Research on Tunnel Lining Cavity Treatment Technology of a Metro Tunnel in Chongqing

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Abstract: The hollowing problem of tunnel lining structure is like a suspended bomb, which may affect the safety of vehicles and the safety of passengers at any time. Therefore, the study of tunnel lining structure cavity management technology has great social significance for ensuring tunnel safety. Taking a metro tunnel in Chongqing as an example, this paper proposes a reasonable lining structure reinforcement scheme of changing partial arches and reinforcing by steel strips after analyzing the environment, the bearing requirements, and the size and location of cavities. Based on the calculation formula of flexural members given by Code for Design of Concrete Structure Reinforcement, reduction system is introduced to calculate safety coefficient of flexural and compression members. The minimum value of structural bearing after treatment is 4.4, which meets the requirement of bearing capacity. Stratum structure method is used to calculate surrounding rock deformation during reinforcement. The maximum horizontal displacement is 1.9 mm, and the vertical displacement is 6 mm. The surrounding rock could be stable when treating defects, and the treatment scheme meets the requirements of bearing capacity and inner clearance. Therefore, the tunnel lining structure cavity can be reinforced by means of shotcrete and steel strips, without interrupting traffic and ensuring driving safety. The success of the treatment provides a useful reference for other similar projects.

1. Introduction
Tunnel lining structure cavity is invisible and difficult to be found by naked eyes during daily maintenance. However, accidents such as block falling will inevitably cause immeasurable losses to high-speed vehicles and passengers [1]. Affected by geological environment and construction technology, cavity is common in tunnel lining. The cavity would cause insufficient bearing capacity or stress concentration of the lining structure, and thus leads to structure crack and fall-block. It is of great practical significance to study the treatment technology of tunnel lining structure cavity and put forward the countermeasures and evaluation methods [2-3].

Scholars at home and abroad have carried out research through theoretical analysis and numerical simulation to study the cause, mechanism and solution of tunnel lining cavity. For example, through model tests, Zhang Xu et al. simulated the structural stress change rule and crack evolution process under the condition of twin voids in the tunnel crown and spandrel. Zhang concluded that the two
cavities could easily cause the internal force redistribution, the insufficient bearing capacity of the structure and the development sequence of cracks in the lining structure [4]. Ning Yan et al. carried out numerical simulation of different cavities through the forward simulation software GPMax3.0 of the geological radar and obtained the feasibility of GPMax3.0 simulated geological radar detection by combining with engineering examples [5]. Lai Jinxing et al. used ANSYS finite element software to analyse the lining cavity of a metro tunnel in Xi’an, and obtained that when there was no cavity in the lining, the stress in the surrounding rock presented a butterfly distribution. They proposed the influence of the size and location of the lining cavity on the surrounding rock and the lining structure [6]. Wang Yingjie made a detailed analysis of Jianshanzi Tunnel based on tunnel address, lining structure construction technology and accident detection results. He obtained the mechanism of lining diseases in expressway tunnel operation, and concluded a set of rapid treatment technology for lining diseases without affecting the normal operation of the tunnel [7]. Although there is research on tunnel lining cavities, studies on specific projects are few. At the same time, the treatment of traditional cavities mostly relies on construction experience, while there are few calculations and analyses on the stability of surrounding rocks during treatment and the structural safety after treatment. The treatment scheme is not supported enough.

The paper classifies the lining cavities in a regional tunnel of Chongqing metro and proposes a treatment scheme suitable for the project to cope with the cavities. Through load structure method and stratum structure method, numerical analyses on lining structure are carried out, and the rationality and feasibility of construction scheme are verified [8-10].

2. Project Profile

2.1 Lining Cavity and Its Classification

According to the test results of lining cavities in section SK6+244.6–SK6+332.6 of the tunnel in Chongqing, there are five under-excavation cavities in this section. As shown in Fig.1, all of them situate in the inside lining structure.

