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Experimental study on motions of tunnel element during immersion standby stage in long wave regime

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ABSTRACT

The motions of a small-freeboard tunnel element are prone to strongly nonlinear wave-body interaction as a result of significant water-on-deck occurrence. To obtain a better prediction for the accurate and safe handling of a tunnel element in severe weather, 3D physical model tests were conducted under regular and irregular waves with long period to estimate the motions of three floating bodies (single tunnel element, pontoon and the tunnel-pontoons assembly) and predict possible resonance. The experimental results demonstrate that, due to the green water loadings, the non-zero mean heave of the tunnel and tunnel-pontoons assembly is significantly affected by roll resonant motion and has a similar dependence on the wave period as the roll in long wave regime. For wave period smaller than the roll period, the mean drift forces have substantial influence on the mean sway of all the three floating bodies, provoking greater offshore mooring tensions. Wave excitation at periods close to resonance of the heave, roll and pitch results in large local peaks in RAOs of the three floating bodies.

1. Introduction

Immersed tube tunnels are composed of pre-fabricated elements placed in trenches that have been dredged on the river or sea bottoms. Comparing to bridges, the key advantage of the immersed tunnel is that there is no limitation for vessel navigation (Ingerslev and FASCE, 2012).

As a key part of the Hong Kong-Zhuhai-Macao Bridge (HZMB) project, the 5990 m-long immersed tunnel is built by 33 rectangular concrete elements, which is of 180 m in length, 72,000 tons weight in air with 0.3 m freeboard. Considering the small freeboard of the element and busy navigation routes in Lingding Bay, specially designed catamaran-type pontoons have been commissioned to reduce the traffic disturbance and provided sufficient buoyancy to support the elements (Hu et al., 2015). When preferable weather comes, the pre-fabricated element will be connected to two pontoons and assembled into the tunnel-pontoons system. It will then be towed to immersion location taking approximately 3–6 h. Despite weather forecasting, wave conditions might worsen for the immersion standby stage after the element towing. Moreover, the element also undergoes changeable weather when moored somewhere between the shipyards and the final immersion location in temporary storage (Nagel, 2011). To address this issue, the motions of the tunnel element system should be investigated under more realistic sea state. Not only the short period wind waves, but also the long period swell transmitted from deep open sea should be considered to ensure a safe and effective operation.

Much research effort has gone into aspects related to the transportation and immersion of the tunnel element by wave actions. Wu et al. (2016) calculated the nonlinear wave forces of a free-floating tunnel element during its towing under various wave conditions. Chen Z et al. (2009a, b) applied potential theory to study the element motions with fixed twin barge under various immersion depths, neglecting the influence of the floating barge. Chakrabarti et al. (2008) and Cozijn and Heo, 2009 conducted both model tests and time-domain simulation to investigate the motions of the tunnel element at different immersion depths. The results indicated that the tunnel-pontoons system was more vulnerable to longer waves. Nagel (2011) performed a 2D frequency domain analysis on the dynamic responses of an immersed tunnel element and concluded that large motions and high suspension tensions occurred when the wave frequency was close to some natural frequency of the element. Song et al. (2014, 2015) and Huang et al. (2016) carried out experiments and numerical simulation on the motions of the tunnel element and the dynamic responses of the hoist ropes under irregular waves, considering various wave heights, wave periods, negative buoyancies and

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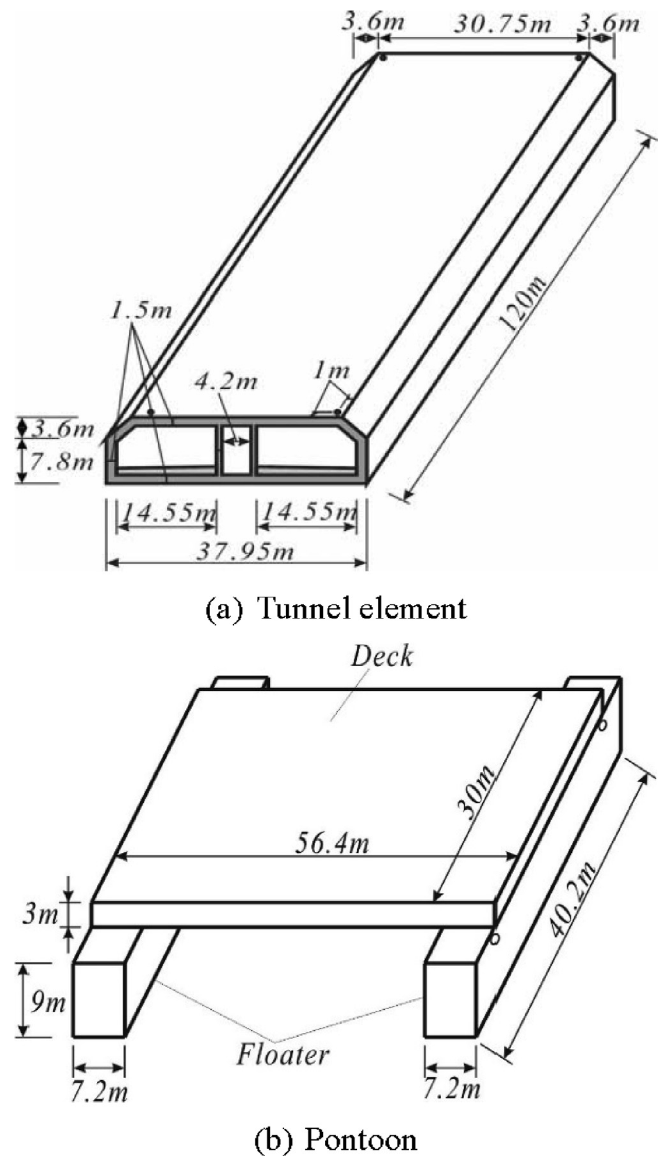

