Internal force – deformation and corresponding control measures of shield tunnel with a 5.8m diameter under lateral pressure loss conditions

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Abstract: In consideration of the deformation reservation, treatment and repair of the shield tunnel structure in the 100-year service life, the designed inner diameter of the shield tunnel structure tends to increase. However, the increase in the diameter will reduce the overall stiffness of the structure and reduce the shield tunnel's mechanical properties under load changing conditions. Taking the 5.8m-inner-diameter shield tunnel in Nanjing as an example, this paper establishes a refined three-dimensional numerical model of the shield tunnel and validates the model with the results from a full-scale experimental test. Mechanical responses of the shield tunnel under the influence of the surrounding engineering activities are analyzed, and the structural maintenance and deformation control strategy are also discussed. The research shows that as the lateral pressure coefficient decreases (i.e. when unloading occurs around the tunnel structure), the stress and deformation curves of the structure have a strong nonlinear characteristic: when the lateral earth pressure loss is about 0% to 21%, the structure is in a near-elastic state, and the deformation and internal force response are not sensitive to load-changing conditions; when the lateral earth pressure loss is 21%~43%, the damage, stress and deformation of the tunnel structure will increase rapidly, indicating that the structure is in the stage of plasticity, which is the critical interval for structural maintenance; when the lateral pressure loss exceeds 43%, the structure reaches total yielding stage. Therefore, the corresponding maintenance and control measures of shield tunnel segment structure are proposed from the aspects of prevention at the source, control in the process and treatment at the end.

1. Introduction
By the end of 2019, a total of 40 cities in mainland China have operated urban rail transit lines with a total mileage of 6736.2 km [1]. With the merits of less land occupation, shorter construction period, and better seismic performance, shield tunnels are widely used in the construction of urban rail transit in China [2]. The metro shield tunnels in the cities like Shanghai, Guangzhou, Nanjing, etc., pass through a large number of soft soil strata with low bearing capacity and high sensitivity [3].

When the surrounding environment of the tunnel structure changes, typically for the excavation of foundation pits brought about by large-scale urban development activities in soft soil areas, the stress...
and displacement field of the layer where the tunnel is located will be inevitably disturbed, causing lateral pressure loss \(^4\), and resulting in significant deformation, thereby affecting the safety of the tunnel structure. A series of diseases such as bolt yielding, joint opening, joint dislocation, water leakage, steel corrosion, segment cracking will happen for the large deformation situation \(^5-10\).

Maintenance of the damage, deformation, and displacement of an underground engineering is difficult. In order to consider the deformation reservation and treatment of the shield tunnel structure during the hundred years of service, it is necessary to increase the inner diameter of the shield tunnel. The structural design of shield tunnels both in domestic and overseas is trending towards expanding the diameters. For example, the internal diameters of 5.8 m, 5.9 m or 6.0 m have been adopted for newly-built metro shield tunnels in China, such as those in Beijing, Shanghai, Shenzhen, Tianjin, Chongqing, Jinan and other cities \(^11-12\). The MRT line of Bangkok's public transportation system has reserved mechanical clearance, and the inner diameter of the tunnel is set to 5.7m \(^13\). The early-built east-west line and north-south line in Singapore chose the tunnel with an inner diameter of 5.2m, while the diameter of the tunnel in the later-built northeast line and other lines is expanded to 5.8m \(^14\).

The inner diameter of the early-built metro shield tunnels in Nanjing is 5.5m, and the thickness of the segment is 350mm. In order to reserve a space for the reinforcement of the shield tunnel structure in soft soil layer, Nanjing Metro Line 9 adopts the segment with an inner diameter of 5.8m. At present, scholars have carried out relevant studies on the mechanical characteristics of the segment structure under top loading/unloading conditions through full-scale tests, modal tests, numerical simulations, etc. \(^15-21\), but most of the studies mainly focus on the small-diameter structures. However, with the expansion of the segment diameter, the overall stiffness of the tunnel structure decreases. Therefore, it is necessary to study the mechanical characteristics of the larger diameter segment of the Nanjing Metro Line 9. This paper establishes a refined three-dimensional (i.e., 3D) shield tunnel numerical model to study the development of internal forces and deformations of the 5.8m-inner-diameter segment structure when lateral unloading occurs. The relevant results can provide reference for the prediction of the stress state and the determination of countermeasures of the shield tunnel with an inner diameter of 5.8m through the soft soil layer.

