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EFFECT OF SEGMENT DISLOCATION ON THE MECHANICAL PROPERTIES OF LINED TUNNELS IN A COMPLEX ENVIRONMENT

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ABSTRACT

In complex environments, tunnels with a lined structure are more affected by the dislocation of a segment. This study uses finite element simulations to further investigate the relationship between environmental changes and segments in lined tunnels. Tunnels with and without a lining are simulated under varying strata resistance, buried depth, and water level conditions. The horizontal and vertical displacements and stress changes in the two tunnels are compared when segment dislocation occurs. The results show that the lateral displacement of the tunnel is relatively stable and less influenced by external loads. However, the longitudinal displacement change is the opposite, and it increases significantly when the displacement exceeds 10 mm. When the lined tunnel is subjected to a large external load and misalignment occurs, the performance of the tube sheet joint bolts deteriorates, resulting in a stress decrease. Furthermore, the lined tunnel exhibits an increased ability to resist deformation and does not exactly follow the law of small displacements from small misalignments. When a large misalignment occurs, the lined tunnel may be damaged by elliptical deformation along the 45° direction, and its internal forces would be much larger than those of the unlined tunnel.

KEYWORDS

Tunnel, Lining dislocation of the segment, Lined construction, Mechanical performance analysis

INTRODUCTION

With the rapid economic development, the utilization of urban underground space is gradually increasing. Lined tunnels include a secondary lining in their structure that can greatly increase the space for pipeline arrangement as well as improve the efficiency of power transmission. However, this unique lining structure also enhances the difficulty of daily operation and maintenance. Construction of a lined tunnel involves the application of the secondary lining, differentiating them from other tunnels. However, construction companies have failed to update the relevant operational experience; thus, the maintenance and overhaul of underground structures has become a primary challenge. The majority of quality problems in tunnels include dislocation of the segment of lining sheets due to shield machine turns, morphological changes, or jacking thrust changes, among others [1,2].

With the operation of lined tunnels, there has been a gradual increase in the occurrence of cracks or even breakage of the lining segment, as well as water seepage and leakage in the tunnel due to dislocation of the segment [3,4]. Current research regarding lined tunnels has mainly focused on cast-in-place and prefabricated structures, with fewer studies on shield construction structures. Diemer [5] first investigated the mechanical and seismic performance of structurally similar water transfer tunnels using a model experimental approach. Sharghi [6] considers the effects of longitudinal offset, circumferential offset and incomplete contact of the support area on segment damage and obtains a numerical model that can accurately predict the performance of sectional tunnel lining. Botuan et al. [7] found that the joint position and axial pressure ratio predominantly affect the mechanical properties of the nodes of laminated slab-type corridors. Galli [8] studied the mechanical properties of the lining structure during tunnel excavation, and obtained a model that can be used to evaluate the lining–soil interaction and the stress distribution in both the lining and the reinforcing structural elements. Yang [9] highlighted two main external factors for structural stress changes in model tunnels under the influence of seismic forces: soil liquefaction in the tunnel and pore water pressure changes. A finite element (FE) model was developed for the formulation of a duct piece to simplify the calculation using the mean circular method [10], which considers the effect of the tube sheet joint on the deformation and bending moment. Morgan [11] assumed that forces on the tunnel lining would produce lateral deformation, causing the circular lining to become elliptical, and derived a closed solution after neglecting tangential stresses and strains. Chen and Majdi used finite elements to simulate the change in stress displacement of two adjacent lining rings when the joint function is considered in three-dimensional tunnel construction [12,13]. Regarding dislocation of the segment, Liu et al. [14] studied individual lining rings as a whole and showed that the maximum amount of dislocation of the segment occurred at the location of the capping block and adjacent blocks. Yuan et al. [15] analyzed the displacement phenomenon of a lining section caused by hydrostatic pressure during shield construction in water-rich strata. Wang [16] analyzed the phenomenon of lining segment displacement caused by grouting pressure and hydrostatic pressure during shield construction in hard rock areas. Zhou [17] examined the mechanism of lining dislocation of a segment and cracking under construction load in different construction stages of a tunnel through a river and proposed corresponding control measures. Arnau [18] analyzed the most influential parameters and their effects on the response of the lining structure when the lining of the segment tunnel is subjected to local loads or different deformations of adjacent rings.

The above results have focused on the effect of external environmental changes on the lining tube sheet itself and the tunnel structure. There is a lack of more detailed research on the stress–strain law for the internal structure of the tunnel due to the change in the misaligned volume. To further investigate the effect of misaligned volume changes on lined tunnels, this study evaluated the changes in mechanical characteristics of different types of tunnels under complex environmental conditions when misalignment occurs via numerical simulations. This work can provide a reference for the operation and maintenance of lined tunnels and their structural stability and durability in similar underground environmental conditions at a later stage.

Finite Element Method

Project Profile

An underground project was completed using the shield machine with a single circular section. The outer ring radius of the tunnel lining is 6 m, the inner ring radius is 5.4 m, and the tube section size is 300 mm × 1200 m. The single lining ring is assembled from six reinforced concrete precast blocks (three standard blocks, two adjoining blocks, and one capping block), and the longitudinal, circumferential, and lining pipe pieces are connected with M24 curved bolts. The soil parameters extracted from the ground investigation report involving this model interval are specified in Table 1.

