Journal of Engineering Science and Technology Review 17 (1) (2024) 30 - 36

Research Article

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Numerical Simulation Study on the Mechanical Properties of the Surrounding Rock in Tunnel Boring Machine Inclined Shaft

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Received 13 October 2023; Accepted 27 February 2024

Abstract

The surrounding rock of a Tunnel Boring Machine (TBM) inclined shaft can be disturbed after excavation, accompanied by significant changes in mechanical properties. The safety of the inclined shaft is directly affected by the stress and displacement changes of the surrounding rock at the vault and haunch areas in the vertical section. To determine changes in stress, displacement, and plastic zone of the surrounding rock in the vertical section of the inclined shaft, a numerical simulation study was conducted based on the FLAC3D finite difference software. Accordingly, the effects of buried depth (H), lateral pressure coefficient of surrounding rock (K), and slope angle of the inclined shaft (α) on the surrounding rock were systematically analyzed. Thereafter, the influencing laws of H, K, and α on stress, displacement, and plastic zone at the vault and haunch were explored. Results show that, when K is constant and H increases from 300 m to 500 m, the maximum shear stress, plastic zone, and radial displacement at the vault and haunch clearly increase. When H is 500 m and K increases from 0.5 to 1.5, the maximum shear stress and radius of the plastic zone at the vault significantly increase by 213.1% and 48.7%, respectively, and the radial displacement at the vault is reduced. In addition, the maximum shear stress and the radius of plastic zone at the haunch decrease slightly, radial displacement at the haunch increases substantially, and displacement at the tunnel wall changes the most. Meanwhile, α significantly affects the stress, displacement, and plastic zone at the vault, but the influence on these aspects at the haunch is minor. Lastly, the obtained results are significant for predicting the construction safety of large-slope inclined shafts and also provide a basis for the optimization design of lining structures.

Keywords: Radial displacement, Maximum shear stress, Plastic zone, Buried depth, Lateral pressure coefficient, Slope angle

1. Introduction

The mining depth and length of coal mines, which are among the important energy sources in China, have increased daily, along with the continuously increasing problems encountered in mining. Inclined shaft development has become the main mining method of large-scale coal mines by virtue of its rapid mining speed and short shaft building period. With the development of mechanized operation techniques for inclined shafts, the Tunnel Boring Machine (TBM) method has also been applied in inclined shaft construction. After TBM inclined shaft excavation, engineering safety will be directly influenced by the stress and displacement of the surrounding rock, especially at critical parts, such as the vault and haunch. Consequently, excessive stress and displacement will easily lead to the damage of the supporting structure and even the collapse of the tunnel wall. Hence, deeply exploring the change laws of mechanical behaviors of the surrounding rock will be crucial for the safety of supporting structures and the overall stability of inclined shafts.

In the TBM inclined shaft excavation, the buried depth and initial rock stress change significantly. Considering the influence of the slope angle of inclined shafts, the change of the mechanical properties of the surrounding rock is markedly complicated. The analysis of the plastic zone of the surrounding rock [1–2] can relatively reflect the final possible failure zone of rock mass, but it cannot directly reflect the displacement of the surrounding rock. By studying the stress and displacement of the surrounding rock in tunnels [3–5], its stability can be evaluated according to the intuitive quantitative results. However, the effects of the buried depth and lateral pressure coefficient of the surrounding rock have not been analyzed comprehensively. TBM inclined shafts generally change from shallow to deep, and the buried depth changes significantly, with which the initial stress of the surrounding rock will also change. Limitations exist in the research on the mechanical behavior changes of the surrounding rock in the cross section [6]. The slope angle of the inclined shaft will result in the different mechanical properties of the surrounding rock in the cross and vertical sections. This difference will vary with the slope angle, which is an important factor affecting the safety of the surrounding rock.

This study establishes a numerical analysis model for a TBM inclined shaft to explore the changes in the mechanical behaviors of the surrounding rock in the vertical section. In particular, changes in the stress, displacement, and plastic zone of the surrounding rock in the vertical section of the inclined shaft are numerically simulated and studied. The corresponding investigation is conducted by fully considering buried depth (H), lateral pressure coefficient of the surrounding rock (K), and slope angle of the inclined shaft (α).