2. 3D Numerical Model of Shield Tunnel

2.1. Solid Model of Stagger-jointed Tunnel

The finite element software Abaqus is employed to establish the refined finite element model of the three integral rings of the tunnel. The three-dimensional solid model of the tunnel has an inner diameter of 5.8m and a segment width of 1.2m. The assembly is of stagger-jointed method and the concave-convex tenons are only set in the longitudinal joint. The bolts are M33 curved bolts, 8.8 grades, and the segments are divided into 6 pieces (1 capping block 21.5°+2 adjacent blocks 68°+3 standard blocks 67.5°). The 3D solid model of the tunnel is shown in Figure 1. The segments are built as solid elements, and the bolts and steel bars are set as beam elements. The calculation conditions are set as follows: the shallow burial condition in the normal operation stage, and the lateral pressure loss conditions for the impact of surrounding engineering activities.

The joint is the weak part of the tunnel structure, which has a significant impact on the deformation and performance degradation of the tunnel structure. The detailed structures of the concave-convex tenons, bolts and hand holes are the key elements that affect the mechanical properties of the joint. Therefore, the accurate simulation of the detailed structure is very important to truly reflect the mechanical properties of the segment structure. Based on the structural design characteristics of the Nanjing Metro 9 shield tunnel segment, this paper fully considers the joint structure details of the longitudinal joint concave-convex tenon, bolt hole, solid bolt, and waterproof gasket groove. The finite element model of a single segment block is shown in Figure 1.
The model of the concrete uses three-dimensional eight-node linearly reduced integral solid element C3D8R, which is suitable for simulating contact problems. The steel rebar is simulated by three-dimensional two-node bar element T3D2, as shown in Figure 2. Embedded Element is used for embedding concrete into the structure to simulate the connection between steel bars and concrete. The connection bolts are simulated by solid elements. The tangential behavior on the contact surface adopts the penalty friction formula in the software, and the friction coefficient is set to be 0.5. The tangential sliding behavior adopts the finite sliding formula, and the normal behavior on the contact surface uses the "hard" contact formula in the software, which means no limit to the amount of contact pressure that can be transmitted between the contact surfaces. When the contact pressure between the contact surfaces turns zero, the two contact surfaces are separated and the constraint is released.

2.2. The constitutive relationship of the concrete

In order to better simulate the cracking and damage of shield tunnel segments, the model adopts the elastoplastic damage constitutive of the concrete [22-23], which is based on Lubliner, Lee and Fenves models. Isotropic elastic damage theory and isotropic tensile-compression plasticity theory are adopted to characterize the inelastic behavior and simulate the tensile cracking and compression crushing of the concrete.

The elastoplastic damage constitutive of the concrete assumes that concrete materials are mainly damaged by tensile cracking and compression crushing. Under uniaxial tension in the elastic stage, the elastic modulus of the material is $E_0$. When the stress reaches the fracture stress $\sigma_{fr}$, the material enters the strain softening stage, and microcracks begin to appear. Under uniaxial compression in the elastic stage, the elastic modulus of the material is also $E_0$. When the stress reaches the yield stress $\sigma_y$, the material enters the strengthening stage and begins to produce microcracks. When the stress exceeds the limit stress $\sigma_{cu}$, the material enters the strain softening stage.

The value of elastic modulus refers to "Code for Design of Concrete Structures" (GB 50010-2010):

$$E_0 = \frac{f_{tu}}{\varepsilon_{tu}}$$

where $f_{tu}$ is standard value of concrete uniaxial tensile strength; $\varepsilon_{tu}$ is tensile strain corresponding to $f_{tu}$.

In damage mechanics, the structure is assumed to be in an undamaged state for non-load condition, and the effective force volume is $\mathcal{A}$. After being loaded, cracks are generated inside the structure, and the
effective force volume of the structure becomes $A^*$. The damage factor $d$ is defined as $A^* / A$ and is introduced in the elastoplastic damage constitutive of concrete to characterize the stiffness degradation of the concrete after damage. In the numerical simulation software, the tensile damage factor $d_t$ and the compressive damage factor $d_c$ are used to describe the different damage characteristics of concrete in tension and compression:

\[
\sigma_t = (1 - d_t)E_0(\varepsilon_t - \varepsilon_t^{pl})
\]

\[
\sigma_c = (1 - d_c)E_0(\varepsilon_c - \varepsilon_c^{pl})
\]

