Calculation and analysis of shear resistance of segment ring joint with shear pin

Shengzhi Wu¹, Haibin Huang¹, Mingnian Wang¹, Shihui Xiao², Dagang Liu¹

¹School of Civil Engineering, Southwest Jiaotong University, Chengdu, China;
²Zhuhai Dahengqin Co. Ltd., Zhuhai, China.

Corresponding author: huanghaibin12@163.com

Abstract: In order to get the effect of shear pins between segments on the shear resistance of segment girth joints. Take the Maliuzhou traffic tunnel project of Zhuhai which with super large diameter and Marine Composite strata as the research object, the longitudinal shear stiffness of tunnel shear considering the shear rigidity of shear pins was obtained through the finite element shear experiment of segment ring. By comparing the calculation results of shear pin and non shear pin between segment ring connections, the conclusion that shear pin setting can effectively decompose and transfer shear force and control the dislocation between segment ring blocks is obtained. The study can be used as reference for the design and construction of shield tunnel.

1. Introduction

As a safe, fast, efficient and environmentally friendly traffic form, urban tunnel has become the primary choice to solve traffic problems in many big cities [1]. In recent years, the large diameter shield tunnel engineering is in the ascendant. The construction of shield tunnel under super large and complex geological environment has been the focus and difficulty of scholars [2], [3]. Relevant research shows that [4]: segment joints are the weak link of shield tunnel lining structure, and the mechanical performance of the joints directly determines the bearing capacity of the tunnel structure. Designers often install concave and convex tenon or shear pins between segment rings to improve the shear resistance of segment ring joints, so as to control the uneven settlement of the tunnel and the dislocation of segment of the large diameter shield tunnel. The shear action at the circumferential joints causes the bending moment at the joints to transfer to the adjacent ring, so the shear action of the ring joints are important to the stress and deformation performance of the segment.

Zhu Yaohong et al. Through the method of model experiment on the concave tenon segment containing ring shear behavior of joints were studied [5]. The full scale tests of the compression, shear and flexural properties of the annular joints of underground concrete pipes are carried out by Buco [6], and the model analysis is carried out. Experimental analyses of an optimized shear load transfer in the circumferential joints of concrete segmental linings was completed by Putke et al.[7]. Salemi et al [8] carried out direct shear tests of segment circumferential joints under different normal stresses, and refined models were established for analysis.

At present, scholars have done some research on the shear resistance of the circumferential joint of the segment with concave and convex tenon, but the research on the shear resistance of the segment ring with shear pin has not been reported in the literature.

Based on the above discussion, we take the Maliuzhou traffic tunnel project of Zhuhai of China as...
In this paper, we establish a refined model of segment connection bolts and shear pin to simulate the segment shear test, and the shear performance of segment ring joints with shear pin is calculated and analyzed by this method.

2. Research background
The single layer lining structure is adopted in the shield tunnel project, the outer diameter of tunnel segment is 14.5m, thickness 0.6m, and the width of segments is 2m. The lining ring of the tunnel is divided into 10 blocks, which are made up of S1~S10 segments and assembled by staggered joints. The strength grade of segment concrete is C55. The connection between segment rings and blocks is made by using oblique bolt.

Due to the complicated geological conditions of tunnel engineering, in the design of segment structure, 19 shear pins are designed for the longitudinal lining torus, except for 38 M27 longitudinal inclined bolts in each ring. As shown in Figure 1.

Usually, the shear action of shear pin is neglected in the calculation and analysis of shield tunnel with shear pin. However, when the stress of the tunnel longitudinal structure is unfavorable, the calculation and analysis of the longitudinal shear action including shear pin will be more in line with the actual engineering.

3. Test design
The loading test of segment circumferential joint is carried out by numerical simulation, and the shear stiffness of segment ring joints with shear pin tunnel is obtained by loading test. The design of the experiment is referred to the literature [9]. The friction coefficient between the segments is $u=0.6$ [10], the segment thickness is 0.6m, the longitudinal width is 2m, and the circumferential length of the segment is 2.5m. The longitudinal connection parts of the half block segment include two M27 bolts and 1 shear pin. According to the actual size of the project, the bolts and shear pin connections are built between the segments (Figure 2). The longitudinal and tangential loading tests of the model are carried out. The loading conditions are shown in Figure 3 and Table 1, and the numerical loading model is shown in Figure 4. The elastic modulus of the bolt is 210GPa, Poisson's ratio is 0.25; the elastic modulus of shear pin is 110GPa, and the Poisson's ratio is 0.3.

| Condition | Longitudinal force /F | Content description |
|-----------|-----------------------|---------------------|
| 1-1       | 0                     | Radial shear test, increasing P1, recording radial dislocation |
| 1-2       | 1800kN                | Radial shear test, increasing P1, recording radial dislocation |
| 1-3       | 0                     | Tangential shear test, increasing P2, recording tangential displacement |
1800kN Tangential shear test, increasing P2, recording tangential displacement

Figure 3. Loading sketch of ring shear test

Figure 4. Stiffness calculation model of segment ring joint

4. Analysis of shear test results
Figure 5 is the result of radial shear test of segment. When the longitudinal force of the segment is 0kN, there is no static friction between the segments, the relative displacement between segments increases with the increase of shear force. When the longitudinal force of the segment model is 1800kN, it is considered that when the shear force does not exceed the maximum static friction force of the segment torus, the dislocation displacement can hardly be observed; when the shear force exceeds the maximum static friction force of the segment torus, the phenomenon of dislocation occurs, and because of the existence of radial bolts and shear pins, the slip motion increases with the increase of shear force, rather than the continuous slip.

According to the load P1, P2 and the corresponding radial and tangential error values, the shear stiffness under various loading conditions at different levels is calculated, as shown in Figure 6 and Figure 7.

