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Segmental joint model tests of immersed tunnel on a settlement platform: A case study of the Hongkong-Zhuhai-Macao Bridge

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A B S T R A C T

Although segmental elements have excellent deformation and anti-crack abilities, differential settlements of immersed tunnels caused by differential compression of soil (or foundation) and surcharge (or discharge) on the natural foundation section should be concerned in the service stage. Especially, when prestressed cables are cut off after immersing construction, shear keys on segmental joints are the only structural guarantee to resist deformation during the occurrence of differential settlements. Currently, uniform criteria are not available for the design of shear keys in segmental joints, and few physical model tests have been performed to examine the mechanical properties of segmental joints in immersed tunnels. This study investigates the mechanical properties of segmental joints in the immersed tunnel of the Hongkong-Zhuhai-Macao Bridge in China. A series of 1:4.69 large-scale segmental joint model tests were conducted on a settlement platform. Shear force distribution and transfer mechanisms on segmental joints were studied, and allowable differential settlements of segments were determined. In addition, failure features of shear keys and reinforcement measures were propounded. The results of this study are useful for structural safety assessment and further application of segmental type immersed tunnels.

1. Introduction

With the development of immersed tunnel, the length of elements tends to be increasingly long. To control cracks caused by thermal effects and shrinkage of concrete, segmental elements were initially introduced into the Rotterdam Metro tunnel in 1966 (Rasmussen and Grantz, 1997). Notable examples of segmental immersed tunnel include the Hemspoor and Piet Hein tunnels in the Netherlands, the Ems tunnel in Germany, the Øresund tunnel between Denmark and Sweden, the Busan-Geoje tunnel in Korea, and so on (Lunniss and Baber, 2013; Kasper et al., 2008). Moreover, the world's longest immersed tunnel, the Fehmarn Belt tunnel in Germany, ranging up to 17.6 km, also uses segmental elements (Chen et al., 2015). Segmental elements built by several discrete segments with the length of 20–25 m are connected by segmental joints. In contrast to construction joints on monolithic elements, segmental joints are allowed to rotate, open, and close when differential settlement occurs (Lunniss and Baber, 2013).

Although an element is much lighter than the soil and water displaced, settlements of many immersed tunnels are significant (Grantz, 2001a). For example, the largest differential settlement on both ends of elements in the Shanghai Outer Ring tunnel reached 245 mm after sand flow construction (Wei and Su, 2014), and that of Ningbo Yongjiang tunnel extended to 182 mm after 11 years of service (Zhang, 2007), with cracks and leakage simultaneously appearing on or near elemental joints. The Tingstad tunnel in Sweden, the Baytown and Fort McHenry tunnels in USA, and the Elbe tunnel in Germany also faced similar situations due to differential settlements (Grantz, 2001b; Schmidt and Grantz, 1979). Segmental joints are inclined to generate displacements during the occurrence of differential settlements, relieving the deformation stress of elemental joints. However, these added segmental joints also increase the potential risks of leakages. Shear keys are structures used to restrict vertical and horizontal displacements among adjacent segments (Xiao et al., 2015, 2017). When settlements of elements are stable and temporary prestressed cables are cut off, shear keys are an important and the only structural guarantee to waterproof safety of segmental joints (Anastasopoulos et al., 2007).

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Presently, no uniform criteria have been available for the design of shear keys of segmental joints. The safety of segmental joints is especially important and worth of extraordinary attention.

Numerous physical model tests have been conducted to reveal the structural characteristics of immersed tunnels during and after construction. Taylor et al. (2005), Yang et al. (2004), and Chou et al. (2011) examined the anti-floating ability of the BART tunnel and the foundation liquefaction of the George Massey tunnel through centrifugal model tests. Hans and Jin (2009), as well as Lykke and Kerk (2005) studied the dynamic responses of the Busan-Geoje fixed link and the Marmaray tunnel using element and barge model tests, respectively. Xiao et al. (2017) and Yuan et al. (2017) determined the mechanical capabilities of elemental joints under the action of axial forces and bending moments by a 1:10 model test. Li et al. (2014) analyzed the distribution laws of sand-flow construction in the Zhoutouzui immersed tunnel through a full-scale model test. Jiang et al., 2001 investigated the failure characteristics of steel shear keys in elemental joints by a full-scale model test. However, physical model tests exclusively for segmental joints are relatively rare and the structural mechanical properties of segmental joints are unclear.

In this paper, the authors put forward the modeling principles and similar materials of shear keys for a series of 1:4.69 model tests of segmental joints in an immersed tunnel. The immersed tunnel of the Hongkong-Zhuhai-Macao Bridge (HZMB) in China is taken as the background. The model test system consists of a settlement platform, a model fabrication and connection system, and a measurement system. The distribution laws and transfer mechanisms of shear forces in segmental joints are summed up. Furthermore, the failure characteristics of shear keys are analyzed and the reinforcement measures are proposed. Finally, the allowable differential settlements of segments depending on the mechanical performance of shear keys are determined. This paper provides a reference for segmental joints of immersed tunnels and the proposed test model can be used for further studies.

