Research on Key Block with Limited Pipe Segment Assembly Space

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Abstract: In order to solve the problem of insufficient assembly space in mechanical connection channel and micro shield construction, a comparison of two solutions was first carried out, namely reducing the width of the segment ring and adjusting the center Angle, insertion Angle and joint Angle of the key block. The results show that adjusting the Angle of center Angle, insertion Angle and joint Angle of the key block is the most effective way to solve the problem of insufficient assembly space. By analyzing the geometric parameters of the segment and the assembly process, the functional relationship between the axial staggered distance of the key block and its partition Angle, insertion Angle, joint Angle, external radius and thickness under critical state and construction state is obtained. The axial staggered distance of the key block under construction state is positively correlated with the partition Angle, negatively correlated with the insertion Angle, negatively correlated with the joint Angle and positively correlated with the segment thickness. The optimal segment geometry design parameters were dete rmined for the 4# connection channel lining segment of Guangzhou Metro Line 3, which provided a solution for segment design when segment assembly space was limited.

Keywords: Segment; Limited Space for Assembly; Key Block; Construction Gap

1. Introduction

The TBM tunneling method has remarkable advantages such as fast construction speed, high construction quality, little construction disturbance and construction safety. It has been widely applied in the construction of large underground space projects like utility tunnels, subway stations and mountain tunnels [1-2]. Shield segments not only play the role of initial support in shield tunnels but also serve as the permanent structure of the tunnels, bearing the loads in the construction stage and the water and earth pressures in the normal service stage [3].

At present, precast reinforced concrete segments are mostly adopted in TBM tunneling construction at home and abroad. Each precast segment is assembled to form a ring, and a ring usually consists of several A-type segments (standard segments), two B-type segments (adjacent segments) and one K-type segment (key segment) [4], as shown in Figure 1. According to different segment assembly methods, as shown in Figure 2, the key K-type segment has the radial insertion type that is inserted from the in-side of the tunnel towards the radial direction, the axial insertion type that is inserted from the axial direction of the tunnel, and the type that combines the former two with the radial insertion first followed by the axial insertion [5].

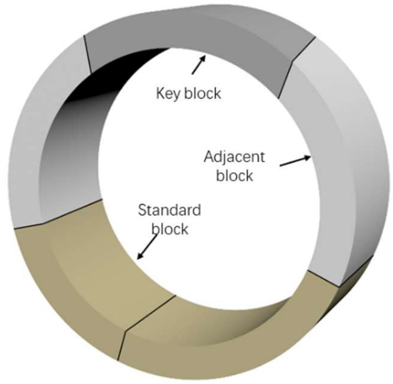
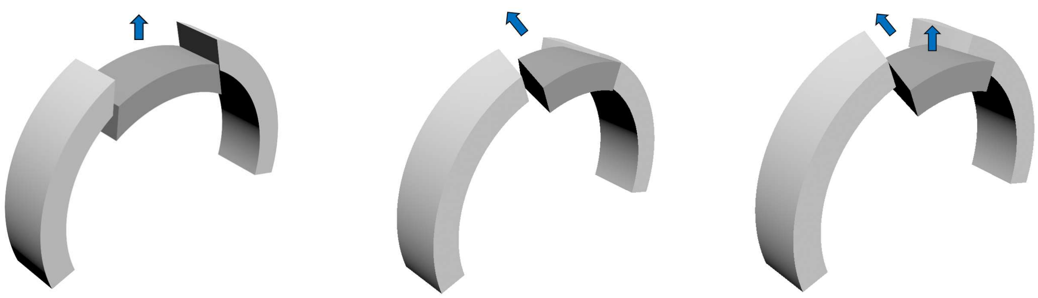


Figure 1: Segment Structure

For the radial insertion type of assembly method, a relatively large joint angle is often set to ensure that the chord length of the upper arc surface of the key segment is less than or equal to that of the lower arc surface. As a result, the tangential force on the connection surface between the key segment and the adjacent segments is relatively large while the normal force is relatively small. The increase in the tangential force will cause the bolts on the connection surface to bear greater shear stress and thus be prone to shear failure. And the decrease in the normal force will make the key segment more likely to fall along the direction of gravity, which may lead to potential safety accidents.

The axial insertion type of assembly method requires a relatively large stroke of the thrust cylinders (at least twice the ring width) to enable the axial insertion of the key segment. This will lead to an increase in the length of the shield machine, and at the same time, the length of the shield shell supported by the segments will also be increased.

Compared with other methods, the assembly method of inserting radially first and then axially has more universal applicability. While ensuring a certain lap amount, it can reliably prevent the key segment from falling off. In addition, this assembly meth-od is also applicable to situations with a relatively small stroke of the cylinders. There-fore, currently in China, the assembly method of inserting radially first and then axially has been applied in numerous TBM tunneling construction projects [6-10].



