Effect of Segment Thickness on Internal Force of Shield Tunnel under Abnormal Loading Conditions

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Abstract. Segment thickness is one of the important parameters of shield tunnel structure design. Segment thickness determines the section stiffness and mechanical performance of shield tunnel structure. Considering the load type of overload and unload, a three-dimensional fine shield tunnel numerical model was established. The full-scale test was used to verify the correctness of the numerical model. In the end, the effect of segment thickness on the internal force of shield tunnel structure under abnormal loading conditions was analyzed. The results show that the internal force of each section of the tunnel structure increases with the increase of the thickness of the segment, and the difference of the internal force between the different segment thickness increases with the increase of the overload and the degree of unloading. Increasing the thickness of segment will delay the breakpoint of the bending moment and axial force (critical instability state). The excessive increase of the segment thickness can lead to a large increase in the internal force of the tunnel structure, resulting in a decrease in the crack resistance of the tunnel structure.

1. Introduction
The relative stiffness of shield tunnel structure and surrounding soil affects the interaction between them, which changes the internal force distribution of tunnel structure [1]. However, the thickness of the segment determines the section stiffness of the tunnel structure. Under the condition of ensuring the normal clearance of the tunnel, properly increasing the segment thickness can effectively improve the overall transverse bending stiffness of the tunnel structure, enhance the deformation resistance of the tunnel structure, and further improve the service performance of the shield tunnel. Therefore, segment thickness is one of the important parameters for shield tunnel structural design [2].

At present, most researches have analyzed the difference of deformation and internal force variation of different segment thickness under design load through theoretical or numerical calculation. For example, document [3] takes an interval tunnel in Shanghai as an example, uses homogeneous ring method to check the structural internal force of shield tunnel, and points out that the increase of segment thickness can improve the stiffness of tunnel segment itself, but too large segment thickness is not conducive to the stress of tunnel structure itself. Document [4] adopts a calculation method that can consider the joint position and stiffness, analyzes the internal force changes under different segment thicknesses, and considers that simply increasing the segment thickness will lead to an increase in bending moment and concrete cracks. Document [5] calculated the influence law of segment thickness on internal force of large diameter tunnel under different surrounding rock levels by using modified conventional method, and gave the optimal segment thickness value. Document [6] compares and analyzes the deformation of pure steel structure segments and mixed segments under different thicknesses by ANSYS calculation.
However, subway construction is generally accompanied by surrounding development, which brings about large-scale adjacent engineering activities such as ground stacking [7-9], excavation and unloading [10-12], etc. When the external load changes too much, the tunnel structure will undergo severe convergence deformation, the internal force distribution of the structure will change greatly, and the segments will crack to varying degrees [13-16]. It can be seen that if the thickness of shield segments is designed according to the standard of design load, the applicability analysis of segments is not fully covered and the ultimate bearing performance of shield tunnel structure is reasonably evaluated.

Therefore, by establishing a refined three-dimensional numerical model of shield tunnel and verifying the model with full-scale tests, this paper analyzes the influence law of different segment thicknesses on the internal force of shield tunnel structure under overload and unloading conditions, with a view to providing reference for the structural design of shield tunnel.

2. 3-D Refined Numerical Model of Shield Tunnel

2.1 Segment Structure Type

The shield tunnel structure adopts an inner diameter of 5.5m and a ring width of 1.2m. The segment standard ring consists of six segments, including one capping block (K), two adjacent blocks (B1, B2), and three standard blocks (A1, A2, A3). The cap block corresponds to a central angle of 21.5, the adjacent block corresponds to a central angle of 68.0, and the standard block corresponds to a central angle of 67.5, as shown in Figure 1. Segment rings are assembled in staggered joints according to the "A-B-A" pattern, and the positions of the adjacent ring capping blocks deviate from plus or minus 22.5 degrees directly above, as shown in Figure 2. The segment blocks are connected with each other by 2 hoop bolts, 12 hoop bolts are arranged for each hoop segment, and a longitudinal bolt is arranged between adjacent two hoop segments at intervals of 22.5 degrees, totaling 16 bolts. The longitudinal joints of the segments are provided with concave-convex tenons, while the circumferential joints are not provided with concave-convex tenons. Segment contains main reinforcement, longitudinal reinforcement, stirrup and bolt hand hole reinforcement. The diameter of main reinforcement and bolt hand hole reinforcement is 16mm, the diameter of longitudinal reinforcement is 10mm, and the diameter of stirrup is 6mm, as shown in Figure 3.

