Study on the selection of inner diameter in shield tunnel segment in soft soil stratum

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Abstract. In the soft soil stratum, problems such as non-uniform settlement, leakage, and loss of bearing capacity occur during a shield tunnel's construction and operation process. The wrong selection of the inner diameter of the shield tunnel segment will even increase the scale of the problem. It has not been clear how the inner diameter of the segment will influence a tunnel's bearing capacity. Thus, a 3D numerical model is built to determine the mechanism between the inner diameter and the bearing capacity. Two kinds of the diameter of shield tunnel, which refer to 5.5m and 5.9m, are analyzed in this model. The results indicate that the deformation mechanism of these two kinds of shield tunnel in both normal loading process and a loading process concerning the surrounding engineering activities; meanwhile, it is found that the shape of the deformed tunnel is like a horizontal ellipse; finally, the deformation mechanism of segment and bolt is further revealed.

1. Introduction

In major cities in soft soil areas, shield tunnels are widely used in urban subway tunnel construction for their advantages of fast construction speed, high automation, good controllability of schedule and cost, low risk, and small influence of construction from outside.

However, studies over the years have shown that shield tunnels in soft soil areas are highly susceptible to uneven settlement under long-term train loading [1, 2] and ground engineering economic activities [3] on the one hand. On the other hand, the frequent unloading around the tunnel during urban construction will also lead to excessive structural deformation of the shield tunnel [4, 5]. When the tunnel's uneven settlement and structural deformation increase to a specific value, it will further cause increased deformation of the segment joints and concrete cracking, which will cause water leakage in the tunnel. Under this circumstance, the settlement will be further increased, and then the structure will gradually lose its bearing capacity [6, 7] and ultimately endanger the safety of underpass tunnel operation.

For the above problems in the shield of soft ground, through performing the full-scale test, Bi et al. [8] discussed the change rule of the bearing capacity of the tunnel under the two conditions, overloading above the tunnel and unloading around the tunnel. It was shown that the segment joints are the weak parts that are damaged first in loading and unloading, and it is necessary to strengthen the safety reserve of the tunnel further. Zhang et al. [4] conducted a numerical analysis and compared the measured results with the numerical results based on the model experiment results. It was found that the results calculated by the method of using vertical earth pressure in soft soil areas were smaller, which was more dangerous in design. Ngoc Anh et al. [9] established a three-dimensional model of shield tunnel in soft soil and simulated the construction process, where the coupling between adjacent segments had a significant effect on the bearing capacity of the tunnel. He et al. [10] investigated the
effect of different loading conditions on the mechanical characteristics of the pipe structure by loading tests, which showed along the width of the pipe, the positive bending moment presented a concave distribution (decreased first and then increased), and the negative bending moment presented a convex distribution (increased first and then decreased), and the axial force presented a convex distribution.

Most studies have focused on loading and unloading around the tunnel in the existing research on tunnel bearing capacity. From the tunnel construction process perspective, some studies have also been carried out on the deficiencies in the existing calculation methods. However, there are few studies on the influence of the inner diameter of pipe segments on the bearing capacity of tunnels.

The pipe segment is the main assembly component of the shield tunnel, so it is reasonably necessary to study the influence of the pipe segment inner diameter on the tunnel bearing performance. Currently, 5.5m inner diameter piece still dominates in shield tunnels in major cities in East China's soft soil region. However, considering the many problems in using a 5.5m inner diameter piece, some cities, led by Shanghai, began to consider adopting the segments with 5.9m inner diameter to reserve space for later secondary lining reinforcement and reduce the cost of later maintenance.

Therefore, based on the shield tunnel of a city in a soft soil area, this paper analyses and discusses the influence of the inner diameter of shield tunnel segment on the bearing capacity of the tunnel, which can provide reference experience for future construction of Urban Rail Transit under similar terrain and geological conditions.

Tunnel construction located in the soft soil area of East China is taken as an example. The upper part is mainly newly deposited fill and Marine silty soft soil in the area adjacent to the subway line, whose soil distribution and main stratigraphic mechanical parameters can be shown in Figure 1. The soft soil characteristics in this region are very similar to the above-mentioned soft ground in East China. Therefore, it is difficult to avoid the problems in similar urban metro tunnels in this area.