(a) Radial insertion (b) Axial insertion (c) Insertion first in the radial direction and then in the axial direction

Figure 2: Segment Assembly Methods

The assembly method of inserting radially first and then axially is also applicable to the construction of mechanical connection passages and micro shield segments. In the construction of mechanical connection passages, the clearance of the main tunnel is limited, resulting in a relatively short stroke of the cylinders. Compared with general TBM tunneling, it is more restricted, thus limiting the space for segment assembly. In micro TBM tunneling, the shield body itself is relatively short, and at the same time, it needs to meet the requirement of a small turning radius. Therefore, the multisegment articulated connection form is often adopted, which will lead to a certain extent of shortening of the shield tail length and thus crowd out the space for segment assembly.

To solve the problem of limited space for segment assembly in the construction of mechanical connection passages and micro TBM tunneling, there are two solutions. One is to reduce the ring width of the segments, and the other is to adjust the central angle, insertion angle and joint angle of the key segment. However, considering factors such as the total number of joints and the number of segment assembly times in tunnel projects, choosing wider segments can significantly reduce the total number of joints and the number of segment assembly times, which helps to improve the overall water-proof ability of the segments and shorten the construction period. Therefore, adjusting the central angle, insertion angle and joint angle of the key segment is the best means to solve the problem of limited space for segment assembly.

Compared with traditional TBM tunneling, in the above two application scenarios, the space for segment assembly is significantly limited. Therefore, the key segment of-ten adopts the assembly method of inserting radially first and then axially. In actual operation, a larger overlapping distance and a smaller axial staggering distance are more inclined to be used, which significantly increases the complexity of assembly. In view of this, considering the influence of design factors such as the ring width, outer radius, thickness and construction clearance of the segments, the relationship between the axial staggering distance of the key segment and its division angle, insertion angle and joint angle is studied to explore the optimal geometric design parameters of the segments, so as to solve the problem of limited space for segment assembly, ensure the optimization of the stress effect of the key segment, and meet the convenience requirements in the construction process.

2. Theoretical Calculation of the Functional Relationship of the Axial Staggered Distance of the Key Segment

2.1 Theoretical Calculation of the Functional Relationship of the Axial Staggered Distance of the Key Segment under Critical Conditions

2.1.1 Calculation Principle

When the key segment is assembled by radial insertion, that is, the key segment and the segment ring are not completely overlapped along the axial direction. After staggering a certain distance along the axial direction, the radial insertion is carried out first, and then the axial insertion is performed. The axial staggering distance between the key segment ring and the segment ring should meet the following condition: the distance from the corner point A of the adjacent segment (the intersection point of the front end face of the adjacent segment during tunneling and the inner arc surface of the segment ring) to the inner side surface of the key segment ring is zero. At this time, it is exactly in the critical state, that is, the construction clearance is zero. As shown in Figure 3.

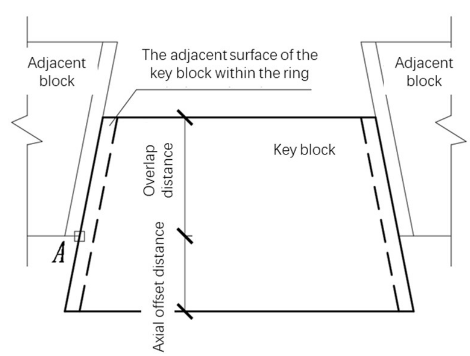


Figure 3: Schematic Diagram of the Axial Staggering Distance Between the Key Block and The Adjacent Blocks

2.1.2 Calculation of the Axial Staggered Distance of the Key Segment under Critical Conditions

The outer surface radius of the segment ring is $r1$, the inner surface radius is $r2$, the width of the segment ring is L, and the thickness is d. The central angle corresponding to the arc length of the cap block is θ. The point A on the inner arc surface of the cap block is located at the end face O of the segment ring, and a spatial Cartesian coordinate system is established with point A (0,0,0) as the origin, as shown in Figure 4. The segment ring extends along the negative X-axis. When the insertion angle of the cap block is 0, the inner adjacent surface of the cap block is (ABCD), where points A and B are located on the end face O of the segment ring, and points C and D are located on the end face O' of the segment ring. The surface (ABCD) coincides with the surface (XAZ), and its normal vector is $\vec{n}\,(0,1,0)$.

Rotate the plane (ABCD) counterclockwise along the vector $\overrightarrow{AB}$ by an angle α to obtain a new adjacent surface inside the key segment ring $(ABC'D')$, whose normal vector is $\vec{n'}\,(\sin\alpha, \cos\alpha, 0)$. That is to say, the insertion angle of the key segment at this time is ',' and the joint angle is 0. Points C' and D' are on the end face O' of the segment ring. The intersection point of the vector $\overrightarrow{C'D'}$ and the plane (XAY) is K.

