Research on Stress Characteristics of Segment Structure during the Construction of the Large-Diameter Shield Tunnel and Cross-Passage

Zhongsheng Tan 1, Zonglin Li 1,*, Wei Tang 2, Xueying Chen 1 and Junmeng Duan 1

1 School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China; zhshtan@bjtu.edu.cn (Z.T.); 15121000@bjtu.edu.cn (X.C.); 17127763@bjtu.edu.cn (J.D.)
2 China Railway Design Corporation, Tianjin 300142, China; tangwei@crdc.com
* Correspondence: 18121092@bjtu.edu.cn; Tel.: +86-135-4605-4850

Received: 10 July 2020; Accepted: 27 July 2020; Published: 28 July 2020

Abstract: With the intensive development of China’s high-speed railway network and intercity railway network, the construction of the large-diameter shield tunnels and cross-passages is gradually increasing. The construction of large diameter shield tunnels and the excavation of cross-passages puts forward higher requirements for the stability and safety of segment structure. Based on the Wangjing tunnel project, this paper studies the segment displacement and mechanical response of the shield tunnel with a diameter of 10.5 m in the process of shield construction and cross-passage construction. The results show that during the construction of large diameter shield tunnels, the vault and invert produce inward displacement, the invert uplift usually is more severe than the vault settlement, and the arch waist on both sides produces outward displacement. Near the segment K (capping block), the mechanical performance of the segment is close to that of the hinge or chain rod, which can only effectively transmit the axial force but cannot resist the bending moment and shear force. During construction of the cross-passage, the maximum deformation and stress of shield tunnel segment are symmetrically located at the interface of the main tunnel and cross-passage. The upper and lower edges of the segment at the interface tend to change from compression to tension. At the same time, the steel bars on the inside and outside of the segment vault and the arch waist change from compressive stress to tensile stress, which can easily lead to segment damage, so these positions can be reinforced by erecting section steel frames before construction.

Keywords: large-diameter; shield tunnel; cross-passage; shield segment; mechanical response

1. Introduction

With the rapid development of infrastructure construction such as highways, railways and urban rail transit, the segment design technology of shield tunnels in China tends to mature. Still, actual engineering cases of large-diameter railway shield tunnels are few. Compared with standard shield tunnel, the segment structure of large-diameter shield tunnels has some new structural features, such as the increase in the number of lining blocks per ring and longitudinal connecting bolts, and the diversification of staggered joint angles between the front and rear rings, which put forward new requirements for the stability of the segment structure. Moreover, the construction of the cross-passage in the large-diameter shield tunnel will remove part of the segment, which will destroy the integrity of the nearby segment, and pose a new challenge to the safety of the segment structure.

In recent decades, the stress characteristics of the segment during the construction of the standard shield tunnel and the cross-passage have been deeply studied according to the engineering examples. The results are as follows: during the construction of the standard shield tunnel (the outer diameter of
the tunnel is 4.1–6.2 m), the stress on the vault of the shield segment is relatively large, the stress on the inverted arch part is relatively small, and the segment always shows the stress characteristics of a large axial force and a small bending moment [1–5]. In the aspect of segmental ring design, the application of steel fiber to prefabricated tunnel segments has been proved to reduce the total reinforcement and improve the tensile strength of the segment [6,7]. In the aspect of numerical calculation, Sun [8] put forward the integral circumferential–longitudinal discontinuous calculation model of segment structure based on the shell-spring model, and improved the simulation method of the joint, while the calculation result is more accurate than that of the traditional beam-spring model. In the aspect of segment structure monitoring, the distributed optical-fiber sensor can effectively monitor the minor deformation of segment ring [9,10]. The limit effective support pressure of the shield tunnel face will increase linearly with an increase in the hydraulic head difference between the shield tunnel face and the ground surface [11,12]. During the construction of cross-passage of a standard shield tunnel (the outer diameter of the tunnel is 4.1–6.2 m), the segment will produce an additional horizontal displacement moving in the direction of the connecting channel [13,14]. The segment at the vault position is subjected to greater compressive stress while segment at the inverted arch position is subjected to greater tensile stress [15,16]. The sequence of the excavation of the cross-passage determines the influence on the left and right main tunnels [17]. The segment at the interface between the cross-passage and main tunnel bears a large bending moment [18,19]. However, none of the above studies involve the influence of large-diameter shield tunnels construction and cross-passage construction on segments, which restricts the technical progress of tunnel engineering.

In this paper, based on the Wangjing tunnel of the Beijing–Shenyang high-speed railway with a diameter of 10.9 m, the mechanical characteristics of the segment structure of a large-diameter railway shield tunnel and the mechanical response of the segment structure of large-diameter railway shield tunnel during the construction of a cross-passage were investigated by comparing the results of numerical analysis with the field testing data. The research results can provide useful guidance for similar projects. The research results of this paper are helpful in improving the quality of tunneling and design [20].

2. Project Overview

The Wangjing tunnel of the Beijing–Shenyang high-speed railway is designed as a double-hole single-track tunnel with a total length of 8100 m. The length of the shield section is 3180 m (DK22 + 710.7 – DK25 + 900), and is constructed by a domestic mud–water shield machine with a diameter of 10.9 m. The plane and profile of the shield tunnel in this section are shown in Figures 1 and 2, and the maximum buried depth of the tunnel is 33.62 m (from the rail surface to the ground). There are six cross-passages along this section, of which the mileage of the third cross-passage is DK24 + 550, and the thickness of the vault cover is about 19.45 m.

The terrain along the tunnel is flat, and the strata along the tunnel are mainly artificial filling layer and Quaternary Holocene alluvial layer. The strata passing through the tunnel are mainly mixed strata such as silty clay, silty sand and fine sand. Between the No. 2 and No. 3 cross-passages, silty clay accounts for about 52.7%, silt accounts for about 10.5%, and fine sand accounts for about 23.8%. The main types of groundwater in this section are upper stagnant water and phreatic water. The upper stagnant water depth is 1.0–7.2 m, the principal aquifer is silt, sand and fill; the phreatic depth is 16.0 m, and the principal aquifer is sandy soil.

