Study on Lining Mechanical Behavior of Super Large Diameter Shield Tunnel during Segment Opening

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Abstract. The mechanical behavior and risks of the lining of the super large shield tunnel during segment opening are still unclear. In order to study the characteristics of the mechanical behavior of the lining of the super-large-diameter shield tunnel during segment opening, take the cross-passage project of Hangzhou Zhijiang Road Water Conveyance Corridor and Road Improvement Project as the engineering background. The MIDAS finite element numerical calculation model of the opening on the double-track main tunnel lining is established. The influence of the opening size and support stiffness on the mechanical behavior of the lining is analyzed separately. The main conclusions are: (1) The maximum deformation of the lining when opening occurs in the middle area directly above the opening. It is necessary to strengthen the deformation monitoring of the segment in this area during construction to prevent excessive deformation or even damage and accidents; (2) The reduction of the opening area within a certain range and the increase of the stiffness of the temporary support can reduce the deformation of the lining after the opening. Based on the determined parameters of the main tunnel lining and opening, the stiffness of the temporary support can be increased to reduce the deformation of the lining opening; (3) Setting up temporary supports and increasing the stiffness of the temporary supports cannot affect the final deformation of the lining after the temporary supports are removed. Therefore, to stabilize the lining in the open area, it is necessary to rely on pouring ring beams.

1. Introduction

Shield construction of tunnels has been widely used in the construction of urban road tunnels with complex environments because of its advantages such as fast excavation speed, low impact on the surrounding environment and high degree of information mechanization [1]. When double-line shield tunneling is adopted, the connecting channel plays a vital role in the emergence of natural disasters and other emergencies in the tunnel [2]. At present, the connecting channel is mostly excavated by undercut method. Before excavating connecting passages with undercutting method, the shield lining segment must first be opened.

Regarding the issue of openings on shield tunnel segments, relevant research work has been done at home and abroad. British Sloan and Andrew [3] studied the influence of soil layer properties on the reinforcement effect under different geological conditions, and adopted freezing, grouting and other connecting channel reinforcement methods according to different geological conditions. Zhang et al. [4] established the three-dimensional finite element model of the intersection of the double-line shield tunnel and the connecting passage with the shield tunnel connecting passage of Guangzhou Metro Line 2 as the engineering background. The influence of the opening size of the special ring segment on the internal force of the main tunnel shield segment is analyzed. He et al. [5] conducted stress...
monitoring on the opening process of the special ring segment of the connecting passage of the Beijing subway, and compared and analyzed the force of the concrete reinforced ring segment adjacent to the special ring steel pipe segment, and obtained the law of stress change caused by the opening of the special ring segment. Wang [6] used numerical methods to analyze the effect of erecting steel supports on the forces and deformations of shield tunnel segments. Wu et al. [7] took the shield tunnel connecting passage of Shenzhen Metro Line 2 as the engineering background, and simulated the effect of step-by-step excavation of grade V surrounding rock connecting passages with mining method, with 30% stress release rate of burrows and 70% stress release rate of initial support on the open segment ring, and the simulation results that are more consistent with the measured data have been obtained. Zhang [8] took a TBM connecting passage of Qingdao Metro as the engineering background, combined with engineering practice, theoretical calculation and numerical simulation, took the analysis of the stress redistribution before and after the opening of the segment as the starting point, simulated and analyzed the mechanical behavior of the step-by-step excavation of the connecting channel, compared two different temporary support schemes, and selected a more optimal scheme. It can be seen scholars at home and abroad have achieved certain results in the research on the opening of the shield tunnel segment.

However, the research work and results related to the opening of the lining segment of the super large-diameter shield tunnel are rarely seen in the literature. Based on the engineering background of the cross-passage project of Hangzhou Zhijiang Road Water Conveyance Corridor and Road Improvement Project, this paper will study the characteristics of the mechanical behavior of the segment-opening lining of the super-large-diameter shield tunnel.

