The effect of the force between rings of large-diameter shield tunnels on the segmental cracking in weak stratum

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Abstract: Large-diameter shield tunneling in weak strata has the risks of segment floating, segment cracking and seepage, affecting the durability of the tunnel structure. In this paper, the statistical analysis of the cracks of a large-diameter shield tunnel segment was carried out, and the thickness of the force transmission liner was studied. The experiment showed that the average number of cracks per ring was the smallest when using a 3mm liner. Based on the structural characteristics of the segment, four types of stresses, namely simple support of segment boss, double-sided cantilever, single-point cantilever and two-point cantilever, and it is verified through on-site statistics, which has certain guiding significance for crack prevention.

1. Introduction

The large-diameter shield segment structure is subject to complex forces, and it is easy to cause accidents such as segment floating, segment cracking and water seepage during the tunneling process in weak stratum, which affects tunnel construction and structural durability. In view of the factors of segment cracks, Wang Kangren\textsuperscript{[1]} et al. proposed the failure mechanism of the cross-joint shield tunnel structure; Niu Zhanwei\textsuperscript{[2]} et al. discussed the floating situation of large-diameter shield tunnels in the Soviet-Eastern Passage project from tunnel engineering and design and The tunneling parameters and control analyzed the factors affecting the floating and cracking of the tunnel segments; Liu Peng\textsuperscript{[3]} et al. analyzed the floating of a certain subway segment from the aspects of geological reasons, segment joint stiffness, and the influence of the force on the left line segment during the construction of the right line. Reasons for cracking in use; Xiao Mingqing\textsuperscript{[4]} et al. proposed that the longitudinal uneven contact load caused by the unevenness of the annular joint surface may be either a construction load or a variable load in the use stage.

The effect of cracks on the tunnel structure. Liu Chuankun\textsuperscript{[5]} proposed that when the crack length is greater than 1/3 of the width, as the crack length increases, the elliptic flatness of the segment will increase sharply under the same load condition, and the ultimate bearing capacity of the structure will gradually decrease. When analyzing the longitudinal joints, Geng Ping et al.\textsuperscript{[6]} compared the calculation
results of the entire ring model and the longitudinal equivalent stiffness beam model, and the difference between the joint opening and bolt stress of the two joints was within 11%. At present, there is less research on the relationship among the force type of the segment boss structure, the thickness of the force transmission liner and the crack.

2. Project Overview

2.1 Tunnel segment design
A tunnel shield segment is designed as a double-sided wedge-shaped universal ring, with an outer diameter of 11800mm, an inner diameter of 10800mm, a ring width of 2m, a wall thickness of 500mm, and a wedge of 40mm. The segment assembly is assembled in the form of 5+2+1, that is, 5 standard rings, 2 adjacent rings, 1 capping ring (K block), and staggered assembly. The lining concrete strength grade is C60 and the impermeability grade is P12. There are bosses with a height of 4mm (the standard block and the adjacent block have three bosses, and the F block has 2 bosses) on the jack surface at the bolt hole position on the longitudinal end face of the tunnel segment to facilitate the transmission of the force of the segment. Increase the shear resistance of the segment.

2.2 Geological condition
The stratum of shield tunneling is mostly water-rich fine sand and silt soft clay, with large pores and strong water permeability. The overlying soil of the tunnel segment is ③2 layers of loose to slightly dense silty sand; ③3 layers of flow plastic, local soft plastic silty silty clay, the overlying stratum structure is loose, and shallow buried section, easy to collapse and deform, the soil and water often gushes together, and easily collapses to the surface when shallow buried. The stratum of the cave body is ③3 layers of flow plastic and local soft plastic silty silty clay; ③4 layers of slightly dense silt sand; ③5 layer flow plastic and local soft plastic silty silty clay; ③6 layers of medium dense silty sand, which is used for shield construction. The overall surface stability is poor, which is easy to disturb the soil layer, and the surface deformation is large. When the balance pressure of the construction is not correct, it is easy to cause the surface uplift or subsidence, and the roof fall will occur in severe cases.

