Tunnelling and Underground Space Technology 82 (2018) 156–169

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

The rationality of semi-rigid immersed tunnel element structure scheme and its first application in Hong Kong Zhuhai Macao bridge project

Erxiang Song[a], Peng Li[a,*], Ming Lin[b], Xiaodong Liu[b]

[a] Department of Civil Engineering, Tsinghua University, Beijing 100084, China
[b] CCCC Hong Kong Zhuhai Macao Bridge Island and Tunnel Project Department, Zhuhai, Guangdong 519080, China

ARTICLE INFO

Keywords:
Immersed tunnel
Semi-rigid element
Hong Kong Zhuhai Macao Bridge
Soil-structure interaction
Finite element modeling

ABSTRACT

In the usual way of immersed tunnel installation, segments are clamped together temporarily by longitudinal prestress tendons which are later cut off at each of the joints after the tunnel element has been placed. This flexible scheme has the advantages of deforming more freely with the ground and reducing the internal force produced in tunnel segments. However, in Hong Kong Zhuhai Macao Bridge (HZMB) project, the depth of tunnel backfill is up to 20 m and is varied along the longitudinal direction due to navigation requirement. Meanwhile, the tunnel founding depth as well as strata is also changing. The conventional flexible scheme may produce larger deformation and reduce the shear capacity safety reserve at the segment joints. Therefore, a novel immersed tunnel structure type named as the semi-rigid scheme is proposed and applied in this project, in which the prestress tendons are kept without being cut off after installation of the tunnel element. In this paper the rationality of the semi-rigid scheme and its application in HZMB project are thoroughly discussed. Taking the tunnel elements E13 and E14 as example, a three dimensional soil- structure interaction finite element modeling is carried out. Influence factors including the prestress control values, the foundation stiffness and the variation of temperature are investigated in order to analyze the mechanical behavior of this novel scheme. Numerical comparisons have shown that the semi-rigid element has the superiorities in increasing both the water tightness and shear resistance safety factor at the segment joints. A newly defined parameter called as the degree of prestressing is finally proposed, which will pave the way for further research on the selection and optimal design of immersed tunnel structure scheme.

1. Introduction

The immersed tunnel has emerged more and more as the most efficient way of crossing under a waterway. Due to the longitudinal variation in subsoil conditions, a transition foundation solution is always needed (Grantz, 2001). Meanwhile, element structural type becomes the key issue which has a great influence on the security of immersed tunnel. Proper selection of element structural type should take the founding strata and ground treatment along the tunnel alignment into account, and several load conditions such as permanent loadings, temperature loads, wave and current loading as well as seismic loading during earthquake should also be fully considered in order to meet the requirements of waterproofing and keep the internal forces at the joints below the threshold.

An immersed tunnel can be steel shell tunnel or concrete tunnel depending on the material used to cast the prefabricated sections. The concrete tunnel elements are constructed as either rigid (monolithic) or flexible (segmental) based on the structural scheme of construction (Lunniss and Baber, 2013). A rigid tunnel element is casted monolithically with several pours over the length of the element and requires external water proofing to ensure water tightness. The casting process of rigid elements is simple and mature. However, the length of the element is a concern as longer elements would develop larger shrinkage stresses when concrete hardens.

The construction of immersed tunnels started as steel shell tunnels using rigid tunnel elements. Michigan Central Railroad Tunnel (Akimoto et al., 2002) is the first full scale immersed tunnel constructed in 1910 in the United States (U.S.), which was built using ten steel shell elements. This development was followed by the construction of 20 more steel shell immersed tunnels in the U.S (Gursoy, 1995). High cost of steel construction promoted the use of reinforced concrete immersed tunnels in Europe where Netherlands leads with most number of immersed tunnels constructed. The Maas Tunnel (Glerum, 1995) built in 1966 in Amsterdam was a 540 m long immersed tunnel, which includes

---

[*] Corresponding author.
E-mail address: lipengcivil@mail.tsinghua.edu.cn (P. Li).

https://doi.org/10.1016/j.tust.2018.08.040
Received 25 December 2017; Received in revised form 11 May 2018; Accepted 17 August 2018

six reinforced concrete tunnel elements of 90 m length. Each of the elements is provided with a fiberglass membrane at its external surface to guard water intrusion. Western Harbor Crossing Tunnel (Zhang and Kumaraswamy, 2001) in Hong Kong is another example which was constructed by monolithic tunnel elements. Its immersed tube section is composed of twelve reinforced tunnel elements, each of which is 113 m long. Tunnels constructed in seismically sensitive areas are always subjected to worming effect. Therefore, the overall stiffness of the tunnel element should be increased in order to control the element deformation. Rigid tunnel element is always adopted in earthquake prone region. For example, most of the immersed tunnel structure scheme in Japan was steel-concrete composites known as sandwich structures (Akimoto et al., 2002), which are composed of two steel plates with concrete in between them. Shear connectors are welded on the inside of the plates which replace the structural steel reinforcement. In addition, shear reinforcing steel plates are welded to the main steel plates which transfer shear stress on the structure. GINA rubber gaskets are used to provide flexible joints between the rigid sandwich elements. Many tunnels including Osaka South Port Tunnel, Kobe Port Minatojima Tunnel, Niigata Port Road Tunnel and Okinawa Naha Tunnel are constructed using this technique. The tunnel elements in Japan are usually 80–110 m long, 28–35 m wide and 9 m high (Kiyomiya, 1995).