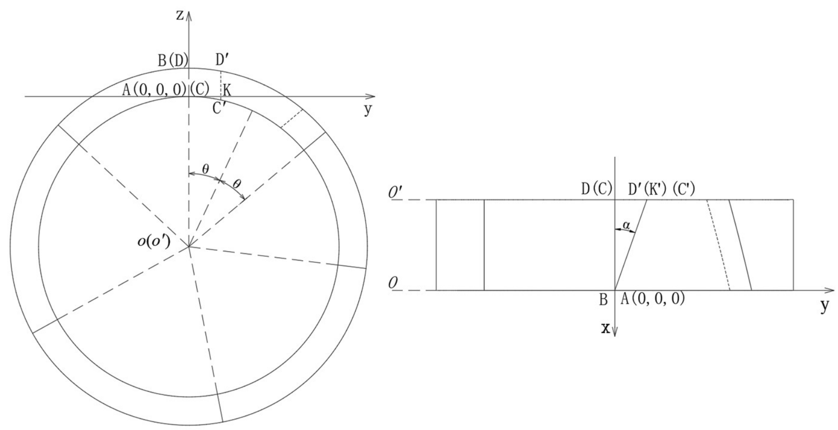


Figure 4: Schematic Diagram of the Overlapping Surface of the Key Block When Considering the Insertion Angle

As shown in Figure 5, rotate the plane $(ABC'D')$ clockwise along the vector $\overrightarrow{AK}$ by an angle β to obtain a new adjacent surface inside the key segment ring $(AB'C''D'')$, whose normal vector is $\vec{n''}\,(\cos\beta\sin\alpha,\ \cos\beta\cos\alpha,\ -\sin\beta)$. At this time, the joint angle β_0 of the key segment is related to the insertion angles α and β. Then the point-normal form equation of the plane （AB′C′′D′′） is:

$$\cos\beta\sin\alpha\, x + \cos\beta\cos\alpha\, y - \sin\beta\, z = 0 \tag{1}$$

The direction vector of the straight line AB is $\overrightarrow{m_1}\,(0,0,1)$. The equation of the straight line AB' is:

$$\begin{cases} \cos\beta\sin\alpha\, x + \cos\beta\cos\alpha\, y - \sin\beta\, z = 0 \\ x = 0 \end{cases} \tag{2}$$

According to Equation (2), the direction vector $\overrightarrow{m_2}$ of the straight line AB' is (0, sinβ, cosβ cosα). Then the included angle between the straight lines $\overrightarrow{m_1}$ and $\overrightarrow{m_2}$ is exactly the joint angle β_0 of the key segment, and the joint angle β_0 satisfies:

$$\tan\beta_0 = \frac{\tan\beta}{\cos\alpha} \tag{3}$$

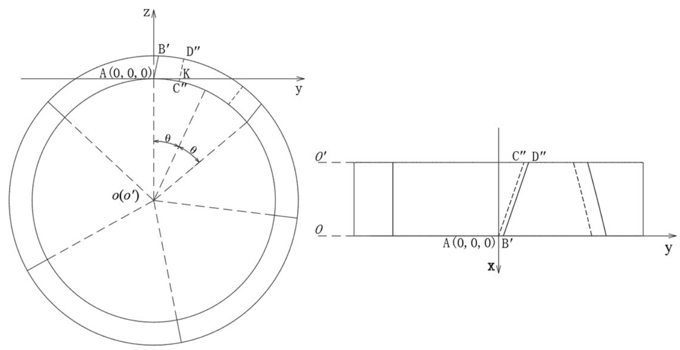


Figure 5: Schematic Diagram of the Overlapping Surface Considering the Joint Angle

As shown in Figure 6, the straight line op1 and the straight line op_2 are on the end face O of the ring. The straight line $op_1(0,\ 0,\ -1)$ coincides with the z-axis, and the straight line $op_2(0, -\sin\theta\,, -\cos\theta)$ is the bisector of the segment angle of the key segment. Point $E(x_E,\ y_E,\ z_E)$is on the plane (AB'C''D'') and is the critical radial insertion point. During the process in which the key segment moves from the assembled state to the critical assembly state along the straight line $op_2(0, -\sin\theta\,, -\cos\theta)$, the plane $(AB^{'}C^{''}D^{''})$ is translated to the plane $\overline{(AB'C''D'')}$. At this time, the distance between the two planes is 0, and point $E(x_E,\ y_E,\ z_E)$ moves to point A (0, 0, 0). Then the initial coordinates of point E satisfy: $y_E = z_E \tan\theta$, that is, the coordinates of point E are $E(x_E, z_E \tan\theta\,, z_E)$. According to Equation (1), we have:

$$\cos\beta \sin\alpha\, x_E + \cos\beta \cos\alpha\, z_E \tan\theta - \sin\beta\, z_E = 0 \tag{4}$$

