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Investigation of the structural effect induced by stagger joints in segmental tunnel linings: First results from full-scale ring tests

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ABSTRACT

It has been found that in the operation of shield tunnels in urban rail traffic system, different assembling segmental tunnel structures demonstrate distinct service qualities. There is still controversy among engineers and scientists regarding the influence of circumferential joints on the overall structural mechanical behavior. This study designed and performed full-scale experiments relating to the structural bearing capacity of stagger joint assembled shield tunnels based on an unloading situation, which combines engineering practices relevant to the current urban metro with circumferential disturbances. The design of tested linings and loading schemes are described. The most important results include the evolution of deformations, structural internal force, and behavior of both the longitudinal and circumferential joints. The failure mechanism of the tested linings is analyzed. The performance of different jointed segmental tunnel linings is further compared. Via the experimental investigation, the structural effect induced by stagger joints in segmental tunnel linings is quantitatively highlighted. And the progressive failure and ultimate capacity of staggered segmental linings are captured under the designed loading situation. It is concluded that circumferential joints of segmental tunnel linings should be designed in order to obtain the deemed structural-unity. What's more, the difference in mechanical behavior is clarified through the performance comparison of different jointed segmental tunnel linings, which offers direct evidences for the serviceability assessment of operated metro tunnels.

1. Introduction

The shield tunneling method has been favored by more and more cities due to its advantages like being automated construction, and having no traffic interference or weather restrictions. This method has become dominant in urban metro systems. This is especially true for soft soil regions like Shanghai, Tokyo and many other cities.

In shield tunneling, lining segment assembly consists of two methods: continuous joints (or cross joints) and stagger joints (or T joints). For the former, the lining structure complies with the 'flexible lining' (Blom, 2002; Arnau and Molins, 2012; Peck, 2015) design concept. It could better mobilize the surrounding soil's bearing capacity, making it more economical. For the latter, the lining structure optimizes stiffness distribution of the circumferential joints. However, there is also possible "bridge gap" effect which can cause crack due to thrusting force during shield drive stage. Since stagger joints reduce the deformation of not only the joints but also the whole structure, the structural waterproofing ability is enhanced consequently. Arnau and Molins (2015) once addressed the so-called interaction mechanism of staggered segmental tunnel linings by 3D numerical model, and obtained that the structural contribution between adjacent rings produces a stiffer response of the lining and an increase of its resistance under localized loads. In the modified routine method, a carry-over factor is used to describe the effects of adjacent rings in stagger-jointed segmental linings, and the factor is normally set to be 1.3 for soft soil area (JSCE, 1996; Koyama, 2003). However, provided tongues and grooves in the circumferential joints, segments with different joints' details possess varying shear transfer capacities. To date, there is still disagreement among the professionals regarding the influence of circumferential joint structures on structural mechanical behavior, or the determination of the value of the carry-over factor.

On the other hand, with more and more shield tunnels being constructed, it has been found that different assembling structures demonstrate distinct service qualities. For example, in the presence of surrounding environmental disturbances, a continuous joint tunnel normally shows large structural deformations and circumferential water seepage, whereas a stagger jointed tunnel has less deformation, but usually has longitudinal segment cracks. The over 500 km metro in

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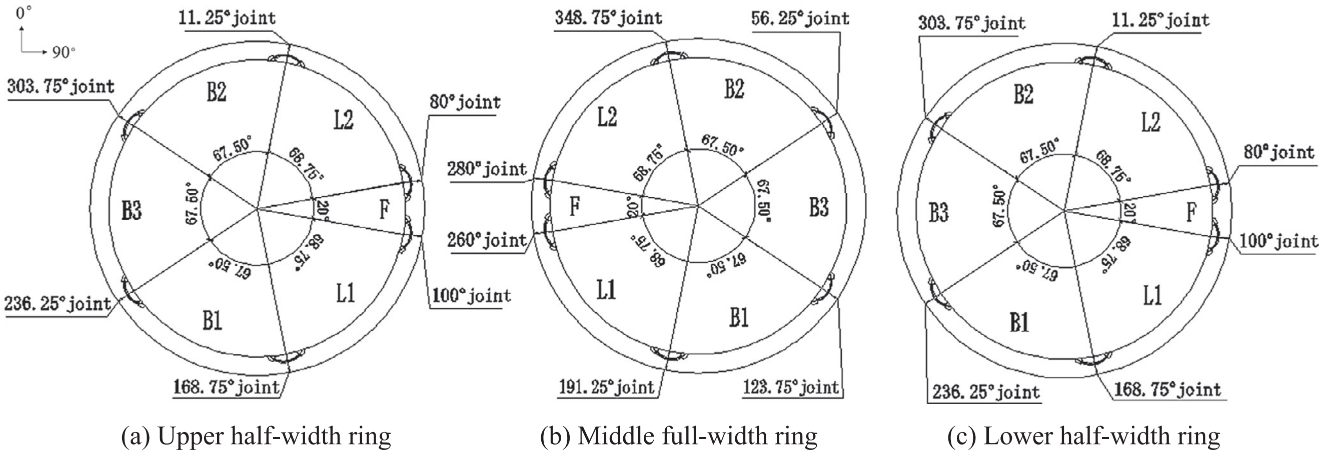

Fig. 1. Segment layout of the tested rings.