3. Analysis of segment cracking
During the tunneling of the 27th to the 80th ring, when the n+1th ring was tunneled (the n+1th ring has not been assembled, the nth ring has been assembled), cracks appeared near the nth ring bolt hole and the n-1th ring bolt hole. In the excavation area (54-80 ring) where the segment floating is serious, there are more cracks near the bolt hole of the n-1th ring. The segmental ring of the segment appeared elongated longitudinal cracks around the bolt holes at the waistline and above, and local leakage occurred. The characteristics of cracks and leakage are as follows:

(1) All of them are longitudinal narrow and long cracks along the tunnel driving direction. The cracks appear on the inner arc surface at the position of the boss bolt hole along the direction of the jack;

(2) The cracks all penetrate through the concrete near the bolt hole in the middle of the segment and
extend to the small and medium positioning holes or grouting holes;

(3) The damaged locations along the bolt holes are mostly concentrated at the waist line and above the tunnel section, and a few are located below the waist line;

(4) During the tunneling process of shield tunneling, the cracks of the segment are caused by the spacer ring (the next propelled ring of the cylinder would have the crack);

(5) Water seepage occurs in part of the longitudinal cracks, which fall along the inner arc surface and gather into droplets.

Figure 2. Segment crack diagram

Count the number, length, location of the cracks, and the positional relationship between cracks and bosses, as shown in the following table 1.

Table 1. Number of cracks

| number | Ring number | Number of cracks | Average length (cm) | Average number (pieces/ring) | Proportion of top cracks | Proportion of close to big ring | Corresponding to the boss |
|--------|-------------|------------------|---------------------|-----------------------------|--------------------------|-------------------------------|--------------------------|
| 1      | 26-53       | 14               | 45.8                | 0.5                         | 28%                      | 78%                           | 94%                      |
| 2      | 54-80       | 29               | 78                  | 1.1                         | 65%                      | 97%                           | 90%                      |
| 3      | 81-95       | 10               | 47.1                | 0.67                        | 64%                      | 100%                          | 88%                      |

4. Transmission pad control

4.1 Transmission liner

In order to improve the flatness between the ring joints of the segment, after the 26th ring cracks, the thickness of the nitrile cork transfer liner was changed on site to study the effect of the transfer liner on the segment cracking. Respectively: 1) 2mm power transmission liners are used in the 26-46th ring and the 70-72th ring; 2) The 47-51th ring non-power transmission liners; 3) 52-53 ring uses a 3mm power transmission liners; 4) The 73-80th ring adopts 4mm force transmission liner.

Figure 3. Transmission liner

Divide the total number of cracks under different force transmission lining sections by the number of rings to get the average number of cracks per ring. The average number of cracks per ring represents the degree of segmental cracking in a certain section.
Table 2. Statistical table of the number of cracks in different transmission liners

| Pad setting | Ring number range | Number of rings used | Total number of cracks | Average number of cracks per ring |
|-------------|-------------------|----------------------|------------------------|----------------------------------|
| No liner    | 47-51             | 5                    | 9                      | 1.80                             |
| 2 mm pad    | 27-46             | 20                   | 9                      | 0.45                             |
| 3 mm pad    | 52-53             | 2                    | 0                      | 0.00                             |
| 4 mm pad    | 73-80             | 8                    | 4                      | 0.5                              |

The average number of cracks per ring is the smallest when the 3mm gasket is installed. The installation of the force transmission gasket helps to alleviate the occurrence of cracks in the segment. The setting of the force transmission liner can improve the force of the segment and help alleviate the occurrence of segment cracks, but it cannot solve the problem of segment cracking.

4.2 Synchronous grouting

The shield machine is located below the design axis between the 1-56 ring, the shield machine floats significantly after the 56th ring, slightly descends at the 70-74 ring, and then continues to rise. When the tunnel reaches the 80th ring, the floating amount reaches the maximum. The front end of the shield floats up 232mm, and the rear end floats up 278mm, exceeding the design building limit by ±150mm.