The standard section of Wangjing tunnel segment was assembled by the typical wedge-shaped segment staggered seam (Figure 3). The segment has an inner diameter of 9.5 m, an outer diameter of 10.5 m, a width of 2000 mm and a thickness of 500 mm. The form of the block division is 1 + 2 + 6 (one cap block, two adjacent blocks and six standard blocks).
The terrain along the tunnel is flat, and the strata along the tunnel are mainly artificial filling layer and Quaternary Holocene alluvial layer. The strata passing through the tunnel are mainly mixed strata such as silty clay, silty sand and fine sand. Between the No. 2 and No. 3 cross-passages, silty clay accounts for about 52.7%, silt accounts for about 10.5%, and fine sand accounts for about 23.8%. The main types of groundwater in this section are upper stagnant water and phreatic water. The upper stagnant water depth is 1.0–7.2 m, the principal aquifer is silt, sand and fill; the phreatic depth is 16.0 m, and the principal aquifer is sandy soil.

The standard section of Wangjing tunnel segment was assembled by the typical wedge-shaped segment staggered seam (Figure 3). The segment has an inner diameter of 9.5 m, an outer diameter of 10.5 m, a width of 2000 mm and a thickness of 500 mm. The form of the block division is 1 + 2 + 6 (one cap block, two adjacent blocks and six standard blocks).

Straight bolts are used to connect longitudinal segments and circumferential segments, which are diagonally connected. The strength grade of the bolt is 8.8. The circumferential segments are connected by two M36 bolts with a total of eighteen per ring, and fifty M30 longitudinal bolts are used.
to connect the segments along the tunnel axis. The front of the standard block segment is shown in Figure 4. The design strength of segment concrete is C50, and the impermeability grade is P12.

Figure 4. The segment front elevation of the standard block of Wangjing shield tunnel.

The No. 3 cross-passage at LDK 24 + 550 (RDK 24 + 565) was selected for this research, and the stratigraphic composition of this section is miscellaneous fill, silty clay, silty sand and silty sand from top to bottom. The tunnel is mainly located in silty clay and silty sand stratum. The buried depth of the tunnel at No. 3 cross-passage is 17.23 m while the buried depth of the cross-passage is 21.83 m.

The cross-section of the cross-passage is arched with a straight wall, which is constructed by the step method. The excavation footage is 1m, the length of the steps is 3 m, and the height of the steps is 2.5 m. After excavation, the initial support was carried out in time, and finally, the secondary lining was constructed. The plan view and profile view of the cross-passage are shown in Figures 5 and 6.

Figure 5. Plan view of cross-passage.
3. Numerical Analysis

3.1. Numerical Model

Considering the contact action between the segment circumferential joint and the segment and bolt, the discontinuous contact model was adopted. The segments and bolts were simulated by the linear elastic solid element, and the elastic resistance of surrounding rock was simulated by the nonlinear spring element. Finally, the solid model of the longitudinal connection bolt and longitudinal contact relationship of the segment was established. The lining blocks and the contact units between segments are shown in Figure 7.

The mixture composed of soil and cement slurry was filled between the ring segment and soil, which was simplified to a homogeneous, equal thickness (the thickness was 0.14 m) and isotropic elastic grouting body in the finite element numerical simulation. The stratum unit, grouting body and secondary lining adopted the solid element. The segment structure and primary support adopted the plate element, and Mohr–Coulomb elastic–plastic model was adopted. The mechanical parameters of the stratum, grouting body, shield segment, and primary support of the cross-passage and secondary lining are shown in Table 1, and the grid division of the segment and cross-passage are shown in Figure 8.

Table 1. Stratigraphic and structural parameters.

| Material Type   | Heavy Degree (kN/m³) | Elastic Modulus (MPa) | Poisson’s Ratio | Cohesion (kPa) | Friction Angle(°) |
|-----------------|----------------------|-----------------------|-----------------|----------------|-------------------|
| Silty clay      | 18.3                 | 14.1                  | 0.3             | 36.5           | 10                |
| Fine sand       | 20.7                 | 19.5                  | 0.3             | -              | -                 |
| Silt sand       | 19.5                 | 50                    | 0.25            | -              | -                 |
| Shield segment  | 25                   | 30,000                | 0.17            | -              | -                 |
| Grouting body   | 22                   | 800                   | 0.32            | 90             | 36                |
| Initial support | 23                   | 21,000                | 0.3             | -              | -                 |
| Secondary lining| 25                   | 30,000                | 0.15            | -              | -                 |
adopted the plate element, and Mohr–Coulomb elastic–plastic model was adopted. The mechanical parameters of the stratum, grouting body, shield segment, and primary support of the cross-passage and secondary lining are shown in Table 1, and the grid division of the segment and cross-passage are shown in Figure 8.

| Material Type | Heavy Degree (kN/m³) | Elastic Modulus (MPa) | Poisson’s Ratio | Cohesion (kPa) | Friction Angle (°) |
|---------------|----------------------|-----------------------|----------------|----------------|------------------|
| Silty clay    | 18.3                 | 14.1                  | 0.3            | 36.5           | 10               |
| Fine sand     | 20.7                 | 19.5                  | 0.3            | -              | -                |
| Silt sand     | 19.5                 | 50                    | 0.25           | -              | -                |
| Shield segment| 25                   | 30,000                | 0.17           | -              | -                |
| Grouting body | 22                   | 800                   | 0.32           | 90             | 36               |
| Initial support | 23                 | 21,000                | 0.3            | -              | -                |
| Secondary lining | 25             | 30,000                | 0.15           | -              | -                |

3.2. Displacement and Stress Analysis of Segments in Shield Construction Process

3.2.1. Segment Displacement

The segment displacement of the discontinuous contact model is shown in Figure 9. It can be seen from the figure that the segment ring was elliptical, and the radial displacement of the invert was larger than that of the vault. The vault and the invert produced the inward displacement, and the two sides of the arch waist produced the outward displacement. When the elastic resistance of the surrounding rock was 30 MPa/m, the maximum displacement of the segment was 1.14 mm, which occurred at the bottom of the arch; the displacement of the arch waist was outward, which was 0.14 mm.