The test results are shown in table 1. The 1# and 2# cavity have transfixed. In the 5# cavity, the depth of waterproof board cavity is 17cm. The 6# cavity, 8cm with woven bag filling. The 8#, 9# and 10# cavity have transfixed. The depth of waterproof board cavity is 12cm.

![Fig.1 Distribution Map of the Cavities](image)
### Table 1 Test Results of Lining Structure Cavities

| Number | Longitudinal Direction×circumferential Direction | Medial Concrete $h_0$ | Cavity Depth $h$ | Lateral Concrete $h_1$ | $\Delta h$ |
|--------|--------------------------------------------------|----------------------|-----------------|------------------------|-----------|
| 1#-2#  | 1.5m×3.0m lcm                                    | 5cm                  | /               | -34cm                  |           |
| 5#     | 2.5m×1.5m                                        | 6cm                  | 10cm            | /                      | -24cm     |
| 6#     | 1.0m×1.6m                                        | 2cm                  | 10cm            | /                      | -28cm     |
| 7#     | 1.2m×1.5m                                        | 3cm                  | 24cm            | /                      | -13cm     |
| 8#-10# | 5.5m×3.5m                                        | 4cm                  | 16cm            | /                      | -20cm     |

#### 2.2 Geological Conditions
The tunnel with cavities is a deep carven without bias. Its surrounding rock grade is IV. The ground elevation at the cavities is 292.7 to 306.5 m, and the terrain is gentle. The tunnel is covered by zero-to-ten-meter-thick overlying soil layer. Generally speaking, the thickness of the soil layer is about 0.5 to 1.5 m. The underlying bedrock is sandy mudstone and medium thick bedded sandstone. The thickness of strata at the top of the tunnel is 25 to 55 m. The forward direction of the tunnel is opposite to the trend of rock strata. The surrounding rock is mainly sandy mudstone with two-to-four-meter sandstone in some parts. The fractures are not developed, and the rock mass is blocky structure with a rock mass integrity coefficient of 0.64 to 0.74.

#### 2.3 Hydrogeological Conditions
The construction site of the regional tunnel lies on the region with hilly slope landform. It is close to the bank slope of the Yangtze River valley with undeveloped surface water system and good surface water discharge. The hydrogeological conditions are simple. There are two types of groundwater in the site: pore water in unconsolidated formation and fissure water in bed rock. Their recharge mainly comes from atmospheric precipitation. The pore water in unconsolidated formation is mainly in the quaternary loose overburden and strong weathered rock stratum whose water content is little. Its water regimen is influenced by atmospheric rainfall. The quaternary soil in the site is of uneven thickness, and the overburden in the area of Haitong Road is of large thickness, reaching 6.4 to 48.6 m. After drilling water level observation, there is no continuous water level of groundwater.

### 3. Treatment Design

#### 3.1 Lining Structure Parameters
The lining type of the tunnel is BC1 with a 400-millimeter-thick secondary lining. The concrete strength grade is C30, and the annular reinforcing steel bar is arranged as c20@150. The lining structure of the tunnel is shown in Fig. 2.
3.2 Treatment Design
As the rail transit is operating, the conventional pumping concrete cannot be realized. In consideration of structure safety, long-term operation and other factors, a treatment scheme of using shotcrete and reinforcing by steel strips is designed. As shown in Fig.3, the concrete in the area without thick secondary lining should be chiseled away first. Then, we would spray concrete. Finally, we would use continuous stainless steel strip to reinforce.