Tab. 1 - Parameters of various layers spanning the tunnel section.5

Type of rock	Force density (γ) (kN/m3)	Cohesion (C) (kPa)	Angle of internal friction (∅) (°)	Lateral pressure at rest (K_0)
Silty clay	19.7	57.8	14.8	0.50
Silty fine sand	19.0	-	26.0	0.40
Gravelly sand	19.0	-	37.5	0.35
Rounded gravel	20.0	-	39.0	0.30

Model Parameters

For the lining segment, concrete material was used for the simulation. The constitutive relation is based on the intrinsic structure model proposed by the American scholar, Hongnestad. The model curve consists of a quadratic parabola and a section of the oblique straight line.

Upward phase:

$$\varepsilon \le \varepsilon_0, \sigma = f_c \left[2\frac{\varepsilon}{\varepsilon_0} - \left(\frac{\varepsilon}{\varepsilon_0} \right)^2 \right] \tag{1}$$

Declining phase:

$$\varepsilon_0 \le \varepsilon \le \varepsilon_u, \sigma = f_c \left[1 - 0.15\left(\frac{\varepsilon - \varepsilon_0}{\varepsilon_u - \varepsilon_0} \right)^2 \right] \tag{2}$$

Here, f_c is the compressive strength. Hongnestad suggested using $\boldsymbol{\varepsilon_u}$ = 0.0038 for theoretical analysis. He also proposed that $\varepsilon_0 = 2\left(\frac{\sigma_0}{E_0}\right)$, where E_0 is the initial elastic modulus. The geometric size of the lining segment (Table 2) and the material properties (Table 3) are the parameters used in the numerical simulation.

Tab. 2 - Geometric dimensions of the segment in the design data

Segment outer diameter/mm	6000
Segment inner diameter /mm	5400
Segment width /mm	1200
Bolt length /mm	464

Tab. 3 - Material parameter

Name of the material	Density (kg/m³)	Elastic modulus (Mpa)	Poisson ratio	Element type
Lining segment	2500	3×10^4	0.17	C3D8R
Bolt	7850	2.1×10^5	0.3	B31

To reduce the complexity of the calculation, the original bolts were replaced with straight bolts according to the conversion formula for curved and straight bolts proposed by Guo [19]. In addition, in practical engineering, the bolts do not interact with the lining segment when deformed by external forces. Therefore, contact between the bolt and bolt hole was not considered in the simulation, and the bolt was simplified using a curved instead of a straight approach. There is no external action in the middle of the bolt, and the end of the bolt is connected to the lining segment cell using the same node. In this paper, the change in segment dislocation is simulated by setting the displacement values in all directions in the boundary conditions.

To reduce simulation tolerances, the modeling scheme of two adjacent rings was abandoned in favour of a monolithic tunnel model with a multi-ring lining segment. The bolts are embedded to connect two adjacent lining rings so that they form a single unit and are jointly stressed. During the numerical simulation, the two contact surfaces of the lined lining segment will approach each other, and additional normal external forces need to be applied to the intrusion area to control the amount of intrusion within the convergence range [20]. The intrusion distances are as follows:

$$p_n = min\alpha l_{AB} \ , \ \alpha = \begin{cases} 1, (X_B - X_A) \cdot n^A \leq 0 \\ 1, (X_B - X_A) \cdot n^A \geq 0 \end{cases} \tag{3}$$

where n is the unit normal vector of A; X_B and X_A are the spatial coordinate vectors of points A and B, respectively.

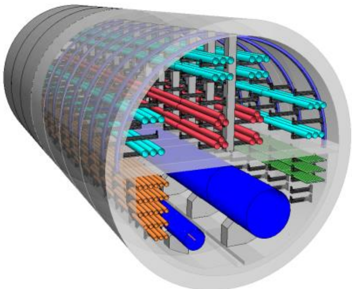

Fig. 1 - Lined tunnel 3D model

The lined tunnel is shown in Figure 1. The lining structure is highlighted using a block in Figure 2(b). It was poured after completion of the main body of the original tunnel, when the overall tunnel structure had not yet reached stability. The newly poured lining structure will share the forces with the tunnel and limit the overall displacement of the tunnel, offsetting some of the internal forces in the lining segment. Most current lining structures have similar mechanical parameters to the initial support. To simplify the calculations, the Hognestad approach was employed for the tunnel constitutive relation. The grid division of the lined tunnel is depicted in Figure 2, with a grid density of 0.4 m.

(a) (b)

Fig. 2 - Mesh division of (a) unlined and (b) lined tunnel

Load Application

To investigate the effect of segment dislocation, incremental dislocations of the segment were set for each scenario as 0, 5, 10, 15, 20, 25, and 30 mm. Variables were separated according to the different environments, with a burial depth of 12 m; a water table height of H = 4, 8, and 12 m; and a ground reaction coefficient $K=i\times10^4$ kN/m^3, $i=[1,5]\in N+$.

Taking the tunnel and lining segment as the main object of study, the load-structure method was considered for load application, considering factors such as strata resistance, burial depth, and water level.

Arch back soil pressure:

$$G = 2\left(1 - \frac{\pi}{4}\right) R_H^2 \gamma = 0.43 R_H^2 \gamma \tag{4}$$

where γ is the soil heaviness (kN/m^3), and R_H is the radius of the lining (m).

Lateral uniform active soil pressure:

$$p_1 = q tan^2\left(45° - \frac{\varphi}{2}\right) - 2c tan\left(45° - \frac{\varphi}{2}\right) \tag{5}$$

where q is the vertical soil pressure.

Lateral triangular distribution of active soil pressure:

$$p_2 = 2 R_H \gamma tan^2\left(45° - \frac{\varphi}{2}\right) \tag{6}$$

Water pressure: hydrostatic pressure mode of action.

Longitudinal restraints were set on both sides of the tunnel and vertical restraints at the bottom, which limited the overall movement of the lined pipe sheet. The earth pressure generated by the strata was simulated using spring units and restrained at the end of the spring cells.