3.2.2. Segment Stress

The circumferential stress of the discontinuous contact model is shown in Figure 10. The circumferential stress range of the segment was $-12.1$–$0.32$ MPa. The tensile stress appeared at the inner edge of the segment at the vault and invert where the maximum value was 0.32 MPa. The maximum compressive stress appeared on the inner edge of the segment at the arch waist where the value was 12.1 MPa. The circumferential stress on the outer edge of the segment was compressive stress.
3.2.2. Segment Stress
The circumferential stress of the discontinuous contact model is shown in Figure 10. The circumferential stress range of the segment was $-12.1 - 0.32 \text{ MPa}$. The tensile stress appeared at the inner edge of the segment at the vault and invert where the maximum value was 0.32 MPa. The maximum compressive stress appeared on the inner edge of the segment at the arch waist where the value was 12.1 MPa. The circumferential stress on the outer edge of the segment was compressive stress.

3.2.3. Segment Internal Force
The assembly method in which the top blocks offset each other by 7.2° was established, and the internal force of the segment was analyzed, as shown in Figures 11 and 12. The axial force of the vault was 1760 kN, the axial force of the arch waist was 1270 kN, and the axial force of the invert was 1330 kN. The left bending moment of the arch waist was slightly larger than that of the right side of the arch waist, and the upper bending moment of the left side of the arch waist was slightly smaller than that of the right side of the arch waist. The positive bending moment of the vault was 40 kN·m; the maximum negative bending moment of the left arch waist was $-181 \text{ kN·m}$; the maximum negative bending moment of the right arch waist was $-172 \text{ kN·m}$; the maximum positive bending moment of segment invert was 78 kN·m.

3.3. Displacement and Stress Analysis of Segments in Cross-passage Construction Process
3.3.1. Segment Displacement
After excavating the soil of the cross-passage, the extreme value of the vertical displacement of the segment is shown in Figure 13.

3.2.3. Segment Internal Force
The assembly method in which the top blocks offset each other by 7.2° was established, and the internal force of the segment was analyzed, as shown in Figures 11 and 12. The axial force of the vault was 1760 kN, the axial force of the arch waist was 1270 kN, and the axial force of the invert was 1330 kN. The left bending moment of the arch waist was slightly larger than that of the right side of the arch waist, and the upper bending moment of the left side of the arch waist was slightly smaller than that of the right side of the arch waist. The positive bending moment of the vault was 40 kN·m; the maximum negative bending moment of the left arch waist was $-181 \text{ kN·m}$; the maximum negative bending moment of the right arch waist was $-172 \text{ kN·m}$; the maximum positive bending moment of segment invert was 78 kN·m.

3.2.4. Bolt Stress
It can be seen from Table 2 that the bolts between the segments of the whole ring were under tension. The maximum circumferential stress of the bolt was 56.5 MPa, and the bolt tension was 57.48 kN according to the bolt area, which occurred in the connecting bolt between A4 and A5. The minimum circumferential stress of the bolt was 34.5 MPa, and the bolt tension was 35.09 kN according to the bolt area, which occurred in the connecting bolt between A1 and B1.

Table 2. The extreme tensile stress of bolts.

| Project          | Tensile Stress | Position            | Maximum value (MPa) | Minimum value (MPa) |
|------------------|----------------|---------------------|---------------------|---------------------|
|                  |                |                     | 56.5                | 34.5                |
|                  |                | Connecting bolts for A4 and A5 |                     |                     |

Figure 10. Circumferential stress of segment (Unit: Pa).

Figure 11. The axial force of segment (Unit: kN).
3.2.4. Bolt Stress

It can be seen from Table 2 that the bolts between the segments of the whole ring were under tension. The maximum circumferential stress of the bolt was 56.5 MPa, and the bolt tension was 57.48 kN according to the bolt area, which occurred in the connecting bolt between A4 and A5. The minimum circumferential stress of the bolt was 34.5 MPa, and the bolt tension was 35.09 kN according to the bolt area, which occurred in the connecting bolt between A1 and B1.

| Project Tensile Stress Position | Maximum value (MPa) | Minimum value (MPa) |
|--------------------------------|---------------------|---------------------|
| Connecting bolts for A4 and A5 | 56.5                | 34.5                |
| Connecting bolts for A1 and B1 |                    |                     |

3.3. Displacement and Stress Analysis of Segments in Cross-Passage Construction Process

3.3.1. Segment Displacement

After excavating the soil of the cross-passage, the extreme value of the vertical displacement of the segment is shown in Figure 13.

After constructing the cross-passage by the step method, the top of the full-ring segment sank and the bottom uplifted, and the maximum settlement and uplift value of the full-ring segment occurred at the top and bottom of the segment ring at the interface. During the step construction, the maximum settlement value of the segment was about 1 mm, and the maximum uplift value was about 6.76 mm.
3.3.2. Segment Stress

- Maximum Principal Stress

After excavating the soil of the cross-passage, the extreme value of the maximum principal stress of the segment is shown in Figure 14. After excavating the soil of the cross-passage, the maximum principal stress of the segment was 423.11 kN/m², which was at the upper and lower edge of the interface between the main tunnel and the cross-passage. The ultimate tensile stress of C50 concrete is 2640 kN/m², so the segment structure was in a safe state under this condition.

