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Hydrodynamic response of a submerged tunnel element suspended from a twin-barge under random waves

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ABSTRACT

It is possible that the excessive dynamic responses of tunnel elements could jeopardize the safety and accuracy of installation procedures used during subsea tunnel construction. To investigate the motion characteristics of the tunnel element, experimental measurements of a moored tunnel element suspended from a twin-barge were conducted in a wave flume at a geometric scale of 1:50. A corresponding numerical model was developed to simulate the dynamic response of the tunnel-barge system in realistic sea conditions, using hydrodynamic parameters from a radiation/diffraction potential model. Multiple linear wave conditions and three immersion depths were tested. The results indicate that the motion response of the tunnel element increases with decreasing immersion depth, and the natural periods of the tunnel, barge and combined tunnel-barge system play key roles in the influence of wave conditions on the motions of the tunnel. It was found that the low-frequency motion of the tunnel element is large in small wave periods. The mooring system under such conditions needs to be considered carefully during system design in order to safely control the motions of the tunnel-barge system in energetic ocean environments.

1. Introduction

It is widely acknowledged that the underwater transportation of tunnel elements has a significant role to play in reducing cross-sea traffic and transit times in busy shipping areas. There are several advantages to using this form of tunnel structure including; the ability to construct tunnel elements onshore, the reduced time required onsite, definite stress characteristics and lower buried depth compared with the shield method (Fu, 2004; Guan, 2004). For these reasons the immersed tunnel element approach has been successfully and widely used in large scale underwater tunnel projects (e.g., Li et al., 2003). Transportation and lowering of the tunnel elements are critical installation procedures requiring a detailed understanding of the behavior of each structural element (Kasper et al., 2008). In offshore locations subjected to changeable weather and extreme waves, the environmental conditions will affect the behavior of tunnel element and its mooring during installation, necessitating accurate control of vessel position.

In addition, during towing from the onshore dockyards to the installation site the constructed elements are typically suspended by barges, pontoons or elevating platforms (Chen et al., 2009). Once on station above the trench, onboard winches and suspension lines are used to control the sinking process. During installation the onset of severe environmental conditions, due to wind, wave and current, could result in interruption of the operation with the immersed tunnel element in a stationary position (Janssen et al., 2006). In this situation safe station keeping is the main concern, and the motion response of the barge and tunnel element under these extreme environmental conditions needs to be understood. Hereby the behavior of the mooring system (used to keep the barge on station), and suspension system (that holds the tunnel element suspended from the barge) needs to be fully characterized, as both will directly influence the motion response of the coupled system. It is therefore prudent that a detailed hydrodynamic analysis of the moored tunnel and barge system is carried out considering a number of scenarios which represent a range of energetic ocean conditions.

Many research studies of immersed tunnel elements have been carried out in the past, and the majority of existing studies focus on the seismic response, underwater interfacing, structure anti-seismic and foundation treatment (Anastasopoulos et al., 2007; Grantz et al., 2001; Do et al., 2015; Li et al., 2014). Considerably less study has been directed at installation procedures and the hydrodynamic characteristics of the immersed tunnel element and its deployment barge still need to be investigated further. Zhou et al. (2001), Xiao and Yang

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(2010) and Zhan et al. (2001) conducted experimental studies on the motion characteristics of immersed tunnel elements subjected to drag loading in rivers. Aono et al. (2003) investigated the stability of Japanese NaHa immersed tunnel elements in the foundation trench, focusing on the influence of different ballast water weights and wave factors and addressing sliding of the tunnel. Based on the Busan-Geoje Fixed Link in Korea, Partha et al. (2008) performed numerical analysis on the immersion process of the tunnel element using MOTSIM software and also simulated the dynamic response of the tunnel as it approached the seabed trench. Their results demonstrated that the negative buoyancy of the tunnel element (in the range of 1–2.5%) directly effects the tension of the four suspension cables. They concluded that in order to avoid slack suspension cables the negative buoyancy of tunnel element should reach 2.5%. Chen et al. (2012) and Peng et al. (2012) carried out numerical and experimental investigations on the dynamic response of tunnel-pontoon systems during an interruption in the lowering process, with the study based on the Hong Kong-Zhu Hai-Macao Bridge project. However, these investigations focused on hydrodynamic response of the tunnel element subjected to regular waves. Realistic seas comprise random waves and consequently studies of tunnel responses need consider the response of such systems in irregular waves.

The investigations presented here outline a series of physical model tests and numerical analysis which focused on the dynamic response of moored tunnel element suspended by a twin-barge subjected to irregular waves. The results presented in this paper build upon an earlier study by the authors (Yang et al., 2015). The experimental setup and typical test conditions are introduced in Section 2. The numerical validation procedure, decaying motion tests and simulation of the tunnel-barge system under irregular waves, are presented in Section3. A comparison of experimental measurements with the outcomes from the numerical studies for three sea states are presented in Section 4. Finally conclusions and discussion on future work are provided in Section 5.