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doi:10.25103/jestr.171.05

2. State of the Art

Many scholars have adopted different numerical software to study the changes in the stress and displacement of the surrounding rock after tunnel excavation. Chen et al. [7] established a three-dimensional model of brittle rock based on the discrete element method and ion current code. Moreover, they studied the spalling failure of the surrounding rock after excavation of the deep-buried tunnel. Their results showed many cracks in the vault, and rock spalling easily occurred at the arch rib. Zareifard [8] analyzed the surrounding rock deformation of a circular tunnel under hydrostatic and non-hydrostatic pressure states based on the finite element model. They likewise proposed an empirical equation, which could determine the position of the maximum displacement of the tunnel wall. Meda et al. [9] developed an experimental program to test the cracks in the surrounding rock under different supporting conditions and different thrusts, enabling them to evaluate the mechanical behavior of lining segments under the TBM thrust. Du et al. [10] used the FLAC3D numerical software to calculate the surrounding rock stress and plastic zone range of a circular tunnel under different support forms, and proposed surrounding rock control measures by combining the calculation results. Doroodian et al. [11] used the damage initiation and spalling limit method to study the surrounding rock damage when TBM tunneling machines with different diameters were driven under different stress conditions, and predicted the damage thickness. The influence laws of the horizontal–vertical stress ratio of the surrounding rock on the damaged zone were summarized. Hedayat et al. [12] proposed a new analytical–numerical method by considering the influence of the local failure of the surrounding rock and the weight of the rock mass in the failure zone. The stress, strain, and deformation of the surrounding rock after the excavation of a deep-buried circular tunnel were determined. Changes in the stress and displacement in the elastic–plastic zone were re-analyzed. Huang et al. [13] used the ANSYS/LS-DYNA numerical simulation software as basis to study the stability of the surrounding rock when a TBM tunneling machine passed through the fault zone. They revealed the influence law of the surrounding rock deterioration degree on the surrounding rock displacement. Cividini et al. [14] numerically simulated and studied the interaction between the lining and surrounding rock during TBM excavation. Their results showed that the insufficient filling between the lining and surrounding rock and the brittleness of the actual lining were the important factors leading to the surrounding rock damage. Moreover, they proposed the corresponding improvement methods. Arsalan et al. [15] established a deep neural network prediction model based on the neural network method, which was used to predict tunnel convergence deformation and applied thereafter to model training and testing combined with actual engineering data. The results showed that the model's accuracy was reliable. Although many kinds of numerical software have been used to study the mechanical behavior changes of the surrounding rock after tunnel excavation, all of the preceding results were based on horizontal tunnels. Moreover, the effects of slope angle and buried depth on the mechanical properties of the surrounding rock have not been considered.

The mechanical properties of the surrounding rock of inclined shafts have been minimally investigated, with the main focus on the analysis of the surrounding rock displacement. Sheng et al. [16] used the FLAC3D software to establish a three-dimensional numerical model of a TBM inclined shaft. In addition, they studied the influence of the lateral pressure coefficient of the surrounding rock on the displacement and stress of the tunnel wall. Their results showed that the lateral pressure coefficient had a greater influence on the vault than on the arch foot. Chen [17] numerically simulated and studied the deformation of the surrounding rock after excavation of an inclined shaft. They found that the deformation at the vault was greater than that at the arch foot. Ma et al. [18] established the finite element model of TBM inclined shaft excavation by considering the buried depth. Although they determined the influence law of buried depth on the surrounding rock displacement in the cross section of the inclined shaft, they did not conduct any in-depth analysis on the plastic zone and stress of the surrounding rock.

The preceding research lacks a systematic investigation into the stress, displacement, and plastic zone of the surrounding rock in the vertical section after the TBM inclined shaft excavation, as well as an analysis of the effect of the slope angle of inclined shaft. Accordingly, a numerical calculation model of a TBM inclined shaft is established using the FLAC3D finite difference software, and different buried depths are simulated with different boundary conditions. Meanwhile, a numerical calculation is performed with the H, K, and α as variables. In addition, the effects of H, K, and α on the mechanical properties of surrounding rock in the vertical section of the TBM inclined shaft are deeply explored. In particular, the change laws of the stress, displacement, and plastic zone of the surrounding rock at the vault and haunch are obtained. These results are expected to provide a theoretical basis for safety prediction and the supporting structure optimization of inclined shafts.

