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Advantages and potential challenges of applying semi-rigid elements in an immersed tunnel: A case study of the Hong Kong-Zhuhai-Macao Bridge

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ABSTRACT

The immersed tunnel of the Hong Kong-Zhuhai-Macao Bridge (HZMB) is the first of its kind constructed using semi-rigid elements and making a breakthrough in the structural theory. This paper explains the reason for applying the semi-rigid elements in an immersed tunnel and provides the design details using the example of the HZMB Tunnel. A theoretical analysis method based on the body-spring model is proposed for segmental joints of the semi-rigid elements. Potential challenges in the application of the semi-rigid elements are identified. Compared with the rigid (monolithic) elements and flexible (segmental) elements, the semi-rigid elements can improve the safety of segmental joints by increasing the flexural rigidity and joint friction. In addition, applying the semi-rigid elements can reduce the construction cost by retaining prestressed cables. Despite the advantages of the semi-rigid elements, some uncertainties arise due to the functional change of prestressed cables from a temporary structure to a permanent one. The location, number, and prestress level of the remaining prestressed cables need to be studied in accordance with the mechanical and waterproofing properties. The long-term prestress loss of prestressed cables should also be taken into consideration, especially the loss of asymmetric prestress in a marine environment. With the development of economy in costal regions, more immersed tunnels will face the similar engineering geological problems as the HZMB Tunnel. Discussing the technology of semi-rigid element has both engineering and theoretical significance to the development of immersed tunnels.

1. Introduction

The elements of reinforced concrete immersed tunnels can be classified into rigid (monolithic) and flexible (segmental) ones, depending on whether there are interconnected longitudinal reinforcement bars between adjacent casting segments (Chen, 2002). Generally, the segments are 20–25 m long and two adjacent segments are connected by segmental joints. As the length of the elements increases (especially > 100 m), there is an increasing risk of concrete cracks caused by drying shrinkage and thermal stress (Lunniss and Baber, 2013). To solve this problem, segmental elements were initially used in the Rotterdam Subway Tunnel in 1966 (Rasmussen and Grantz, 1997). Moreover, the segmental elements have higher deformation capacity than the monolithic ones in the case of differential settlements of foundations (Lunniss and Baber, 2013).

Prestressed cables are mainly used in immersed tunnels to ensure the integrality of segments during floating and placing. The prestressed cables are usually cut off when elements are placed on the foundations and settlements are stable. If the prestressed cables are retained and the stiffness of the elements is between the rigid and flexible types, the concept of semi-rigid elements is proposed (Chen et al., 2015). To date, prestress has been applied to the elements in more than 10 immersed tunnels, such as the Harbour Tunnel in Cuba, the Lafontaine Tunnel in Canada, the Mass Transit Tunnel in Hong Kong, and the Tama Tunnel in Japan. However, in these tunnels, prestress was used only to improve the anti-crack and anti-seismic abilities of the monolithic elements (Rasmussen and Grantz, 1997; Lunniss and Baber, 2013). In addition, the Piet Hein Tunnel, which was built in Amsterdam, the Netherlands in 1997, is the first immersed tunnel with semi-rigid elements. However, the semi-rigid elements were used to reduce the construction phase in the Piet Hein Tunnel, making no breakthrough in the structural theory (Chen et al., 2015).

The immersed tunnel of the Hong Kong-Zhuhai-Macao Bridge (HZMB) is the first of its kind constructed with semi-rigid elements and making a breakthrough in the structural theory. In recent years, details were reported on the application of the semi-rigid elements in

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immersed tunnels based on the HZMB Tunnel. Zhang et al. (2015) studied the water tightness and unbonded ability of joint fittings for semi-rigid elements by a series of model tests. Tang and Yang (2015) and Huang et al. (2016) introduced technical emphasis on the tensioning and duct grouting of prestressed cables for semi-rigid elements. Additionally, Zhou et al. (2015) analyzed the influence of prestressed cables on the mechanical properties of segmental joints using the ABAQUS 3D models.

This paper explicates the reason of applying semi-rigid elements in an immersed tunnel and their design details by taking the HZMB Tunnel as an example. We provide a theoretical analysis method for the segmental joints of semi-rigid elements and discuss the advantages and potential challenges of applying semi-rigid elements. The semi-rigid element using in the HZMB Tunnel has not only significance on engineering practice, but also has a great breakthrough in the structural theory of immersed tunnels.

2. Application background of semi-rigid elements

2.1. Potential differential settlements of the HZMB Tunnel

Equal settlements have no harm to tunnel structures, but superfluous differential settlements may cause structural damage or leakage on structures and joints (Feng et al., 2017a,b). This is despite the fact that the element is much lighter than the soil and water it displaces (Grantz, 2001a). Significant differential settlements have been found in many immersed tunnels worldwide. For instance, the largest differential settlement on both ends of the Shanghai Outer-Ring E-7 element reached 245 mm after sand jetting (Wei and Su, 2014), and that of the Yongjiang Tunnel in Ningbo, China was 181.5 mm after 11 years of service (Zhang, 2007; Shao and Li, 2005). In the above two cases, leakages and cracks occurred close to elemental joints. Similarly, leakages appeared at the bottom of joints when the Baytown Tunnel in USA showed a settlement of 450 mm and an angular distortion of 1.6×10^{-3} rad (Schmidt and Grantz, 1979). Moreover, differential settlements resulted in varying degrees of leakages and cracks on joints or elements of the Tingstad Tunnel in Sweden, the McHenry Tunnel in USA, and the Elbe Tunnel in Germany (Grantz, 2001b). As it is difficult to repair immersed tunnels, the occurrence of large cracks and leakages may lead to enormous disasters and immeasurable losses.

