Causes analysis of shield tunnel cracks in deep stratum with high water pressure

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Abstract. In the process of shield tunneling, there is a risk of cracks and diseases caused by geological changes, construction process, design and other factors, and leads to the construction process and even engineering accidents. This paper analyzes the cracks on the top of the segment under the geological conditions of deep burial and high water pressure by analyzing the cracks of a traffic rail project in Shenzhen, and analyzes the reasons for the cracks under normal construction. Based on the conventional stress model of segment and the screening of surrounding geological and hydrological conditions, the model assumption of local stress of integral segment is made, and the modified idiom and beam method are adopted. The results show that under the geological condition of fractured water stratum, the sudden change of water pressure caused by rainstorm and the joint action of broken rock block and segment floating will lead to the reduction of segment top space and direct contact with rock stratum, which will exceed the normal pressure range of segment and lead to cracks in the top segment.

1. Introduction

Shield tunnel accounts for more and more in municipal engineering, so the disease problems caused by shield tunnel are more and more concerning. Lu Qingshan, Li Lixin, et al.[1] analyzed the influence factors of the cracks in the loading process of the lining segment in the analysis of the loading cracks of the subway shield lining segment; Nong Xingzhong[2], in the calculation, analysis and reinforcement of the cracked segment of the shield tunnel, analyzed that the over excavation and insufficient grouting of the tunnel are one of the causes of the segment cracking; He Chuan, Liu chuankun, et al.[3] analyzed the influence of the number of cracks on the segment structure mechanics. The influence of crack location on segment failure mode was analyzed by Cao Songyu, Wang Shimin, etc.[4]; The failure mode model experiment of shield tunnel segment structure was studied by Liu chuankun, He Chuan, etc.[5], which mainly studied the mechanical condition and bearing capacity of segment under different crack length; The numerical simulation and analysis of structural disease of subway shield tunnel in soft soil layer by Li Qingtong[6]. In this paper, based on the causes of cracks in a deep tunnel in Shenzhen, the influencing factors of cracks in high water pressure, deep buried completely weathered mixed granite stratum are analyzed.
2. Project overview
A rail transit project is located in Guangming District, Shenzhen. It is laid along Guangming avenue to the north, with a total length of 1168 meters. The cracks are mainly distributed between 0-400 rings of the right line of the project, and the area is under the Chaishan mountain. The distribution is as follows: 9-2-2 strongly weathered mixed granite (half rock and half soil), 9-2-3 strongly weathered mixed granite (massive), 9-2-3 strongly weathered mixed granite (semi rock and half soil) from top to bottom include 9-3 moderately weathered mixed granite, 9-2-1 strongly weathered mixed granite (earthy), 9-2-3 strongly weathered mixed granite (massive), 9-3 moderately weathered mixed granite, and 9-4 slightly weathered mixed granite.

![Figure 1. Geological structure of tunnel buried depth](image1)

The groundwater in this section mainly includes pore water of loose rock, bedrock fissure water and structural fissure water. The dynamic characteristics of groundwater level are closely related to the local rainy season, and the time of peak and valley of water level is basically the same as that of rainfall. The annual water level varies from 2.5 m to 3.8 m.

3. Crack investigation

3.1 Investigation of cracks
The shield tunnel has an outer diameter of 6200 mm, an inner diameter of 5500 mm, a segment thickness of 350 mm and a segment lining width of 1500 mm. No cracks were found in the construction process of the ring where the cracks were located, and no cracks were found in the subsequent construction of the adjacent ring. The cracks appeared after about 200 rings were pushed backward, and the blocks were found to fall one by one. It was found that the main distribution of cracks tended to be between 0-400 rings, among which 161-261 rings were more closely distributed. The figure below shows the situation of segment falling on site.

![Figure 2. Lining ring segment partition](image2)

3.2. Data statistics
According to the field investigation and detection, the cracks generally appear in the first 400 rings, among which the cracks between 161-261 rings are relatively dense. According to the excavation
direction records, the crack distribution is mainly at the top of the shield tunnel, accounting for 90.24% of the total number of cracks, the upper right side accounts for 2.44%, and the upper left side accounts for 7.32%; the overall side close to the large ring is 90%, and a small amount of cracks are pasted. According to the statistics of shield segment partition, the cracks are most common in adjacent blocks, which are 31.71% in L1 block, 7.32% in L2 block, 26.83% in B1 block, 21.95% in B2 block and 12.2% in B3 block, respectively. There are no cracks in K block. The crack length in 76-161 ring is mainly 20cm-40cm, 161-261 ring is mainly 60-80cm, and a few of them are 150cm in length, of which the minimum width is 0.1mm and the maximum width is 3mm. The crack width is measured by crack width measuring instrument and other equipment. According to the statistical results, combined with the practical engineering experience, the maximum stress point of the whole ring of the shield segment is generally at the lower part, and the maximum deformation is also at the lower part. Therefore, it is very special that the cracks similar to the project appear at the top. In order to simulate the actual crack situation, the finite element software is used for simulation calculation and analysis. The next section will focus on the numerical simulation of the crack by the finite element software calculation and analysis of the process.