The remainder of this study is organized as follows. Section 3 introduces the establishment of the FLAC3D numerical calculation model and the numerical simulation scheme. Section 4 presents a practical engineering background and studies the influence of H, K, and α on the stress, displacement, and plastic zone of the surrounding rock at the vault and haunch in the vertical section. Lastly, section 5 presents the summary and conclusion of this study.

3. Methodology

The slope angle of the inclined shaft project in China is 6°, and the single-shield TBM is used to drive for 6,109 m, the maximum buried depth is 660 m, and multiple rock strata are crossed. Supporting is implemented using single-layer segments, the outer diameter of the lining segment is 7.3 m, and the ring width and thickness are 1.5 m and 0.35 m, respectively.

3.1 Establishment of the numerical simulation model

The position and spatial coordinate direction of the inclined shaft are shown in Fig. 1, in which section 1-1 is a cross section perpendicular to the axis of the inclined shaft and section 2-2 is a vertical section parallel to the o-xz plane. The excavation radius of the inclined shaft is 3.65 m, the established model takes the center of the inclined shaft as the coordinate origin O (0,0,0), and the cross section in the o-xz plane is modeled as a circle. On the basis of the Saint-Venant principle, the calculation model range was 73 m × 10 m × 73 m ($x \times y \times z$), and the surrounding rock grids near the inclined shaft are densified by considering the calculation accuracy and time. The surrounding rock of the inclined shaft is modeled by solid elements and simulated based on the Mohr–Coulomb model. The lining structure is modeled by solid elements and simulated by elastic models. The three-dimensional numerical model diagram is shown in Fig. 2.

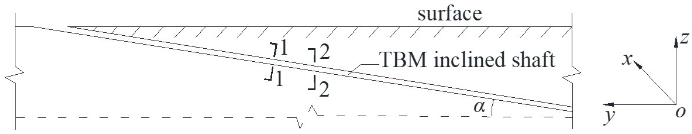


Fig. 1. Position and coordinate direction of the TBM inclined shaft

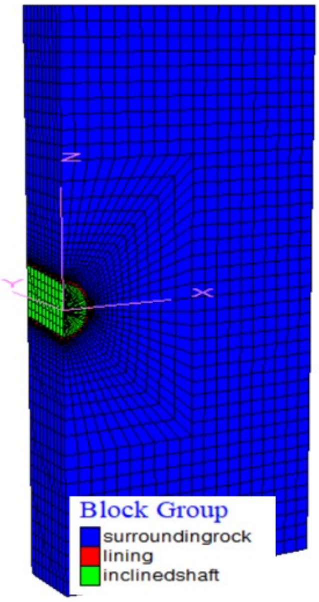


Fig. 2. Three-dimensional numerical model

This study mainly explores the surrounding rock in deep-buried strata. The model established is part of the area under a certain depth. After modeling, the initial displacement field is obtained by applying confining pressure and self-weight stress. In addition, the displacement and velocity are reset after the initial balance calculation. Thereafter, the inclined shaft is excavated and supported, and the stress and displacement values of the lining and surrounding rock after excavation are solved. *Z*-directional displacement is fixed at the bottom boundary of the model, and *z*-directional stress boundary condition is imposed on the upper boundary of the model. Considering the effect of tectonic stress with the continuous increase in the buried depth, the pressure of the surrounding rock in the horizontal and vertical directions is unequal. Hence, an *x*-directional stress boundary condition is applied to the left and right boundaries of the model. Similarly, a *y*-directional stress boundary condition is applied in the front and back of the model with the following expressions:

$$\begin{cases} p_{z|z=36.5} = -P \\ u_{z|z=-36.5} = 0 \\ p_{x|x=\pm 36.5} = -KP \\ p_{y|y=0,y=-10} = -KP \end{cases} \tag{1}$$

where p_x is the x-directional stress, p_y is the y-directional stress, p_z is the z-directional stress, u_z is the z-directional displacement, P is the z-directional initial stress, and the minus indicates compressive stress.

