Research Article

Mechanical Behavior of the Special Segment Structure during Upward Shield Tunnel Construction

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The upward shield method in horizontal tunnels has the advantages of small ground space occupation, low construction cost, and short construction period, which expresses substantial economic benefits. The special segments of horizontal shield tunnels corresponding to the upward shield method construction area have special design requirements, and different internal force calculations and analyses should be carried out. To determine the mechanical behavior of the special segment structure of horizontal shield tunnels during the construction of upward shield tunnels, the theoretical calculation formula of the internal force of the special segment structure is deduced based on the average uniform rigidity ring method. Moreover, the bending moment and axial force of special segments are numerically simulated and analyzed using Midas GTS NX software. Finally, the theoretical formula and finite element calculation results are compared and analyzed. The results show that the internal force values of the open segment ring and the adjacent segment ring of the special segment are quite different during upward shield tunnel construction. Furthermore, compared with the arch crown and arch bottom of the segment ring, the stress at the arch waist of the segment ring is the most unfavorable. The stress difference between the open segment ring and the adjacent segment ring may cause unbalanced deformation, leading to damage to the segment ring radial joint. In the design and construction, attention should be given to the shear strength of the segment ring radial joint and the bending stiffness of the ring joint at the arch waist.

1. Introduction

The upward shield method refers to using a vertical shield machine to start from an underground horizontal shield tunnel and excavate the shaft upward. Its application is currently mainly concentrated in Japan. Although a method similar to the upward shield method named the standpipe lifting method has been widely used in China [1–3], few studies have been conducted on the upward shield method. Although there are similarities between the upward shield method and the standpipe lifting method, some differences exist [3].

A horizontal tunnel section with a longitudinal length of 3 times the shaft diameter near an area constructed with the upward shield method is the special section of the horizontal shield tunnel studied in this paper. The opening area and the reaction force area are shown in Figure 1. Compared with that of the ordinary horizontal shield tunnel segment, the internal force of the special segment of the horizontal shield tunnel is more complicated, and the design also has special requirements. Suppose that the analysis and design of the internal force of the segment are improper. In that case, cracks or damage to the horizontal tunnel will occur in the upward shield construction, directly affecting the shield tunnel’s quality and life. Therefore, it is necessary to carry out targeted internal force calculations and analyses to design a special segment of the horizontal tunnel in upward shield construction.

The existing horizontal shield tunnel segment design at domestic and foreign levels can be categorized into the following nine methods: the uniform rigidity ring method [4–6], the improved uniform rigidity ring method [7], the average uniform rigidity ring method [4, 8], the multihinge ring method [9–11], the elastic hinge ring method [12], the
Table 1.

The characteristics of these methods and the way to consider the circular joints and the radial joints are shown in [18]. The assumptions of each load are as follows:

1. The stratum resistance is distributed in the range of $\pi/4$ to $3\pi/4$ on the left and right sides of the ring top (triangular distribution). According to local deformation theory, the stratum resistance is proportional to the passive displacement of the stratum.

2. The lateral water and soil pressure is distributed on the whole ring.

beam-spring method [13–15], the shell-spring method [16], the flat shell-joint element-foundation system method [17], and the flat shell-elastic hinge-foundation system method [18]. The characteristics of these methods and the way to consider the circular joints and the radial joints are shown in Table 1.

The segment design of the shield method is always developed or improved based on the following four methods: the uniform rigidity ring method, the average uniform rigidity ring method, the multihinge ring method, and the beam-spring method.

Ye et al. [10] applied the average uniform rigidity ring method and utilized three kinds of segmental ring test models, including straight-jointed ring, stagger-jointed ring, and uniform ring models, to test the segmental ring by modeling and to study its mechanical behaviors. The equivalent stiffness of the segment lining ring $\eta EI$ and the $\eta$ value are also analyzed. Ye Fei et al. also concluded that, in the multihinge ring method, the rigidity of the joint is ignored, and the joints are assumed to be hinges. Hou et al. [7] improved the simplification of joints in the calculation model of segments and deduced the formulas for solving inner forces and displacement problems by the improved uniform rigidity ring method. Ding and Rao [12] applied the elastic hinge model to analyze the inner force of shield tunnels. The results show that the calculation results of the elastic hinge model are reasonable. Hao Wen et al. [13] established the finite element model of the beam-spring method and studied the influence of rotation, pressure, and shear springs.

Although there is already some research on the segment ring design, knowledge of the structural mechanism of tunnel openings is limited [19, 20]. During the construction of upward shield tunnels, the construction of tunnel openings is inevitable. Thus, it is necessary to study the mechanical characteristics of the special segment structure, that is, the tunnel openings, to help engineers design the segment rings.

The structure of this paper is as follows. In Section 2, combined with the existing design research on the internal force of the shield tunnel segment and based on the average uniform rigidity ring method, the theoretical internal force of the special segment of the horizontal shield in construction using the upward shield method is deduced. In Section 3, the calculation results of the special segment structure are analyzed. Section 4 applies the numerical simulation method to analyze the stress and deformation of the special segment ring of the horizontal shield in construction using the upward shield method. Moreover, the variation law of the internal force of the special segment lining segment is explored in this section. The results can provide a theoretical reference for designing special segments of horizontal tunnels constructed by the upward shield method.