Shanghai, China is currently dominated by continuous joint shield tunnels, while in adjacent Hangzhou, Ningbo and Nanjing the primary structure of metro tunnels have adopted stagger joints. Why do shield tunnels with different assembling methods or different joints' detailing have different service capacities? This creates engineering challenges, particularly with regard to establishing corresponding performance assessment indexes for different operated tunnel structures.

A direct way to investigate the mechanical behavior of tunnels is to conduct full-scale experiments. Such tests allow quantification of the safety of segmental structures during construction and design stages. Blom et al., 1999 conducted full-scale experiments on the Green Heart Tunnel in the Netherlands. The study emphasized the influence of construction on the mechanical behavior of segmental tunnel linings. Schreyer and Winselman (2000) performed full-scale experiments on the Elbe River Tunnel in Germany to verify the bearing capacity and stability of tunnel structures. The tests offered basic information on the design and construction of the tunnel. Nishikawa (2003) carried out full-scale experiments on the Kyoto subway shield tunnel in Japan, where the structural behavior of rectangle segmental tunnel linings was investigated. The safety of the linings and the reliability of the design method were also evaluated. Lu et al. (2011) performed full-scale experiments on the Shanghai Yangzi River Tunnel in China, which was the largest segmental tunnel lining at the time of its construction. The experimental results have verified that the safety margin of the structure, at different construction and serviceability stages, was sufficient. To consider the influence of the longitudinal force and the action of surrounding soil, Arnau and Molins (2011) conducted a real-scale test on an experimental section placed on the new Line 9 of Barcelona's subway tunnels based on an in situ loading test. This has made it possible to assess the structural performance of these steel-fiber reinforced segmental tunnel linings. The above experimental investigations put more emphasis on the mechanical behavior of tunnel linings under standard conditions of construction and standard service conditions. The objectives of most works were to prove the suitability of the design of investigated tunnels.

To study the serviceability of operating segmental tunnels under the influence of nearby urban construction, Liu et al. (2016) conducted full-scale tests to determine the ultimate bearing capacity of continuously-jointed segmental tunnel linings. It is found that damage of the tested linings is caused by the failure of joints. And the study has shown that segmental lining structures are more vulnerable to lateral unloading than to overload conditions. To understanding the behavior of existing tunnels subjected to in-service deformations, Afshan (2017) and Yu et al. (2017) conducted half-scale ring tests to the ultimate capacity of segmental grey cast iron tunnel lining rings subjected to large deformations, which provided insight into the behavior of a grey cast iron segmental ring during distortions commonly observed in reality. However, no study has investigated the inter-ring action mechanism for stagger joint assembled tunnels, or the ultimate bearing capacity under circumferential disturbances, and no clear answer has been revealed regarding the perspective of structural bearing mechanisms.

Combining engineering practices relevant to the current urban metro with circumferential disturbances, this study designed and performed full-scale experiments relating to the structural bearing capacity of stagger joint assembled shield tunnels, based on an unloading situation as a result of foundation pit excavation. The stability theory of structural components and the method of incremental analysis were used to analyze the test results (Timoshenko, 1961; Chakrabarty and Drugan, 1988). The objective was to understand the structural behavior and ultimate bearing capacity of shield tunnels under unloading conditions, thereby clarifying the development process of structure performance. The following is the specific experiment scheme and loading scheme, as well as the experimental results. Finally, the bearing capacity of different structures are analyzed and discussed by comparing this work to the results of continuous joint assembling tunnels.

2. Experimental program

2.1. Experimental specimen

As shown in Fig. 1, the tested rings had an outer diameter of 6.2 m and an inner diameter of 5.5 m. The segment thickness was 0.35 m, and the ring width was 1200 mm. The whole ring was comprised of a key segment (F) with a 20° central angle, two adjacent segments (L1 and L2) with a 68.75° central angle and three standard segments (B1, B2 and B3) with a 67.5° central angle. The segment materials were C50 concrete and HRB400 steel bars, where HRB400 stands for hot rolled ribbed steel bars with its yield strength of 400 MPa.

Rubber water-stops were inserted between each ring and segment, which were then connected using grade 5.8 M30 bolts. A total of 16 bolts were placed longitudinally at 22.5° intervals. The distance between the bolt center and the segment inner wall was 140 mm. A tongue-and-groove structure was used for the segment circumferential joints, while a plain joint was used for longitudinal joints (Fig. 2).

A Full-width ring 1.2 m in width and upper/lower half-width rings 0.6 m in width were employed for the tested stagger-jointed lining structures. In term of the assembling way, the standard assembling mode of a straight line in practical shield tunnels was adopted during the test. That is, the key segment of upper/lower half-width ring was located at 90°, while the key segment of middle full-width ring was located at 270°, as shown in Fig. 1. Meanwhile, the upper and lower half-width rings were rotated by 180° relative to the middle ring. A side view can be seen in Fig. 3.