3.2 Numerical simulation scheme

The buried depth changed significantly owing to the considerable length of the inclined shaft. At different buried depths, the primary rock stress varies substantially. To comprehensively explore the effects of *H*, *K*, and *α* on the stress and displacement of the surrounding rock, the numerical calculation is performed under different buried depths, and the results are compared and analyzed. The specific numerical simulation scheme is as follows.

(1) Numerical calculations are conducted at *H* = 300 m and 500 m and *K* = 0.50, 0.75, 1.00, 1.25, and 1.50 to explore the effects of *H* and *K* on the stress, plastic zone, and displacement of the surrounding rock.

(2) Numerical calculations are carried out at *H* = 300 m and 500 m and *α* = 6°, 12°, and 18°. The results are compared with the horizontal tunnel (*α* = 0°) results to probe the effects of *H* and *α* on the stress, plastic zone, and displacement of the surrounding rock.

The mechanical parameters of the surrounding rock adopted in the study are listed in Table 1.

Table 1. Mechanical parameters of the surrounding rock

Bulk modulus /GPa	Shear modulus /GPa	Cohesion /MPa	Internal friction angle /°	Volume weight /kN/m^3	Poisson's ratio
1.67	1.25	2.0	30	25	0.21

4. Result Analysis and Discussion

Stress is redistributed after excavating the TBM inclined shaft. Moreover, stress of the surrounding rock is concentrated at the vault and haunch, and the displacement is large. Therefore, only changes in the stress, displacement, and plastic zone of the surrounding rock at the vault (*z*-axis) and haunch (*x*-axis) in the vertical section are explored.

4.1 Effects of *H* and *K*

4.1.1 Effects of *H* and *K* on maximum shear stress (σ_θ)

The numerical calculation results show that radial stress is small and tangential stress is large in the surrounding rock at the vault and haunch. This situation is the key to lead the damage of the surrounding rock. Therefore, this study emphasizes on the change laws of tangential stress in the surrounding rock at the vault and haunch. Figure 3 shows the changes in the maximum tangential stress at the vault ($\sigma_{\theta t}$) and at the haunch ($\sigma_{\theta h}$). The curves in Fig. 3 indicate that at a fixed K value, $\sigma_{\theta t}$ and $\sigma_{\theta h}$ evidently grow with an increase in H. When K = 1.50, H increases from 300 m to 500 m, $\sigma_{\theta t}$ increases by 76.5% and $\sigma_{\theta h}$ increases by 63.3%. When H remains unchanged, $\sigma_{\theta t}$ increases substantially with an increase in K. The greater the H, the greater the growth amplitude of $\sigma_{\theta t}$, which reaches 213.1% when H = 500 m. $\sigma_{\theta h}$ decreases by a small margin with an increase in K.

