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Mechanical behavior of quasi-rectangular segmental tunnel linings: Further insights from full-scale ring tests

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ABSTRACT

Compared with traditional circular shield tunnels and rectangular shield tunnels, quasi-rectangular shield tunnels have advantages in space efficiency, bearing capacity and applicability in urban areas. This new type of cross-section was first utilized in Ningbo Metro Line 3 in China, a full-scale ring test of corresponding lining structure was conducted to investigate the bearing mechanism of the structure preliminarily. In order to investigate the influence of segmental reinforcement, longitudinal joint position and shear bearing capacity of a T block on the mechanical behavior of a structure, two more full-scale ring tests are conducted. The failure process, structural convergence deformation, joint deformation and bolt strain of the lining structure are obtained. The bearing mechanism and robustness of the structure under unexpected circumstances are analyzed as well. The experimental results show that: (1) Optimization of segmental reinforcement and bolt position has little effect on the mechanical performance at elastic stage. (2) With the same joint configuration, an increase in the segmental reinforcement has a minor effect on the performance of the longitudinal joint. The robustness of the structure is not improved significantly either. (3) When the shear bearing capacity of the T block is guaranteed, the optimization of longitudinal joint bolt position can improve the mechanical performance of the structure significantly. When the overall rigidity of the structure is raised, the ultimate bearing capacity increases by 30% and the failure mode is ductile. As a conclusion, in order to increase the robustness and overall safety of a quasi-rectangular segmental tunnel lining, shear bearing capacity of T blocks should be strengthened to ensure that the segment would reach its bending moment bearing capacity first. The bolt hole of the positive moment joint should be moved inward while that of the negative moment joint should be moved outward as well.

1. Introduction

Urban railways have become the first choice for relieving traffic congestion, especially in old urban areas. However, population and buildings are highly concentrated in these areas where buildings leave small space for roads and underground pipelines are intensive. Therefore, how to cross these congested areas has become a major problem in current urban railway construction. For conventional two circular shield tunnels, the total width of the tunnels is about 18–20 m. Under narrow roads, shield machine is unable to dig through and surrounding buildings will be disturbed by construction. Underground space is limited with the construction process and secondary excavation will cause secondary disturbance to the surrounding soil and buildings. Thus, a change in the form of cross-section has become necessary. The use of a two-way tunnel can reduce the distance between train lines, and increase the distance between shield tunnels and nearby buildings, while avoiding secondary excavation impact on existing buildings. There are three types of two-way tunnels: one large circular shield tunnel, DOT (Double-O-Tube) shield tunnel and rectangular/ quasi-rectangular shield tunnel. It has to be emphasized that a quasi-rectangular tunnel has the following advantages: (1) high utilization of underground space, (2) shallow buried depth and great ability to be excavated through narrow blocks, (3) easier control in relation to soil stick and earth settlement compared to DOT tunnel (Chow, 2006, Ye et al., 2015). As a result, it is of great significance and economic value to explore and study the tunneling technology of quasi-rectangular shield tunnels.

Non-circular shield tunneling was applied and developed rapidly in Japan in the 1990s and it still leads the world. So far, Japan has built about 20 rectangular shield tunnels. For example, in a flood-control

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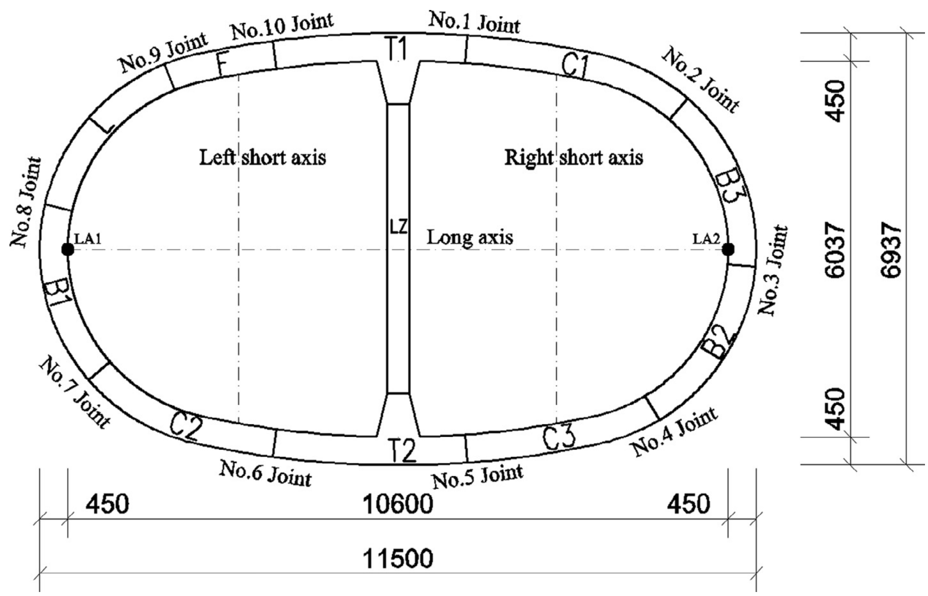