As another structure scheme, flexible tunnel element is constructed by assembling several small reinforced concrete segments into one element. Multiple pours can be avoided this way and external water proofing of the element is no longer required. The segments are clamped together to resist the transportation and floatation loads by longitudinal prestress tendons, which are cut once the tunnel element has been placed in its final position. In this way a flexible tunnel element is formed which is more adaptable to differential settlements of the foundation as compared to its monolithic counterpart.

Flexible tunnel elements have many successful experiences in immersed tunnel projects in Europe and Asia. Singapore's Tuas Cable Tunnel (Hulme and Burchell, 1999), which was built in 1998, was constructed by using flexible tunnel elements. The total length of this immersed tunnel is 2.1 km, and it is composed of eighteen straight tunnel elements (each of 100 m length) and four curved tunnel elements. The Oresund Bridge (Marshall, 1999) connecting Copenhagen and Malmo in Sweden is a rail-cum bridge crossing link with a length of 16 km. The western side of this link consists of a 3.51 km long immersed tunnel, which was constructed by twenty reinforced concrete flexible elements. Each of the elements is composed of eight segments which are connected through temporary prestressing cables. The 3.24 km long immersed section of Geoje-Busan Tunnel (Kasper et al., 2009) in Busan, Korea is comprised of 18 elements with a length of 180 m each. The maximum water depth at tunnel bottom is 50 m. Each tunnel element is composed of eight prefabricated segments which are 22.5 m long, connected by temporary prestress tendons which are cut after the final placement of the elements. Shear keys are provided between the segment joints to transmit shear forces. In addition to the W9U water seal, an OMEGA water proofing membrane is also installed which provides certain tensile strength against longitudinal extension or compression of the segment joint. Some other immersed tunnel projects constructed worldwide are listed in Table 1.

From Table 1, it appears that at a chronological order, the use of flexible element becomes more and more popular. The reason lies in the omission of external water proofing treatment which makes the element construction more economical and reduces the construction time. The rigid elements require water proofing treatments to ensure water tightness and durability of the concrete. Use of steel membranes and water proofing sprays was common for the purpose which is expensive and nondurable. For the flexible elements the use of continuous waterstop at segmental joints ensures water tightness of the element. Moreover, the provision of some axial movement at the segment joints will prevent the development of tensile stresses which may cause cracking through the concrete section in the longer term.

The immersed tunnel of HZMB project has a span of 5990 m, and is composed of 33 reinforced concrete tunnel elements each with a dimension of 180 m × 37.95 m × 11.4 m. It is the world's longest and deepest underwater highway immersed tunnel till now (Hu et al., 2015; Yu et al., 2016). The longitudinal section of the tunnel is shown in Fig. 1. HZMB immersed tunnel has a transition section at the head of the artificial islands where different foundation solutions are adopted and the thickness of the placed backfill is uneven. This makes the stress conditions in the tunnel structures more complex. The maximum depth required for the navigational purposes is 20 m. Meanwhile, the deposition of sediments should also be taken into consideration during the operation life of the structure, which increases the overlying load on the tunnel structure (5–6 times the immersed tube load). Particularly, due to navigation requirement a maximum depth of 20 m of sediment backfill will be dredged. Load changes in the tunnel longitudinal direction will also result in larger internal force in the tunnel. All the above situations will threat the waterproofing provided at the joints and make the selection of immersed tunnel structure a great challenge.

In view of this, China Communications Construction Consortium (CCCC) Hong Kong Zhuhai Macao Bridge Island and Tunnel Project Department proposed and adopted a unique concept in HZMB immersed tunnel project in order to further improve the safety margin, which is called as semi-rigid element scheme (CCCC HP&DI, 2012). This paper systematically introduces the characters of existing conventional immersed tunnel structural scheme and the successful implementation of the semi-rigid element scheme in HZMB project. An investigation in numerical analysis has shown the mechanism and superiority of the semi-rigid scheme by comparing with the flexible and rigid element schemes.

2. Concept of semi-rigid immersed tunnel

2.1. Characters of conventional immersed tunnel structure schemes

The monolithic tunnel element is a continuous structure that acts as a beam supported on the foundation, and is articulated at element joints. Measures are taken to control cracking during construction, and each element is protected against water intrusion by using external membranes. However, tunnel element with larger stiffness will attract larger internal forces, large tensile stresses may develop in the tunnel element. These tensile stresses can be avoided by reducing the tunnel element length, through which the requirements of reinforcement and prestress can be controlled within reasonable values (Rasmussen, 1997).

Segmental elements differ to their monolithic counterparts in that the element is composed of several reinforced concrete segments which are clamped together by temporary prestress tendons. These tendons are cut after the tunnel elements have been placed in their final position. Therefore, articulation occurs not only at the element joints but also at the segment joints. The segmental element can be called as flexible element, in which the bending moments at the segmental joints can be released by joint opening so as to control the longitudinal bending moments as well as tensile stress at a lower level. Likewise, tunnel element with smaller stiffness will attract larger deformation. Under large backfill and in temperature fall condition the segmental joints might both produce larger deformation which threatens water tightness, and develop large shear forces which are beyond the total capacity of the OMEGA and shear key gaskets (Saveur and Grantz, 1997; Lunniss and Baber, 2013).

HZMB immersed tunnel is a worldwide unique project in view of its large and varied backfill depth which differs from the common shallow immersed tunnels. A series of problems would be encountered if conventional immersed tunnel design is employed. The HZMB tunnel is subjected to a large backfill load, temperature load and varied foundation stiffness. A rigid tunnel element in such conditions would demand a strict crack control which can only be ensured by large number