- Minimum Principal Stress

After excavating the soil of the cross-passage, the extreme value of the minimum principal stress of the segment is shown in Figure 15. After excavating the soil of the cross-passage, the minimum principal stress of the segment was −3544.2 kN/m², which was at the left and right edge of the interface between the main tunnel and the cross-passage. The ultimate compressive stress of C50 concrete is 32,400 kN/m², so the segment structure was in a safe state under this condition.

3.3.3. Segment Internal Force

- Axial Force

After excavating the soil of the cross-passage, the extreme axial force of the segment is shown in Figure 16. The maximum axial force of the segment was 8.1 kN, which appears at the upper edge of the interface, and the minimum axial force was −2022.3 kN, which appears at the left edge of the interface.
3.3.3. Segment Internal Force

- **Axial Force**
  After excavating the soil of the cross-passage, the extreme axial force of the segment is shown in Figure 16. The maximum axial force of the segment was 8.1 kN, which appears at the upper edge of the interface, and the minimum axial force was $-222.3$ kN, which appears at the left edge of the interface.

- **Bending Moment**
  After excavating the soil of the cross-passage, the extreme value of the bending moment of the segment is shown in Figure 17. The top and bottom of the segment are the positive bending moment, and the left and right side arch waists of the segment are the negative bending moment. The maximum positive bending moment was 49.8 kN·m, which appears at the bottom of the segment, and the maximum negative bending moment was $-45.2$ kN·m, which appears at the edge of the interface side of the segment.

3.3.4. Bolt Stress

After excavating the soil of the cross-passage, the extreme value of the axial tensile stress of the bolt is shown in Table 3. The tensile stress of bolt at the bottom of the segment was highest, which was 67.8 MPa. The tensile stress of bolt at the edge of the opening side of the segment was smallest, which is 9.2 MPa.

| Project | Tensile Stress | Position |
|---------|----------------|----------|
| Maximum value (MPa) | 67.8 | Segment bottom |
| Minimum value (MPa) | 9.2 | Interface position side edge |

Figure 16. Segment axial force (Unit: kN).

Figure 17. Segment bending moment (Unit: kN·m).
4. Field Test of Segment Stress during Shield Construction

4.1. Scheme of Field Test

4.1.1. Segment Earth Pressure

The vibrating string earth pressure box was used to test the earth pressure, and the measuring range was 1.6 MPa. Figure 18 shows the arrangement of measuring points of the single ring segment. The single ring segment is arranged with nine measuring points, which are located at the outer center of each segment, and four rings are embedded on the left line and the right line of each test section, respectively.

![Figure 18. The layout of measuring points for earth pressure and internal force of segments.](image)

4.1.2. Segment Internal Force

The vibrating string concrete strain gauge was used to test the axial force and the bending moment of the segment. Eighteen measuring points were arranged in one ring segment, and four rings were buried in the left and right tunnel, respectively, which are located at the centre of the inner and outer side of each segment. The vibrating string steel bar meter was used to test the steel bar stress. Eighteen measuring points were arranged in one ring segment, and four rings were buried in the left and right tunnel, respectively, and the measuring points were located at the centre of the inner and outer sides of each segment. Figure 18 shows the arrangement of the measuring points of the segment.

4.1.3. Internal Force of Bolts

The stress changes of longitudinal and circumferential bolts were tested by a gasket type unidirectional stress meter. Nine bolt measuring points were arranged in the circumferential and longitudinal direction of each ring segment respectively, and four rings were buried in each tunnel on the left and right lines, respectively. The measuring points were located at the circumferential bolt holes and longitudinal bolt holes of each segment. Figure 19 shows the arrangement of the measuring points of the bolts.
was asymmetric. The surrounding rock pressure on the left and right sides was higher than that on the left side, so the surrounding rock pressure of each assembly block increased at first and then decreased and finally tended to be stable. Among them, the surrounding rock pressure reached the maximum when the segment was assembled and reinforced by grouting, which shows that the grouting operation has a significant influence on the contact pressure between the segment and the surrounding rock.

4.2. Surrounding Rock Pressure

Figure 20 shows the test results of the surrounding rock pressure of rings 669–672. From the test results of the surrounding rock pressure of rings 669–672, it was known that the surrounding rock pressure of four ring segments was between 0.14 and 0.32 MPa. The maximum surrounding rock pressure was located at the bottom of the ring 672 segment, while the surrounding rock pressure of the vault was ordinarily small. The surrounding rock pressure on the right side of the tunnel usually was higher than that on the left side, so the surrounding rock pressure on the left and right sides was asymmetric.

Figure 20 shows the test results of the surrounding rock pressure of rings 669–672. From the test results of the surrounding rock pressure of rings 669–672, it was known that the surrounding rock pressure of four ring segments was between 0.14 and 0.32 MPa. The maximum surrounding rock pressure was located at the bottom of the ring 672 segment, while the surrounding rock pressure of the vault was ordinarily small. The surrounding rock pressure on the right side of the tunnel usually was higher than that on the left side, so the surrounding rock pressure on the left and right sides was asymmetric.

Figure 21 shows the time-history curve of the surrounding rock pressure of ring 671. With the shield tunneling, the surrounding rock pressure of each assembly block increased at first and then decreased and finally tended to be stable. Among them, the surrounding rock pressure reached the maximum when the segment was assembled and reinforced by grouting, which shows that the grouting operation has a significant influence on the contact pressure between the segment and the surrounding rock.
Symmetry 2020, 12, x FOR PEER REVIEW 13 of 26

(c) (d)

Figure 20. Measured surrounding rock pressure diagram of the ring 669–ring 672 segments (Unit: MPa). (a) Surrounding rock pressure of the ring 669 segment, (b) Surrounding rock pressure of the ring 670 segment, (c) Surrounding rock pressure of the ring 671 segment, (d) Surrounding rock pressure of the ring 672 segment.

Figure 21. The variation curve of the surrounding rock pressure of the ring 671 segment with the increase in the drivage ring number.