![Figure 3. Statistical chart of fracture information](image)

4. Calculation and analysis of segment stress
The key problem of using numerical simulation software to analyze shield tunnel segment is whether the structure itself can reflect the actual stress state of segment. The tunnel lining structure with the most serious cracks is taken as the calculation model, and two models are adopted, i.e. modified conventional method and beam spring method.

![Figure 4. Numerical simulation of conventional stress of integral segment](image)

According to the geological parameters of the site, the conventional stress model of the shield segment is shown in the figure. The position of the maximum axial force, bending moment, shear force and overall deformation is at the bottom of the ring, so the most prone position to crack is at the bottom, which is completely inconsistent with the actual position of the crack. Therefore, in order to get the simulation diagram consistent with the actual situation, we make the following assumption: under the condition of the general stress of the whole segment, a large concentrated force appears at the top of the
shield segment, breaking the original balance of the shield segment, and the generated force is enough to cause cracks at the top of the shield segment.

In the whole simulation process, increasing hydrostatic pressure is used to simulate the interaction of water and soil. At the same time, the stress range is reduced to the upper half of the loop, and the stress range is gradually reduced from ± 90 ° to 0 ° to find the critical value of the corresponding width crack. That is to verify the critical point of the stress range of the upper segment when the crack gradually increases to 3mm.

![Figure 5. Assumption of the top of integral segment under the action of extra force](image)

Using the same soil parameters, lateral earth pressure coefficient and foundation reaction coefficient, and fixed hydrostatic pressure value, we can calculate the angle at which the whole ring stress range of shield segment begins to appear, which is consistent with the stress situation of cracks at the top. When the force range is reduced to ± 20 ° under the action of the modified idiom, a force model conforming to the actual situation appears. The results show that the internal force of the segment is as follows:

The maximum axial force is 1324.7kn at element 360, and the minimum bending moment is -843.288kn at element 317;

The maximum bending moment is at the top element 1, -4645.04kn · m. The minimum axial force is at element 49, -5549.25kn · m. The results show that the internal force of the segment is as follows:

![Figure 6. Numerical simulation analysis on the top of integral segment under the action of extra force](image)

In beam - in the spring method calculation model, the longitudinal seam spring is applied to simulate the segment splicing, and the same number of longitudinal seam spring units are set at the top of the whole ring segment to simulate the segment cracks.
As shown in the figure, longitudinal seam spring is set at the top of segment unit 1, 3, 6, 358, and it is also assumed that additional pressure load is applied at the top of segment to cause cracks, and numerical analysis is carried out. Similarly, firstly, the hydrostatic pressure value is fixed, and the stress range is reduced from ± 90 degrees in turn, until the maximum axial force and bending moment begin to appear on the top of the simulation diagram, and the maximum axial force and bending moment under the condition of 3mm crack width are calculated by changing the hydrostatic pressure value. The results show that the internal force of the segment is as follows:

The maximum axial force is 92.474\( \text{kn} \) at element 3, and the minimum axial force is -221.104\( \text{kn} \) at element 89;

The maximum bending moment is -8808.67.04\( \text{kn} \cdot \text{m} \) at the top element 2, and the minimum bending moment is -9317.97\( \text{kn} \cdot \text{m} \) at the top element 92;

The results show that the internal force of the segment is as follows:

According to the diagram of axial force and bending moment, the maximum axial force and bending moment are at the top, which is consistent with the actual cracking position. The back calculation results show that the required pressure for crack formation is 2961.592\( \text{KN} \). The pressure on the top of the integral segment is about 786.596\( \text{kn} \) under the conventional stress model. According to the practical engineering experience, when the force of shield segment is about 3000\( \text{KN} \), and the pressure is far beyond the conventional top force, cracks will appear at the top.