The horizontal and vertical soil and water pressures in an actual project are considered as surface loads combined with gradient orders acting on the solid unit, and the lining segment is restrained, as in Figure 3.

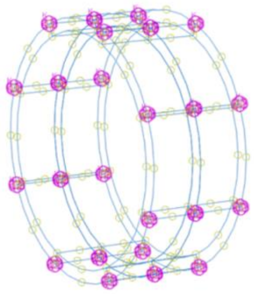

Fig. 3 - Lining segment constraint diagram

Simulation of the Effect of Dislocation of the Segment on Lined Tunnels under Changes in Strata Resistance

Tunnel Without Lining

Gunding springs were used to simulate the strata resistance, the values were formulated through the type of interval overburden in the ground survey report and set in linear increments. To ensure the uniqueness of the formation resistance variables and the accuracy of the results, the groundwater level was maintained at 8 m. When the tunnel as a whole is not misplaced and K = 1 × 10^4 kN/m^3, it can be seen from Figure 4 that the tunnel arch waist and arch foot positions produce a larger displacement. This phenomenon is due to the deformation of the concrete in the middle of the tunnel by the bending moment generated from the earth pressure. The ground resistance coefficient is controlled at a constant value, and the overall tunnel is subjected to the upper active earth pressure, which is displaced downward by the equivalent load generated by the upper soil layer of the tunnel. The additional stress of the soil on the tube pieces is large at the top and small at the bottom; the upper area of the tunnel is subjected to larger vertical pressure, and the lower part is

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subjected to passive earth pressure, resulting in a larger displacement of the arch waist and arch foot. The location where the maximum displacement of the structure occurs coincides with the pipe piece connection, and the inspection of the displacement area and nearby areas should be increased during operation to avoid accidents caused by connection failure.

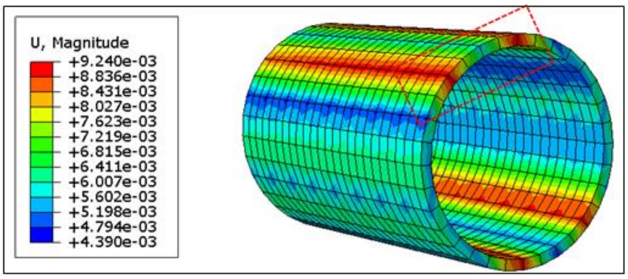
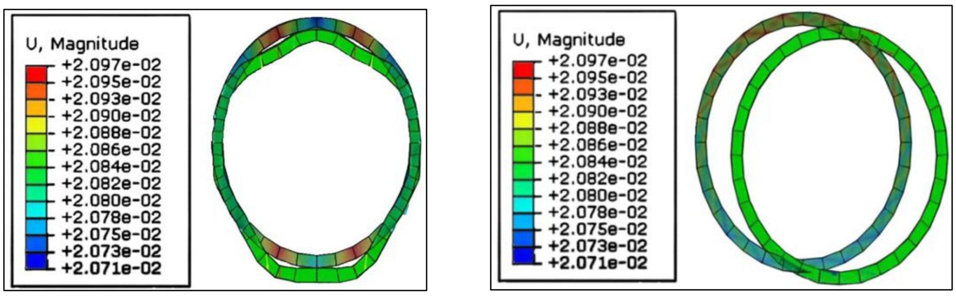


Fig. 4 - Displacement of unlined tunnel without misplacement of platform

When dislocation of the segment occurs, the lining segment responds more sensitively to the load, producing an oblique downward deflection of approximately 45° along the direction of the dislocation of the segment at the arch waist and arch shoulder. As the force increases in the red area marked in Figure 3, the lining ring is cut into multiple parts and its integrity is destroyed: irregular deformation occurs, as depicted in Figure 5(a). If no dislocation of the segment occurs, the lining ring is an intact part, the overall force is uniform, and its displacement is in the form of flat movement, as presented in Figure 5(b).



(a) (b)

Fig. 5 - Displacement comparison between misplaced and non-misplaced segments under external load: (a) during and (b) without segment dislocation

(1) Variation in tunnel lining segment displacement

The comparative results of the overall maximum horizontal displacement of the tunnel, varying the amount of dislocation of the segment and the strata resistance factor conditions, are displayed in Figure 6. At the segment dislocation of 30 mm, the maximum lateral deflection of the tunnel occurs at the shoulder and foot of the arch near the dislocation of the segment ring, exhibiting positive correlation with the amount of dislocation of the segment and a distribution that decreases toward the shoulder of the arch, centered on the dislocation of the segment ring. When the dislocation of the segment is less than 10 mm, the horizontal displacement increases at a slower rate and the overall height of K_1 is above K_2, indicating a limiting effect of the strata resistance on the horizontal displacement of the structure. When the dislocation of the segment is greater than 10 mm, the difference between the working conditions increases, indicating a faster rate of increase in horizontal displacement. A comparison of the height difference between K_1 and K_5 shows that the strata resistance can act as a more significant restraint on the lining segment. When the ground resistance is raised to 5×10^4 kN/m^3, the increase in horizontal displacement of the lining is reduced by approximately one-fifth. This is similar to the phenomenon in actual engineering.