2. Theoretical Calculation of the Internal Force of Lining Segment Rings in Special Sections

First, the internal force of the horizontal tunnel segment ring is calculated according to the average uniform rigidity ring method. The existence of the opening above the special segment ring is considered, and the internal force calculation formula is modified to obtain the internal force calculation formula of the special segments.

2.1. Loading System for Special Section Lining Segments.

In construction with the upward shield method, the special segment ring is mainly subjected to the following seven pairs of loads (Figure 2): (1) the self-weight $g$ and foundation reaction force $p_1$; (2) the vertical water and soil pressure $q_1$ and foundation reaction force $p_1$; (3) the vertical opening soil unloading $q_2$ and foundation reaction force $p_2$ caused by excavation; (4) the lifting reaction force $P$ and foundation reaction force $p_3$; (5) the triangular distribution lateral water and soil pressure $q_3$; (6) the uniform lateral water and soil pressure $q_4$; and (7) the stratum resistance $q_r$. Loads (1)–(4) are referred to as vertical loads, and loads (5)–(7) are referred to as lateral loads.

The assumptions of each load are as follows:

1. The stratum resistance is distributed in the range of $\pi/4$ to $3\pi/4$ on the left and right sides of the ring top (triangular distribution). According to local deformation theory, the stratum resistance is proportional to the passive displacement of the stratum.

2. The lateral water and soil pressure is distributed on the whole ring.
Table 1: Comparison of nine segment design methods.

| Number | Methods                                | Circular joints     | Radial joints       | Features                                                                 |
|--------|----------------------------------------|---------------------|---------------------|---------------------------------------------------------------------------|
| 1      | Uniform rigidity ring method           | Do not consider     | Do not consider     | It is widely used in Japan and is mostly used in sewer tunnels. Since the influence of the circular joints is not considered, it can be utilized to design segments with straight joints |
| 2      | Improved uniform rigidity ring method  | Considered through reducing the lining stiffness | Do not consider | There may be problems in the calculation results of the axial force value calculated by this method in the range of 90°-180° with the vertical angle |
| 3      | Average uniform rigidity ring method   | Considered through reducing the lining stiffness | Considered through increasing or decreasing the bending moment | It can be used to design linings for small tunnels and relatively large tunnels. It can be utilized to design staggered segments |
| 4      | Multihinge ring method                 | Considered through a hinge | Considered through a hinge | It can be used to design linings in hard rock, and it can be utilized to design segments with straight joints |
| 5      | Elastic hinge ring method              | Considered through a rotating spring | Considered through a rotating spring | Compared with those of methods 1 and 3, the calculation results of method 5 are closer to the real value |
| 6      | Beam-spring method                     | Considered through a rotating spring | Considered through a shear spring | It can be used to design linings for large tunnels. It is suitable for large-scale tunnels |
| 7      | Shell-spring method                    | Considered through the discrete to joint units method | Considered through the discrete to joint units method | It considers the segment ring as a cylindrical shell. Theoretically, the internal force of the segment can be calculated more accurately, but it is difficult to determine the stiffness of the segment joint. If the unit is sufficiently small, it will lead to a sharp increase in the calculation amount |
| 8      | Plate shell-joint system method        | Considered through the block-to-block joint model | Considered through the ring seam model | It is a three-dimensional model, the segment ring is regarded as a flat shell, and the effect of the joint is considered by constructing the segment lining joint element model |
| 9      | Flat shell-elastic hinge-foundation system method | Considered through the elastic hinge model | Considered through the elastic hinge model | It is a three-dimensional model based on the Reissner–Mindlin plate element. The joint effects between each segment are considered through elastic hinge elements |

Figure 2: Load system of the lining segment ring of special sections.
2.2. Internal Force Calculation of Special Section Lining Segments. Considering that the lining segment ring structure of the special section is a secondary statically indeterminate structure, the elastic center method is used to analyze the internal force of the lining segment ring of the special section. The displacement coordination equation at the elastic center is established:

\[
\begin{align*}
\delta_{11}X_1 + \delta_{12}X_2 + \Delta_{1P} &= 0, \\
\delta_{21}X_1 + \delta_{22}X_2 + \Delta_{2P} &= 0,
\end{align*}
\]

where \(\delta_{11}\) and \(\delta_{12}\) are the displacements of the basic structure along with the \(X_1\) and \(X_2\) directions under the action of the unit force \(X_1\) alone; \(\delta_{21}\) and \(\delta_{22}\) are the displacements of the basic structure along the \(X_1\) and \(X_2\) directions under the action of the unit force \(X_2\) alone; and \(\Delta_{1P}\) and \(\Delta_{2P}\) are the displacements along the \(X_1\) and \(X_2\) directions of the basic structure when the load acts alone. \(M_\theta\) and \(N_\theta\) at the angle \(\theta\) between the segment ring section of the special segment and the vertical axis can be obtained:

\[
\begin{align*}
M_\theta &= M_p + X_1 - X_2 R \cos \theta, \\
N_\theta &= X_2 \cos \theta + N_p,
\end{align*}
\]

where \(M_p\) and \(N_p\) are the bending moments and axial force generated by the external load on the segment ring in the basic structure, respectively; \(M_\theta\) and \(N_\theta\) are the bending moments and the axial force at the angle \(\theta\) with respect to the vertical axis on the segment ring section, respectively; \(\theta\) is the angle between the section segment ring and the vertical axis. The bending moment is positive with the inner tension, and the axial force is positive with the pressure; \(R\) is the calculated radius of the segment ring.