Fig. 1. Sketch of the tunnel element and the pontoon (in prototype).

immersion depths. However, there are limited investigations on the hydrodynamic response of the moored tunnel-pontoons assembly under immersion standby stage, which is actually critical for the security of the installation. Xiao et al. (2010) obtained the experimental measurements of the mooring line tensions for towing, standby and immersion of the tunnel element across Yong River under regular wave and current conditions. Chen et al. (2012) presented measurements and CFD simulation on the horizontal drift force on the mooring lines of the tunnel-pontoons assembly during immersion standby. Song et al. (2016) conducted experiments to analyze the mooring tensions of the tunnel-pontoons assembly under waves and currents during immersion standby and proposed an optimal mooring configuration. Unfortunately, the motions of the sole element and tunnel-pontoons assembly in long wave regime has not been addressed and will be investigated in the present study.

In practice, it is important to be aware that many nonlinear phenomena occur along with green-water loadings on the small-freeboard floating structures in rough waves, such as slamming, violent impact force, wave breaking, water-air mixing and associated turbulence (Zhao et al., 2014). Although some numerical model studies have been developed to investigate the wave-induced nonlinear motions of the 2D floating body (Sueyoshi et al., 2008; Hu and Kashiwagi, 2009; Zhao et al., 2014), in general, it is still very challenging to set up a numerical simulation to predict its 6-DOF motions accurately. Therefore, in the present study, a series of experiments are conducted to examine the motions of the tunnel-pontoons assembly and the sole element exposed to regular and irregular waves. The results illustrate that due to water-on-deck occurrence, the non-zero mean heave value of the bodies has a similar dependence on the wave period as the roll, and a local peak occurs near the roll natural period (T_w=T_{roll}) in long wave regime. Moreover, the sway is substantially influenced by mean drift forces for $T_w \leq T_{roll}$, leading to considerable mean sway and great offshore mooring tension. The resonant responses are observed in heave, roll and pitch of the floating bodies in long wave regime. In addition, the hydrodynamic characteristics of the three floating bodies subjected to irregular waves were discussed with measured motions by FFT. In the following, we shall first describe the experiments before discussing the results.

2. Experiments

2.1. Scale of the floaters and mooring lines

Froude Similitude is the most appropriate for physical model tests on floating coastal structures. Based on the Wave Model Test Regulation (2001), the model scale $\lambda \geq$ 1:80 is recommended for the large floating vessel of 50–100 thousand tons to eliminate the scale effect. In the current experiments, the model scale was determined as λ = 1:60 after considering the dimensions of basin and tunnel element as well as the capacity of the wave-maker. The tunnel element model was manufactured from acrylic and concrete, and the pontoons were made

Table 1
Main parameters of the tunnel element and pontoons characteristics.

Variable	Symbol	Unit	Tunnel element		Pontoon	
			prototype	simulated	prototype	simulated
Length	L	m	120	2.00	56.4	0.94
Width	B	m	37.95	0.63	40.2	0.67
Height	H	m	11.4	0.19	12	0.20
Draft	df	m	11.1	0.185	5	0.083
Mass	M	kg	50542000	234	2952000	13.66
Mass moment of inertia around x axis	Ixx	kg ·m^2	7.81×10^9	10.0	1.43×10^9	1.84
Mass moment of inertia around y axis	Iyy	kg ·m^2	6.06×10^{10}	77.9	3.57×10^8	0.46
Mass moment of inertia around z axis	Izz	kg ·m^2	6.80×10^{10}	87.4	1.70×10^9	2.18
Vertical coordinate of center of mass (from the bottom)	V_{CG}	m	4.58	0.076	7.47	0.124
Vertical coordinate of center of buoyancy (from the bottom)	V_{CB}	m	5.43	0.090	2.5	0.042