2. Project Overview

Hangzhou Zhijiang Road Water Conveyance Conveyor and Road Improvement Project starts from Meiling South Road and ends at Shuicheng Road, with a total length of about 6.3 km. Among them, the underground tunnel starts west of Zhipu Road in the west, and is laid along Zhijiang Road to the east to Fuxing Road. The total length is about 5.6 km, including 2.0 km of open cut section and 3.6 km of shield tunneling section. The main line shield adopts a circular shield section with an outer diameter of 14.5 m, the wall thickness of the segment is 0.6 m. Figure 1 is the schematic diagram of the direction of Zhijiang Road Water Conveyance Conveyor and the Road Improvement Project.

![Figure 1. Schematic diagram of the direction of Zhijiang Road Water Conveyance Conveyor and Road Improvement Project.](image)

The proposed vehicle and pedestrian crossing is located on the west side of Qiantang River Bridge, with a mileage of NK4+510, a channel length of about 40.2 m, a clear height of 4.6 m for the opening section, and a clear height of 6.0 m for the channel section. The buildings surrounding the passage include Mao Yisheng Monument, Hangzhou Liberation Monument and Qiantang River Bridge, the distances are respectively 29 m, 43 m and 90 m. The buried depth of the channel is about 27 m, and
the stratum is 29a-3-2 middle weathered upper siltstone. Figure 2 is layout of the longitudinal section of the cross aisle.

![Figure 2. Layout of the longitudinal section of the cross aisle.](image)

3. Analysis of Lining Mechanical Behavior of Super Large Diameter Shield Tunnel During Segment Opening

3.1. Establishment of Finite Element Model

MIDAS finite element numerical calculation software is used for modeling analysis. Considering the elimination of boundary effects, the model size is taken as: x×y×z=160 m×50 m×80 m. The boundary conditions of the model are: the four sides and the bottom are all fixed in normal direction, that is, the four sides are horizontally restrained and vertical free, and the bottom is vertically restrained and horizontally free. The rock-soil mass adopts the modified Mohr-Coulomb model, the lining adopts the elastic model, and the temporary support adopts the beam element and elastic model. The numerical calculation model is shown in figure 3.

![Figure 3. The overall finite element model.](image)
The model parameters of rock and soil mass and structure are shown in table 1 and table 2.

### Table 1. Model parameter of rock and soil mass.

| Geotechnical layer                      | Simulation unit | Constitutive model                  | Natural density $\gamma$ (kN/m$^3$) | $c'$ (kPa) | $\phi'$ (°) | $E_{50}$ (MPa) | $E_{oed}$ (MPa) | $E_{ur}$ (MPa) | $G_0$ (MPa) |
|-----------------------------------------|-----------------|-------------------------------------|-------------------------------------|------------|------------|---------------|---------------|---------------|-------------|
| Gravel fill                             | Solid unit      | Modified Mohr-Coulomb               | 19.3                                | 5          | 29         | 7             | 7             | 35           | 70          | 0.8         |
| Strongly weathered siltstone            | Solid unit      | Modified Mohr-Coulomb               | 20.6                                | 35         | 20         | 19            | 19            | 57           | 114         | 0.5         |
| Moderately weathered upper siltstone    | Solid unit      | Modified Mohr-Coulomb               | 26                                  | 100        | 38         | 80            | 80            | 240          | 480         | 0.5         |
| Moderately weathered lower siltstone    | Solid unit      | Modified Mohr-Coulomb               | 26                                  | 100        | 38         | 80            | 80            | 240          | 480         | 0.5         |

### Table 2. Model parameter of structure.

| Structure name                           | Simulation unit | Constitutive model | Natural density $\gamma$ (kN/m$^3$) | $E$(GPa) | $\nu$ |
|------------------------------------------|-----------------|--------------------|-------------------------------------|----------|------|
| Shield segment                           | Solid unit      | Elasticity         | 25                                  | 27.6     | 0.2  |
| Temporary steel support                  | Beam unit       | Elasticity         | 78.5                                | 206      | 0.3  |

3.2. Analysis of the Influence of Opening Size on the Mechanical Behavior of Lining

In order to analyze the influence of the increase of the opening size on the mechanical behavior of the lining structure and the soil during the opening process, the opening sizes are considered to be 2 m×2 m, 4 m×4 m, 6 m×6 m, 8 m×8 m, respectively. Modeling is used for calculation, mainly analyzing the calculation results of lining segments.
Figure 4. Cloud diagrams of lining deformation after segment opening.