The representative points on the segment ring of the special segment are selected for internal force calculation and research. They are located at the opening, vault, arch bottom, and arch waist of the segment ring of the special segment, as shown in Figure 3.

Considering the small opening in the upward shield method, the segment at the opening is approximated as a “curved sheet.” The absence of this “curved sheet” causes the structure to deform significantly under lateral loads and “release” the internal forces. Therefore, based on the calculation of the internal force of the complete ring, this paper considers the influence of the opening (Figure 4) and focuses on the correction of the internal force calculation formula of the lateral load.

2.2.1. Internal Force Calculation Formula for the Lateral Load. The influence of the opening on the internal force of the segment ring under the lateral load is analyzed from the two aspects of the segment ring axial force and the bending moment.

In terms of axial force, the open lining segment ring in the shield tunnel is at a low axial force level [21]. According to the opening position in Figure 1 and the action direction of the lateral load in Figure 2, the lateral load has a great influence on the axial force of the segment ring. Simultaneously, considering the particularity of the opening, the calculation of the axial force of the segment ring is divided into \(A_2\) points and other points.

The “cantilever effect” regarding the bending moment occurs in the open lining segment ring in shield tunnels [21].

(1) The formula for the lateral water and soil pressure \(q_3\), which is subjected to a triangular distribution, can be deduced as follows:

First, the axial force at point \(A_2\) caused by the triangular distribution of the lateral water and soil pressure is calculated [4]. The formula for calculating the axial force of a complete ring under the action of the triangular distribution of the lateral water and soil pressure is as follows:

\[
N_{q3c} = \frac{1}{16} \left( \cos \theta + 8 \cos^2 \theta - 4 \cos^3 \theta \right) q_3 R_c,
\]

where \(N_{q3c}\) (kN/m) is the axial force of the complete ring under the action of the triangular distribution of the lateral water and soil pressure; \(q_3\) (kN/m²) is the triangular distribution of the lateral water and soil pressure; and \(R_c\) (m) is the average of the inner and outer radii of the ring.

The axial force of the open segment ring is calculated by subtracting the average axial force \(N_{q3c}\) of the
open segment from the axial force of the complete ring, as shown in Figure 5.

This paper approximates the open segment as a “curved sheet,” while the actual open segment is circular. Thus, the axial force correction coefficient $\lambda$ of the open segment is introduced. Its value is the ratio of the inner diameter of the opening to the arc length of the “curved sheet.” Therefore, after introducing the axial force correction coefficient $\lambda$ of the opening segment, the axial force loss value $N_{q3c}$ caused by the opening can be calculated as follows:

$$N_{q3c} = \lambda \left[ 2 \int_{0}^{\theta} N_{q3} ds \right] s = R_c d\theta,$$

where $N_{q3c}$ (kN/m) is the axial force lost due to the opening after introducing the correction coefficient $\lambda$ of the axial force of the opening segment under the action of the lateral Earth pressure of the triangular distribution.

Therefore, after considering the influence of openings at point $A_2$, the axial force caused by the lateral water and soil pressure of the triangular distribution can be calculated according to the following formula:

$$N_{q3} = N_{q3c} - N_{q3c},$$

where $N_{q3}$ (kN/m) is the axial force at point $A_2$ caused by the triangular distribution’s lateral water and soil pressure considering the opening influence.

Moreover, the opening reduces the axial force of the segment ring to a certain extent. After introducing the correction coefficient $\lambda$, the calculation formula of the axial force of the remaining points under the action of the lateral water and soil pressure of the triangular distribution is as follows:

$$N'_{q3} = \frac{\lambda}{16} \left[ \cos \theta + 8 \cos^2 \theta - 4 \cos^3 \theta \right] q_3 R_c,$$

where $N'_{q3}$ (kN/m) is the axial force at the remaining points except $A_2$, which is caused by the triangular distribution’s lateral water and soil pressure considering the opening influence.

Since the section of the segment ring on the vertical axis of symmetry only sinks downward without horizontal displacement and rotation, the bottom section of the ring can be regarded as the fixed end. By solving the mechanical problems of both the “cantilever effect” and the fixed end, it can be concluded that the bending moments at the end of the segment ring in these two cases are $q l^2/12$ and $q l^2/2$ ($q$ is the lateral load, $l$ is the segment ring diameter). That is, the “cantilever effect” under the open condition increases the bending moment of the segment by $5q l^2/12$, thus introducing the influence coefficient $\mu$ of the bending moment of the open segment, whose value is equal to the bending moment of the segment considering the “cantilever effect” increase factor.