![Figure 1. Sketch map of a geological section.](image)

Therefore, when dealing with such a problem, from the perspective of construction tolerance, secondary lining reinforcement space, tunnel pipeline arrangement, and evacuation space settings, the inner diameter of the segments is considered to be increased to 5.9 m. In general, the segments with 5.9m inner diameter are still a minority in China. There is no clear understanding of the force pattern of the pipe segment in this cross-section form, and its force characteristics need to be further studied. To further understand the characteristics of using these two types of cross-sections in soft soil, this paper established a numerical model to analyze the force performance and deformation law of 5.5m and 5.9m inner diameter shield tunnels in the soil layer based on the current situation of segment inner diameter selection and the geological characteristics of the city. On the other hand, the relationship between the cross-sectional deformation of the tunnel and joint opening, bolt stress, and concrete stress would be analyzed from the aspect of tunnel structural deformation.
2. Establishment of finite element model

Based on the actual soil conditions, the FEM model is established to study the mechanical performance and deformation of two kinds of shield tunnels with an inner diameter of 5.5m and 5.9m, and analyse the relationship between tunnel deformation and joint opening, bolt stress, and concrete stress.

First, determine the size and boundary conditions of the model. Two tunnel sizes in the model are shown in Table 1. In the model, the top and bottom of the segment are constrained by horizontal displacement, the waist on both sides is constrained by vertical displacement, and the front and back end faces are constrained by axial displacement.

| Inner diameter/m | External diameter/m | Segment thickness/m |
|------------------|--------------------|--------------------|
| 5.5              | 6.2                | 0.35               |
| 5.9              | 6.6                | 0.35               |

Then determine the physical parameters of the structure. The segment structure size is based on the actual size in the numerical modelling. The concrete constitutive model adopts the multi-segment line model, and the constitutive bolt model adopts the multi-segment line model considering the elastic-plastic characteristics. The constitutive parameters are shown in Table 2.

| Material     | E1/GPa | E2/GPa | Turning stress/MPa | Poisson's ratio |
|--------------|--------|--------|--------------------|-----------------|
| Beton (C55)  | 35     | 0.1628 | 25.6               | 0.2             |
| Bolt         | 206    | 2.06   | 400                | 0.3             |

In the model, segment and bolt models adopt solid elements, and the surface contact behavior is set between adjacent segments and between segments and bolts. The friction coefficient of the contact surface is 0.4, which is used to simulate the opening and separation in tunnel deformation. The prestress of the bolt is 215kn in the calculation. The component of the model is shown in Fig 2.

The two cross-section forms and load conditions are shown in Fig 3. For each tunnel size, the change of the ratio of lateral load to vertical load reflects the construction disturbance activities around the tunnel structure (such as foundation pit unloading, etc.), and the specific simulated conditions are shown in Table 3:

| Inner diameter /m | Segment thickness /m | Load ratio     |
|-------------------|-----------------------|----------------|
| 5.5               | 0.35                  | 0.66–0.5       |
| 5.9               | 0.35                  | 0.66–0.58      |
3. Results analysis

3.1. Tunnel internal force

The internal forces of tunnels with different inner diameters under the same load and soil conditions are compared. Table 4 shows the simulated conditions and the internal force results of the two tunnels with different inner diameters. The results show that the maximum bending moment of the tunnel with different inner diameter occurs near the joint between the adjacent block and standard block, which is also the area with the most significant transverse convergent deformation, and the maximum axial force occurs at the two sides of the arch waist.

| Inner diameter /m | Segment thickness /m | The ratio of lateral load to vertical load | Maximum bending moment/kN·m | Axial force/kN | eccentricity /m |
|------------------|----------------------|------------------------------------------|-----------------------------|---------------|----------------|
| 5.5              | 0.35                 | 0.66                                     | 282.8                       | 2133          | 0.133          |
|                  |                      | 0.63                                     | 305.1                       | 2146          | 0.142          |
|                  |                      | 0.6                                      | 341.7                       | 2346          | 0.146          |
|                  |                      | 0.54                                     | 416.2                       | 2691          | 0.155          |
|                  |                      | 0.5                                      | 508.1                       | 2753          | 0.185          |
| 5.9              | 0.35                 | 0.66                                     | 370.9                       | 2551          | 0.145          |
|                  |                      | 0.63                                     | 421.5                       | 2735          | 0.154          |
|                  |                      | 0.6                                      | 485.4                       | 2998          | 0.162          |
|                  |                      | 0.59                                     | 508.2                       | 3093          | 0.164          |
|                  |                      | 0.66                                     | 282.8                       | 2133          | 0.133          |

By comparing the two simulated results, it can be seen that under the same segment thickness and calculation conditions, the maximum bending moment and axial force of the segment increased with the increase of the tunnel inner diameter; with the increase of the surrounding disturbance, the lateral earth pressure tunnel bore decreased, and the internal force of tunnel increased linearly. Therefore, maximum moments of two kinds of the inner diameter of tunnels under different loading conditions are shown in Fig 4.