The segment near segment K (capping block) bore less surrounding rock pressure. The surrounding rock pressure value of the ring 669 segment near the segment K was the lowest, which was 0.13 MPa, which is only 43.3% of the maximum surrounding rock pressure of this section. The surrounding rock pressure value of the ring 670 segment near segment K was 0.14 MPa, which is 50% of the maximum surrounding rock pressure of this section. The surrounding rock pressure value of the ring 671 segment and the ring 672 segment near segment K was also lower than the average value of this section.

4.3. Internal Force of Segment

Figures 22 and 23 show the test results of the internal force of the segment. From the test results of the internal force of the segment, it was known that the axial force distribution of the segment was relatively uniform, and the pressure was in the range of 533.4–3414.2 kN. The negative bending moment was concentrated at the arch waist on both sides, and the arch vault and invert were mostly positive bending moments. The maximum negative bending moment was $-214.23$ kN·m, which was located at the left arch waist of the ring 672. The maximum positive bending moment was 106.72 kN·m, which was located at the bottom of the ring 672. The sudden change of the axial force of the capping block K of ring 670 and ring 671 was more massive, which may be due to the failure caused by the external force acting on the pre-embedded instrument during hoisting or during the jacking of the segment K.

Figure 22. Cont.
Figure 22. Measured axial force diagram of ring 669–ring 672 segments (Unit: kN). (a) The axial force of the ring 669 segment, (b) The axial force of the ring 670 segment, (c) The axial force of the ring 671 segment, (d) The axial force of the ring 672 segment.

Figure 23. Measured bending moment diagram of ring 669–ring 672 segments (Unit: kN·m). (a) The bending moment of the ring 669 segment, (b) The bending moment of the ring 670 segment, (c) The bending moment of the ring 671 segment, (d) The bending moment of the ring 672 segment.

4.4. Steel Bar Force

Figures 24 and 25 show the force of the steel bars. The test results of the force of the steel bars show that the steel bars on the inside and outside of the four ring segments were in a state of compression, and the force was uniform. The range of axial force of steel bar is 1.52–13.10 kN, and the maximum value appears in the range of 45° to the central axis. The diameter of the main bar on the inside and...
outside of the segment was 28 mm. The maximum compressive stress of the inner steel bar was 21.27 MPa, and the maximum compressive stress of the outer steel bar was 18 MPa, which has a more extensive safety reserve than the designed ultimate stress (360 MPa).

Figure 23. Measured bending moment diagram of ring 669–ring 672 segments (Unit: kN·m). (a) The bending moment of the ring 669 segment, (b) The bending moment of the ring 670 segment, (c) The bending moment of the ring 671 segment, (d) The bending moment of the ring 672 segment.

Figure 24. Measured force diagram for the inside steel bar of the ring 669–ring 672 segments (Unit: kN). (a) Force for inside steel bar of the ring 669 segment, (b) Force for inside steel bar of the ring 670 segment, (c) Force for inside steel bar of the ring 671 segment, (d) Force for inside steel bar of the ring 672 segment.

The force of the segment steel bar near segment K was less than that of other segments. The forces on the inner and outer steel bars of segment K of ring 671 were only 3.12 kN and 3.62 kN, while those of segment K of ring 672 were 5.12 kN and 6.62 kN.

4.5. Bolt Stress

The variation law of bolt stress of rings 669–672 was similar, so ring 671 was selected for representative analysis. Figure 26-27 show the variation curve of bolt stress and measured bolt force of the ring 671 segment. The bolt stress test results of ring 671 show that the stress of ring 671 segment bolt changed significantly, it increased at first and then decreased with the shield tunneling. The influence of excavation on the bolt stress decreased gradually as the excavation stress tended to be stable. The stress of the segment K was less than that of the standard block. The circumferential stress of the bolt was slightly higher than the longitudinal stress because, under the action of surrounding rock pressure, the deformation of the shield tunnel was mainly radial deformation, so the deformation of the circumferential bolt was more significant, and the stress was more significant. In contrast, the deformation of the tunnel axis was minimal, so the longitudinal bolt deformation was small, the stress was small, and the longitudinal bolt was greatly affected by the thrust of the shield jack.
The influence of excavation on the bolt stress decreased gradually as the excavation stress tended to be stable. The stress of the segment K was less than that of the standard block. The circumferential stress of segment K changed significantly, it increased at first and then decreased with the shield tunneling.

The force of the segment steel bar near segment K was less than that of other segments. The forces on the inner and outer steel bars of segment K of ring 671 were only 3.12 kN and 3.62 kN, while those of segment K of ring 672 were 5.12 kN and 6.62 kN.

4.5. Bolt Stress

The variation law of bolt stress of rings 669–672 was similar, so ring 671 was selected for representative analysis. Figures 26 and 27 show the variation curve of bolt stress and measured bolt force of the ring 671 segment. The bolt stress test results of ring 671 show that the stress of ring 671 segment bolt changed significantly, it increased at first and then decreased with the shield tunneling. The influence of excavation on the bolt stress decreased gradually as the excavation stress tended to be stable. The stress of the segment K was less than that of the standard block. The circumferential stress of the bolt was slightly higher than the longitudinal stress because, under the action of surrounding rock pressure, the deformation of the shield tunnel was mainly radial deformation, so the deformation of the circumferential bolt was more significant, and the stress was more significant. In contrast, the deformation of the tunnel axis was minimal, so the longitudinal bolt deformation was small, the stress was small, and the longitudinal bolt was greatly affected by the thrust of the shield jack.

Figure 25. Measured force diagram for the outside steel bar of the ring 669–ring 672 segments (Unit: kN). (a) Force for outside steel bar of the ring 669 segment, (b) Force for outside steel bar of ring 670 segment, (c) Force for outside steel bar of the ring 671 segment, (d) Force for outside steel bar of the ring 672 segment.