Therefore, when $0 \leq \theta \leq \pi$, after introducing the influence coefficient $\mu$ of the bending moment of the open segment, the calculation formula of the bending moment of the open segment ring under the action of the lateral water and soil pressure of the triangular distribution is as follows:

$$M_{q3} = \frac{1 + \mu}{48} \left(6 - 3 \cos \theta - 12 \cos^2 \theta + 4 \cos^3 \theta \right) q_{4} R_c^2,$$

where $M_{q3}$ (kN·m/m) is the bending moment of the open segment ring, which is caused by the lateral water and soil pressure of the triangular distribution considering the opening influence.

(2) The formula for the uniform lateral water and soil pressure $q_4$ can be deduced as follows:

First, the axial force at point $A_2$ caused by the uniform lateral water and soil pressure is calculated. The formula for calculating the axial force of a complete ring under the action of the uniform lateral water and soil pressure is as follows [4]:

$$N_{q4} = q_4 R_c \cos^2 \theta,$$

where $N_{q4}$ (kN/m) is the axial force of the complete ring under the uniform lateral water and soil pressure; and $q_4$ (kN/m²) is the uniform lateral water and soil pressure.

Loss of Axial Force:

$$N_{q4} = \lambda \left[ 2 \int_{0}^{\theta} N_{q4} ds \right] s = R_c d\theta,$$

where $N_{q4}$ (kN/m) is the axial force lost due to the opening under the action of the uniform lateral water and soil pressure.

Therefore, the axial force caused by the uniformly distributed lateral water and soil pressure at point $A_2$ after considering the effect of the opening can be calculated according to the following formula:

$$N_{q4} = N_{q4} - N_{q4},$$

where $N_{q4}$ (kN/m) is the axial force at point $A_2$, which is caused by the uniform lateral water and soil pressure considering the opening influence.

After introducing the force correction coefficient $\lambda$ of the open segment at the other points, the calculation
formula of the axial force of the open segment ring under the action of the uniform lateral water and soil pressure is as follows:

\[ N'_{qs} = \lambda q_{r} R_c \cos^2 \theta, \]  
(11)

where \( N'_{qs} \) (kN/m) is the axial force at the remaining points, which is caused by the uniform lateral water and soil pressure considering the opening influence.

When \( 0 \leq \theta \leq \pi \), after introducing the influence coefficient \( \lambda \) of the bending moment of the open segment, the calculation formula of the bending moment under the action of the uniform lateral water and soil pressure is as follows:

\[ M_{qs} = \frac{1}{4} \mu \left( 1 - 2 \cos^2 \theta \right) q_{r} R_c^3, \]  
(12)

where \( M_{qs} \) (kN-m/m) is the bending moment of the open segment ring, which is caused by the uniform lateral water and soil pressure considering the opening influence.

The formula for the ground resistance \( q_{r} \) can be deduced as follows:

According to the calculation of the horizontal displacement at the horizontal diameter point of the segment ring (corresponding to points \( C_2 \) and \( D_2 \) in Figure 3) in the average uniform rigidity ring method and combined with the load system in the text, the calculation formula of the horizontal displacement at the horizontal diameter point of the segment ring of the special segment in the upward shield construction is as follows:

\[ \delta = \frac{2(\pi \cos \theta - \sin \theta) - 2q_{c} - q_{r} + \pi g}{24(\eta \mu + 0.0454 k R_c^4)}, \]  
(13)

where \( p_1, p_2, \) and \( p_3 \) are the foundation reaction force (kN/m²) of the vertical water and soil pressure, the unloading of the soil caused by the vertical excavation, and the jacking reaction force, respectively; \( g \) (kN/m²) is the dead weight of the horizontal shield segment; \( k \) (kN/m) is the stratum (elastic) bed coefficient; \( E \) is the bending stiffness per unit width (kN-m); \( \eta \) is the bending stiffness efficiency; and \( \delta \) is the horizontal displacement of the horizontal diameter point of the segment ring (m).

First, the axial force at point \( A_2 \) caused by ground resistance is calculated. The formula for calculating the axial force of a complete ring under the action of the ground resistance is as follows [4]:

\[ N_{qr} = 0.3536 \cos \theta k \delta R_c, \]  
(14)

where \( N_{qr} \) (kN/m) is the axial force of the remaining points, which is caused by the ground resistance considering the opening influence.

Loss of Axial Force:

\[ N_{qrc} = \lambda \int_0^{\theta} N_{qr} ds = R_c d\theta, \]  
(15)

where \( N_{qrc} \) (kN/m) is the axial force lost due to the opening under the action of the ground resistance.

Therefore, the axial force caused by the ground resistance at point \( A_2 \) after considering the influence of the opening can be calculated according to the following formula:

\[ N'_{qr} = N_{qr} - N_{qrc}, \]  
(16)

where \( N_{qr} \) (kN/m) is the axial force at point \( A_2 \) caused by the ground resistance when considering the influence of the opening.

When \( \pi/12 < \theta < \pi/4 \), after introducing the axial force correction coefficient \( \lambda \) of the open segment into the remaining points, the calculation formula of the axial force caused by the ground resistance is as follows:

\[ N'_{qr} = 0.3536 \lambda \cos \theta k \delta R_c, \]  
(17)

where \( N'_{qr} \) (kN/m) is the axial force of the remaining points, which is caused by the ground resistance considering the opening influence.

