48	17.23	8.26	6.75	6.80

Table 1 shows the comparison result of horizontal and vertical Morison's wave force between analytically evaluated and experimentally measured values. The wave parameters in this result is H = 100 mm and T = 1.15 s. In both directions, the wave force is separated to drag force and inertia force by using the Equations (1) and (2), respectively. The horizontal wave force $F_{H\_Morison}$ shows that the inertia force is much larger than the drag force, therefore it can be concluded that the wave inertia force determines the magnitude of the load acting on SFT structures in many cases. The drag force accounts for about 3.6~3.8% of the total loads, which can be predicted by calculating the Keulegan-Carpenter value (Kc) of the incident wave (Brancaleoni, 1989). Difference rate between analytical and experimental results is 11% in the drag force, while it is 17.48% and 17.23% in the inertia and the total force, respectively.

In the vertical force, total value becomes about 1/10 of the horizontal force, and the portion of the inertia force in both cases is little bit larger than that in the horizontal force. The phenomenon may be related to the ratio between gap distance (e) from the bottom and the diameter (D), and the portion of lift force gets much larger when e/D approaches zero. The difference rate between two results is 8.3% in the lift force, 6.8% in the inertia force, and 6.8% in total force. Except the horizontal inertia force, about 10% difference rate is still low for the first trial, and characterization of single/dual SFTs with the accurate estimation of the wave loads will be achieved through the additional studies.

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