Point $E(x_E, z_E \tan\theta\,, z_E)$ is on the cylindrical surface of the outer diameter of the segment，then:

$$z_E^2 \tan^2\theta + (z_E + r_2)^2 = r_1^2 \tag{5}$$

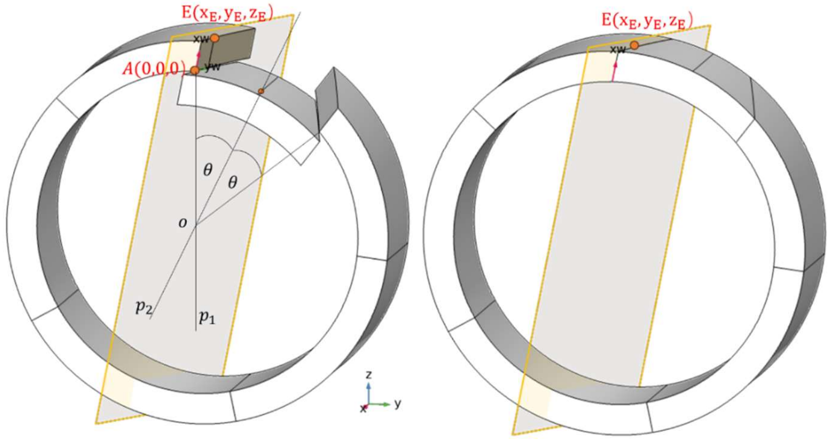
The coordinates of point E can be solved by Equations (3), (4) and (5) as follows:

$$\begin{cases} x_E = z_E \dfrac{\tan\beta_0 - \tan\theta}{\tan\alpha} \\ y_E = z_E \tan\theta \\ z_E = -(r_1 - d)\cos^2\theta \\ + \cos\theta \sqrt{r_1^2 - \sin^2\theta\,(r_1 - d)^2} \end{cases} \tag{6}$$

According to Equation (6), the axial staggered distance L_{stag} of the key segment under the critical state is:

$$L_{stag} = (-x_E) = -\left(-(r_1 - d)\cos^2\theta + \cos\theta \sqrt{r_1^2 - \sin^2\theta\,(r_1 - d)^2}\right) \times \frac{\tan\beta_0 - \tan\theta}{\tan\alpha} \tag{7}$$

In Equation (7), when L_{stag} is less than 0, its value is taken as 0; when L_{stag} is greater than L, its value is taken as L.



(a) Critical state of assembly (b) State after assembly is completed

Figure6: Schematic Diagram of the Insertion of the Key Block When Considering the Joint Angle

2.2 Theoretical Calculation of the Functional Relationship of the Axial Staggered Distance of the Key Segment under Construction Conditions

2.2.1 Calculation Principle

According to the theoretical calculation of the functional relationship of the axial staggered distance of the key segment under the critical state in Section 1.1, it can be known that the calculated axial staggered distance of the key segment at this time does not take the construction clearance into account, that is, the construction clearance is zero. However, in actual construction, due to the existence of construction errors, a certain degree of redundancy needs to be considered, and the construction clearance is generally set to be 10-30 mm. After the construction clearance is determined, the axial staggered distance of the key segment under the construction state can then be calculated.

2.2.2 Calculation of the Axial Staggered Distance of the Key Segment under Construction Conditions

The displacement vector of the translation of the key segment along the straight line $op_2(0,-\sin\theta,-\cos\theta)$ is $\overrightarrow{EA}\ (-x_E,\ -y_E,-z_E)$. The plane $(AB^{'}C^{''}D^{''})$ is translated to the plane $\overline{(AB^{'}C^{''}D^{''})}$. Under the critical state, the construction clearance is 0, and the plane $\left(AB^{'}C^{''}D^{''}\right)$ coincides with the plane $\overline{(AB'C''D'')}$. The point-normal form equation of the plane $\overline{(AB'C''D'')}$ is:

$$\cos\beta\sin\alpha\,x+\cos\beta\cos\alpha\,y-\sin\beta\,z=0 \tag{8}$$

Translate the plane $\overline{(AB'C'D'')}$ along the positive direction of the x-axis by ΔL_{stag}, and the obtained plane $(A\widetilde{B^{'}C^{''}}D^{''})$ has a point-normal form equation as follows:

$$\cos\beta\sin\alpha\left(x-\Delta L_{lap}\right)+\cos\beta\cos\alpha\,y-\sin\beta\,z=0 \tag{9}$$

The distance t from point $A(0,0,0)$ to the plane $(A\widetilde{B^{'}C^{''}}D^{''})$ is the construction clearance.

$$t=\cos\beta\sin\alpha\,\Delta L_{stag}=\frac{\sin\alpha\,\Delta L_{stag}}{\sqrt{1+\tan^2\beta_0}}=\frac{\sin\alpha\,\Delta L_{stag}}{\sqrt{1+\cos\alpha^2\tan^2\beta_0}} \tag{10}$$

$$\begin{cases}\Delta L_{stag}=kt\\ k=\dfrac{\sqrt{1+\cos\alpha^2\tan^2\beta_0}}{\sin\alpha}\end{cases} \tag{11}$$

According to Equation (7) and Equation (11), the axial staggering distance L_{stag}^t that satisfies the construction clearance t when the key segment is inserted at this time is:

$$L_{stag}^t=L_{stag}+\Delta L_{stag}=\frac{t\sqrt{1+\cos\alpha^2\tan^2\beta_0}}{\sin\alpha}-\left(-(r_1-d)\cos^2\theta+\cos\theta\sqrt{r_1^2-\sin^2\theta\,(r_1-d)^2}\right)\times\frac{\tan\beta_0-\tan\theta}{\tan\alpha} \tag{12}$$

In Equation (12), when $L_{stag}^t<0$, its value is taken as 0; when $L_{stag}^t>$L, its value is taken as L.

