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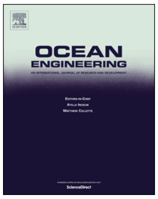

Short communication

Experimental study on the mooring tension of tunnel element during immersion standby

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ABSTRACT

Based on the project of Hong Kong–Zhuhai–Macau Link, an experimental study was carried out on the mooring tension of tunnel element during immersion standby. There are two key objectives in the present study. One is to investigate the effect of the sea states on the mooring tension of the tunnel–pontoons system under various mooring configurations during immersion standby. Pure wave and combined wave and current conditions were applied in the tests. The experimental results show that both wave and current play key roles on the mooring tensions of the tunnel–pontoons system, which was not highlighted in the past. After comparing the maximum mooring tensions of the tunnel–pontoons system under various mooring configurations, the second objective is to recommend the optimal mooring configuration for the tunnel–pontoons system, which help to minimize the sinking risk of the tunnel element during immersion standby.

1. Introduction

To meet the high transportation demand among Hong Kong, Macau and Zhuhai, the Hong Kong–Zhuhai–Macau Link is constructed to connect these three cities in South China. Upon completion, the traveling time between Hong Kong and Macau/Zhuhai would be sharply shortened to approximately 40 min from the current 4.5 h. This mega transport infrastructure consists of two bridge sections with a total length of 29.6 km and a 6-km immersed tube tunnel section crossing the offshore water of Ling Ding Yang. The submerged tunnel is to be placed on the trenched bottom under 40 m water depth. The size of the largest element of this immersed tunnel is of 180 m in length, 11.4 m in height and 72,000 t weight in air. All elements are to be constructed in nearby yards on shore, towed to the immersion location, and then moored on the sea surface above the trench on standby for immersion. The standby duration basically ranges in 3–6 h, during which the tunnel–pontoons system is exposed to harsh offshore wave and weather conditions. Under such open sea conditions, the mooring lines might experience excessive tension or even breakage and the element with small freeboard could lose its stability and might turn over, as has happened before (Ingerslev, 2012). Therefore, it is necessary to investigate the mooring tension of the tunnel–pontoons system under various mooring configurations and then determine the optimal configuration for the tunnel–pontoons system during immersion standby.

Regarding the topic of tunnel element installation, the majority of the existing studies focus on the immersion and transportation of the elements. Studies on the immersion standby are scarce, although the standby stage is critical for the security of the installation process. Zhan and Wang (2001) and Zhou et al. (2001) conducted experimental studies on the dynamic responses of the tunnel–pontoons system in river environments. Song et al. (2014) and Huang et al. (2015) investigated the motion responses of immersing tunnel element and the cable tensions of hoist wires under random wave conditions. Chen et al. (2009a, 2009b) performed numerical analysis on the hydrodynamic response of the immersing tunnel element in both frequency and time domains. Cozijn and Heo (2009) carried out both model tests and time-domain simulation to investigate the motion behavior of the tunnel–pontoons system and the cable tension of the mooring lines and hoist ropes at different stages of immersion. Their results showed that the tunnel–pontoons system was more vulnerable to longer period waves. Based on the engineering background of Busan–Geoje Link, Nagel (2011) conducted analytical study on the influence of swell and wind waves on the dynamic behavior of the immersing tunnel element. It was found that some natural frequencies of the tunnel–pontoon system were close to the frequency of in-situ swell waves in which large motions of the element and high mooring tensions occurred. Hakkaart (1996, 1997) investigated the transportation of tunnel elements in offshore

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conditions. In his studies, the tunnel elements were carried by a submersible barge rather than floated freely. Xiao et al. (2010) performed one of the few investigations that examined towing, standby and immersion of the tunnel element under regular wave and current conditions. The distribution of the mooring lines tension was obtained based on the experimental measurements. However, the optimization of the mooring configuration was not investigated. Chen et al. (2012) carried out measurements and CFD simulation on the horizontal drift force of a tunnel–pontoons system during immersion standby. Their results showed that the drift force of the tunnel–pontoons system is smaller than that of a single element without pontoons due to the smaller vortexes induced at both sides of the pontoons. The mooring tensions of the tunnel–pontoons system were however not addressed.

As evidenced by the above analysis, there is currently a lack of specific study on the mooring tensions of the tunnel–pontoons system during immersion standby, for example, combined wave and current effects under random wave conditions and optimization of the mooring configuration etc. The present study aims to fill two major research gaps. The influence of wave height and period as well as current on the mooring tension of the tunnel–pontoons system is firstly investigated under different mooring configurations during immersion standby. Various wave climates and current velocities were applied. These experimental results were not reported in the past, but are identified in the present study through extensive investigation. After comparing the mooring tensions of the tunnel–pontoons system under various mooring configuration, the second area being investigated is the determination of the optimal mooring configuration for the tunnel–pontoons system, which is key important for the safety of the tunnel element during immersion standby. The experimental activity on scaled model is first given in Section 2. The experimental results and discussion are then presented in Section 3. In the end, the main conclusions for design considerations are drawn in Section 4.