Figure 5. Cloud diagrams of lining deformation after support removal.
It can be seen from Figure 4 and Figure 5 that the maximum deformation of the lining occurs in the middle area above and below the opening. The maximum deformation of the lining is shown in Figure 6. It can be seen the maximum deformation after the opening of the segment and the maximum deformation after removing the support gradually increase with the increase of the opening area. After the opening of the segment, when the opening area is small (in this study, the opening area is less than about 36 m², this area value may depend on factors such as lining diameter, thickness, buried depth, and mechanical parameters of surrounding rock, which can be further studied later), after the opening of the segment and the removal of the support, the maximum deformation of the lining is linearly related to the area of the opening. When the opening area is large (the opening area in this study is greater than about 36 m²), the maximum deformation after the opening of the tube segment does not increase significantly with the increase of the opening area, indicating that when the opening area is larger than a certain value, the temporary steel support can effectively prevent the deformation of the tube segment from increasing. After the support is removed, the deformation continues to increase with the increase of the opening area.

3.3. Analysis of the Influence of Support Stiffness on the Mechanical Behavior of Lining
In order to analyze the influence of the stiffness of the temporary internal support on the mechanical behavior of the lining structure and the soil during the opening process, considering the steel support diameters of 400 mm, 580 mm, 600 mm, 630 mm, and 800 mm, respectively, modeling and calculation are performed, mainly analyze the calculation results of lining segments. Figure 7 is cloud diagrams of lining deformation after segment opening with different steel support diameters. Figure 8 is cloud diagrams of lining deformation after support removal with different steel support diameters.

![Figure 6. The relationship between the maximum deformation of the lining and the opening area.](image-url)
Figure 7. Cloud diagrams of lining deformation after segment opening.
Figure 8. Cloud diagrams of lining deformation after support removal.

Figure 9. The relationship between the outer diameter of the steel support and the maximum deformation of the lining.

Figure 9 shows the maximum deformation of the lining after the opening of the segments with different support diameters. It can be seen that as the rigidity of the steel support increases, the maximum deformation of the lining gradually decreases after the opening. However, after the steel
support is removed, the maximum deformation of the lining remains basically unchanged, that is, the maximum deformation of the lining after the removal of the support is basically independent of the rigidity of the steel support. Further analysis shows that even if there is no temporary steel support before the opening, the maximum deformation of the lining is very close to that of the support is set first and then removed. The support stiffness can effectively reduce the deformation of the lining when opening, but the presence or absence of temporary support does not affect the maximum deformation of the final lining.

4. Conclusions
In order to study the mechanical behavior characteristics of the lining of the super-large diameter shield tunnels during segment opening, this paper takes the Hangzhou Zhijiang Road Water Conveyance Corridor and Road Improvement Project as the engineering background, and establishes the MIDAS finite element numerical calculation model of the opening on the main tunnel lining. The influence of opening size and support stiffness on the mechanical behavior of lining are analyzed separately, and the main conclusions are as follows:

1. The maximum deformation of the lining during the opening occurs in the area directly above the opening. It is necessary to strengthen the deformation monitoring of the segment in this area during construction to prevent its excessive deformation or even damage and causing accidents;
2. The reduction of the opening area within a certain range and the increase of the rigidity of the temporary support can reduce the deformation after the opening of the lining. On the basis that the parameters of the main tunnel lining and opening have been determined, the rigidity of the temporary support can be increased to reduce the deformation of the lining when opening;
3. Setting up temporary supports and increasing the stiffness of temporary supports can effectively reduce the deformation of the lining after the opening, but cannot affect the final deformation of the lining after the temporary support is removed. Therefore, to stabilize the lining in the opening area, it is necessary to rely on pouring ring beams.

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