3. Engineering Overview

In the section between Panyu Passenger Transport Station and Guangzhou Xincheng West Station on the east extension section of Guangzhou Metro Line 3 (hereinafter referred to as the "Panyu-Guangzhou section"), the distance between the main tunnel lines at the No. 4 connecting passage is approximately 37.71 meters. The angle between the axis of the connecting passage and the axis of the left main tunnel is 90°, and the angle between it and the axis of the right main tunnel is 84°. The clear inner diameter of the main tunnel is 5.4 m. The TBM tunneling method is used to construct the connecting passage. The length of the shield machine body is about 4.2 m, the stroke of the oil cylinder is 0.8 m, and the excavation diameter is 3.29 m. The outer radius of the lining ring of the connecting passage is 1.575 m, the inner radius is 1.325 m, and the thickness of the segment is 250 mm. It is necessary to determine the appropriate width of the segment ring, the assembly method of the key segment, its segmenting angle, insertion angle and joint angle to ensure that the key segment can be successfully assembled under the condition of this oil cylinder stroke.

The original scheme of the segment adopted a ring width of 550mm, which was divided into five equal parts, including two standard blocks, two adjacent blocks, and one key block. The central angle of the key block was 72°, as shown in Figure 7. The insertion angle of the key block was 30°, and the joint angle was 31°. By conducting statistics on the damage of the segments during construction, it was found that the damage at the corners of the key block was the most prominent form of segment damage. The main reasons are as follows:

(1) The design of parameters such as the geometric angles of the key block was unreasonable. The relatively large insertion angle and joint angle led to sharper corners, making it difficult to arrange the reinforcing bars during segment processing, reducing the strength and being prone to stress concentration and damage.

(2) The transportation and assembly space was limited, and the segments collided and were squeezed against each other or against the equipment, resulting in segment damage.

(3) The construction accuracy was not high, and the joints of the segments were subjected to uneven forces, causing damage.

Based on the existing construction equipment conditions, the geometric parameters of the segments are optimized to reduce the problems prone to stress concentration, thus optimizing the stress state of the segments.

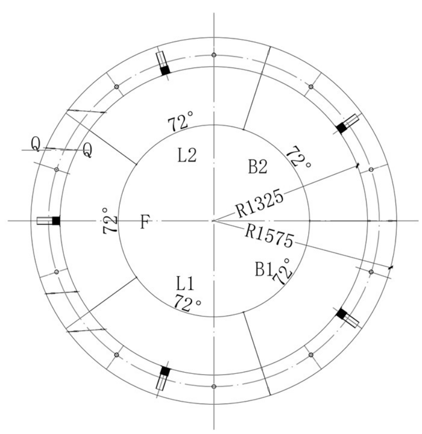


Figure7: Schematic Diagram of Segment Partitioning for the Connecting Passage

4. Analysis of the Influencing Factors of the Axial Staggering Distance of the Key Block

4.1 Influence of the Width of the Segment Ring

When considering different outer diameters and thicknesses of segments as well as the segmenting angle, insertion angle and joint angle of the key block, it can be known from Equation (7) and Equation (12) that both the axial staggering distance L_{stag} in the critical state and the axial staggering distance L_{stag}^{t} of the key block in the construction state are independent of the width L of the segment ring.

However, since the axial movement range of the segment is also affected by both the stroke of the axial thrust cylinder and the width of the segment ring, that is, L_{stag}^{t} cannot be too large. Its upper limit is jointly restricted by the stroke of the cylinder and the width of the segment ring. In order to enable the key block to be smoothly inserted between the two adjacent blocks, the axial staggering distance L_{stag}^{t} of the segment needs to satisfy the following relationship:

$$L_{stag}^{t} \le S - L - a \tag{13}$$

In the above formula, L represents the width of the segment ring; S represents the stroke of the cylinder, and a represents the reserved clearance between the cylinder and the segment (referred to as the "cylinder clearance" for short). According to the requirements of on-site construction, the cylinder clearance $a \ge 100\text{mm}$. For the No. 4 connecting passage in the Panyu-Guangzhou section, we can obtain that:

$$L_{stag}^{t} \le 800\text{mm} - L - a \tag{14}$$

If the key block is assembled in the axial insertion manner, that is, $L_{stag}^{t} = L$, it can be known from Equation (14) that the width of the segment ring needs to be less than 350 mm. At this time, if the width of the segment ring is too small, it will reduce the construction efficiency, be unfavorable for waterproofing and reduce the structural strength of the segments. Therefore, the axial insertion method is not advisable to be adopted.

