Analysis of the Influence of the Unsymmetrical Surface Surcharge on the Structure of the Subway Tunnel

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Abstract. Field case of staggered jointed lining of metro shield tunnel with an unexpected unsymmetrical surface surcharge is introduced in details at first. The finite element model of beam-spring is used to reproduce the surface surcharge process. Results show that the tunnel deviates from the surface surcharge under the action of unsymmetrical surface load. The displacement of adjacent rings A and B is different, which caused tunnel disease such as segment dislocation and water leakage. In the design state, the bending moment and axial force of A and B rings are close to each other, after unsymmetrical surface surcharge, the bending moment of ring B with key segment on the lower surface pressure side is larger than ring A. When the crack width is 0.2 mm, the corresponding horizontal expansion and vertical convergence are 33 mm (5.3D ‰) and 34 mm (5.5D ‰). When the horizontal expansion value is greater than 50 mm (8D ‰), ring B will enter into the stage of rapid development of cracks, which should be closely monitored and treatment measures should be taken when necessary. The bearing capacity of ring A and ring B is different after surface surcharge, which is suggested to be considered in the subsequent structural reinforcement.

1. Introduction
By the end of 2019, there are 208 urban rail transit lines in operation in a total of 40 cities in mainland China with the total length of 6736.2 km [1]. The problems of large deformation, cracking, water leakage and other diseases of shield tunnel structure caused by sudden large amount of surface surcharge are particularly prominent [2-5]. There were 16 times of sudden surface surcharge along Shanghai Rail Transit in 2014 [6]. Among them, unsymmetrical surface surcharge occurs occasionally [7]. The unsymmetrical additional stresses destroy the original balance of the shield tunnel structure. When serious, it will cause joint opening, segment cracking and bolt failure, which will seriously affect the safety of rail transit. At present, the research tends to focus on symmetrical loads, and less attention is paid to unsymmetrical loads. Wei et al. [8] studied the theoretical calculations method of transverse force on shield tunnel caused by eccentric load, which is lack of verification by measured data. For the shield tunnel with A-B staggered assembling, due to the different positions of key segments and circumferential joints of the two adjacent rings, the damage level of the two adjacent rings is also different under the action of unsymmetrical load. Based on the site detection data of urban
rail transit diseases, the deformation and stress characteristics of the tunnel under the action of unsymmetrical surface surcharge is analysed, the causes of the tunnel diseases are discussed, which has important engineering practice significance.

2. Project Description
The depth of metro shield tunnel is 8.1-10.4 m, and the overlying soil layers are filling, clay and silt. Precast C50 reinforced concrete segments are used, with inner diameter of 5.5 m, outer diameter of 6.2 m and ring width of 1.2 m. A-B staggered assembling is adopted (figure 1). The two adjacent rings are an assembly cycle. The key segment of ring A is located on the side with high surface surcharge, and that of ring B is located on the side with low surface surcharge. 12 circumferential bolts connect the segments, and 16 grade longitudinal bolts connect the rings.

Due to a large amount of surface surcharge above the tunnel, serious defects such as cracks, water leakage, joint dislocation, joint opening and track bed separation occur, which endanger the operation safety. According to the site detection of structural disease, longitudinal cracks were found in the adjacent segments L1 and L2 at the top of the tunnel, the length of longitudinal crack in the seriously damaged section reaches 1.2 m reaching the whole segment width and the deepest crack is about half of the segment thickness. The number of cracks in ring A account for 25% of the total number, while those in ring B account for 75%. The maximum crack width of ring A is 0.4 mm, and that of ring B is 2.0 mm. All cracks with width greater than 1.0 mm are distributed on block L2 of ring B. The number of cracks in ring B is obviously more than that in ring A, and the average crack width is obviously larger than that in ring A. The maximum separation of track bed is 28.74 mm, which is located in ring A. The maximum external expansion of tunnel contour is 9.61 cm (15D ‰), which includes the deformation before surface surcharge. The longitudinal joints between F-L2 and F-L1, especially between F-L2, are significantly larger than other longitudinal joints. The maximum joint dislocation occurs at the circumferential joint with the value of 11 mm, and the key segment protrudes downward.