When \( \pi/4 < \theta < \pi/2 \), after introducing the axial force correction coefficient \( \lambda \) of the open segment into the remaining points, the calculation formula of the axial force caused by the ground resistance is as follows:

\[ M_{qr} = (1 + \mu) (0.2346 - 0.3536 \cos \theta) k \delta R_c^2, \]  
(19)

where \( M_{qr} \) (kN-m/m) is the bending moment of the open segment ring, which is caused by the ground resistance considering the opening influence.

When \( \pi/4 < \theta < \pi/2 \), after introducing the influence coefficient \( \mu \) of the bending moment of the open segment, the calculation formula of the bending moment caused by the ground resistance is as follows:

\[ M_{qr} = (1 + \mu)(-0.3487 + 0.5 \sin^2 \theta + 0.2357 \cos^3 \theta) k \delta R_c^2. \]  
(20)

2.2.2. Internal Force Calculation Formula for the Vertical Load.

The special vertical loads caused by the upward shield method in construction mainly include the unloading of the vertical excavation soil and the foundation reaction force, the lifting reaction force, and the foundation reaction force. Among them, the lifting reaction force consists of the weight of the vertical shield machine, the Jack’s weight, the weight of the vertical shield segment, the frontal thrust, and the friction force. To avoid damage to the horizontal shield tunnel in the upward shield construction, a leveling layer is set at the bottom of the horizontal tunnel to disperse the jacking reaction force, as shown in the gray part in Figure 6.

The internal force calculation is divided into point \( A_2 \), point \( B_2 \), and other points according to the magnitude and action position of the jacking reaction force. First, the internal forces at points \( A_2 \) and \( B_2 \) under the action of the
lifting reaction force and the foundation reaction force are calculated.

The axial force and bending moment of the vault under the action of the lifting reaction force and the foundation reaction force of the complete ring are relatively small. In addition, the position of point $A_2$ is similar to that of the vault. The internal force calculation formula of the vault can be used to approximate the axial force and bending moment at $A_2$. According to references [4, 22], the calculation formulas of the axial force and bending moment at points $A_2$ and $B_2$ can be obtained as follows:

\[
\begin{align*}
N_{PA} &= 0.00467PR_c, \\
M_{PA} &= 0.00232PR_c^2, \\
N_{PB} &= 0, \\
M_{PB} &= 0.05531PR_c^2,
\end{align*}
\]

where $N_{PA}$, $M_{PA}$, $N_{PB}$, and $M_{PB}$ are the axial force (kN/m) and bending moment (kN·m/m) of points $A_2$ and $B_2$ under

\[
\begin{align*}
N_g &= \begin{cases} 
\left(\theta \sin \theta - \frac{1}{6} \cos \theta\right)gR_c, & 0 \leq \theta \leq \frac{\pi}{2}, \\
\left(-\pi \sin \theta + \theta \sin \theta - \frac{1}{6} \cos \theta + \pi \sin^2 \theta\right)gR_c, & \frac{\pi}{2} \leq \theta \leq \pi.
\end{cases}
\end{align*}
\]

\[
\begin{align*}
N_{q1} &= q_1R_c \sin^2 \theta, \\
N_{q2} &= -q_2R_c \sin^2 \theta, \\
N_P &= -PR_c \sin^2 \theta,
\end{align*}
\]

where $N_g$, $N_{q1}$, and $N_{q2}$ are axial forces (kN/m) caused by the self-weight and foundation reaction force, vertical water and soil pressure with their foundation reaction force, vertical excavation soil unloading and its foundation reaction force axial force, respectively; $N_P$ is the axial force of the remaining points caused by the lifting reaction force and foundation reaction force, respectively.

The axial forces $N_g$, $N_{q1}$, $N_{q2}$, and $N_P$ of the remaining points caused by the vertical load are as follows:

\[
\begin{align*}
M_g &= \begin{cases} 
\left(\frac{3\pi}{8} - \theta \sin \theta - \frac{5}{6} \cos \theta\right)gR_c^2, & 0 \leq \theta \leq \frac{\pi}{2}, \\
\left(-\frac{\pi}{8} + (\pi - \theta) \sin \theta - \frac{5}{6} \cos \theta - \frac{1}{2} \pi \sin^2 \theta\right)gR_c^2, & \frac{\pi}{2} \leq \theta \leq \pi.
\end{cases}
\end{align*}
\]

\[
\begin{align*}
M_{q1} &= \frac{1}{4}(1 - 2 \sin^2 \theta)q_1R_c^2, \\
M_{q2} &= -\frac{1}{4}(1 - 2 \sin^2 \theta)q_2R_c^2, \\
M_P &= \frac{1}{4}(1 - 2 \sin^2 \theta)PR_c^2,
\end{align*}
\]

Figure 6: Schematic diagram of the leveling layer.
where \( M_p, M_{q1}, \) and \( M_{q2} \) are bending moments (kN·m/m) caused by the self-weight and foundation reaction force, vertical water and soil pressure, and their foundation reaction force, vertical excavation soil unloading and its foundation reaction force, respectively.

\( M_p \) is the bending moment of the remaining points caused by the reaction force of jacking and the foundation (kN·m/m).