The force of the segment steel bar near segment K was less than that of other segments. The forces on the inner and outer steel bars of segment K of ring 671 were only 3.12 kN and 3.62 kN, while those of segment K of ring 672 were 5.12 kN and 6.62 kN.

4.5. Bolt Stress

The variation law of bolt stress of rings 669–672 was similar, so ring 671 was selected for representative analysis. Figures 26 and 27 show the variation curve of bolt stress and measured bolt force of the ring 671 segment. The bolt stress test results of ring 671 show that the stress of ring 671 segment bolt changed significantly, it increased at first and then decreased with the shield tunneling. The influence of excavation on the bolt stress decreased gradually as the excavation stress tended to be stable. The stress of the segment K was less than that of the standard block. The circumferential stress of the bolt was slightly higher than the longitudinal stress because, under the action of surrounding rock pressure, the deformation of the shield tunnel was mainly radial deformation, so the deformation of the circumferential bolt was more significant, and the stress was more significant. In contrast, the deformation of the tunnel axis was minimal, so the longitudinal bolt deformation was small, the stress was small, and the longitudinal bolt was greatly affected by the thrust of the shield jack.

Figure 26. The variation curve of bolt stress of the ring 671 segment with the increase in the number of drivage rings. (a) Variation curve of circumferential joint bolt stress of the ring 671 segment with the increase in drivage ring number, (b) Variation curve of longitudinal joint bolt stress of the ring 671 segment with the increase in drivage ring number.
5. Field Test of Segment Stress during the Construction of the Cross-passage

5.1. Scheme of Field Test

The left tunnel rings 670, 671, 672, 673 and the right tunnel rings 669, 670, 671 and 672 were selected for the test, and the arrangement of the measuring points was the same as Section 4.1.

5.2. Surrounding Rock Pressure

After the completion of the construction of the cross-passage, the surrounding rock pressure data of the left and right line tunnel were measured (Figure 28).

From the test data of the left-line tunnel, it can be seen that the surrounding rock pressure of the segment around the cross-passage was between 0.06 and 0.56 MPa, and the maximum value of surrounding rock pressure was in the ring 673 segment. From the test data of the right-line tunnel, it can be seen that the surrounding rock pressure of the segment around the connecting channel was between 0.06 and 0.40 MPa, and the maximum surrounding rock pressure appeared in the ring 672 segment. The surrounding rock pressure of the left line was higher than that of the right line.

The change curve of the surrounding rock pressure of the ring 671 segment is shown in Figure 29. Before the construction of the cross-passage, the surrounding rock pressure fluctuated in a small range. When the shield tunnel segment was removed, the original stress state of the surrounding rock was broken, which could easily destroy the segment structure. During the construction of the cross-passage, the surrounding rock pressure at the upper and lower edge of the segment was on the high side, and the surrounding rock pressure at the upper edge was higher than the surrounding rock pressure at the lower edge. The upper soil was excavated first when excavating the soil of the cross-passage. The segment was also removed in the order of first up and then down so that the upper segment was air-facing at first, and the pressure of the upper surrounding rock was slightly higher than that of the lower surrounding rock.
Symmetry 2020, 12, x FOR PEER REVIEW 18 of 26

Figure 28. Measured surrounding rock pressure diagrams of the segment rings in left and right line tunnels (Unit: MPa). (a) Surrounding rock pressure of the ring 671 segment of left-line tunnel, (b) Surrounding rock pressure of the ring 673 segment of left-line tunnel, (c) Surrounding rock pressure of the ring 670 segment of right-line tunnel, (d) Surrounding rock pressure of the ring 672 segment of right-line tunnel.

Figure 29. The variation curve of the surrounding rock pressure of the ring 671 segment with the increase in construction days.

5.3. Internal Force of Segment

After the completion of the construction of the cross-passage, the internal force data of the segments of the left and right line tunnel were measured (Figures 30 and 31). From the test data of the left-line tunnel, it can be seen that the segment structure was under pressure, the range of axial
force of the segment was between 291.5 and 763.1 kN, and the minimum occurred at the upper and lower edges of the segment removed. According to the test data of the right-line tunnel, the structure of the segment was under pressure. The range of the axial force of the segment was 302.3–622.6 kN, and the distribution law of the axial force of the segment was consistent with that of the left-line tunnel. After removing the segment, the segment tended to move to the removal area and be pulled, so that the pressure on the upper and lower edge of the segment was reduced.

Figure 30 shows that the vault and bottom of the left line tunnel were positive bending moments, the arch waist of the segment was a negative bending moment. The maximum negative bending moment was $-50.26$ kN·m, which was located at the waist of the ring 673 arch, and the maximum positive bending moment was 30.05 kN·m, which is located at the vault of ring 673.

Figure 31 shows that the vault and invert of the right line tunnel were positive moments; the arch waist of the segment was a negative bending moment. The maximum positive bending moment was 46.58 kN·m, which was located at the vault of ring 672, and the maximum negative bending moment was $-43.62$ kN·m, which was located at the vault of ring 672.

**Figure 30.** Measured internal force diagram of the ring 671 and ring 673 segments of the left-line tunnel. (a) The axial force of the ring 671 segment (Unit: kN), (b) The bending moment of the ring 671 segment (Unit: kN·m), (c) The axial force of ring 673 segment (Unit: kN), (d) The bending moment of the ring 673 segment (Unit: kN·m).
5.4. Steel Bar Force

After constructing the cross-passage, the force of steel bar on the inside and outside of the segment of the left and right line tunnel is shown in Figures 32 and 33.
Figure 32. Measured force diagram of the inner and outer steel bars of the ring 671 and ring 673 segments in left-line tunnel (Unit: kN). (a) Force of the inner steel bar of the ring 671 segment, (b) Force of the outer steel bar of the ring 671 segment, (c) Force of the inner steel bar of the ring 673 segment, (d) Force of the outer steel bar of the ring 673 segment.