5. **Cause elimination and analysis of segment cracks**

According to the numerical simulation analysis, it can be concluded that the actual cracks may be caused by the excessive pressure load on the top of the shield segment. Therefore, it is estimated that the excessive pressure at the top of shield segment is the cause of cracks.
Conventional factors that lead to excessive pressure on the top of shield segment include excessive thrust of shield cylinder, concentrated load caused by direct contact of segment top with rock surface due to segment floating, and water and soil collapse and accumulation at the top.

1) Excessive thrust of shield machine oil cylinder

The uneven thrust of shield machine oil cylinder leads to uneven stress at the top and bottom. However, according to the field actual thrust statistics and comparison of the difference between the upper and lower pressures, it can be seen that the lower pressure of the shield segment with cracks is greater than the upper pressure, as shown in the figure in red. Therefore, the cracks in this project are not caused by excessive thrust of shield machine.

Figure 9. Pressure difference between upper and lower parts of shield machine

2) Caused by segment floating

According to the existing calculation formula of segment floating, the allowable floating amount of segment is calculated and compared with the actual floating amount of segment, as shown in the figure below:

Figure 10. Compare the formula of actual segment floating from 0-400 rings with the allowable figures

The segments with cracks are marked with red dots in the figure. By comparing the allowable floating amount, it can be seen that most of the segments with cracks are above the allowable floating amount. However, it can be seen from the figure that the floating amount of most segments is large, but there is no crack. Moreover, the floating amount of the segments 243 and 251, which are the most seriously damaged segments in the project, is within the allowable range. Therefore, the cracks of 243 and 251 ring segments can not be attributed to the floating segment.

3) Local load mutation occurred in the top stratum

According to the analysis of the local geological and stratigraphic structure and the local hydrological situation before and after the fracture, there was a continuous rainstorm before the fracture. According to the geological exploration, the geology in Chaishan mountain was easily affected by the local rainfall,
resulting in a sudden rise of groundwater in a short time, which caused the fracture water to scour the broken rock zone in the mountain. Thus, the fracture water and rock wash down and accumulate, which leads to the joint action of the accumulated rock fracture zone and fracture water on the top of the shield segment tunnel, and the local excessive load, resulting in cracks.

6 Conclusion
Through the data model calculation, combined with the actual stratum and hydrological conditions, the influencing factors of the cracks in the deep buried and high-water pressure stratum are analyzed:

(1) In the process of shield tunnel construction, the surrounding geological and stratigraphic conditions will change with the influence of weather, resulting in complex stratigraphic conditions different from the original survey period, thus affecting the construction situation.

(2) In the process of shield tunneling, the slip of grouting slurry may cause the segment to float up, thus reducing the gap between the segment and the upper stratum, so that the upper rock mass and water pressure can act directly on the top of the segment to produce local load and cause cracks.

There would be several suggestions to solve this problem:

(1) Five pieces of steel ring segment are installed in the position of No.243 ring and No.251 ring, the steel leg is used to reinforce the bottom. Meanwhile, the anchor bolt is inserted into the steel segment, and the depth is penetrated into the tunnel segment from the inner plane of the steel segment.

(2) In the subsequent synchronous grouting process, double slurry injection is adopted to ensure that the grouting quantity reaches the standard. At the same time, according to the hole inspection behind the top of the segment, the secondary grouting method is adopted to fill the cavity.

Reference:
[1] Lu Qingshan, Li Lixin, Xu Piyuan, et al. Cracks Analysis of Loading On Subway Shield Lining Segment [J]. Chinese Journal of Underground Space and Engineering, 2011, 07 (04) : 676-680
[2] Nong Xingzhong. Analysis of Shield Tunnel Cracking Segment and Reinforcement Design [J]. Urban Mass Transit | Urban Mass Trans, 2010, (04) : 29-33
[3] He Chuan, Liu Chuankun, Wang Shimin, et al. Influence of Crack Number on Mechanical Properties of Shield Tunnel Segment Structure [J]. China J. Highw. Transp, 2018, 31(10):210-219
[4] Cao Songyu, Wang Shimin, Liu Chuankun, et al. Influence of crack location on failure mode of shield tunnel lining structure [J]. Journal of Southeast University (Natural Science Edition), 2020, 50(01):120-128
[5] Liu Chuankun, He Chuan, Wang Shimin, et al. Model test study on failure mode of segment structure of shield tunnel with crack length [J]. Journal Central South University (Science and Technology), 2019, 50(06): 1447-1456
[6] Li Qingtong. Numerical Modeling Analysis of Structural Defects of Shield Tunnel in Soft Soil Area [J]. Railway Standard Design, 2021, 65(1) : 95-103