The construction sequence is as follows. Firstly, chisel away concrete that is 30cm in and out of the area without thick secondary lining (no damage to steel bar of the secondary lining). Secondly, assemble reinforcing steel according to the originally designed reinforcement parameters, and then apply interfacial agent to the lining surface and spray C40 plain concrete (the cumulative thickness of the concrete shall be no less than 40cm). Thirdly, grind off two-to-three-centimeter-thick secondary lining concrete on the lining surface, and then, paste 40-centimeter-wide stainless steel belts to reinforce lining.
4. Numerical Simulation Analysis

4.1 Parameter Selection and Security Coefficient Calculation

Through MIDAS, a numerical simulation software, the bearing capacity of reinforced structure is calculated by load structure method, and the stability of surrounding rock during treatment is calculated by stratum structure method. Based on the calculation results, the safety of lining structure after treatment is evaluated [11-13]. The parameters of checking calculation are listed in Table 2. As bulk densities are not specified in the original design specification, the bulk density of medium-weathered sandy mudstone is specified as 25.9 kN/m³ and that of medium-weathered sandstone is 25.2 kN/m³ by referring to the values of surrounding similar projects. As the tunnel is located in the medium-weathered sandy mudstone and medium-weathered sandstone, the elastic resistance coefficient is set as 280 MPa/m for checking calculation.

| Geotechnical Parameters | Bulk Density (kN/m³) | Elastic Modulus (GPa) | Poisson's Ratio μ | Cohesion c (kPa) | Internal Friction Angle φ (°) |
|-------------------------|----------------------|-----------------------|------------------|-----------------|-----------------------------|
| Medium-weathered Sandy Mudstone | 25.9 | 1.203 | 0.37 | 350 | 26 |
| Medium-weathered Sandstone | 25.2 | 2.223 | 0.1 | 1260 | 34 |

In consideration of the actual situation of pasting steel belt when calculating the bearing capacity of a member subjected to large eccentric compression, the reduction factor is introduced to the calculation of safety factor of the tunnel lining with steel-belt-bounded reinforcement. The calculation formula is shown in formula (1). Other calculation formulas and parameters are the same as the checking calculation of normal section reinforcement of large eccentric compression member in Code for Design of Concrete Structure Reinforcement [14].

\[ KN \leq \alpha f_{sp} b x + f'_{y0} A'_{x0} - f'_{y0} A_{x0} - f_{sp} A_{sp} \psi_{sp} \]  

(1)

Where: \( K \) --safety factor; \( N \) --design value of axial pressure after reinforcement (kN); \( \alpha \) --stress characteristic coefficient of members; \( A_{x0}, A'_{x0} \) --section area of tensile and compressive steel bar of the original members (\( \text{mm}^2 \)); \( f_{sp} \) --design value of tensile strength of strengthened steel plate (\( \text{N/mm}^2 \)); \( f_{x0} \) --design value of axial compressive strength of concrete of original members (\( \text{N/mm}^2 \)); \( f'_{y0} \) --design value of compressive strength of longitudinal reinforcement in compression zone of original member (\( \text{N/mm}^2 \)); \( A_{sp} \) --section area of tension steel plate (\( \text{mm}^2 \)); \( b \) --width of rectangular section (\( \text{mm} \)); \( \psi_{sp} \) --the reduction coefficient.

4.2 Checking Calculation of Lining Structure Reinforcement Safety

Through load structure method, the stress situation of the secondary lining structure after the treatment of the five cavities is calculated. The calculation model is shown in Fig. 4.
TypeⅠcavity lying in the outside lining structure is near the primary support. 3# and 4# cavity are typeⅠcavity. TypeⅡcavity lying in the inside lining structure is near the clearance. It is caused by woven bag filling. 11# and 12# cavity belong to typeⅡ. After the treatment, the bending moment, axial force and shear force of the structure are calculated. Results are shown in Fig.5.