Figure 33. Measured force diagram of the inner and outer steel bars of the ring 670 and ring 672 segments in right-line tunnel (Unit: kN). (a) Force of the inner steel bar of the ring 670 segment, (b) Force of the outer steel bar of the ring 670 segment, (c) Force of the inner steel bar of the ring 672 segment, (d) Force of the outer steel bar of the ring 672 segment.

From the test data of the left tunnel, it can be seen that the axial force of the inner and outer steel bar of the ring 671 and ring 673 segments was between −18.27 and 47.35 kN. The inner steel bar of
ring 671 and ring 673 displays the tension state at the left arch shoulder and the left arch foot, and the outer steel bar of the ring 673 displays the tension state at the vault. From the test data of the right tunnel, it can be seen that the axial force of the inner and outer steel bars of the ring 670 and the ring 672 segment was between −4.36 and 32.78 kN. The inner steel bar of ring 670 was in the tensile state at the right arch shoulder, the outer steel bar of the ring 670 was in the tensile state at the right arch waist, and the inner steel bar of the ring 672 was in the tensile state at the right arch waist.

A steel bar with a diameter of 28 mm was used in the design. Through calculation, the maximum pressure of the left and right side steel bars was 76.89 MPa, which meets the requirements of the ultimate tensile stress (360 MPa), and the maximum tensile stress was 29.67 MPa, which meets the requirements of the ultimate compressive stress (360 MPa). The inside and outside steel bars have sufficient safety reserves. Figure 34 shows the stress time history curve of the steel bar on the inside and outside of ring 673. As can be seen from the figure, before the construction of the cross-passage, the force of the steel bar fluctuated in a small range, and the inner and outer steel bars were under pressure. When removing the shield tunnel segment, the original stress state changed and the inner and outer steel bars were tensioned in some positions of the segment ring. It is easy to cause segment structural damage. During the construction of the cross-passage, the force of the steel bar changed little. After the completion of the construction, the force of the steel bar tended to be stable.

Figure 34. The force variation curve of the steel bars on the inside and outside of the ring 673 segment with the increase in construction days. (a) Force on the inner steel bar of the ring 673 segment, (b) Force on the outer steel bar of the ring 673 segment.

5.5. Bolt Stress

After the completion of the construction of the cross-passage, the forces of the segment longitudinal joint bolts and circumferential joint bolts on the left and right lines are shown in Figures 35 and 36.

According to the test data of the left tunnel, the stress of the longitudinal joint bolt was between 29.3 and 39.2 MPa. The maximum value occurred in ring 671, and the minimum occurred in ring 673. The stress of the circumferential joint bolt was between 28.3 and 39.7 MPa. The maximum value occurred in ring 671, and the minimum occurred in ring 673. According to the test data of the right tunnel, the stress of the longitudinal joint bolt was between 29.4 and 35.8 MPa. The maximum value occurred in ring 672, and the minimum occurred in ring 670. The stress of circumferential joint bolt was between 28.9 and 35.7 MPa. The maximum value occurred in ring 670, and the minimum occurred in ring 672. The stress of the circumferential joint bolt was greater than that of the longitudinal joint bolt. The yield stress of the bolts used in the field construction was 640 MPa, and the maximum stress of the left and right longitudinal joint bolts and circumferential joint bolts was less than the yield stress, so there was a large safety reserve. The stress law of the longitudinal joint bolt and the circumferential joint bolt of the left and right line tunnels were the same. The stress of the circumferential joint bolt was higher than that of the longitudinal joint bolt. The stress of the left line bolt was slightly larger than
that of the right line bolt, the stress of the upper and lower edge bolts of the segment at the interface was higher, and the stress of bolts of K block was smaller.

**Figure 34.** The force variation curve of the steel bars on the inside and outside of the ring 673 segment with the increase in construction days. (a) Force on the inner steel bar of the ring 673 segment, (b) Force on the outer steel bar of the ring 673 segment.

**5.5. Bolt Stress**

After the completion of the construction of the cross-passage, the forces of the segment longitudinal joint bolts and circumferential joint bolts on the left and right lines are shown in Figures 35 and 36.

**Figure 35.** Measured bolt stress diagram of the ring 671 and ring 673 segments of the left-line tunnel (Unit: MPa). (a) The stress of longitudinal joint bolts of the ring 671 segment, (b) The stress of circumferential joint bolts of the ring 671 segment, (c) The stress of longitudinal joint bolts of the ring 673 segment, (d) The stress of circumferential joint bolts of the ring 673 segment.

**Figure 36.** Cont.
During the construction of a large-diameter shield tunnel, the segment ring may change elliptically: the vault and invert will produce inward displacement, the radial displacement of invert usually is more severe than that of the vault, and the outward displacement occurs at the waist on both sides of the arch.

If near the K block, the mechanical performance of the segment is close to that of the hinge or chain rod, which can only effectively transfer the axial force but cannot resist the bending moment and shear force, so the joint has a noticeable weakening effect on the integrity of the segment.

During the construction of the cross-passage, the maximum deformation and stress of the shield tunnel and the cross-passage were investigated by carrying out numerical calculations and a field test. The main findings of the study can be summarized as follows:

1. During the construction of a large-diameter shield tunnel, the segment ring may change elliptically: the vault and invert will produce inward displacement, the radial displacement of invert usually is more severe than that of the vault, and the outward displacement occurs at the waist on both sides of the arch.

2. If near the K block, the mechanical performance of the segment is close to that of the hinge or chain rod, which can only effectively transfer the axial force but cannot resist the bending moment and shear force, so the joint has a noticeable weakening effect on the integrity of the segment.

3. During the construction of the cross-passage, the maximum deformation and stress of the shield segment on the left and right lines may be symmetrically located at the interface of the main tunnel and the cross-passage. The upper and lower edge of the segment at the interface tends to change from compression to tension.