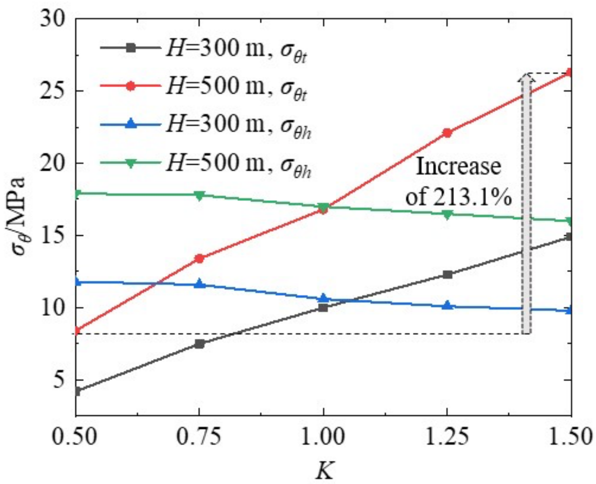
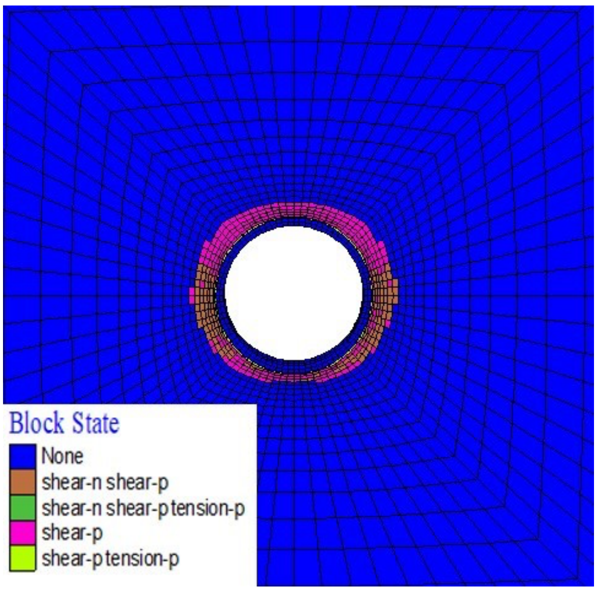


Fig. 3. Effects of H and K on σ_θ

4.1.2 Effects of *H* and *K* on the radius of the plastic zone (*R*)

When K = 1, α = 6°, and H = 300 m and 500 m, the plastic zone distribution of the surrounding rock in the vertical section of the inclined shaft is as shown in Fig. 4. The results show that when H increases from 300 m to 500 m, the plastic zone of the surrounding rock at the vault and haunch clearly increase. The plastic zone of the surrounding rock is distributed symmetrically from left to right but asymmetrical from top to bottom, which is ascribed to the influence of α.



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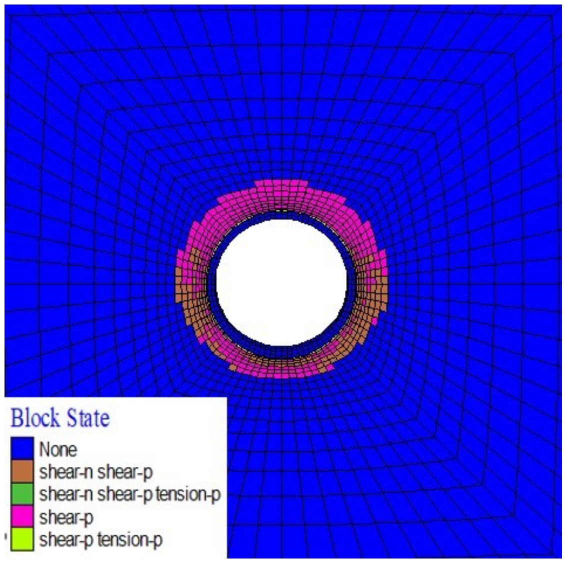


(b)

Fig. 4. Plastic zone of the surrounding rock. (a) H = 300 m. (b) H = 500 m

When H = 300 m and 500 m and K = 0.50, 0.75, 1.00, 1.25, and 1.50, the radii of the plastic zone at the vault (R_t) and at the haunch (R_h) change, as shown in Fig. 5. The results reveal that at the same K value, the greater the H value, the greater the R value at the same position. Meanwhile, R_t increases significantly with an increase in K. When H = 500 m, the growth amplitude of R_t reaches 48.7%. R_h shows a gradual declining trend with an increase in K.