Fig.4 Calculation Model of Linear Load Structure

Fig.5 Distribution Map of Lining Force

After reinforcing the lining structure, the safety coefficient and crack width of the lining structure at the five cavities are calculated. The results are listed in Table 3.

| Section’s Position | Cover Thickness | Steel Bar Arrangement | Bending Moment (kN·m/m) | Axial Force (kN/m) | Safety Coefficient | Crack Width |
|--------------------|-----------------|-----------------------|------------------------|-------------------|-------------------|-------------|
| Vault              | 40              | C20@150               | 112.4                  | 430.2             | 4.40              | 0.09        |
| Spandrel           | 40              | C20@150               | -128.5                 | 649.9             | 5.39              | 0.09        |
| Side Wall          | 40              | C20@150               | -95.0                  | 884.7             | 7.16              | Meet the demands |
| Invert             | 40              | C20@150               | 78.7                   | 890.4             | 7.68              | Meet the demands |

As we can see in the above table, the minimum safety coefficient is 4.40, larger than 2.0, the value required by the code. The maximum crack width is 0.09 mm, which is less than 0.2 mm, the required value. Therefore, the bearing capacity of the structure meets the requirements of the code.

4.3 Checking Calculation of Lining Structure Reinforcement Deformation

Through stratum structure method, the displacement of surrounding rock and expansion of plastic zone during the treatment is calculated. In the calculation, plane strain model is adopted to simulate the stratum, beam element is used to simulate the primary support structure, and plane strain unit is chosen to simulate the secondary lining structure. Anchor taken as safety reserve is not considered during calculation [15].

The calculation procedure of stratum structure method is as follows:
initial ground stress (displacement reset) → down-line excavation → down-line primary support → down-line secondary lining → up-line excavation → up-line primary support → up-line secondary lining → cavity lining removal → shotcrete reinforcement. The plastic zone distributions of the lining structure during cavity removal and after shotcrete reinforcement is shown in Fig.6.

![Fig.6 Plastic Zone Distribution](image)

It can be seen in the above figure that the positions of plastic zone of the secondary lining on the left line did not change during cavity removal and after shotcrete reinforcement. They are all at haunch. However, during cavity removal, the haunch enters the plastic phase. After shotcrete and steel belt reinforcement, the effect becomes obvious, and the haunch has no plastic failure.

The results of deformation calculation during cavity removal and after shotcrete reinforcement are shown in Table 4.

| Evacuation            | Horizontal Displacement/mm | Vertical Displacement/mm |
|-----------------------|----------------------------|-------------------------|
|                       | Positive Direction | Negative Direction | Positive Direction | Negative Direction |
| Cavity Removal     | 1.9                      | -1.5                    | 6.7                 | -6.0                |
| Shotcrete Reinforcement | 2.0                      | -1.6                    | 6.7                 | -6.1                |

In the process of lining removal, the maximum horizontal displacement of surrounding rock increases 0.1mm from 1.9mm to 2.0mm in positive direction and from 1.5mm to 1.6mm in negative direction. The maximum vertical displacement of surrounding rock does not change in positive direction, while increases 0.1mm in negative direction. Therefore, the risk of surrounding rock instability is low if the construction is properly controlled in the process of removing the original cavity.

5. Conclusion

Through load structure method and stratum structure method, the bearing capacity of the structure after treatment is calculated. The following conclusions are drawn based on the calculation results, survey data of the regional tunnel, test report and the design scheme of cavity treatment.

(1) After the treatment of cavity defects, the minimum safety coefficient of the structure is 4.40, which is larger than 2.0, the value required by the code. The maximum crack width of the structure is 0.09 mm, less than the control value of 0.2 mm specified in the code. They meet the requirements of the code.

(2) The maximum horizontal displacement of surrounding rock increases 0.1mm from 1.9 mm to 2.0 mm in the positive direction and from 1.5 mm to 1.6 mm in the negative direction. The maximum vertical displacement of surrounding rock does not change in the positive direction, which is 6.7 mm, yet it increases 0.1 mm in the negative direction. There is a low risk of surrounding rock instability if the construction is properly controlled.

The treatment of operating tunnels with little time, heavy tasks and great influence requires great attention to construction quality to prevent any secondary damage during construction. After the
treatment is finished, the external steel plate, cement mortar and shotcrete should be ensured to be free from peeling, dropping and other quality defects.

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