![Figure 4. Maximum moments of tunnels with two kinds of inner diameter under different loading conditions](image1)

![Figure 5. Relationship between the inner diameter and horizontal deformation under different load ratios](image2)
3.2. Tunnel deformation

Considering the shield tunnel with two diameters, the relationship between the deformation at the tunnel transverse section and the inner diameter of the tunnel is analyzed, as shown in Fig 5 and Fig 6. The change of load ratio (the ratio of lateral load to vertical load) reflects the different disturbances around the tunnel structure.

According to Fig 5 and 6, under the same load condition, the deformation of the 5.5m inner diameter tunnel is smaller than that of the 5.9m inner diameter tunnel. For example, when the load ratio is 0.58, and the inner diameter of the tunnel is 5.9m, the horizontal deformation is about 80mm, and the vertical deformation is about 55mm. When the load ratio decreases, the plate's deformation develops too fast to achieve model convergence. Comparative analysis shows that a 5.5m inner diameter tunnel has stronger resistance to external disturbance than a 5.9m inner diameter tunnel.

Normalize the horizontal deformation of the tunnel, as shown in Fig 7. It can be seen from Fig. 7 that when the segment thickness is 0.35m, the inner diameter decreases from 5.9m to 5.5m, the horizontal deformation decreases by 37% ~ 62%, and the smaller the lateral earth pressure is, the more the horizontal deformation decreases. Thus, it shows that the influence of tunnel inner diameter on the deformation of the tunnel cross section is very significant, which should be fully considered in comparing and selecting tunnel cross-section forms.

Based on the previous study, the further analysis focuses on the tunnel's deformation with an inner diameter of 5.5m, whose segment thickness is 350mm. Four aspects, (1) The relationship between the change of the horizontal diameter and the change of the vertical diameter; (2) the relationship between the horizontal deformation of the tunnel and the maximum opening of the joint; (3) the relationship between the horizontal deformation of the tunnel and the maximum stress of the bolt, and (4) the relationship between the horizontal deformation of the tunnel and the maximum stress of the concrete, are analysed.

Fig 8 shows the relationship between the change of horizontal diameter and the change of vertical diameter of the 5.5m inner diameter tunnel. The horizontal coordinate is the change in horizontal diameter. The vertical ordinate is the absolute value of the ratio between the change in horizontal diameter and the change in vertical diameter, indicating the compression degree of the tunnel under the external load. It can be seen from fig 7 that with the decrease of the ratio of lateral load to vertical load, the tunnel deformation is in the form of a transverse ellipse. On the other hand, when the deformation is small, the ratio of the two becomes larger, and then the ratio of the two tends to be stable, and the ratio of the two is between 1.07 and 1.30.
Fig 9 shows the relationship between the transverse deformation of the 5.5m inner diameter tunnel and the maximum joint opening. It is observed that there is a positive correlation between the change of the horizontal tunnel diameter and the joint opening. It is defined as the critical horizontal deformation of the tunnel when the joint is opened for 6mm, and the critical deformation is 62.1mm.

Fig 10 shows the relationship between the maximum opening of the tunnel's joint and horizontal diameter deformation with an inner diameter of 5.5m. It shows that with the increase of the tunnel's horizontal deformation, the bolt's maximum stress increases, and the tunnel deformation is closely related to the bolt stress. Thus, when the bolt strength reaches the plastic limit, the tunnel will have accelerated deformation.

From Fig 9 to Fig 11, the tunnel deformation under different critical states can be obtained by combining the evaluation indexes of the tunnel structure. From the above calculation, it can be roughly seen that in the horizontal deformation of the tunnel, the opening of the joint first reaches the requirements of the waterproof standard, followed by the yielding of the bolt. Then, with the further development of the transverse deformation of the tunnel, the concrete stress reaches its strength design value and then reaches its strength expected value, which leads the concrete joint damage, and finally, the bolt stress reaches its ultimate strength value.

4. Conclusion
Through numerical analysis, the following conclusions and suggestions can be obtained:
(1) When the inner diameter of the tunnel decreases from 5.9m to 5.5m, the horizontal deformation decreases by about 30% to 60%. Moreover, when the external disturbance is severe, the deformation variation of the tunnel with an inner diameter of 5.5m is smaller, indicating that the tunnel with an inner diameter of 5.5m has stronger resistance to the external disturbance.

(2) Considering the disturbance of tunnel construction, the horizontal deformation of the tunnel is larger than the vertical deformation, and the critical convergence deformation of the tunnel is 62.1mm.

(3) During the process of tunnel horizontal deformation, the joint open firstly reaches the waterproof standard, and bolt secondly appears to yield. With the increase of the lateral deformation of the tunnel, the concrete stress reaches the design value of strength and then reach the standard values of strength, which lead concrete joint damage. Finally, the bolt stress reaches its ultimate strength values.

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