The HZMB Tunnel is a key engineering project of the Hong Kong-Zhuhai-Macao fixed link and it comprises 33 elements. There are 28 elements in the straight section and five elements in the curved section, with a curve radius of 5000 m. The length of this tunnel is 5990 m; it is one of the longest and most complicated immersed tunnels in the world, with a designed service life of 120 years. This tunnel is also the world's third deepest immersed tunnel, with the maximum depth of 45 m, after the Marmaray Tunnel in Turkey (58 m) and the Busan-Geoje Tunnel in Korea (50 m) (Gokce et al., 2009; Ingerslev, 2005; Kasper et al., 2008). For this reason, trench excavation (maximum depth of 23 m) and gravel paving are challenging, and the control of construction errors remains difficult. Most of the elements rest upon approximately 60-m-thick soft layers mainly comprising muck, mucky soil, silty clay, mealy sand, medium sand, and coarse sand, and there are great discrepancies between different layers (Yan et al., 2016). To better control settlements and transit ground stiffness between adjacent tunnel sections (Chen et al., 2015; Lin et al., 2012), a corresponding foundation strategy is determined and demonstrated in Table 1 (Yan, 2017; Li and Liang, 2013; Wang et al., 2017), According to the geological conditions. The geological and foundation conditions of the HZMB Tunnel are shown in Fig. 1 (CCCC SFES&DI, 2009). Furthermore, future trench excavation of the Tonggu and Lingding West Fairway may cause load discontinuity and the uplift of certain elements. The average back-silting speed of this area is approximately 1.35 m every year, which also leads to significant discontinuity surcharge accompanied by deposition caused by trench excavation. Therefore, potential differential settlements of the HZMB Tunnel are worthy of attention.

2.2. Reasons of retaining prestressed cables

The segmental joints of the HZMB Tunnel consist of Ω seals, injectable rubber-metal gaskets, reinforced concrete shear keys, and prestressed cables (Fig. 2). Compared to the construction joints within the monolithic elements, the segmental joints have no continuity reinforcement; this allows the joints to articulate, open, and close when settlement occurs. Although the rotation is permitted, the vertical and horizontal displacements between adjacent segments are prevented or restricted by shear keys (Xiao et al., 2015; Zhang et al., 2018). Shear keys are the only structure to ensure waterproof safety of the segmental joints, after the elements are placed on the foundation and the temporary prestressed cables are cut off (Anastasopoulos et al., 2007). However, the height of the vertical shear keys should be less than 1/3 of the height of the tunnel walls, so the dimension of the vertical shear keys on the segmental joints is restricted not only to the height of tunnel walls but also to the location of Ω rubber gaskets (Lunniss and Baber, 2013). Consequently, the load-bearing ability of the shear keys is limited, and if differential settlements exceed the allowable range, the shear keys will be damaged and even fail completely.

Given the specific geological conditions and load-bearing ability of the segmental joints, the temporary prestressed cables are retained in the HZMB Tunnel. Meanwhile, the prestressed cables have notable influences on the structural performance and further service ability of the segmental joints, which transform from a temporary structure to a permanent structure.

3. Design of semi-rigid elements

3.1. Design of posttensioning prestressed cables

The length of the elements in the HZMB Tunnel is 180 m. Each element is composed of eight segments with a length of 22.5 m. When the segments are pushed into the shallow dry dock, they are assembled into one element through posttensioning prestressed cables. The joints of the semi-rigid elements (elemental joints and segmental joints) have no difference from those of flexible elements, apart from the design of prestressed cables. Duct grouting of the prestressed cables is needed after tensioning construction, and prestressed cables of the flexible elements are cut off when settlements are stable.

There are 60 prestressed cables paralleled to the horizontal line of the segments. Each prestressed cable is composed of 25 steel stranded wires (φ_s 15.2) with high strength (standard strength of 1860 MPa) and low stress relaxation. Prestressed cables are tensioned symmetrically from both sides, when the concrete strength reaches 90% of C45. The tension control stress is 1265 MPa and the initial stress is taken as 25% of the control stress. Hydraulic jacks with the capacity of 650 t are chosen according to the tension force of 4322.5 kN (Huang et al., 2016). The prestressed cables are tensioned in four stages, and the prestress level is controlled by the prestressing force and the extending amount. When the prestressing force is attached to the design force, the discrepancy between the actual and theoretical extending amounts should be less than 6% (32. 22 mm).

3.2. Joint fittings of prestressed cables

In the HZMB Tunnel, prestress ducts made of plastic corrugated pipes are embedded in the segments during casting and connected by specially designed joint fittings (manufactured by VSL Hong Kong Ltd., China) at the segmental joints (CCCC HC, 2013). Polypropylene random pipes with a slightly smaller diameter are installed inside the plastic corrugated pipes to resist deformations caused by concrete pressure and hydration heat. The reason for applying this partially unbounded prestressing structure, other than a full-length bounded structure, is that