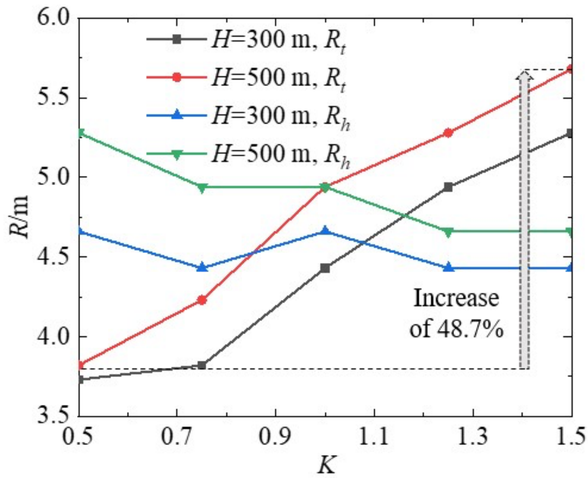
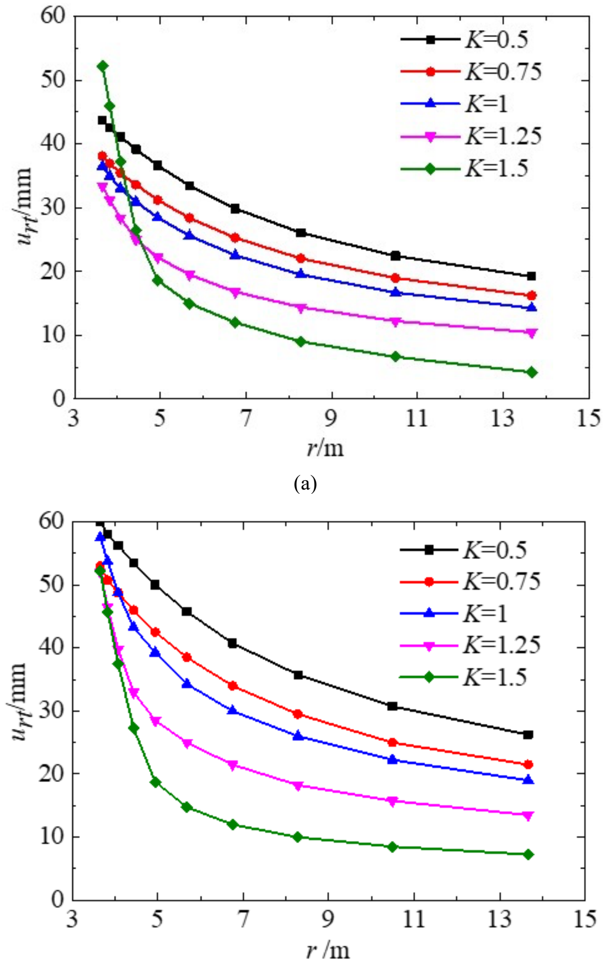


Fig. 5. Effects of H and K on R

4.1.3 Effects of *H* and *K* on the radial displacement of the surrounding rock (u_r)

After the inclined shaft is excavated, the surrounding rock converges and deforms into the tunnel, and radial displacement is the key factor affecting engineering safety. This study focuses on exploring the change laws of the radial displacement of the surrounding rock at the vault and haunch in the vertical section. Moreover, the displacement is positive if facing inward and negative if facing outward. Fig. 6 shows the influence curves of K on the radial displacement (u_{rt}) of the surrounding rock at the vault in the vertical section when H = 300 m and 500 m. The curves in Fig. 6

show that u_{rt} always faces inward, peaks at the tunnel wall, and gradually declines outward. At an unchanged *H* value, u_{rt} shows an overall declining trend with an increase in *K*. However, within a 4.5-m range near the tunnel wall, u_{rt} initially decreases and thereafter increases. The reason is that with an increase in *K*, the scope of the plastic zone at the vault is large, and the local rock mass at the tunnel wall shows a failure state, leading to increasing displacement. When *K* is unchanged, u_{rt} at the same position evidently increases with an increase in *H*.