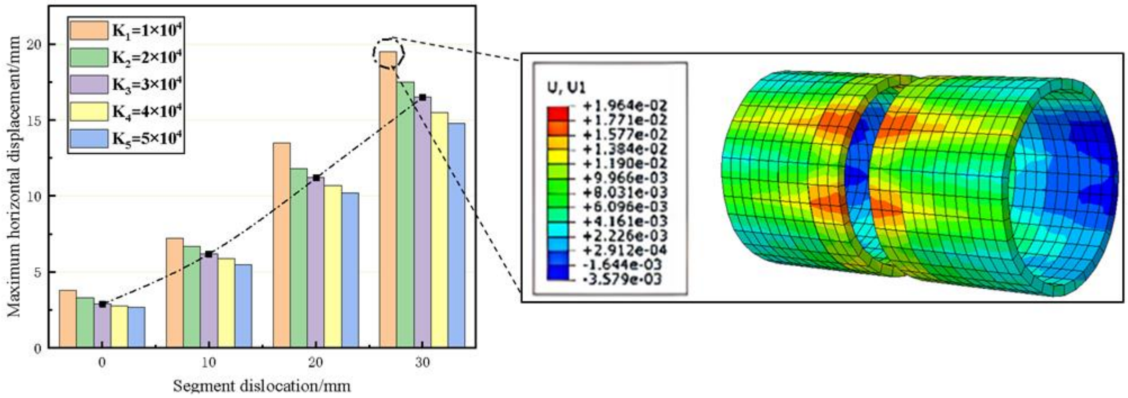


Fig. 6 - Strata resistances and horizontal displacements of unlined tunnel

Figure 7 presents the results of the comparison of the maximum vertical displacement of the tunnel as a whole under the change in strata resistance. At 30 mm dislocation of the segment, a large vertical displacement occurs at the position of the arch waist and foot of the tunnel, and the elliptical deformation of the tunnel section caused by the displacement increases the displacement at the top of the arch. The 2% and 3% decreases in K_5 compared with K_4 and K_2, respectively, indicate that the structure needs to provide higher internal forces than the general environmental conditions to generate displacement under the constraint of larger ground resistance. In summary, comparing the smaller variation in horizontal and vertical displacements with the amount of dislocation of the segment suggests that the strata resistance factor is a more significant constraint on vertical displacement.

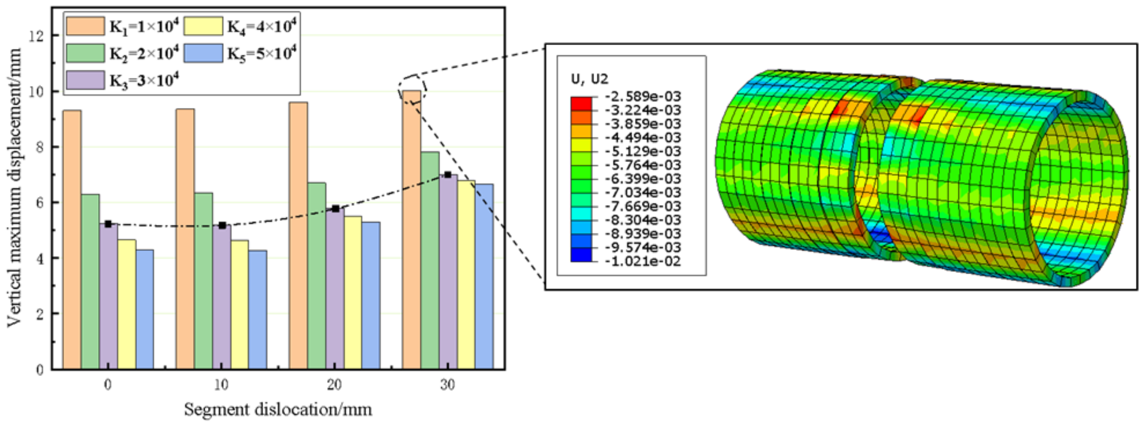


Fig. 7 - Vertical displacement of unlined tunnel with different lining segments

(2) Variation in main stress of tunnel lining segment

The maximum principal stress of the tunnel tube sheet under different stratigraphic resistance is divided into several zones: linear growth, smooth, and failure, as depicted in Figure 8. In the linear growth region, the amount of dislocation of the segment is small and the overall tunnel response to it is insignificant. The maximum principal stress increases linearly, and the lining segment deforms elastically; thus, the effect of strata resistance can be largely ignored. When the stress enters the smooth zone, the tunnel reaches a certain structural strength. For a small range, the increase in the amount of misalignment will not affect the change in stress; thus, the overall trend is gentler. At this time, the tube sheet can withstand stress close to the limit. When entering the failure zone, with increasing dislocation of the segment, the dislocation ring produces a larger deformation, and the tunnel loses the overall structure. At this time, the tunnel can be seen as two parts, both individually stressed, resulting in a decline in overall resistance to external forces, and hence the K_4 and K_5 curves present downward trends. In this region, the change in strata resistance can influence the main stress changes, and the greater the resistance, the more pronounced the stress failure phenomenon. The stress cloud in the dashed box in the figure indicates that the misalignment disrupted the tunnel integrity, causing a discontinuity of sudden stress changes, and the stress is divided into several individual parts by the misalignment ring. The $K_1K_2K_3$ curve is a stable trend because the structure can maintain the equilibrium state due to the small external load.With the increase of strata resistance, the overall structure of the tunnel is completely destroyed, and the internal stress of the tunnel is released, so the curve decreases.