2. The experimental activity on scaled model

2.1. Experimental assumptions

For typical experimental study of large marine structures under wave action, the model test should satisfy the following criteria: (1) the geometric similarity criterion-the tunnel element, two pontoons and the trench should be constructed according to the same scaling; (2) the motion and dynamic similarity criterion-assuming the inertia is dominant and viscous effect can be ignored, the Froude number $F_r = V/\sqrt{gL}$ of the prototype and model should be identical, where V is the movement velocity, g is acceleration of gravity, and L is the characteristic length scale of the object; (3) cable similarity criterion-the mooring rope model should be produced and simulated according to geometry, inertial and elastic similarity.

Based on the above similarity criteria, models of a tunnel element, two pontoons and the mooring system were constructed with a scale of $\lambda = 65$ and the scales for various physical quantities were summarized in Table 1. The tunnel–pontoons system model was moored at the center of the basin. A sketch of the experimental setup is shown in Fig. 1.

2.2. Test setup

The tests were carried out at the State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, China. The basin was 40 m long, 28 m wide and 1.2 m deep. A piston type 3D wave-maker was installed in front of the wave basin to generate the desired waves. The wave generation system was equipped with the Active Wave Absorption Control System (AWACS) to reduce reflection from the wave pistons. Absorbing materials were placed on sides of the basin as well as on the beach to minimize the wave reflection and radiation. Adopted with the circulation flow system, the currents can be generated in 360° direction in the wave basin.

The tunnel–pontoons system consists of a tunnel element and two pontoons as shown in Figs. 2 and 3. The tunnel element model was made of acrylic and concrete and the two pontoons were made of light wood. The mechanical properties of the tunnel element, such as mass, center of gravity (COG), center of buoyancy (COB) and radii of inertia, were simulated based on the prototype values. The weight distributions and stability of pontoons were also accurately calibrated according to the prototype values. The main parameters of the tunnel element and pontoon model are summarized in Table 2.

During the stage of immersion standby, the tunnel element was hold by two pontoons as well as moored by six mooring lines. The top view of the mooring layout is illustrated in Fig. 3. The mooring system consists of four transverse lines (#1–4) restricting the sway motion and two longitudinal lines (#5–6) controlling the surge motion. Line #5 was anchored on top of an installed tunnel element in the longitudinal direction. The anchor point of Line #6, however, was chosen outside of the trench to avoid breaking the screed seabed. Lines #1–4 are 350 m in length and lines #5–6 are 100 m and 292 m respectively.

Table 1
Summary of scales for different physical quantities.

Physical quantity	Symbol[a]	Scale
Length (dimension, water depth, wave height etc.)	L_r/L_m	λ
Density	ρ_r/ρ_m	1
Mooring line elasticity coefficient	k_r/k_m	λ^2
Angle	φ_r/φ_m	1
Force (gravity, mooring tension etc.)	F_r/F_m	λ^3
Time (wave period etc.)	T_r/T_m	$\lambda^{1/2}$
Velocity	V_r/V_m	$\lambda^{1/2}$

[a] Subscripts of "r" and "m" refer to prototype and model respectively.

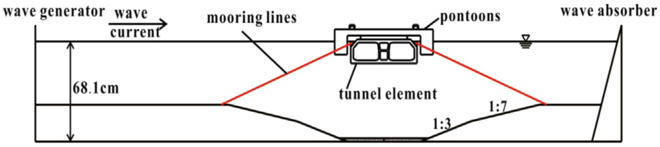

Fig. 1. Sketch of the experimental setup (cross section).

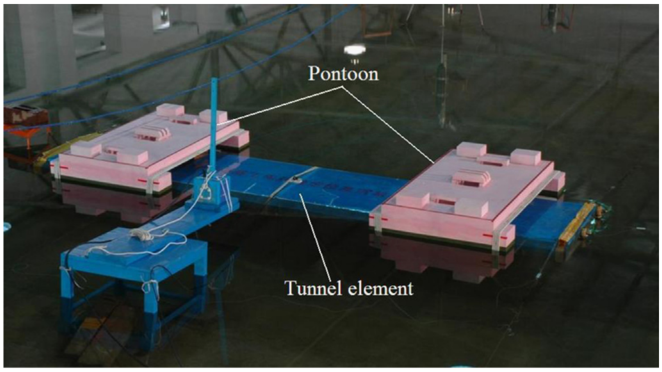

Fig. 2. Photograph of the model tunnel element and pontoon system.