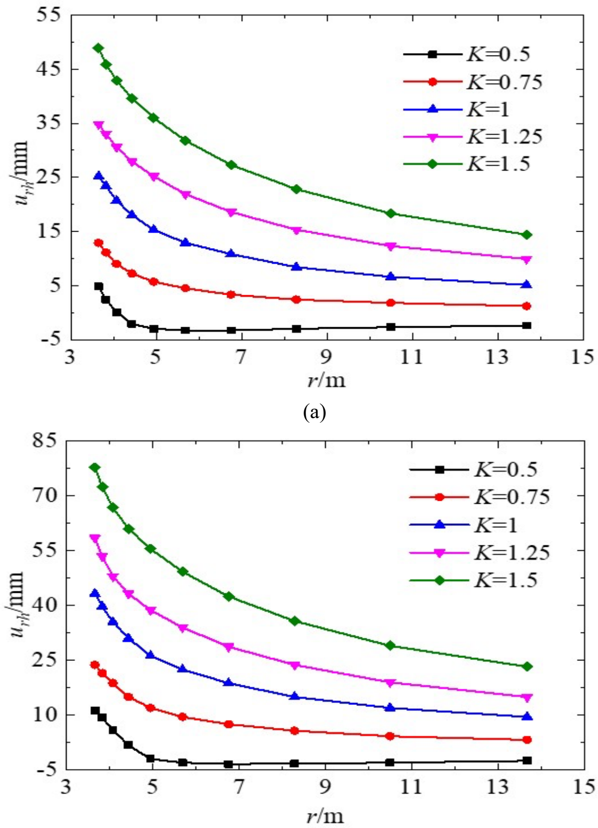


(a)

(b)

Fig. 6. Effects of *H* and *K* on u_{rt}. (a) *H* = 300 m. (b) *H* = 500 m

Fig. 7 shows the influence curves of *K* on the radial displacement (u_{rh}) of the surrounding rock at the haunch when *H* = 300 m and 500 m. As shown in Fig. 7, u_{rt} always faces inward, peaks at the tunnel wall, and gradually declines outward. At the same position, u_{rt} continuously grows with an increase in *K*. Note that when *K* = 0.5, the displacement of the surrounding rock within a 4-m range from the axis of the inclined shaft faces inward and faces outward beyond the 4-m range. The displacement of the surrounding rock gradually decreases with an increase in the distance from the axis of the inclined shaft. The reason is that the surrounding rock in the inclined shaft is subjected to supporting counterforce provided by the supporting structure. Under the action of large vertical pressure, the surrounding rock at the haunch of the inclined shaft gradually experiences outward displacement changes. Under small lateral pressure, displacement change cannot be completely arrested, so the partial surrounding rock at the haunch presents an outward displacement change.



(a)

(b)

Fig. 7. Effects of *H* and *K* on u_{rh}. (a) *H* = 300 m. (b) *H* = 500 m

4.2 Effect of *α*

4.2.1 Effect of *α* on σ_θ

Fig. 8 shows the variation of $\sigma_{\theta t}$ and $\sigma_{\theta h}$ in the vertical section of the inclined shaft when *H* = 300 m and 500 m and *α* = 0°, 6°, 12°, and 18°. The results show that with an increase in *H*, $\sigma_{\theta t}$ and $\sigma_{\theta h}$ grow apparently. When *H* is unchanged, $\sigma_{\theta t}$ and $\sigma_{\theta h}$ increase with an increase in *α*, and $\sigma_{\theta t}$ changes substantially. When *H* = 500 m and *α* increases from 0° to 18°, the growth amplitude of $\sigma_{\theta t}$ reaches 35.2%. This result indicates that relative to horizontal tunnels (*α* = 0°), the slope angle exerts a significant effect on stress at the vault but the effect on stress at the haunch is minor.