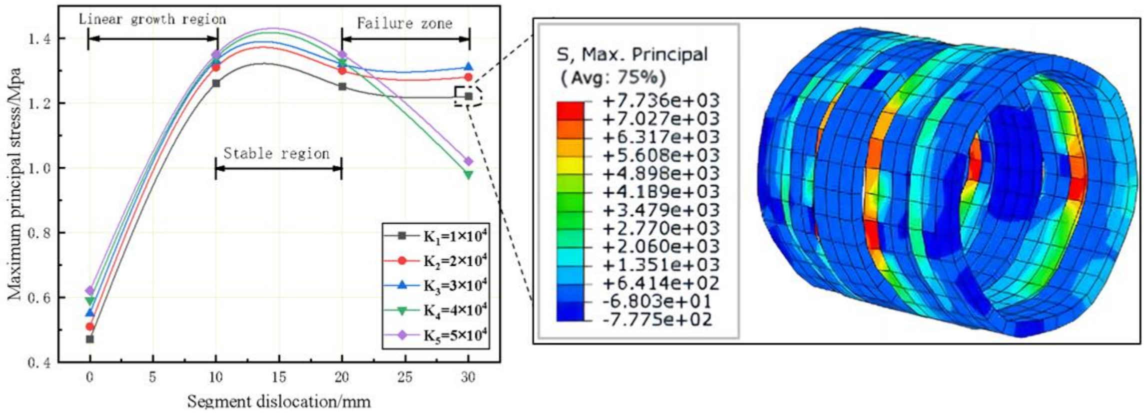
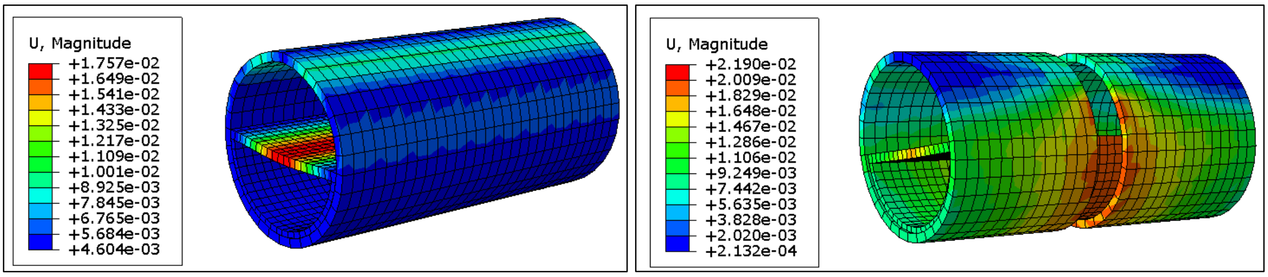


Fig. 8 - Maximum principal stresses in unlined tunnel under different strata resistances

Tunnel With Lining

The lined structure will increase the lateral stiffness of the tunnel and limit the development of dislocation of the segments, offsetting some of the displacements. However, its limiting effect can show differential results at different misbolts. When the misbolts are zero, the maximum displacement occurs at the position of the tunnel arch shoulder, and there is a large change in the position of the arch foot compared to the unlined tunnel, as shown in Figure 9(a). As the dislocation of the segment continues to increase, large displacements occur near the lined structure and the distribution changes dramatically, as shown in Figure 9(b). Cross section stiffness decreases with increasing dislocation. The stress field is redistributed when subjected to external loading, resulting in large deformation.



(a) (b)

Fig. 9 - Maximum displacement of pipe corridor under different fault levels: segment dislocations of (a) 0 and (b) 30 mm

(1) Variation in displacement of lined tunnel segment

The horizontal displacements of the tunnels do not vary significantly for different strata resistances and dislocations of the segment volumes, as shown in Figure 10. The reason for this is because the lined structure restricts the tunnel and produces oblique elliptical variations while weakening the horizontal displacements, but the overall trend is the same as that for the unlined tunnel. With a dislocation of the segment of less than 10 mm, the trend of the horizontal displacement is slightly lower than in the next stage due to the balancing effect of the lined structure, which corroborates the conclusions drawn earlier. At this stage, the greater the horizontal resistance, the smaller the displacement in that direction. The resistance coefficient and displacement gradually increase when the zone dislocation exceeds 10 mm. This is mainly because the lining structure and the tunnel form a stressed whole, displacing the dislocation ring and increasing the uniformity of the adjacent ring. When the external load increases, displacement of the area near the dislocation ring occurs simultaneously; therefore, the maximum displacement increases.

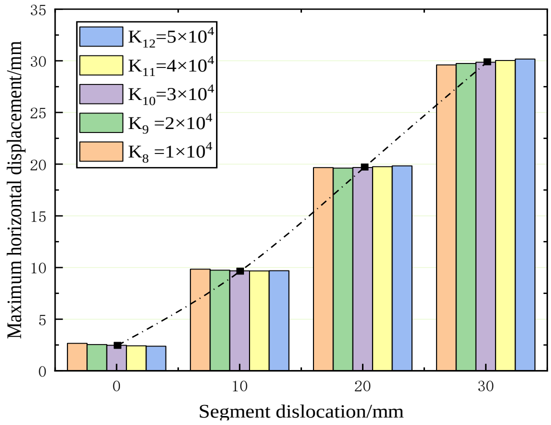
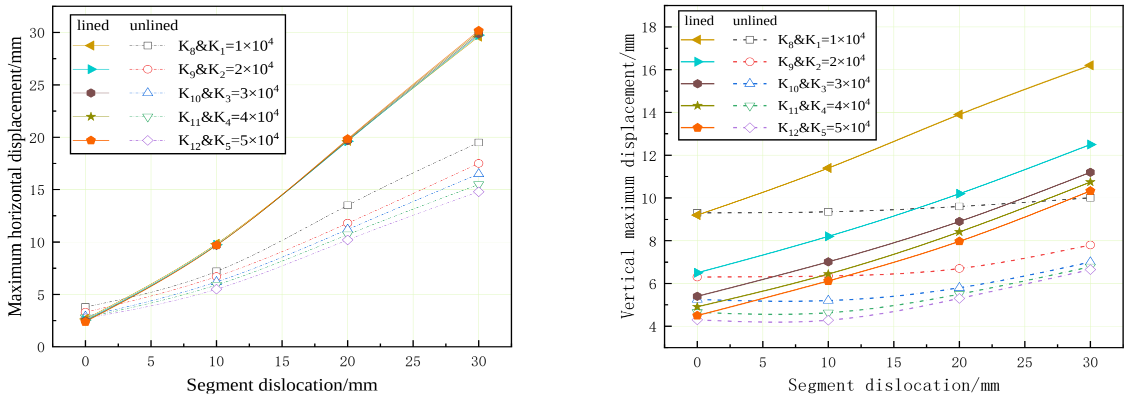