2. HZMB immersed tunnel

The immersed tunnel, a key engineering of the HZMB that connects three cities crossing the Lingding Sea in South China, has a designed service life of 120 years. The total length of this immersed tunnel is 5990 m, composed of 33 elements with the length of 180 m each, and connected by 33 elemental joints, 231 segmental joints, and one terminal joint. Most of elements rest upon approximately 60-m-thick soft layers, mainly comprising muck, mucky soil, silty clay and sand. The bedrock is mainly composed of medium weathering schist and granite in the Sinian system, under the soft layers. The geological and foundation conditions of the HZMB tunnel are shown in Fig. 1 (CCCC SFES&DI, 2009). It can be seen that there are great discrepancies and obvious discontinuities between different layers (Yan et al., 2016). To better control settlements and transit ground stiffness between adjacent tunnel sections (Lin et al., 2012), a foundation treatment strategy (Table 1) is adopted according to the geological conditions. Besides, in order to acquire soil parameters, undisturbed soils from 95 marine boreholes have been used for numerous static and dynamic laboratory tests (CCCC SFES&DI, 2009). The mechanical properties of soil layers under the HZMB immersed tunnel is provided in Table 2.

The largest buried depth of the tunnel is approximately 45 m, which makes it the world's third deepest immersed tunnel, after the Marmaray tunnel (58 m) and the Busan-Geoje tunnel (50 m) (Gokce et al., 2009; Ingerslev, 2005; Kasper et al., 2008). The great buried depth of the HZMB tunnel increases the difficulties of trench dredging (maximum depth 23 m) and gravel layer paving construction. Three grade slopes (1/3–1/2.5, 1/7–1/5, and 1/3) are arranged to guarantee the stability of the trench (Hu et al., 2015a). Moreover, locking backfills and a 1.0 m protection blanket are installed to protect elements from lateral movements and anchor dropping (Fig. 2). The anti-floating safety factor is 1.1 in the service stage.

Differential settlements of the HZMB tunnel on the natural ground section is worth of great attention during its service stage, because of the discontinuity of deep natural soil layers, uneven trench excavations, construction errors of gravel foundations, discharge loads of future fairway excavations, uneven back-silting, and so on (Hu et al., 2015a; Yan et al., 2016). The detailed design loads on the HZMB immersed tunnel are provided in Table 3.

To investigate the structural performance of segmental joints under the effect of differential settlements, three segments located at the natural subsoil foundation and immersed on the 1.5 m gravel layer were selected. The cross-section of segmental joints in the HZMB tunnel is shown in Fig. 3. In the segmental immersed tunnel of the HZMB, an element is constituted by eight segments with the length of 22.5 m each. The segmental joints of the HZMB tunnel include OMEGA seals, injectable rubber-metal gaskets, reinforcement concrete shear keys, and temporary prestressed cables.

3. Model test system

3.1. Modeling principles

Considering the safety and successful implementation, the model test was designed in accordance with the following principles:

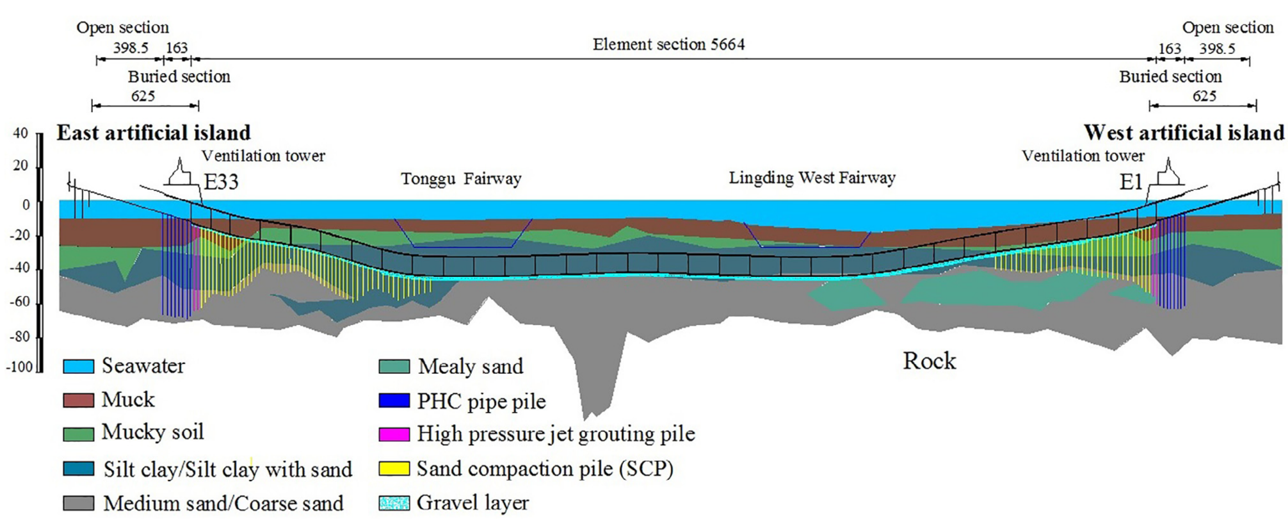

Fig. 1. Geological and foundation profile of the HZMB immersed tunnel (m).