To avoid the above adverse effects, the method of first in the radial direction and then in the axial direction is adopted for assembly. It is initially proposed that the width of the segment ring remains 550 mm. At this time, the axial staggering distance of the key block need to conform to:

$$L_{stag}^{t} \le 250\text{mm} - a \tag{15}$$

4.2 Influence of the Construction Gap

According to Equation (11), and taking the construction gap $t = 10\text{mm}$, the function value of $\Delta L_{stag}(\alpha, \beta_0)$ can be obtained ， as shown in Figure 8. The smaller the insertion angle α is, the more sensitive the influence of the construction gap on the axial stagger distance ΔL_{stag} is to the change of α. The amplification effect k of the construction gap on the axial stagger distance is mainly related to the insertion angle α. The larger the α is, the smaller the k is. Appropriately increasing the segment insertion angle α can reduce the amplification effect k of the construction gap on the axial stagger distance. In addition, ΔL_{stag} is positively correlated with the joint angle β_0, but is less affected by the joint angle. And since generally α and β_0 are not usually too large, $\sqrt{1 + \cos\alpha^2 \tan^2\beta_0} \approx 1$. In order to ensure that $k \le 5$, then:

$$\alpha \ge acsin\left(\frac{1}{5\sqrt{1 + \cos\alpha^2 \tan^2\beta_0}}\right) \approx acsin(0.2) = 11.540° \tag{16}$$

It can be known from Equation (16) that generally ensuring that the insertion angle α is greater than 12° can make ΔL_{stag} less than 5 times the construction gap.

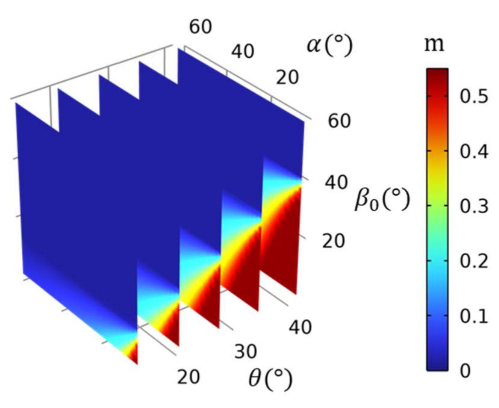


Figure9: Function Graph of $L_{stag}(\theta, \alpha, \beta_0)$

When $\theta \in (10°, 45°)$, $\alpha \in (3°, 60°)$, $\beta_0 \in (1°, 60°)$, and t = 10 mm, the value of $L_{stag}(\theta, \alpha/\theta, \beta_0/\theta)$ is shown in Figure 10. In the construction state, while ensuring that $\alpha \geq 12°$, the value of $L^t_{stag}(\theta, \alpha/\theta, \beta_0/\theta)$ is shown in Figure 11. Both $L_{stag}(\theta, \alpha/\theta, \beta_0/\theta)$ and $L^t_{stag}(\theta, \alpha/\theta, \beta_0/\theta)$ basically do not change with the variation of θ. When θ, α, and β_0 are increased or decreased in the same proportion, $L_{stag}(\theta, \alpha/\theta, \beta_0/\theta)$ and $L^t_{stag}(\theta, \alpha/\theta, \beta_0/\theta)$ basically remain unchanged. That is to say, in the critical state or in the construction state (with the requirement of $\alpha \geq 12°$ in the construction state), the same axial stagger distance can be ensured by increasing or decreasing the block angle of the key segment, the insertion angle and the joint angle in the same proportion.

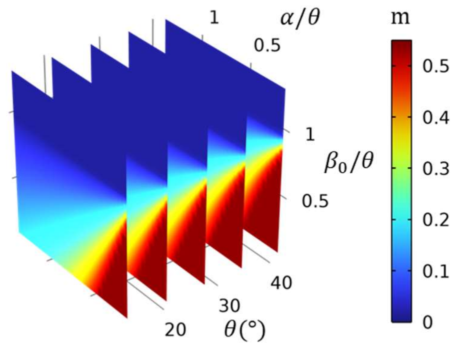
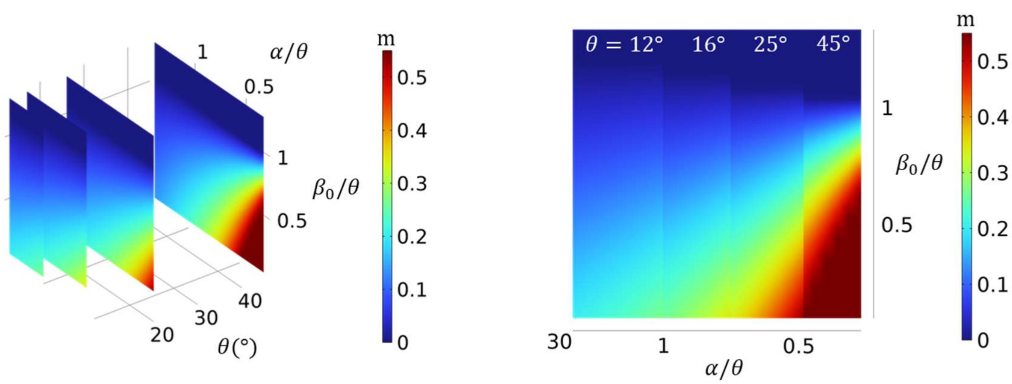