Finally, by superimposing the internal forces of the segment ring under the lateral load and the vertical load, the internal force of each point of the final segment ring of the special segment can be obtained.

### 3. Calculation Analysis of the Special Segment Structure

The internal force of the lining segment ring for the horizontal tunnel special section of an example is calculated by applying the method proposed in this paper. Considering that the soil around the tunnel is sandy soil, according to China’s “Basic Information of Bridges and Culverts in Highway Design Manual,” the coefficient of the subgrade is 5 × 10^{-3} kN·m^{-3}. Without considering the effect of the ground overload, the soil bulk density \( \gamma = 19 \) kN·m^{-3}, and the coefficient of static Earth pressure \( K_0 = 0.43 \). The upward tunnel starts from a horizontal tunnel with a buried depth of 9 m and is excavated upward. The outer radius \( R_1 \) of the horizontal tunnel is 4.5 m, the inner radius \( R_2 \) is 4 m, the calculated radius \( R_c \) is 4.25 m, and the length of each ring segment is 2 m. The lining segment ring of the special section of the horizontal shield tunnel is made of concrete material, and the bulk density is 25 kN·m^{-3}.

The upward shield method is used to excavate 18 rings upward. The length of each ring segment is 0.5 m, the outer radius \( r_1 = 1 \) m, and the inner radius \( r_2 = 0.9 \) m [23]. The segment of the upward shield method is concrete material, and the bulk density is 25 kN·m^{-3}. The leveling layer material is steel, and the top surface size is 3 m × 3 m. The main parameters of the vertical shield machine are as follows [24]: the weight of the shield machine is 25.0 t, and 8 sets of QF140/500 jacks are selected, each weighing 110 kg. In addition, to ensure that the shield machine is tunneling upward, its frontal thrust needs to be 5~20 kPa larger than the overlying soil [11], which is 10 kPa. The friction coefficient \( f \) during upward excavation is 0.2 [25]. After calculation, the influence coefficients of the bending moment of the open segment are \( \mu_{A2} = \mu_{B2} = 0.42 \) and \( \mu_{C2} = \mu_{D2} = 0.17 \), and the correction coefficient of the axial force of the open segment is \( \lambda = 0.8 \).

According to Formulas (3)–(24), the axial force and bending moment at points \( A_2, B_2, C_2, \) and \( D_2 \) of the split ring can be obtained by setting \( \theta = \pi/12, \pi/2, \) and \( \pi \) in the formula.

When the length of the segment ring is 1 m, the calculated internal forces are shown in Table 2. The final results refer to the superposition value of the internal forces of the segment ring under the above-mentioned seven loads in this paper. It can be seen that the internal forces at points \( C_2 \) and \( D_2 \) are equal. Thus, only point \( C_2 \) is analyzed in this paper.

When comparing the bending moments caused by the vertical loads and the final results, it can be seen in Table 2 that the bending moment values caused by the vertical loads at points \( A_2, B_2, \) and \( C_2 \) are 12.6 times, 41.4 times, and 6.3 times of the final results, respectively. Moreover, the directions of the bending moments caused by the vertical loads are opposite to the final results.

When comparing the bending moments caused by the lateral loads and the final results, Table 2 shows that the bending moment values caused by the lateral loads at points \( A_2, B_2, \) and \( C_2 \) are 13.6 times, 42.4 times, and 7.3 times of the final results, respectively. Additionally, the directions of the bending moments caused by the lateral loads are the same as the final results.

In terms of the axial forces, the segment is compressed both under the vertical loads and the lateral loads. The axial forces caused by the vertical loads at points \( A_2, B_2, \) and \( C_2 \) account for 23.7%, 1.7%, and 100% of the final results, and the axial forces caused by the lateral loads at points \( A_2, B_2, \) and \( C_2 \) account for 76.3%, 98.3%, and 0% of the final results, respectively.

The bending moments and axial forces caused by various loads in Table 2 are depicted in Figures 7 and 8. In Figure 7, it can be seen that the bending moment values of point \( A_2 \) are between that of point \( B_2 \) and point \( C_2 \). Compared with point \( B_2 \), the bending moment changes of point \( C_2 \) show the opposite trend. The final results of the bending moments at points \( A_2 \) and \( B_2 \) are negative, while the final result of the bending moments at point \( C_2 \) is positive. Among them, the final result of the bending moment at point \( A_2 \) is the smallest, and that at point \( C_2 \) is the largest.

Figure 8 shows that the change of the axial force value at point \( A_2 \) when under various loads is small, while the change of the axial force values at point \( B_2 \) and point \( C_2 \) when under various loads is relatively large. Among the seven loads in Table 2, loads 5, 6, and 7 have a greater influence on the axial force at point \( B_2 \), and load 2 have a greater impact on the axial force at point \( C_2 \). In terms of the axial force values, the final results of the axial force values at points \( A_2, B_2, \) and \( C_2 \) all present positive values. The final result of the axial force at point \( C_2 \) is the largest, and the final result of the axial force at point \( A_2 \) is the smallest.

### 4. Numerical Simulation Analysis

To determine the most dangerous working condition in the upward shield method and verify the correctness of the theoretical calculation results, MIDAS GTS NX software was used to perform a numerical simulation analysis of the upward shield method construction process.