3. Numerical Calculation Models
According to the site detection, five ring segments in the seriously damaged section are selected as the research object, and the beam-spring three-dimensional finite element model is established. The segments are simulated by beam elements, circumferential joint and longitudinal joint are simulated by spring elements, and foundation resistance is simulated by spring, as shown in figure 2. The tunnel depth is 9.6m, the water and soil pressure is calculated according to the soil parameters provided in the geotechnological reconnaissance report. In order to simulate the reinforcement of steel bars, the elastic modulus of concrete is increased according to the principle of stiffness equivalence. Considering the bending resistance, shear and compressive performance of the joint, parameters of the joint are inversed according to the tunnel deformation data detected on site which is shown in table 1.

The tunnel is subjected to vertical earth pressure, lateral earth pressure, pore water pressure and arch bottom reaction pressure before surface surcharge. After the unsymmetrical loading on the tunnel, in addition to the above stress, vertical additional stress and horizontal additional stress are also considered, shown in figure 3.
Table 1. Parameters of the joint.

| Joint type          | Bending stiffness coefficient kN.m/rad | Tensile compression stiffness coefficient kN/m | Shear stiffness coefficient kN/m |
|---------------------|----------------------------------------|-----------------------------------------------|---------------------------------|
| Circumferential joint | $1.5 \times 10^3$                     | $1 \times 10^7$                              | $1.1 \times 10^4$               |
| Longitudinal joint   | -                                      | $1 \times 10^3$                              | $4.5 \times 10^4$               |

4. Analysis of Tunnel Deformation and Internal Force

4.1. Tunnel Deformation

Figure 4 is the vector diagram of the total displacement caused by unsymmetrical surface surcharge. Under the action of unsymmetrical load, the displacement of the tunnel deviates from the surface surcharge, and the tunnel changes from elliptical state to oblique elliptical state. The displacement of arch crown is the largest and that of arch bottom is the smallest. The maximum displacement of ring A is 11.15 cm, and that of ring B is 10.25 cm. The minimum displacement of ring A is 3.78 cm, and that of ring B is 3.29 cm. Due to the displacement difference between adjacent ring A and ring B, the joint of segment appears dislocation, water leakage and other diseases.

Table 2 shows the comparison between the calculated value of horizontal expansion and vertical convergence and the measured value. The calculated value of horizontal expansion of tunnel after surface surcharge is 8.4 cm, the measured value is 9.6 cm, and the error is 9%. The calculated value of vertical convergence is 9.9 cm, which is close to the measured value of 9.7 cm, and the error is 2%, which meets the needs of engineering.

According to the site detection results, there is a good correspondence between the segment ring with obvious track bed separation and the segment ring with large section deformation. Due to the unsymmetrical surface surcharge, the segments become ellipse, and the tunnel expands outward in the horizontal direction. The track bed is cast-in-place concrete, which is separated from the segment at the construction joint and does not expand horizontally with the segment, resulting in the separation between the track bed and the segment.
Table 2. Comparison between calculated value and measured value.

| Item                   | Calculated value (cm) | Measured value (cm) | Error |
|------------------------|-----------------------|---------------------|-------|
|                       | Before surface surcharge | After surface surcharge |       |
| Horizontal expansion   | 2.7                   | 8.4                 | 9%    |
| Vertical convergence   | 2.5                   | 9.9                 | 2%    |