Figure 1. Schematic of the whole ring of shield tunnel
In order to analyze the influence of segment thickness on the internal force of shield tunnel under different loads (regardless of the change of waterproof gasket groove with segment thickness), three segments with different thicknesses were selected for modeling, with segment thicknesses of 350mm, 400mm and 450mm respectively, as shown in Figure 4.

**Figure 2. Shield segment assembling form**

![Shield segment assembling form](image)

**Figure 3. Schematic of standard block segment reinforcement**

![Schematic of standard block segment reinforcement](image)

**Figure 4. Structural of different segment thickness**

![Structural of different segment thickness](image)

2.2 Segment Model and Material Parameters

Joint is the weak link of segment structure, and the accuracy of detail structure simulation is very important to truly reflect the mechanical properties of segment structure. Therefore, this paper fully considers the joint structure details such as longitudinal mortise, bolt hand hole, waterproof gasket groove, etc., and establishes a refined finite element model of three-ring segment by using large-scale...
general finite element software Abaqus. The single-ring segment finite element model is shown in Figure 5, and the three-ring finite element model is shown in Figure 6.

![Figure 5. Refined finite element model of single ring segment](image)

![Figure 6. Three-ring finite element model](image)

Segmental concrete is calculated using elastoplastic damage constitutive model [17]. The main reinforcement of the segment is HRB335 reinforcement, while the longitudinal reinforcement and stirrup are HPB235 reinforcement, ignoring the bolt hand hole reinforcement. The physical and mechanical parameters of other materials are shown in Table 1. The elastic modulus of the material after yield hardening is reduced to 0.01 times of the initial value, and its stress-strain relation curve is shown in Figure 7.

| Material          | Elastic modulus $E$/GPa | Poisson ratio $\mu$ | Yield strength $f_y$/MPa | Tensile strength $f_u$/MPa |
|-------------------|-------------------------|---------------------|--------------------------|---------------------------|
| 5.8 grade bolts   | 200                      | 0.3                 | 400                      | 500                       |
| HRB235steel bar   | 210                      | 0.3                 | 235                      | 370                       |
| HRB335steel bar   | 200                      | 0.3                 | 335                      | 455                       |
Assuming that the stress-strain constitutive relation curves of bolts and steel bars under monotonic loading are consistent, as shown in Figure 8, the elastic-plastic characteristics of materials are characterized by three fold lines to simulate the yield, hardening and softening phenomena of bolts and steel bars during loading [18]. The expression of stress-strain relation in each stage is as follows:

\[
\sigma_s = \begin{cases} 
  E_s \varepsilon_s & \varepsilon_s \leq \varepsilon_y \\
  f_y & \varepsilon_y < \varepsilon_s \leq \varepsilon_{uy} \\
  f_y + k(\varepsilon_s - \varepsilon_{uy}) & \varepsilon_{uy} \leq \varepsilon_s < \varepsilon_u \\
  0 & \varepsilon_s > \varepsilon_u 
\end{cases}
\]

where: \( E_s \) is the elastic modulus, \( \sigma_s \) is the stress, \( \varepsilon_s \) is the strain, \( f_y \) representative value of yield strength, \( \varepsilon_y \) corresponding yield strain, \( \varepsilon_{uy} \) starting point of material hardening stage, \( \varepsilon_u \) corresponding peak strain and \( k \) is the slope of material hardening stage.