When in tension strengthening stage, the relationship between equivalent plastic strain $\varepsilon_t^{pl}$ and cracking strain $\varepsilon_t^{ck}$ is as follows:

\[
\varepsilon_t^{pl} = \varepsilon_t^{ck} - \frac{d_t\sigma_t}{(1 - d_t)E_0}
\]

When in compression strengthening stage, the relationship between equivalent plastic strain $\varepsilon_c^{pl}$ and inelastic strain $\varepsilon_c^{in}$ is as follows:

\[
\varepsilon_c^{pl} = \varepsilon_c^{in} - \frac{d_c\sigma_c}{(1 - d_c)E_0}
\]

Based on the Equation (4)-(5), the relationship between uniaxial compression, tensile stress, strain and damage factor of C50 concrete can be made.

The concrete damage constitutive adopts the non-associative flow law to control the inelastic volume deformation of concrete, and the Drucker-Prager plastic potential function $G$ is used to control the direction of plastic flow, namely:

\[
G = \left[ (\kappa\sigma_0 \tan \psi)^2 + \bar{q}^{-2} \right]^{1/2} - \bar{p} \tan \psi
\]

where $\kappa$ is the flow offset; $\sigma_0$ is the uniaxial stress at material failure; $\psi$ is the dilatancy angle on the $\bar{p} - \bar{q}$ plane under high lateral pressure; $\bar{p}$ is the average stress; $\bar{q}$ is the average equivalent effective stress. The concrete strength grade of the segments in Nanjing Metro Line 9 is C50, so the values of other concrete parameters in the finite element model are as follows: elastic modulus $E_0 = 34.5$ GPa; Poisson’s ratio $\mu = 0.2$; dilatancy Angle $\psi = 0.2$; flow offset $\kappa = 0.1$.

2.3. Load Setting of the Working Condition

The numerical calculation adopts the load-structure model, as shown in Figure 3. The top of the tunnel bears the vertical water and soil pressure, and the bottom bears the foundation reaction force. The horizontal load is distributed in a symmetrical trapezoid shape on both sides, and the load is uniformly distributed along the longitudinal direction of the tunnel.

![Fig. 3 Load-structure model](image-url)
2.4. Verification of the numerical model with full-scale test
In order to verify the correctness and reliability of the three-dimensional refined numerical model, a three-ring shield tunnel with an inner diameter of 5.5m and a thickness of 0.35m was tested in a full-scale experiment. The test results are compared with those obtained from the three-dimensional refined numerical model. The loading devices for the three-ring full-scale test include reaction frame, jacks, bottom support, load-bearing beam devices, etc., as shown in Figure 4. The draw-wire displacement sensors are arranged to measure the convergence deformation, as shown in Figure 5. The foil strain gauges are arranged to measure the strain of the bolt. Due to the limitation of the test equipment, 24 loading points are distributed equidistantly around the tunnel model to simulate the actual load of the shield tunnel structure. In addition, 6 vertical loading points are arranged to simulate the longitudinal restraint between the segment rings.

Fig. 4 Loading instrument of full-scale model test

Fig. 5 Installation of full-scale test convergence deformation measuring points

![Fig. 6 Comparison chart of bolt stress](image-url)
Figures 6 and 7 show the bolt stress comparison diagrams and the convergence deformation comparison diagrams of the full-scale test and the refined numerical model respectively. It can be seen that the finite element calculation results are basically consistent with the full-scale test results, indicating that the refined numerical model is valid and feasible.

3. Influence of Lateral Pressure Loss on Tunnel

3.1. Analysis section and soil parameters

The cross-section diagram of the selected shallow buried section is shown in Figure 8. The whole tunnel passes through 2-2b4 muddy silty soil, covered with 4.3m thick 1-1 miscellaneous fill and 5.3m thick 2-2b4 muddy silty clay. The underground water level is 1.9m. The load calculation uses full overburden assumption, and the parameters of relevant soil layers are shown in Table 1. In order to analyze the influence of lateral pressure loss condition on deformation and stress of the shield tunnel structure, seven groups of conditions with gradual loss of lateral pressure coefficient are selected for analysis, which are 0.70, 0.65, 0.60, 0.55, 0.50, 0.45 and 0.40 respectively.

| Layer Number | Natural Density /kN/m³ | Compression Modulus /Mpa | Internal Friction Angle /° | Cohesion /kPa |
|--------------|--------------------------|--------------------------|---------------------------|---------------|
| ①-1          | 18.8                     | 4.4                      | 17.3                      | 18.9          |
| ②-2b4        | 17.9                     | 4.0                      | 17.3                      | 13.3          |
| ②-3b3-4      | 18.4                     | 3.9                      | 18.0                      | 13.9          |
3.2. Development of segment damage
Considering the boundary effect, the response of the middle ring is taken as the research object. Intuitively, the distribution nephogram of the concrete plastic zone under different lateral pressure loss conditions is drawn, as shown in Figure 9.