2. Summaries

2.1. Experimental setup

The model tests were conducted in the ocean environmental flume of the State Key Laboratory of Coastal and Offshore Engineering at Dalian University of Technology in China. A summary of the experimental setup is provided in this section but for further information the reader is directed to (Yang et al., 2015). The wave flume was 50 m long, 3.0 m wide and 1.0 m deep (Fig. 1a). A piston-type wave maker was used to generate the desired incident waves at one end of the flume with an absorbing device for wave dissipation at the other end of the flume. In Fig. 1b a front view of the immersed tunnel element supported by the twin barge and suspension cables arranged is shown in the middle of the flume, in addition to the mooring lines which were used to anchor the tunnel element and barge system to the flume bottom.

The tunnel element model was manufactured from cement mortar and reinforced with water resistant polymer on the tunnel's outer surface. The thickness of the concrete tunnel walls was set to obtain the correct model weight. The wave-induced motion of the twin-barges was also studied in these tests, with the barge models fabricated from two hollow and airtight cuboid floating barges joined by a connecting steel frame. The model scale of the tunnel element was determined by the tank dimensions, particularly its length and consequently a Froude scale factor of 1:50 was selected. The main parameters of immersed tunnel element and twin-barge model are listed in Table 1.

The 6 degree-of-freedom movements of the immersed tunnel element are heavily influenced by the motions of the twin-barge with loads transferred to the tunnel element via the suspension cables. Fig. 1c shows the arrangement of suspension cables and mooring lines of the tunnel-barge system used in the model tests. In this set of experiments thin wire ropes were selected to represent the suspension cables. Anchor chains with a representative scaled mass per unit length were used to simulate the mooring lines for the twin-barge. The axial elasticity of both suspension cables and mooring lines were represented by using calibrated linear springs with appropriate stiffness properties. Parameters of the mooring lines and suspension cables are provided in Table 2. It should further be noted that due to different submersion stages, the suspension cable length of the tunnel element was altered with the different immersion depths. Three spring force-extension curves for the different immersion depths are shown in Fig. 2.

The motion response of the tunnel-barge system was monitored by the 'Untouched 6-D Measurement System (6D-UMS)' which based on the principle of binocular vision (Fig. 1d) (Yang et al., 2015). The sampling rate of the real-time measurement system was 30 Hz, the translation motion precision (surge, heave and sway) of the 6D-UMS can be controlled to be less than 0.3% full-scale (FS), and the precision of the rotation quantity (yaw, pitch and roll) can be controlled to be less than 1.2% FS.

2.2. Tests for comparison

According to the Froude similarity criterion used (1:50), the water depth in the flume was set to 0.8 m, corresponding to a water depth of 40 m at the hypothetical installation site. In order to avoid the combined effects of wave diffraction and reflection near the flume side in close proximity to the tunnel model, the minimum immersion depth and maximum significant wave height in the experiment were chosen as d=20 cm and H_s=5 cm, respectively. In this case the ratio of significant wave height and immersion depth is 0.25. In the tests the irregular waves were simulated (Fig. 3) and the wave conditions used for the comparison are listed in Table 3.

A single incident wave direction was used (θ=0°). The significant wave height at full scale varied from 1.5 to 2.5 m with a 0.5 m interval and three wave peak periods as T_P=0.85 s, 1.0 s and 1.1 s were considered (flume scale). In this experiment, the angle of mooring lines with the xyz-axis was fixed at β=45° which, from a previous study (Yang et al., 2014) was determined as the optimum arrangement of mooring lines for the system. A JONSWAP spectrum was chosen to simulate the targeted irregular waves with a peak enhancement factor of γ=3.3. The comparison curves of measured and target spectrum with three typical wave conditions agree well, as is shown in Fig. 4.

3. Modelling approach

A scaled numerical model of the tunnel element submerged by twin-barge was generated (see Fig. 5a and b). The coordinate system oxy is at the undisturbed water surface. The x-axis and y-axis are directed along the length (surge) and the width (sway) of the tunnel element, respectively, with the z coordinate orientated upwards as the positive direction. The incident waves propagate along the flume in the position y direction. The center of gravity (COG) of the experimental twin-barge model in free-floating conditions was at 0.025 m below the static water lever in the flume. The same draft of twin-barge was set in the numerical model. The coordinate of the mooring line attachment points (Fig. 5c) of the tunnel-barge system in static water are detailed in Table 4.

The hydrodynamic properties of simplified twin-barge and tunnel element model were calculated by the diffraction/radiation potential code WAMIT, and used by the time-domain mooring modelling tool Orcaflex™ to simulate the dynamic response of the coupled system. Matlab was used to calculate the mesh of both tunnel and twin-barge, utilizing the symmetry of these geometries about the x- and y-axis (Fig. 5d). For hydrodynamic parameter calculation the twin-barge mesh does not include the connecting steel frame which connected the two floating barges (Fig. 6), because it was observed during the