4.2. Tunnel Bending Moment

Figures 5-6 show the bending moment distribution of ring A and ring B before and after surface surcharge. The maximum positive bending moments of ring A and ring B are 105.43 kN·m and 103.23 kN·m respectively. The maximum negative bending moment of ring A is -214.82 kN·m, and that of ring B is -190.99 kN·m. The bending moment of ring A and ring B are close to each other under symmetrical load. The maximum positive bending moment of ring A and ring B is 297.52 kN·m, and that of ring B is 366.24 kN·m, which is 23% larger than that of ring A. The maximum negative bending moment of ring A is -282.16 kN·m, and that of ring B is -491.82 kN·m, which is 74% larger than that of ring A. It can be seen that the bending moments of adjacent ring A and ring B are no longer close under unsymmetrical load. Due to the existence of joint, the bending moment of ring A with key segment on the side with greater pressure is smaller than that of ring A. The bending moment of ring B with key segment on the other side is significantly larger than that of ring A. This is also the reason why the number of cracks in ring B is significantly greater than that in ring A.

4.3. Tunnel Axial Force

Figures 7-8 show the axial force distribution of ring A and B before and after surface surcharge. The maximum axial forces of ring A and ring B are 1098 kN and 1081 kN respectively, which are located at the arch waist. The maximum axial force of ring A increased by 23% to 1350 kN, and that of ring B increased by 53% to 1654 kN. The minimum value of axial force of ring A and ring B is basically unchanged before and after surface surcharge.
4.4. Crack Calculation

According to Code for design of metro, the maximum allowable crack width of shield tunnel segment is 0.2 mm. According to the calculation formula of crack width in code for design of concrete structures, when the crack width of tunnel segment is 0.2 mm, the corresponding bending moment is 122 kN·m. Figure 9 shows the curve of maximum positive bending moment to horizontal expansion, and figure 10 shows the curve of maximum positive bending moment to vertical convergence. When the crack width is 0.2 mm, the corresponding horizontal expansion is 33 mm (5.3D‰), and the vertical convergence deformation is 34 mm (5.5D‰). When the horizontal expansion and vertical convergence deformation are less than 50 mm (8D‰), the bending moments of rings A and B are close. When the horizontal expansion value is greater than 50 mm, the bending moment of ring B is significantly higher than that of ring A, which indicates that ring B has entered the stage of rapid crack development. It is necessary to closely monitor the deformation and disease development of tunnel structure and take necessary treatment measures according to the monitoring results.

![Figure 9](image1.png)
**Figure 9.** Maximum positive bending moment-horizontal expansion curve.

![Figure 10](image2.png)
**Figure 10.** Maximum positive bending moment-vertical convergence curve.

5. Conclusions

An engineering case of large deformation, segment cracking, and water leakage of urban rail transit shield tunnel caused by unsymmetrical surface surcharge is introduced. The process of surface surcharge in this case is reproduced using finite element method. The deformation and stress characteristics of A and B rings of shield tunnel with staggered concrete lining are analysed, and the causes of diseases are discussed.

Under the action of unsymmetrical loading, the displacement of the tunnel deviates from the soil, the displacement of the arch crown is the largest, and that of the arch bottom is the smallest. The displacement of adjacent rings A and B is different, which cause tunnel disease such as segment dislocation and water leakage.

Due to the unsymmetrical surface surcharge, the segments become ellipse, and the tunnel expands outward in the horizontal direction. The track bed is cast-in-place concrete, which is separated from the segment at the FIG construction joint and does not expand horizontally with the segment, resulting in the separation between the track bed and the segment.

In the design state, the bending moment and axial force of A and B rings are close to each other, after unsymmetrical surface surcharge there are obviously different. The bending moment of ring B is obviously larger than that of ring A. When the crack width is 0.2 mm, the corresponding horizontal expansion value and vertical convergence value are 33 mm (5.3D‰) and 34 mm (5.5D‰). When the horizontal expansion value is greater than 50 mm (8D‰), ring B will enter into the stage of rapid development of cracks, which should be closely monitored and treatment measures should be taken if necessary.
In the case of large deformation, the structural damage level (such as the number of cracks, crack depth, etc.) of the structure is different, so the residual bearing capacity of ring A and ring B is different. This difference should be considered in the subsequent structural reinforcement.

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