When the lateral pressure coefficient decreases from 0.70 to 0.55 (the lateral pressure loss is about 0 ~ 21%), there is no plastic zone in the segment, and the stress of the concrete is in the elastic stage.

When the lateral pressure coefficient decreases to 0.55 (the lateral pressure loss is about 28%), the plastic zone first appears in the middle segment, and the area of the plastic zone is small. While the lateral pressure coefficient decreases from 0.55 to 0.40 (the lateral pressure loss is about 28% ~ 43%), the plastic zone of the segments develops continuously, which spreads from the middle of the segment and joint to the whole segment, from a partial small scale to a longitudinal run-through of the segment. The development rate of the quantity and range of the plastic zone is accelerating.

![Fig. 9 Stress nephogram of the tunnel ring under different lateral pressure loss conditions](image)

(a) lateral pressure coefficient 0.65; (b) lateral pressure coefficient 0.60; (c) lateral pressure coefficient 0.55; (d) lateral pressure coefficient 0.50; (e) lateral pressure coefficient 0.45; (f) lateral pressure coefficient 0.40

3.3. Development of segment stress
The stress changes at the vault, bottom and both waists (inside the segment) of the arch of the tunnel with the lateral pressure coefficient are further described in Figure 10.

![Fig. 10 Variation of stress at different positions of the tunnel ring with different lateral pressure coefficients](image)

When the lateral pressure coefficient decreases from 0.70 to 0.55 (the lateral pressure loss is about 0-21%), the segment stress increases approximately linearly. The stress of the left waist increases from 15380 kPa to 22160 kPa; the stress of the right waist increases from 18370 kPa to 22020 kPa; the stress of the vault increases from 12446 kPa to 16779 kPa; and the stress of the bottom increases from 14520 kPa to 18730 kPa.

When the lateral pressure coefficient decreases from 0.55 to 0.40 (the lateral pressure loss is about 28% ~ 43%), the development of segment stress presents a fast nonlinear trend. The stress of the left waist reaches 40740kpa and the stress of the right waist reaches 40070kpa, with an increase of more than
80%. The stress of the vault reaches 66485kpa, and the stress of the bottom reaches 68070kpa, with an increase of about 290%.

3.4. Development of segment deformation

The deformation of the middle tunnel ring is output and drawn under the condition of lateral pressure loss, as shown in Figure 11. It can be seen that the convergence deformation mainly occurs in the direction of the vault, bottom and the waists, which shows a horizontal-duck-egg-shaped deformation form, decreasing at the top and bottom, and expanding at both waists.

![Nephogram of tunnel ring deformation](image1)

Fig. 11 Nephogram of tunnel ring deformation

In order to better compare and analyze the deformation of the tunnel, the absolute value of deformation is normalized, and the development process of convergence deformation under different lateral pressure loss conditions is plotted in Figure 12:

![Development of the convergence of the arch waist as the load increases under different lateral pressure coefficients](image2)

Fig. 12 Development of the convergence of the arch waist as the load increases under different lateral pressure coefficients

When the lateral pressure coefficient decreases from 0.70 to 0.55 (the lateral pressure loss is 0 ~ 21%), the convergence deformation of arch waist develops linearly with the increase of load, which is easy to monitor and control.

When the lateral pressure coefficient decreases from 0.55 to 0.40 (the lateral pressure loss is about 28% ~ 43%), the convergence deformation of the arch waist presents a nonlinear growth trend with the lateral pressure loss, which shows the acceleration of the development rate. Especially, when the coefficient of lateral pressure reaches 0.4 (43%), the convergence change rate of the structure increases sharply, and the structure enters into the total yielding state. The authors have also made a trial calculation for the case of greater lateral pressure loss (50%), and the calculation do not converge.
Therefore, it can be concluded that when the lateral pressure loss reaches 43%, the structure will enter into the total yielding state.

3.5. Development of Bolt Stress

The stresses of the longitudinal and circumferential joint bolt are output and drawn under different lateral pressure loss conditions, as shown in Figure 13.