Fig. 1. Schematic diagram of test tunnel ring.

sewerage tunnel in Narashino City in the suburbs of Tokyo, an 11.0 m × 7.08 m rectangular tunnel was constructed. In the project, a single DPLEX shield was used to excavate a couple of tunnels with a 4.2 m wide and 3.8 m high rounded rectangular cross-section (Kashima et al., 1996). From Rokujizo Station to Ishida Station in the East West Line of Kyoto subway, a 9.9 m × 6.5 m rectangular tunnel was built (Nakamura et al., 2003). In Metropolitan Tokyu Toyoko Line Shibuya-Daikanyan extension line project, a rectangular section with a dimension of 10.3 m × 7.1 m was applied. However, insufficient published literature on mechanical properties and design models of corresponding tunnel structures can be found. In 2016, a quasi-rectangular shield tunnel was the first to be successfully applied in Ningbo Rail Transit Line 3 in China. As the mechanical performance and design method of quasi-rectangular shield tunnel lining structures is not clear, a full-scale ring test is conducted (Liu et al., 2018). The design model and ultimate bearing capacity of the structure under overburden condition are obtained, which lays the foundation for further development of this new type of tunnel. It is also found that longitudinal joints and haunches of T blocks are the weak parts of the lining structure (As shown in Fig. 1, there are four haunches on the structure where critical cross-section 1, 5, 6 and 10 are located). In order to ensure a successful application of the new structure, failure mechanism and overall safety of the structure are key issues to be resolved. In a shield tunnel lining, a ring is composed of a number of segments and neighboring segments are connected by longitudinal joints. Therefore, the bearing mechanism of a structure is determined by both the segments and longitudinal joints, which are the main focus of this research.

Conducting a full-scale ring test is an efficient way to determine the bearing mechanism of a tunnel lining. Experimental studies on tunnel lining structures of Elbe Tunnel in Germany were conducted in laboratories (Schreyer and Winselmann, 2000). For Shanghai Yangzi River Tunnel, the largest segmental tunnel lining at the time, a full-scale ring experiment was performed. The experimental results verified the safety of the structure under several operation conditions (Lu et al., 2011). With growing attention to serviceability of segmental tunnel linings, several full-scale ring tests were conducted by Xian Liu to determine the ultimate bearing capacity of continuously jointed segmental tunnel linings under different surrounding environment (Liu et al., 2016). According to the above-mentioned studies, existing research mainly focuses on the design model of shield tunnels, optimization design of segments, mechanical performance of the whole structure, failure mechanism and ultimate bearing capacity, as well as the durability of shield tunnel structures. Little has been done on the effect of segmental reinforcement to the structural bearing mechanism of tunnel structures.

As for mechanical performance of longitudinal joints, there have been many studies on the composition form and structural optimization of longitudinal joints. In order to investigate mechanical behavior of longitudinal joints with and without transmission cushion, different methods were adopted to analyze the relation between stress, strain, internal force and bending angle of joints, using two different joints (Zhong et al., 2006). Based on experimental monitoring, a progressive model was proposed to investigate the development of longitudinal joint opening with bending moment under different axial stress levels, and longitudinal joint opening in Ultimate Limit State (Li et al., 2015). Full-scale joint tests were also conducted to investigate the bearing capacity of the longitudinal joint in a quasi-rectangular shield tunnel. Failure mechanism, mechanical behavior and ultimate bearing capacity of longitudinal joints were analyzed as well (Lin et al., 2016). When it comes to the fact that longitudinal joints are the weak parts of a shield tunnel, more attention is paid to its bearing mechanism. At present, research of longitudinal joints mainly focuses on joint stiffness, joint strength, failure process, influence on the distribution of internal force and mechanical properties of the whole structure. However, there is no research on the influence of bolt position on the mechanical performance. The quasi-rectangular shield tunnel is a new type of structure in shield tunneling. It combines the advantages of circular and rectangular tunnel, and will surely be widely used in the future. Based on existing research, positive and negative bending moment of different joints under operation condition is known. By moving the position of the bolts, the connecting bolt of a joint can be fully utilized and the mechanical performance of the joint can be optimized. Therefore, it is necessary to investigate the influence of the bolt position on the bearing mechanism of a quasi-rectangular segmental tunnel lining.

Based on the first full-scale ring test of Ningbo quasi-rectangular segmental tunnel lining, the ultimate bearing capacity of the tunnel was reached. The bearing mechanism and weakness of the lining were revealed. In this research, two more full-scale ring tests are carried out by improving the reinforcement of the segment and optimizing the position of the longitudinal joint bolt. Based on the fact that shear failure phenomenon appeared at the haunch of T2 block in the first full-scale ring test, shear stirrup at two T blocks is strengthened in the third test to increase the shear bearing capacity.

In this paper, the failure mechanism of the quasi-rectangular tunnel