#### 4.1. Model Basic Information

Tunnels are affected by many factors during construction and operation. Only a few working conditions meet the two-dimensional simulation conditions. The calculation results under most working conditions using two-dimensional finite element simulation differ from the measured values [26]. In this paper, a three-dimensional calculation model is used to calculate the internal force of the lining segment ring of a special section.

The Mohr–Coulomb model is used to simulate the soil element; the lining segments are regarded as an isotropic material, the elastic model is used for analysis, and the 2D plate element is extracted to calculate the internal force of
the subsequent lining segment ring. The specific material parameters are shown in Table 3.

The mesh division is shown in Figure 9, and the construction stage of the upward shield method is set. The numerical results of the internal force of the horizontal shield lining segment ring in construction by the upward shield method can be obtained by the analysis.

4.2. Determination of the Most Dangerous Conditions. Figure 10 shows the maximum axial force and bending moment of the horizontal shield lining segment ring during the tunneling of the first ring in upward shield construction: the maximum bending moment is 175.4 kN-m, and the maximum axial force is 470.0 kN. Therefore, it is determined that the first ring of upward excavation (that is, the 0.5 m upward excavation working condition) is the most dangerous working condition in upward shield construction. The axial force and bending moment of the lining segment ring of the special section of the horizontal shield tunnel under this condition are analyzed.

4.3. Data Analysis

4.3.1. Comparative Analysis of Theoretical and Numerical Calculation Results. Figures 11 and 12 show the finite

| Number | Load pair | Internal force calculation value |
|--------|-----------|---------------------------------|
|        |           | \( M \) (kN-m)                  | \( N \) (kN)                  |
| 1      | Self-weight \( g \) and foundation reaction force \( P_f \) | \( M_{A1} = 69.0 \), \( M_{B1} = 99.5 \), \( M_{C2} = M_{D2} = -88.7 \) | \( N_{A21} = -5.0 \), \( N_{B21} = 6.6 \), \( N_{C21} = N_{D21} = 83.4 \) |
| 2      | Vertical soil pressure \( q_1 \) and foundation reaction force \( P_f \) | \( M_{A2} = 668.7 \), \( M_{B2} = 772.2 \), \( M_{C2} = M_{D2} = -772.2 \) | \( N_{A23} = 48.7 \), \( N_{B23} = 0 \), \( N_{C22} = N_{D22} = 726.8 \) |
| 3      | Vertical opening soil unloading \( q_3 \) and foundation reaction force \( P_f \) caused by excavation | \( M_{A3} = -54.7 \), \( M_{B3} = -63.2 \), \( M_{C3} = M_{D3} = 63.2 \) | \( N_{A33} = -4.0 \), \( N_{B33} = 0 \), \( N_{C32} = N_{D32} = -59.5 \) |
| 4      | Lifting reaction force \( P \) and foundation reaction force \( P_f \) | \( M_{A4} = 3.6 \), \( M_{B4} = 85.9 \), \( M_{C4} = M_{D4} = 137.1 \) | \( N_{A4} = 1.7 \), \( N_{B4} = 0 \), \( N_{C4} = N_{D4} = -129 \) |
| 5      | Triangular distribution lateral soil pressure \( q_4 \) | \( M_{A5} = -165.6 \), \( M_{B5} = -258.2 \), \( M_{C5} = M_{D5} = 182.3 \) | \( N_{A5} = 15.9 \), \( N_{B5} = 161.3 \), \( N_{C5} = N_{D5} = 0 \) |
| 6      | Uniform lateral soil pressure \( q_4 \) | \( M_{A6} = -410.9 \), \( M_{B6} = -474.6 \), \( M_{C6} = M_{D6} = 391.0 \) | \( N_{A6} = 47.5 \), \( N_{B6} = 251.6 \), \( N_{C6} = N_{D6} = 0 \) |
| 7      | Stratum resistance \( q_r \) | \( M_{A7} = -164.7 \), \( M_{B7} = -183.2 \), \( M_{C7} = M_{D7} = 191.9 \) | \( N_{A7} = 70.2 \), \( N_{B7} = 72.2 \), \( N_{C7} = N_{D7} = 0 \) |
| Sum    |           | \( M_{A2} = -54.6 \), \( M_{B2} = -21.6 \), \( M_{C2} = M_{D2} = 104.6 \) | \( N_{A2} = 175.0 \), \( N_{B2} = 493.7 \), \( N_{C2} = N_{D2} = 621.7 \) |
element calculation results of the axial force and bending moment of the lining segment ring of the special section of the horizontal shield tunnel under the first ring condition of upward shield tunneling. The finite element calculation results and the theoretical calculation results in this paper are compared and analyzed, and the analysis results are shown in Figures 13 and 14.

Figures 13 and 14 show that the theoretical calculation results in this paper are in good agreement with the finite element calculation results, which verifies the correctness of

### Table 3: Various material parameters.

| Material         | Poisson’s ratio | Elastic modulus (MPa) | Bulk density (kN/m³) |
|------------------|-----------------|-----------------------|----------------------|
| Soil             | 0.3             | $3 \times 10^4$      | 19                   |
| Special segment  | 0.28            | $3.25 \times 10^7$   | 25                   |
| Ordinary segment | 0.2             | $3.45 \times 10^7$   | 25                   |
| Steel            | 0.3             | $2.06 \times 10^8$   | 78.5                 |

Figure 8: Axial force caused by each load.