Figure10: $L_{stag}(\theta, \alpha/\theta, \beta_0/\theta)$ Under the Critical State



(a) $L^t_{stag}\left(\theta, \frac{\alpha}{\theta}, \frac{\beta_0}{\theta}\right)$ (Isometric drawing) (b) $L^t_{stag}(\theta, \alpha/\theta, \beta_0/\theta)$（Left view）

Figure 11: Axial Staggering Distance Under the Construction State ($\alpha \geq 12°$)

If the insertion angle of the segment is too large, the small end face of the key segment will be too small. This will lead to a decrease in the strength of the segment at the small end position. Meanwhile, the corner of the large end face will become sharp and is prone to damage during transportation and assembly. Therefore, the insertion angle should not be too large, and its block angle and insertion angle should satisfy the following formula:

$$2L \tan \alpha \leq (r_1 - d) \sin \theta \quad (17)$$

Under the action of the stratum pressure outside the segment, if the joint angle of the segment is too large, the normal stress on the circumferential side surface of the key segment will decrease and the tangential stress will increase, causing the bolts to bear relatively large shear stress. Therefore, generally, the joint angle β_0 of the segment should not be too large and should conform to:

$$\beta_0 \leq \theta - 5° \quad (18)$$

5. Optimization of the Geometric Parameters of the Closure Segment

5.1 Blocking Angle, Insertion Angle, Joint Angle

For the segmenting angle, insertion angle and joint angle of the key block of the lining ring of the

No. 4 connecting passage in the Fangcun-Guangzhou South Railway Station section, it is advisable that they meet the requirements of Equation (15), Equation (17) and Equation (18), so that the key block can be inserted smoothly during construction, is not easily damaged during transportation and assembly, and remains relatively stable under the action of stratum pressure. In addition, the existence of the cylinder clearance "a" is to ensure that there is an appropriate gap between the axial jacking cylinder and the rear end face of the segment to be assembled when the cylinder retracts, which facilitates the construction. It can be seen from Equation (15) that the cylinder clearance is inversely proportional to L_{stag}^{t}. According to the construction requirements, the cylinder clearance should be greater than 100 mm, that is, L_{stag}^{t} should be less than 150 mm.

The angle parameters that meet the above conditions and the axial staggering distance of the key block in the corresponding construction state are shown in Figure 12 and Table 1. In order to obtain a smaller insertion angle α and joint angle β_0, it is necessary to increase L_{stag}^{t} (that is, reduce the cylinder clearance) and decrease the segmenting angle.

The calculation results show that from Scheme 1 to 12-1, all the conditions are met. When L_{stag}^{t} remains the same, reducing the segmenting angle of the key block can make the insertion angle and the joint angle smaller. However, this may lead to an increase in the number of segments in a single ring or an increase in the size of the adjacent blocks, which is not conducive to transportation.

Therefore, L_{stag}^{t} can be increased as much as possible (by reducing the cylinder clearance). Still adopt the form of five equal segments (72°). Adjust the insertion angle to 25° and the joint angle to 26°. After optimization, it is reduced by 5° compared with the initial design scheme. During assembly, the axial staggering distance of the key block is 148.93 mm (with the cylinder clearance being 101.07 mm). After the angle design parameters of the segments are optimized, the stress concentration phenomenon caused by sharp corner is reduced, which can further solve the problem of damage during the transportation and assembly of the segments.

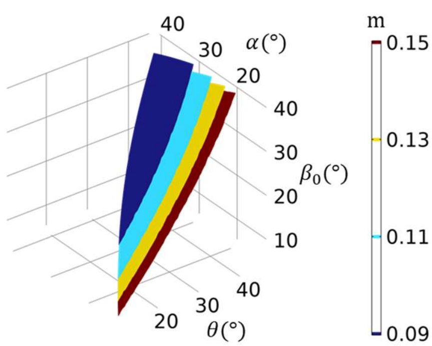


Figure 12: Axial Staggering Distance Under the Construction State that Meets the Corresponding Conditions