Fig. 10 - Horizontal displacement of lined tunnel with strata resistance

(2) Lined tunnel displacement variation and comparative analysis

As shown in Figure 11(a), the starting points of the curves are basically the same. Thus, the maximum horizontal displacement does not change significantly when the tunnel is subjected to varying resistance in the lining state, and the effect is relatively small. In addition, the maximum displacement of the lined tunnel varies in parallel with the amount of dislocation of the segment, as shown by the solid line in the diagram in 45° increments, indicating that the lined structure results in a more coordinated tunnel displacement. The different resistance conditions have less influence on the lined tunnel, and the lined structure improves the tunnel's adaptation to the ground. However, with the gradual increase in segmental misalignment, the overall maximum horizontal displacement curve for the lined tunnel is higher than that for the unlined tunnel. Thus, the lining structure promotes the influence of segmental misalignment on the tunnel, leading to the expansion of segmental misalignment on both sides and a decrease in the constraint.



(a) (b)

Fig. 11 - Comparison of (a) horizontal and (b) vertical displacements in tunnels with different strata resistance

Figure 11(b) presents the vertical displacement with varying strata resistance. When no misalignment occurs, the lining structure has less influence on the tunnel structure under the same value of ground resistance, and the maximum vertical displacement of both is approximately equal. This is demonstrated by the coincidence of curves K_1 and K_8, K_2 and K_9, and the starting point. When the dislocation of the segment is less than 10 mm, a downward trend appears in the vertical displacement of unlined tunnels, while the opposite is true for lined tunnels. Comparing the horizontal and vertical displacements, it is clear that the lining improves the uniformity of tunnel displacements, but the overall displacement values and trends increase. Therefore, more attention should be paid to the occurrence of zone misalignments in the acceptance, operation, and maintenance of lined tunnels. Smaller section misalignments can also lead to larger lining section distress and structural damage.

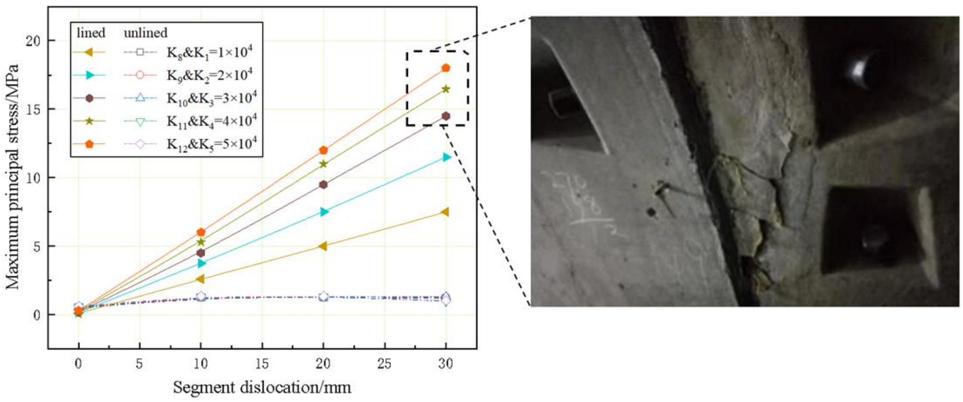


Fig. 12 - Comparison of maximum principal stresses in tunnel with different strata resistances

(3) Lined tunnel variation in main stress and comparative analysis

As shown in Figure 12, the lining structure significantly influences the trend and magnitude of the maximum principal stresses in the tunnel, with a positive correlation between the principal stresses in the structure and the amount of dislocation of the segment. The increased lateral stiffness of the lined structure improves the stability of the structure, and thus, a greater internal force is required to produce the same amount of displacement. However, this can also lead to irregular deformation of the lined tunnel, causing stress concentration in adjacent misaligned rings and pulling

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down the lining section, which would create cracks and other stability hazards. In the area highlighted, the lining section is very susceptible to damage.

Simulation of the Effect of Lining Dislocation of the Segment on Lined Tunnels under Changing Groundwater Levels