Figure 9: Mesh generation of a numerical model for the upward shield method.

Figure 10: Maximum internal force under various working conditions in the upward shield method.
the calculation method in this paper. In the upward shield method, points $A_2$ and $B_2$ of the open segment ring show smaller axial force and larger negative bending moment, while points $C_2$ and $D_2$ show larger axial force and positive bending moment.

### 4.3.2. Comparative Analysis of the Lining of Different Segment Rings in Special Sections

The internal force of the adjacent segment ring reference point is extracted from the numerical results and compared with that of the open segment ring. The comparison results are shown in Figures 11-13.

- **Figure 11:** Axial force contour plot of the lining segments in special sections.
- **Figure 12:** Bending moment contour plot of the lining segment of special sections.
- **Figure 13:** Comparison of the finite element calculation results and theoretical calculation results of the axial forces at points $A_2$, $B_2$, $C_2$, and $D_2$.
Finite Element Calculation Results

Theoretical calculation results

Figure 14: Comparison of the finite element calculation results and theoretical calculation results of the bending moments at points $A_2$, $B_2$, $C_2$, and $D_2$.

Reference value: 0

Figure 15: Comparison of the axial force values of each reference point of the lining segment ring in special sections.

Reference value: 0

Figure 16: Comparison of the bending moment values of each reference point of the lining segment ring in special sections.
Figures 15 and 16. Figures 15 and 16 show that there is a large difference between the internal forces of the open segment ring and the adjacent segment ring. Compared with the adjacent segment ring, the minimum axial force value at the opening of the open segment ring is 168.9 kN, the maximum bending moment value at the arch waist is 115.7 kN·m, and the maximum axial force value at the arch bottom is 469.1 kN. The top of adjacent segment ring vaults show maximum axial force and minimum bending moment values of 464.9 kN and $-110.5$ kN·m, respectively; the arch waist shows the maximum axial force value, 704.5 kN, and the arch bottom shows the minimum bending moment value, $-128.7$ kN·m.

The axial force values at points $C_i$ and $D_i$ of the segment ring of the special segment in the upward shield method are approximately 2 to 3 times those at points $A_i$ and $B_i$. The results show that the opening in the upward shield method aggravates the "transverse elliptical" deformation of the segment ring in the special section of the horizontal tunnel. Under the action of the lateral load term, the “transverse elliptical” deformation of the special segment ring can be alleviated to a certain extent.

Tang et al. [27] conducted a numerical simulation of segment rings. They concluded that the horizontal convergence caused by excavation near the shield tunnel increases significantly as the value of $\eta$ decreases. Both the opening obtained with the upward shield method and the reduction in the $\eta$ value aggravate the "horizontal elliptical" deformation of the segment ring.

5. Conclusions

In this paper, the force analysis of the lining segment ring of the special section of the horizontal shield in upward shield construction is carried out based on the average uniform rigidity ring method. The calculation formula of the internal force of the special section lining segment ring under different loads is studied. The theoretical calculation of the internal force of the special segment lining segment ring is carried out with the calculation example. The following conclusions can be drawn:

(1) MIDAS GTS NX software is used to carry out numerical simulation of the internal force of the lining segment in the special section in upward shield construction, and the most dangerous working conditions in the upward shield construction are determined. The numerical simulation results are compared with the theoretical calculation results. The results provide a reference for the design of the lining segment of the special section in the upward shield method.

(2) In constructing the upward shield method, the internal force values of the open segment ring and the adjacent segment ring are quite different. The results show that attention should be given to the bending resistance of the adjacent segment rings at the arch top and arch bottom in the upward shield method and the compressive performance of the segments at the arch waist. For the open segment ring, more attention should be given to the bending resistance of the segment at the waist and the compression resistance of the segment at the arch bottom.

(3) Compared with that at the arch top and the arch bottom of the special segment ring, the stress at the arch waist of the special segment ring in the upward shield method is the most unfavorable. Because there are segment joints near the arch waist, the integrity and rigidity of the corresponding area are reduced and easily damaged. Therefore, in the special section of the horizontal shield, engineers should pay more attention to the integrity and rigidity of the segment at the arch waist, and segment joints should not be set near this point as much as possible. In addition, the opening in the upward shield tunneling method causes a large difference in the internal force of the open segment ring and the adjacent segment ring. The radial deformation of the horizontal shield segment ring section is unbalanced, resulting in radial cracks in the segment ring. Therefore, in upward shield construction, the shear strength and deformation performance of the radial joint of the special segment ring of the horizontal shield should be strengthened.

(4) In this paper, only the internal force of some special segment ring reference points is selected for theoretical calculation and analysis. Due to the complexity of the stress on the lining segment of the special segment of the horizontal shield during upward shield construction, the internal force of other parts still needs to be studied in the future. In addition, the influence of the shape characteristics and opening size in the upward shield method on the entire segment ring of the special segment still needs to be further studied.

Data Availability

The data used in this research are provided within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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