The maximum stress value of the longitudinal and circumferential joint bolt under the lateral pressure loss conditions are further drawn in Figure 14.
Fig. 14 The influence of the change of the lateral pressure coefficient on the stress of the bolt

For circumferential joint bolt, the stress values are basically unchanged with the lateral pressure coefficient, in a range of 18000 kPa to 20000 kPa. The reason for this phenomenon is that the load boundary conditions of the numerical model do not take into account the longitudinal nonuniformity of spatial distribution of the soil layers. Therefore, it is difficult to reflect the longitudinal nonuniformity of the tunnel deformation and the following structural stress change caused by the longitudinal nonuniformity of spatial distribution of the strata in this numerical analysis.

For longitudinal joint bolt, when the lateral pressure coefficient decreases from 0.70 to 0.65 (the lateral pressure loss is 0~7%) the maximum stress of the bolt is almost unchanged, which remains at about 8000 kPa, indicating that the segment joint is not wide open and the bolt has not yet played a tension-resisting role. With the gradual loss of lateral pressure, the lateral convergence of the segment ring increases gradually. The maximum stress increases rapidly with an accelerated rate trend. However, it is worth mentioning that even in the total yielding stage of the structure (lateral earth pressure coefficient 0.4), the maximum stress of the bolt is 285800 kPa, which is far lower than the yield strength of the bolt 400000 kPa, indicating that the bolt of Nanjing 5.8m-inner-diameter shield tunnel has sufficient safety reserves.

4. Countermeasures and suggestions

The calculation results above are summarized in Figure 15. The service performance of the Nanjing 5.8m-inner-diameter shield tunnel structure gradually deteriorates with the loss of lateral pressure, and it is mainly divided into the following stages:

1. When the lateral pressure loss is 0~7%, the longitudinal joint bolts do not start to function. When the lateral pressure loss is greater than 7%, the longitudinal joint bolt stress develops rapidly and nonlinearly, but there is still sufficient safety reserve when the entire ring structure yields.

2. When the lateral pressure loss is 0~21%, the segment concrete is not damaged, and its stress and convergence deformation are in the slow linear development stage, which can be regarded that the entire structure is in the elastic stage. The structural performance is easy to monitor and control at this stage.

3. When the lateral pressure loss is 21%~43%, the damage of the segment concrete develops and spreads rapidly, and the structural stress and the entire ring deformation both increase rapidly and nonlinearly. It can be regarded that the entire structure is in the plastic development stage, and the difficulty in monitoring and controlling the structural performance increase.

4. When the lateral pressure loss exceeds 43%, the entire ring of the structure yields and the operation in the tunnel should be shut down for maintenance.

Fig. 15 Characteristics of segment performance degradation under lateral pressure loss
Based on the structural performance degradation characteristics mentioned above, the maintenance and control measures of shield tunnel segment structure are proposed from the aspects of prevention at the source, control in the process and treatment at the end:

1. In terms of prevention at the source, it is recommended to control the engineering activities around the tunnel. To be specific, 20% lateral pressure loss can be used as a reference to control the scale and proximity of related activities;

2. In terms of control in the process, 20% lateral pressure loss can also be used as a reference to provide a design basis for the isolation and reinforcement measures of surrounding engineering projects.

3. In terms of treatment at the end, it is recommended that the related departments perform prompt treatments for structural diseases and deformations at the early stage of structural damage (elastic development stage) to prevent the nonlinear increase in the difficulties in control and management after the structure enters plastic stage.

5. Conclusion
Through the establishment of a three-dimensional numerical model, the segment force and deformation features of a 5.8m inner diameter shield tunnel in Nanjing Metro Line 9 in soft soil strata under different lateral pressure loss conditions are studied:

(1) When the lateral pressure loss is about 0%~21%, the tunnel structure is in a near-elastic state, and the deformation and internal force response are not sensitive to the load change.

(2) When the lateral pressure loss is 21%~43%, the damage, stress and deformation of the tunnel structure will increase rapidly, indicating that the structure is in the plastic development stage, which is the key interval for structural maintenance.

(3) When the lateral pressure loss exceeds 43%, the structure reaches total yielding, and the operation of the metro tunnel should be shut down for maintenance;

Therefore, the maintenance and control measures of the shield tunnel segment structure are proposed from the aspects of prevention at the source, control in the process, and treatment at the end.

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