4. During the construction of the cross-passage, the steel bars on the inside and outside of the segment vault and the arch waist might change from compressive stress to tensile stress, which can easily lead to segment damage, and these positions can be reinforced by erecting section steel frames before construction.

**Figure 36.** Measured bolt stress diagram of the ring 670 and ring 672 segments of the right-line tunnel (Unit: MPa). (a) The stress of longitudinal joint bolts of the ring 670 segment, (b) The stress of circumferential joint bolts of the ring 670 segment, (c) The stress of longitudinal joint bolts of the ring 672 segment, (d) The stress of circumferential joint bolts of the ring 672 segment.

6. Conclusions

In this paper, based on the Wangjing Tunnel, the mechanical characteristics of the segment structure of a large-diameter railway shield tunnel and the mechanical response of the segment structure of a large-diameter railway shield tunnel during the construction of the cross-passage were investigated by carrying out numerical calculations and a field test. The main findings of the study can be summarized as follows:

**Author Contributions:** Conceptualization, Z.T. and Z.L.; data processing, Z.L.; funding acquisition, Z.T. and W.T.; investigation, X.C. and J.D.; software, X.C. and J.D.; supervision, Z.T.; validation, Z.L.; writing—original draft, Z.L.; writing—review and editing, Z.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** The authors acknowledge the financial support provided by the Project of Science and Technology Research and Development Program of China Railway Corporation (2014G004-K).

**Conflicts of Interest:** The authors declare no conflict of interest.
References

1. Ding, K.; Wang, Y. Analysis of segment internal forces of shield tunnel crossing underneath high speed railway. *J. Mechatr.* 2014, 2, 241–245. [CrossRef]

2. Xiong, Q. Study on the Characteristics of Middle and Small Diameter Shield Tunnel. Master’s Thesis, South China University of Technology, Guangzhou, China, 2014. (In Chinese)

3. Lu, D.Y. Analysis on Mechanical Characteristics and Cracking Phenomena of Segment Structure for Shield Tunnel during Construction Period. Ph.D. Thesis, Southwest Jiaotong University, Chengdu, China, 2019. (In Chinese)

4. Li, Y.J.; He, P.; Qin, D.P. Stress analysis of metro shield tunnel segment—Based on 3D discontinuous contact computational model. *Appl. Mech. Mater.* 2011, 1446, 1828–1833. [CrossRef]

5. Wang, F.; Cui, T.J. Numerical simulation on the stress and strain of lining structure with double shield tunnelling construction. *Adv. Mater. Res.* 2013, 2109, 2425–2429.

6. Plizzari, G.A.; Tiberti, G. Steel fibers as reinforcement for precast tunnel segments. *Tunn. Undergr. Space Technol.* 2006, 21, 438–439. [CrossRef]

7. Gruebl, F. Segmental Ring Design (New Challenges with High Tunnel Diameters). In Proceedings of the World Tunnel Congress 2012, Bangkok, Thailand, 20–23 May 2012.

8. Sun, J.S.; Guo, H.J. Shell-spring calculation model for segment lining of shield tunnels. *Chin. J. Undergr. Space Eng.* 2019, 15, 1048–1054.

9. Wang, T.; Shi, B.; Zhu, Y. Structural Monitoring and Performance Assessment of Shield Tunnels during the Operation Period, Based on Distributed Optical-Fiber Sensors. *Symmetry* 2019, 11, 940. [CrossRef]

10. Wang, X.; Shi, B.; Wei, G.; Chen, S.-E.; Zhu, H.; Wang, T. Monitoring the behavior of segment joints in a shield tunnel using distributed fiber optic sensors. *Struct. Control. Heal. Monit.* 2017, 25, e2056. [CrossRef]

11. Mi, B.; Xiang, Y. Analysis of the Limit Support Pressure of a Shallow Shield Tunnel in Sandy Soil Considering the Influence of Seepage. *Symmetry* 2020, 12, 1023. [CrossRef]

12. Wang, L.; Han, K.; Xie, T.; Luo, J. Calculation of Limit Support Pressure for EPB Shield Tunnel Face in Water-Rich Sand. *Symmetry* 2019, 11, 1102. [CrossRef]

13. Li, Z.L.; Wright, P.; Soga, K. Three-dimensional finite element analysis of the behaviour of cross passage between cast-iron tunnels. *Can. Geotech. J.* 2016, 53, 930–945. [CrossRef]

14. Yue, F.T.; Qiu, P.Y.; Yang, G.X.; Ding, G.Y.; Zhang, Y. Numerical calculation of tunnel cross-passage construction underneath river. *J. China Coal. Soc.* 2005, 30, 710–714.

15. Xu, Y.Q. Study on Force and Deformation Regularity of Tunnel Lining Structure Using Divided-Period Freezing Construction in Long-Distance Connecting Aisle. Master’s Thesis, China University of Mining and Technology, Xuzhou, China, 2015. (In Chinese)

16. Yin, Y. Study on the Influence of Freezing Method Construction on Tunnel and Ground Surface with the Connected Aisle of Great Height Difference. Master’s Thesis, China University of Mining and Technology, Xuzhou, China, 2018. (In Chinese)

17. Wang, L. The Mechanical Behavior Study of Intersecting Segment of Shield Tunnel and Cross-Passage. Master’s Thesis, Shijiazhuang Tiedao University, Shijiazhuang, China, 2018. (In Chinese)

18. Guan, Q. Study on Force and Deformation Law of Lining Structure in Freezing Construction for Contacting Passage of Through-River Tunnel. Master’s Thesis, China University of Mining and Technology, Xuzhou, China, 2014. (In Chinese)

19. Lv, H. Study on Construction Mechanics for Cross-Passage of Tunnel. Master’s Thesis, Tongji University, Shanghai, China, 2006. (In Chinese)

20. Oggeri, C.; Ova, G. Quality in tunnelling: ITA-AITES Working Group 16 Final report. *Tunn. Undergr. Space Technol.* 2004, 19, 239–272. [CrossRef]