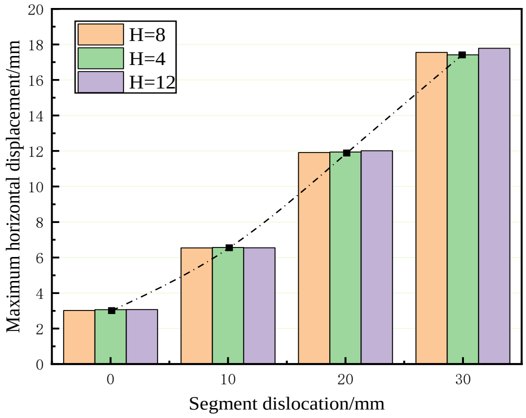
Tunnel Without Lining

(1) Variation in tunnel lining segment displacement

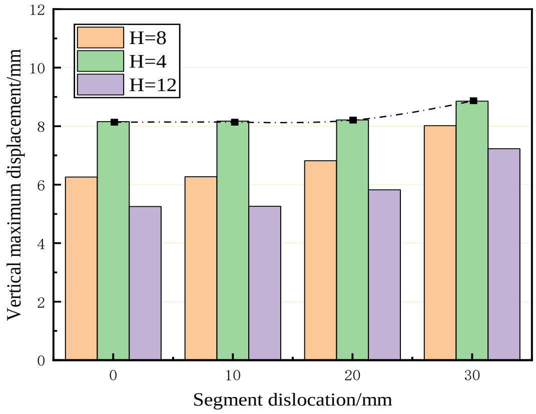
The level of the groundwater table represents the amount of head around the tunnel soil and determines the strength of the erosion action. Groundwater can cause erosion of the lining segment and joint bolts, weakening the performance of the reinforcement inside the lining segment, and jeopardizing the durability and stability of the tunnel structure. The choice of groundwater level is based on the depth of 16 m, set to 4, 8, and 12 m above the top of the tunnel, and the strata resistance was taken as $K=2\times10^4$ kN/m^3.

Groundwater acts as a circumferential pressure on the lining segment with a linearly increasing distribution of the analytical field. The change in groundwater level is modelled by varying the load acting on the lining segment.

As can be seen from Figure 13(a), the rise in groundwater level can partially offset the soil load and reduce the force in the arch waist area, and the effect is significant with the rise in water level. More specifically, under the same misplaced amount, the change in water level hardly affects the change in horizontal displacement, the maximum water level difference in the figure is $\triangle$H=12-4=8 m, but the horizontal displacement only differs by 2%.



(a)



(b)

Figure 13 - (a) Horizontal and (b) vertical tunnel displacement changes with water level.

The trends for the effects of water level and strata resistance on vertical displacement are similar, as demonstrated in Figure 13(b): the maximum vertical displacement at fixed water level is positively correlated with the amount of misplaced platform. When the amount of dislocation of the segment exceeds 20 mm, the vertical displacement of the tunnel under all water level conditions exhibits a large change and a significant increase. Under the influence of changing water level, the overall vertical displacement of the tunnel is not significant when the amount of dislocation of the segment is less than that required by the specification. However, if the amount of misplaced platform exceeds the limit, the tunnel immediately generates large vertical displacements that increase with the water level, seriously threatening the stability and durability of the structure.

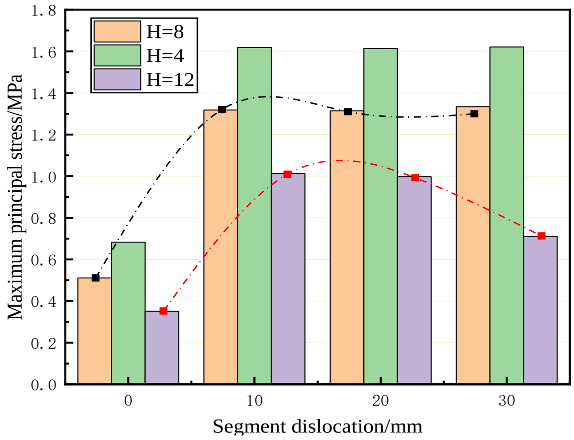


Figure 14 - Variation in maximum principal stress of unlined tunnel at different water levels.

(2) Stress change in tunnel lining segment

Figure 14 shows that the maximum principal stress in the misaligned ring varies significantly depending on the dislocation of the segment. In contrast to changes in stratigraphic resistance, changes in groundwater level present a greater range of numerical fluctuations and a more pronounced effect on the misaligned rings. When the amount of dislocation of the segment is zero, the maximum stress in the lining segment of H=4 m, compared with at H=12 m, increases by 85.1%. When the dislocation of the segment exceeds 10 mm, the δ–Δ curve of the dislocation of the segment ring tends to decrease and increases as the water level increases. This is because an increase in the water table leads to a decrease in the equivalent force and a reduction in the ground load.

Tunnel with Lining

(1) Lined tunnel displacement variation and comparative analysis

From Figure 15, the maximum horizontal displacement increases with the amount of dislocation of the segment in both tunnels under different water level conditions. When the dislocation of the segment is less than 10 mm, the maximum horizontal displacement increase is smaller. When the amount of misalignment of the segments exceeds 10 mm, the horizontal displacement increases, that is the slope increases. However, if the type of tunnel and the amount of segment misalignment are certain, the horizontal displacement value can remain constant in a small range. In addition, the higher horizontal displacement values for lined tunnels are because within the small dislocation of the segment, the lined structure improves the stability of the tunnel and the displacement is slightly lower than that in unlined tunnels. With a gradual increase in the amount of segment dislocation, the strength of the lined structure reaches its limit, can no longer guarantee its own stability, and begins to change; the horizontal displacement increases with the direction of the dislocation of the segment ring. If no action is taken at this point, there will be a high risk of damage to the arch shoulders, as shown in the figure.