![Figure 7. Stress-strain curve of reinforcement](image)

![Figure 8. Stress-strain curve of shield tunnel reinforcement](image)

2.3 External load conditions
The numerical calculation adopts the "load-structure" model [19]. as shown in Figure 9, the top of the tunnel bears vertical water and soil pressure, the bottom bears foundation reaction \( P_2 \), the horizontal loads \( P_3, P_4, P_5 \) distributed symmetrically in trapezoid form on both sides are the tunnel dead weight, \( P_6 \) is the lateral stratum resistance caused by tunnel deformation, and the loads are distributed uniformly along the longitudinal direction of the tunnel. The buried depth and load of the tunnel are shown in Figure 10 and Table 2.
After the tunnel structure reaches the normal bearing condition, the overload condition is simulated by continuously increasing the vertical loads \( P_1 \) and \( P_2 \) and keeping \( P_3 \) and \( P_4 \) unchanged. By keeping \( P_1 \) and \( P_2 \) unchanged and reducing \( P_3 \) and \( P_4 \), the unloading situation is simulated.

### 3 Model validation

#### 3.1 Full-scale Test Plan

In order to verify the correctness of the numerical model, a full-scale test load was carried out on the segment of the 3rd ring shield and compared with the numerical calculation structure.

In order to simulate the real stress state of the shield tunnel structure, 24-point concentrated symmetrical loading is adopted to simulate the actual external loads and dead weight of the shield tunnel structure, such as stratum load, soil resistance, surface loading and unloading, etc. The test loading device is shown in Figure 11.

![Figure 11. Full-scale test loading device](image)

### Table 2. Load Values (kPa)

|   | \( P_1 \) | \( P_2 \) | \( P_3 \) | \( P_4 \) | \( P_5 \) |
|---|---|---|---|---|---|
|   | 277.5 | 286.25 | 180.38 | 254.93 | 25.94 |

In the experiment, 24 loading points were divided into 3 groups, \( P_1 \), \( P_2 \) and \( P_3 \) respectively. the distribution of loading points is shown in Figure. 12. At the same time, in order to simulate the longitudinal restraint force between adjacent rings, 6 vertical loading points were used in the full-scale
test to simulate the longitudinal restraint effect between segment rings. as shown in Figure. 13, the design load of each vertical loading point is 25t.

![Figure 12. Test horizontal loading point](image1)

![Figure 13. Test vertical loading point](image2)

The whole loading process of the test is divided into three stages:
(1) Load the vertical load to the design value, and P1 is graded from 0kN to F2. During the process, P2=0.7×P1 and P3=(P1+P2)/2=0.85×P1 are maintained, and the load increment of P1 at each stage is 0.1 times of F1.
(2) P1 is loaded from F2 to F1. In this process, P2=0.7×P1 and P3=(P1+P2)/2=0.85×P1 are still maintained, and the load increment of P1 per stage is 0.05 times of F1.
(3) Continue to load P1 until the limit failure state. In this process, P2=0.7×P1, P3=(P1+P2)/2, and the load increment of P1 is 0.05 times of F1.
Where: F1 is the design load and F2 is 0.8 times of the design load.

3.2 Comparative Analysis of Experiment and Numerical Calculation

Figures. 14 and 15 are comparative of convergence deformation and main reinforcement stress curves of full-scale test and numerical simulation. From the diagrams, it can be seen that the finite element calculation results are basically consistent with the full-scale test results, indicating that the model is reasonable and feasible.

![Figure 14. Horizontal convergence deformation comparison curve of test and numerical calculation](image3)

![Figure 15. Stress comparison curve of main reinforcement between test and numerical calculation](image4)