Table 1: Axial Staggering Distances for Different Angle Parameters

Design scheme	Blocking angle 2θ /deg	θ /deg	α /deg	β_0 /deg	L^t_{stag} /mm
1	56.00	28.00	22.96	22.96	90.0
2	64.00	32.00	26.22	26.22	90.0
3	72.00	36.00	29.56	29.56	90.0
4	56.00	28.00	21.76	21.76	110.0
5	64.00	32.00	24.88	24.88	110.0
6	72.00	36.00	28.11	28.11	110.0
7	56.00	28..00	20.68	20.68	130.0
8	64.00	32.00	23.68	23.68	130.0
9	72.00	36.00	26.78	26.78	130.0
10	56.00	28..00	19.72	19.72	150.0
11	64.00	32.00	22.58	22.58	150.0
12	72.00	36..00	25.56	25.56	150.0
12-1	72.00	36..00	25.00	26.00	148.93

5.2 Segment Thickness

When the segmenting angle is 72°, the insertion angle is 25°, the joint angle is 26°, $t = 10\text{mm}$， $r_1 \in (1\text{m}, 3\text{m})$, $d \in (0.1\text{m}, 0.5\text{m})$， the axial staggering distance $L^t_{stag}(r_1, d)$ of the key block in the construction state can be obtained from Equation (12), as shown in Figure 13. The size of $L^t_{stag}(r_1, d)$ is less affected by the outer radius r_1 of the segment and is mainly affected by the thickness d of the segment. L^t_{stag} is positively correlated with d. Reducing the thickness of the segment can also reduce the axial staggering distance of the key block in the construction state.

By calculating the instantaneous rate of change of L^t_{stag} with respect to d, we can get $\left(L^t_{stag}\right)'_d \in (0.13, 0.16)$, that is, at this time, the reduced value is only about 1/7 of the reduced value of the segment thickness. Slightly reducing the thickness of the segment has little impact on the axial staggering distance. However, reducing the thickness of the segment too much will reduce the structural strength and is not conducive to the waterproofing of the segment. Therefore, without changing the thickness of the segment, the segment with a thickness of 0.25 m is still adopted.

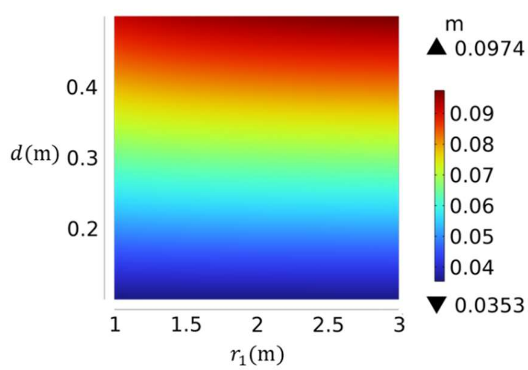


Figure 13: Variation of L^t_{stag} With the Outer Radius and Thickness of the Segment

6. Conclusions

This paper focuses on the problem of insufficient assembly space for segments during the construction of connecting passages by mechanical methods and with micro-TBM tunneling. Relevant research on the assembly method of the key block and the axial staggering distance of the key block has been carried out, and the conclusions are as follows:

1)On the basis of determining that the assembly method of the key block is to insert it radially first and then longitudinally, there are two ideas for solving the problem of insufficient assembly space for segments. One is to reduce the width of the segment ring, and the other is to adjust the central angle, insertion angle and joint angle of the key block. The results show that adjusting the central angle, insertion angle and joint angle of the key block is the best means to solve the problem of insufficient assembly space for segments.

2)Through the analysis of the geometric parameters of segments and the assembly process, the functional relationships between the axial staggering distance of the key block in the critical state and the construction state and its segmenting angle, insertion angle, joint angle, outer radius and thickness have been obtained.

3) In the construction state, the axial staggering distance of the key block is positively correlated with the segmenting angle, negatively correlated with the insertion angle, negatively correlated with the joint angle, and positively correlated with the thickness of the segment. Moreover, it is more sensitive to changes in the insertion angle. The insertion angle and joint angle of the key block should not be too large to avoid the stress concentration phenomenon caused by sharp corners and to keep it stable under force. Ensuring that the insertion angle is greater than 12° can make the axial staggering distance less than 5 times the construction clearance. In the critical state or the construction state (with the requirement of $\alpha \geq 12°$ in the construction state), basically the same axial staggering distance can be ensured by increasing or decreasing the segmenting angle, insertion angle and joint angle of the key block in the same proportion.

4)For the lining segments of the No. 4 connecting passage in the "Fangcun-Guangzhou South Railway Station" section of Guangzhou Metro Line 3, the influencing factors of the axial staggering distance of the key block were explored. Finally, the geometric design parameters of the key block were determined as follows: the ring width is 0.55 m, the outer radius is 1.575 m, the thickness is 0.25 m, the construction clearance is 10 mm, the cylinder clearance is 101.07 mm, the segmenting angle is 72°, the insertion angle is 25°, and the joint angle is 26°. The assembly method of radial first and then axial is adopted to ensure that the key block can be assembled smoothly in the limited space.

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