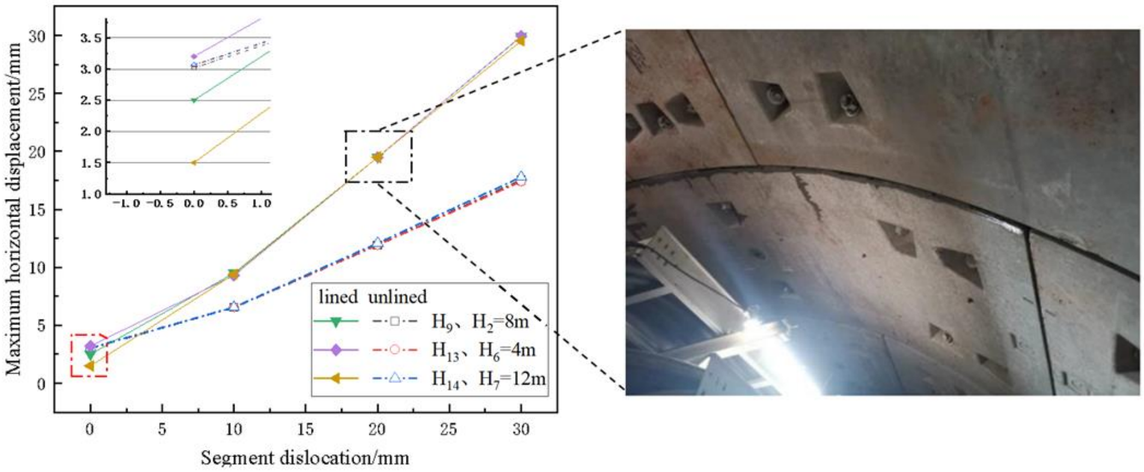


Fig. 15 - Comparison of maximum horizontal displacements in tunnel

As shown in Figure 16, the overall displacement of the lined tunnel tends to increase linearly with the amount of segmental misalignment. The unlined tunnel has a relatively flat change due to the oblique elliptical deformation of the tunnel caused by the lining structure. When no misalignment occurs, curve H_7 is above H_{14} indicating that the lined tunnel is structurally better under smaller external loads. When the amount of misalignment exceeds 20 mm, the vertical displacement of the lined tunnel in all cases exceeds that of the unlined tunnel. This phenomenon demonstrates that in practice, it is more important to increase the monitoring of lined tunnels near large misalignments to prevent displacement overruns.

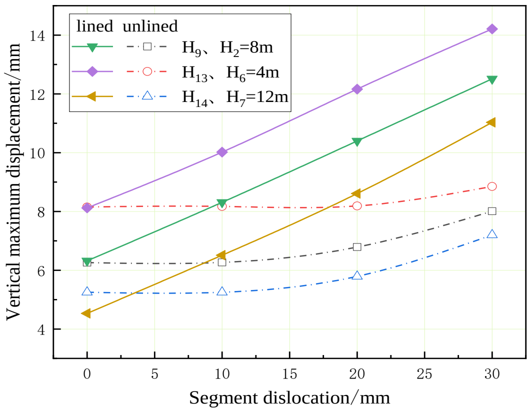


Fig. 16 - Comparison of maximum vertical displacement in tunnel

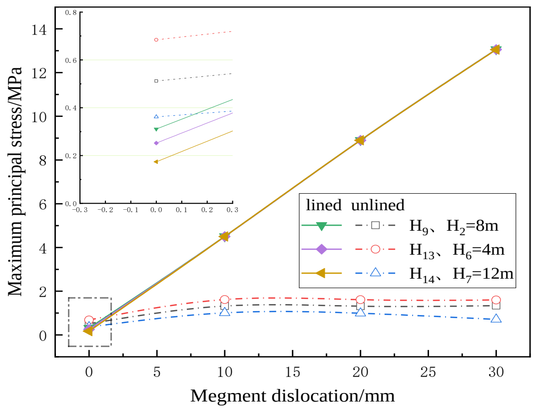


Fig. 17 - Comparison of maximum principal stress in tunnel

(2) Lined tunnel variation in main stress and comparative analysis

As indicated in Figure 17, the pouring of the lining structure did not have a significant effect on the main tunnel stresses under varying water table, but the range of change was more limited. As the amount of misbolts increases, the maximum principal stress in the misbolted ring of the lined tunnel changes more significantly, increasing rapidly with the amount of misbolts. The main stresses in the unlined tunnel are largely unaffected by changes in the amount of dislocation of the segment. When the dislocation of the segment is zero, the main stresses in the lined tunnel are low, as the lining structure shares some of the stresses. As the amount of segment dislocation increases, the lining structure reacts to increase its own principal stresses.

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CONCLUSION

In this work, the mechanical properties of lined tunnels and the locations prone to damage when a tube sheet is misaligned were analyzed in the context of a completed lined tunnel. In addition, the effects of the change in misplaced volume on the structures of the two tunnels were compared and analyzed under different ground resistance and groundwater level conditions. The following conclusions were drawn:

(1) In the same environment, the displacement and stress of the lined tunnel are greater than those of the unlined tunnel, and the rate of change of both increases as the dislocation increases. However, for small displacements of the structure, the lining structure will increase the deformation resistance of the tunnel, as shown by the fact that part of the displacement curve is below the unlined tunnel. Therefore, when maintaining lined tunnels, the cracks and broken segments should be repaired and replaced in time to avoid the overall damage.

(2) The trends of the horizontal and vertical displacements of the lined tunnels in different environments were the same, wherein the amount of misalignment increased the displacement. The rate of change of the displacement of the tube sheet is bounded by 10 mm: the change is small when it is less than 10 mm and increases significantly when it is more than 10 mm. The horizontal displacement of the tunnel is less affected by external influences, while the vertical displacement exhibits the opposite trend. The main influencing factor causing the difference between the two is the load on the tunnel.

(3) The lined tunnel itself has a certain ability to balance the misalignment. This is mainly reflected in the significant increase of the main stress when a small misalignment (10 mm) occurs in the structure, and the peak value is reached in the adjacent lined pipe piece at the misalignment location. Under a large misalignment and external load, the mechanical properties of the tube sheet joint start to deteriorate, resulting in a stress drop with a slow growth rate.

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