Figure 4. Shield machine and segment deviate from the design axis

After the 53rd ring, the actual elevation of the segment ring is obviously greater than the design elevation. This phenomenon occurs because, on the one hand, the maximum wedge of the continuous multi-ring is located at the bottom of the segment ring during the segment assembly process, which causes the actual elevation to be higher than the design elevation; on the other hand, the shield machine floats up and drives the segment to rise. As a result, misalignment occurs between adjacent loops, causing the actual elevation to be higher than the design elevation.

Table 3. Synchronous grouting slurry

| Ring number range | Slurry number | Slurry ratio (Cement: Fly Ash: Sand: Water: Bentonite) | Setting time (h) |
|-------------------|--------------|------------------------------------------------------|-----------------|
| 1-26              | 1            | 154:288:840:494:78                                   | 9               |
| 27-60             | 2            | 179:263:840:494:78                                   | 8               |
| 61-80             | 3            | 204:238:840:78:494                                   | 6.5             |

The coagulation time of No. 1, 2, and No. 3 slurries decreased in turn, and the buoyancy of the slurry on the three sections of the 1-26 ring, 27-60 ring, and 61-80 ring when the stern tube segment was pulled out decreased in turn. Shortening the coagulation time of the slurry is beneficial to suppress the rise of the tube segment. At 60 loops, the setting time was shortened to 6.5 hours, but the phenomenon of tube floats remained unchanged.

In the 69th to the 80th ring, the shield tail grouting volume is greatly reduced, but it is still greater than the theoretical grouting volume. The 69-73 ring synchronous grouting volume is small.
Synchronous grouting is beneficial to the attitude control of the shield, but it cannot eliminate the segment cracks.

5. The influence of the unevenness of the annular joint boss on the cracking of the segment

5.1 Analysis of the force type of the boss structure
The force of the segment is related to the force of the three bosses of the segment itself or the three bosses of a smaller ring. It is assumed that the three bosses at the corresponding positions of the adjacent small ring number ring N-1 of the B2 ring segment are completely flat. When the three bosses of the B2 segment itself are uneven, it will cause uneven load distribution on the B2 segment. The three bosses at the corresponding positions of the adjacent small ring number ring N-1 of the B2 segment are completely flat, which can be used as supports for B2 segments, no matter how uneven the three bosses of the B2 segment itself, how uneven the load on them, under the above-mentioned force transmission path, the B2 segment will not cracked. That is, the cracking of the segment has little effect on its own three bosses, and it is mainly affected by the three bosses of the adjacent small ring number.
5.2. On-site crack verification

Statistic of the on-site cracks, using the boss force type to analyze, (Based on the statistic of the on-site cracks and analysis of using boss force type) 86% of the cracks can be explained by four types of force (simple support, double-sided cantilever, single-point cantilever and two-point cantilever). However, 14% of the cracks cannot be explained. Explained by the above-mentioned force form could get the conclusion below. The results can be drawn from mechanical analysis: the combination of bosses at the corresponding position of the adjacent small ring of the cracked segment has a significant effect on the cracking of the segment.

![Figure8. Statistics of force form of cracked segment](image)

6. Conclusion

1) The cracks are mainly distributed in the upper half of the tunnel, and the length is mainly greater than 28cm. Note that they should be distributed on the side close to the big ring. The number of cracks corresponding to the boss accounts for about 90%.

2) The average number of cracks per ring is the smallest when the 3mm gasket is installed. The installation of the force transmission gasket helps to alleviate the occurrence of cracks in the pipe segment.

3) The uplift of the shield caused many cracks at the top and bottom of the tunnel, and the length of the cracks increased.

4) The 86% of the cracks can be explained by the four types of force (simple support, double-sided cantilever, single-point cantilever and two-point cantilever), and 14% of the cracks cannot be explained by the above-mentioned force form, that is, the cracked segments are adjacent to each other. The combination of bosses at the corresponding position of the small ring and the ring has a significant effect on the cracking of the tube segment.

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