4. Influence of Segment Thickness on Internal Force of Shield Tunnel

4.1 Variation Law of Bending Moment and Axial Force under Overload Condition

The variation rules of section bending moment and axial force of tunnel structures with different segment thicknesses with vertical load are shown in Figure. 16-21 respectively.
As can be seen from Figures 16-21, in the normal bearing stage, the bending moment and axial force of each section of segments with different thicknesses increase linearly with the increase of vertical load. After entering the overload stage, the tunnel structure gradually enters the elastoplastic stage.
state, the section bending moment increases and the trend is faster and faster, and the fluctuation of section axial force increases. When the vertical load reaches 330.4kPa (350mm thick), 365.8kPa (400mm thick) and 401.2kPa (450mm thick), 1.57 times, 1.74 times and 1.91 times of the designed vertical load respectively, it can be seen that the bending moments of 0, 45, 90, 135, 180, 225 and 315 sections increase sharply while the bending moments of 270 sections decrease instead. The axial forces of sections 0, 90 and 180 increase to form reverse bending points and then decrease rapidly, while the axial forces of sections 45, 135, 225 and 315 fluctuate and then increase rapidly, which indicates that the tunnel structure reaches the critical point of instability failure. This state is defined as "critical instability state", the left boundary of the shaded part in the Figure indicates that the tunnel structure is in "critical instability state", while the right boundary of the shaded part indicates that the tunnel structure is in "ultimate failure state". Therefore, the larger the thickness of the segment, the larger the corresponding critical buckling load, and the inflection point of bending moment and axial force will lag.

The distribution of bending moment and axial force of tunnel structures with different segment thicknesses under different loads are shown in Figures. 22 and 23 respectively.

4.2 Variation Law of Bending Moment and Axial Force under Unloading Condition

The variation law of cross-sectional internal force of different segment thicknesses under unloading condition with horizontal load is shown in Figure. 24-29 respectively. From the Figure we can see that the horizontal load in abscissa refers to the horizontal stratum load borne by the waist position of the tunnel.
Figure 24. Bending moment variation of tunnel section when segment thickness is 350mm under unload

Figure 25. Axial force variation of tunnel section when segment thickness is 350mm under unload

Figure 26. Bending moment variation of tunnel section when segment thickness is 400mm under unload

Figure 27. Axial force variation of tunnel section when segment thickness is 400mm under unload

Figure 28. Bending moment variation of tunnel section when segment thickness is 450mm under unload

Figure 29. Axial force variation of tunnel section when segment thickness is 450mm under unload

As can be seen from Figures. 24-29, with the increase of unloading degree, the horizontal load decreases continuously, the section bending moment increases continuously. Except that the axial
force of 90° and 270° sections increases with the decrease of the horizontal load, the axial force of other sections decreases with the decrease of the horizontal load, and the decreasing trend becomes slower with the increase of the thickness of the segment. When the horizontal load decreases from 185.0kPa to 105.9kPa (350mm thick), 79.8kPa (400mm thick) and 55.5kPa (450mm thick), respectively, the section bending moment begins to increase rapidly, and the axial force curve of some sections turns and begins to increase reversely, indicating that the tunnel structure reaches the "critical instability state" and begins to undergo instability failure. After that, when the horizontal load continues to decrease to 78.6kPa, 53.8kPa and 27.7kPa, the tunnel structure reaches the "ultimate failure state".

Figures. 30 and 31 are sectional bending moment and axial force distribution diagrams of tunnel structures with different segment thicknesses under different loading conditions under unloading conditions respectively. It can be seen that under the unloading condition of "critical instability state", the section bending moment and axial force also increase with the increase of segment thickness, and the difference between bending moment and axial force becomes more obvious with the further increase of unloading level. In addition, the bending moment and axial force near the 90 section position in the "critical instability state" are much larger than those in other sections.

![Figure 30](image1.png)
![Figure 31](image2.png)

**Figure 30. Bending moment distribution curves of tunnel structures with different segment thicknesses under unload**  
**Figure 31. Axial force distribution curves of tunnel structures with different segment thicknesses under unload**

5. Conclusions

In this paper, by establishing a three-dimensional refined numerical model of shield tunnel, the influence law of different segment thickness on the internal force of shield tunnel structure under overload and unloading conditions is studied, and the following conclusions are obtained:

1. In the process of overload and unloading, the internal force of each section of tunnel structure increases with the increase of segment thickness, and the internal force difference among different segment thickness increases with the aggravation of overload and unloading degree.

2. The increase of segment thickness will make the sudden change point of bending moment and axial force (namely critical instability state) of shield tunnel lag.