Figure 5. Calculation results of radial shear displacement
According to the calculated results (Figures 6 and 7), the shear stiffness of the ring joints is fitted to the longitudinal bolts of the segment, then, the shear stiffness of the segment to the single bolt is taken as $K_r = 2.34 \times 10^8 / m$, $K_t = 3.34 \times 10^8 / m$.

The experimental design is invariant, and the shear pin is removed during the calculation. The shear stiffness of the segment connection bolts without considering shear pin is $K^{1}_r = 2.92 \times 10^7 / m$, $K^{1}_t = 3.08 \times 10^7 / m$. The shear stiffness provided by the bolt is much smaller than the shear pin, because the slenderness ratio of bolt is large and the bolt hole has assembly gap.

5. Application effect of shear pin
The longitudinal beam-spring model is used to calculate the longitudinal internal force and deformation of the tunnel.

The existence of the bedrock surface longitudinal mutation of Monkey Island tunnel, here are reasonably simplified to formation. In the longitudinal section of the Maliuzhou tunnel, there is the case of the bottom bedrock protruding. In the article, we simplified the strata, and select the calculated section shown in Fig.9 to calculate the internal force and deformation of the longitudinal structure of the tunnel. In Figure 8, the longitudinal length of the tunnel is 200m, with a total of 100 ring segments, and the tunnel depth is 15m. The segment ring longitudinal joint compression stiffness for $K_c = \infty$, the tensile stiffness $K_t = 7.904 \times 10^9 N/m$, and the rotational stiffness $K_m = 1.538517 \times 10^{10} N\cdot m/\text{rad}$. The shear stiffness of the tube ring longitudinal joint is obtained by multiplying the individual bolt shear stiffness described above by the number of bolts, and the coefficient of subgrade reaction is shown in Table 2.

$$q = b \gamma h = 14.5 m \times 16.3 kN/m^3 \times 15m = 3588.75 kN/m$$

| Lithology                     | Coefficient of subgrade reaction $K$ (MPa/m) |
|-------------------------------|---------------------------------------------|
| Gravelly clayey soil          | 40.6                                        |
| Completely decomposed granite | 78.0                                        |

Figure 6. Radial shear force displacement curve of longitudinal joint
Figure 7. Tangential shear force displacement of longitudinal joint curve

Figure 8. Longitudinal calculation section of tunnel

Table 2 Coefficient of subgrade reaction

Figure 9.
Strongly weathered granite 122.0

**Figure 9.** Calculation results of shear force (left – no shear pin, right -shear pin)

As can be seen from Figure 9, the maximum shear of the segment is 600.155KN when the tunnel has no shear pin, and the maximum shear force is 569.075KN when the shear pins are set between the segments. Combined with the trend of longitudinal settlement of the segments (Figure 10), we can get the conclusion that the setting of shear pins can effectively decompose and transfer shear force, control the dislocation between segment ring blocks, and also facilitate the alignment in the process of segment assembly.

**Figure 10.** Calculation results of longitudinal settlement of tunnel

6. Conclusions
(1) Through the finite element shear experiment of segment ring, the shear stiffness of segment ring shear considering the shear pin between rings is obtained, and the shear stiffness of the ring joint is fitted to the bolt between the segments, so as to facilitate the calculation and analysis.

(2) Through the calculation and analysis, it can be concluded that the setting of shear pins can effectively decompose and transfer the longitudinal shear of the segment, and control the action of the dislocation between the segments of the tunnel.

**Acknowledgments**

Foundation items: The National Natural Science Foundation Project (51578458); Project supported by the Shanghai Tunnel Engineering Co. Ltd. and Zhuhai Dahengqin Co. Ltd. (2015-sk-4). Application development of key projects in Chongqing(cstc2014yykfB30003).

**References**
[1] HE Chuan, WANG Bo, 2013. Research progress and development trends of highway tunnels in China. Journal of Modern Transportation; 21(4), PP. 209-223.
[2] Committee of investigation of shield method, from design to construction, 1997. Investigation of
shield method, from design to construction. Kobe: The Japanese Geotechnical Society; PP. 2-5.

[3] LIANG K S, YOU Y F, GUO W S., 2012. The risk control of an undersea shield tunnel passing through hard granites and core stones: A case history// Proceedings of the ITA-AITES 2012 World Tunnel Congress. Bangkok: Engineering Institute Of Thailand; PP.325–327.

[4] BI Xiangli, LIU Xian, WANG Xiuzhi, et al., 2014. Experimental investigation on ultimate bearing capacity of continuous-jointed segmental tunnel lining. China Civil Engineering Journal, China; 47(10), PP. 117–127.

[5] ZHU Yaohong, ZHANG Chen, LIU Xian, et al., 2017. Experimental study on shear property of circumferential joint in general ring segment under the staggered assembling. China Journal of Railway Science and engineering, China; 14 (02), pp. 315-324.

[6] BUCO J, EMERIAULT F. 2014. Full-scale experimental determination of concrete pipe joint behavior and it’s modeling. Journal of Infrastructure Systems; 14(3), PP. 230–240.

[7] PUTKE D I T, BÖHUN R, MARK D I H P., 2015. Experimental analyses of an optimized shear load transfer in the circumferential joints of concrete segmental linings. Structural Concrete; 16(4), PP. 572–582.

[8] SALEMI A, ESMAEILI M, SERESHLI F., 2015. Normal and shear resistance of longitudinal contact surfaces of segmental tunnel linings. International Journal of Rock Mechanics & Mining Sciences; 77, PP. 328–338.

[9] LI Dongmei, 2011 Test and analysis of shear resistance of segment joints of Shanghai Yangtze River Tunnel. China Underground engineering and tunnels, China; (01), PP. 15-17+52.