3. The increase of bending moment and axial force in the process of segment thickness increasing from 400mm to 450mm is obviously larger than that in the process of segment thickness increasing from 350mm to 400mm, which indicates that excessive increase of segment thickness will greatly increase the internal force of the tunnel structure, resulting in the decrease of crack resistance of the tunnel structure.

6. References

[1] Huang Z H, Liao S M 2000 Effect of Segment Thickness on Mechanical and Service Performance of Tunnel. Architectural Technology, 31(7):471-472.
[2] Zhu S Y 2002 Current Situation and Development of Segment Structure Design for Shield Tunnels in China. *Modern Tunnel Technology*, 39(6):23-27.

[3] Huang Z H, Liao S M, Liu G B 2000 Optimization of Segment Thickness of Shanghai Soft Soil Shield Tunnel. *Geotechnical Mechanics*, 21(4):326-330.

[4] Zhao G X, He C 2003 Optimization Analysis of Tunnel Segment Design [J]. *China Railway Science*, 24(6): 61-66.

[5] Chen W T, Fu Z Q, Ma J X 2017 Study on Segment Thickness Design of Large Diameter Double Shield TBM Tunnel. *Railway Architecture*, 57(10):60-62.

[6] Zhao Z P, Liu G B, Bai Y 2018 Segment Design of Large Diameter Shield Tunnel with High Water Pressure. *Highway Traffic Technology*, 34(S01):102-110.

[7] Huang D W, Zhou S H, Lai G Q 2017 Degradation Mechanism and Characteristics of Shield Tunnels under Surface Overload. *Journal of Geotechnical Engineering*, 39(7): 1173-1181.

[8] Zhang M G, Zhou S H, Huang D W 2016 Analysis of Influence of Surface Overload on Subway Shield Tunnel. *Geotechnical Mechanics*, 37(8): 2271-2278.

[9] Wang R L, Zhang D M 2013 Study on Lateral Deformation Mechanism and Control Index of Shield Tunnels in Soft Soil under Overload. *Journal of Geotechnical Engineering*, 35(6):1092-1101.

[10] Dai Z R 2017 Study on Fragmentation Mechanism of Subjacent Shield Tunnel Segment Caused by Large-scale Excavation and Unloading on Surface. *China Railway Science*, 38(4): 62-69.

[11] Shen G G, Ding J F 2016 Measurement and Analysis of Impact of Loading and Unloading on Existing Shield Tunnels. *Journal of Nanjing Institute of Engineering*, 14(04):61-64.

[12] Yao A J, Zhang J T, Guo H F 2018 Study on Unloading-Loading Effect of Foundation Pit Excavation above Subway Shield Tunnel. *Geotechnical Mechanics*, 39(7):2318-2335.

[13] Liu C, Lai J X, Liu Q 2013 A review of research situation on shield tunnel diseases. *Applied Mechanics and Materials*, 6:438-439.

[14] Dong F, Fang Q, Zhang D L 2017 analysis of disease state of Beijing subway tunnel. *Journal of civil engineering*, 50(06):108-117.

[15] Yang Y B, Zhou B, Xie X Y 2016 Study on Transverse Deformation and Cracking Characteristics of Shield Tunnels under Adjacent Foundation Pit Construction. *Journal of Rock Mechanics and Engineering*, 35(S02):4082-4093.

[16] Yang X, Gao Y 2012 Discussion on Causes of Segment Cracking in Shield Tunnels during Subway Operation. *Urban Rail Transit Research*, 15(7):26-29.

[17] Jin H, Yu S, Zhou S H 2019 Research on mechanics of longitudinal joint in shield tunnel by the nonlinear spring equivalent method. *KSCE Journal of Civil Engineering*, 23(2):902–913.

[18] Jin H, Yu K W, Gong Q M 2018 Load-carrying capability of shield tunnel damaged by shield shell squeezing action during construction. *Thin-Walled Structures*, 132:69-78.

[19] Yu S, Jin H, Zhou S H 2019 Morphology of Rust Layer in Shield Segment Reinforced by Chloride Ion and Miscurrent. *Engineering Mechanics*, 36(7):174-183.