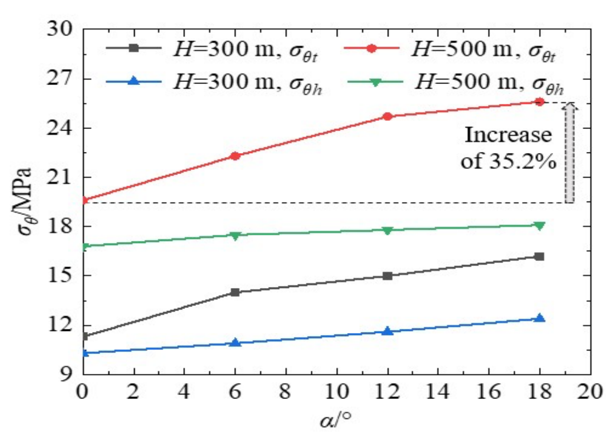


Fig. 8. Effect of *α* on σ_θ

4.2.2 Effect of *α* on *R*

Fig. 9 shows the *R* value at different positions of the surrounding rock in the vertical section of the inclined shaft when *H* = 300 m and 500 m, *K* = 1.25, and *α* = 0°, 6°, 12°, and 18°. The results show that with an increase in *α*, R_t and R_h show an increasing trend, and $R_t > R_h$. The greater the *α* value, the more *R* changes significantly. When *H* = 500 m and *α* increases from 0° to 18°, R_t increases by 42.9% and R_h by 28.2%. This result indicates that the slope angle has a significant effect on the scope of the plastic zone at the vault and haunch of the surrounding rock. At a large slope angle, high requirements are proposed for the supporting structure of the surrounding rocks for the sake of engineering safety.

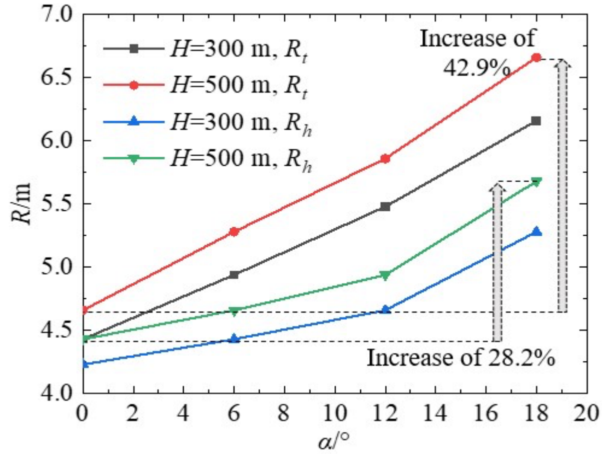
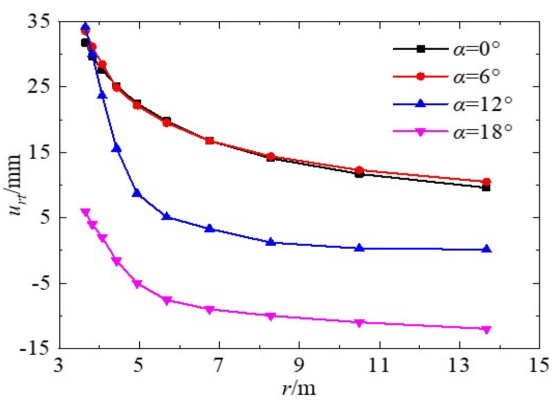


Fig. 9. Effect of *α* on *R*

4.2.3 Effect of *α* on u_r

Fig. 10 shows the effect of *α* on u_{rt} when *H* = 300 m and 500 m. Note that the curves in Fig. 10 show that u_{rt} is significantly affected by *α*. With an increase in *α*, u_{rt} at the same position gradually decreases; the greater the *α* value, the greater the reduction in u_{rt}. When *α* grows to 18°, the displacement of the surrounding rock in some zones is turned from inward displacement to outward displacement. The reason is that at a large slope angle, the lining structure at the vault provides a large supporting force, resulting in the outward displacement of the surrounding rock. Fig. 11 presents the effect of *α* on u_{rh} when H = 300 m and 500 m. The curves in Fig. 11 show that u_{rh} is influenced insignificantly by *α*. The greater the buried depth, the smaller the effect of *α*.



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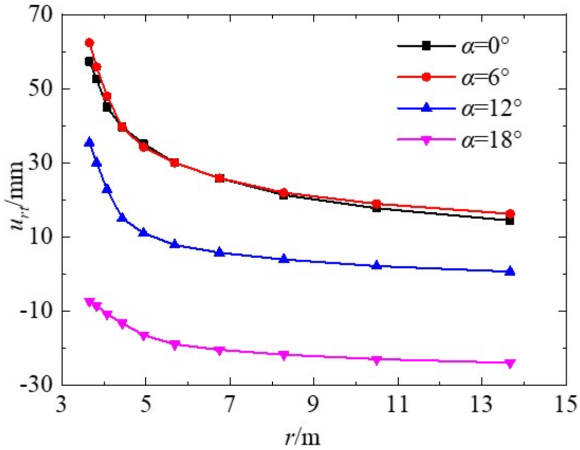

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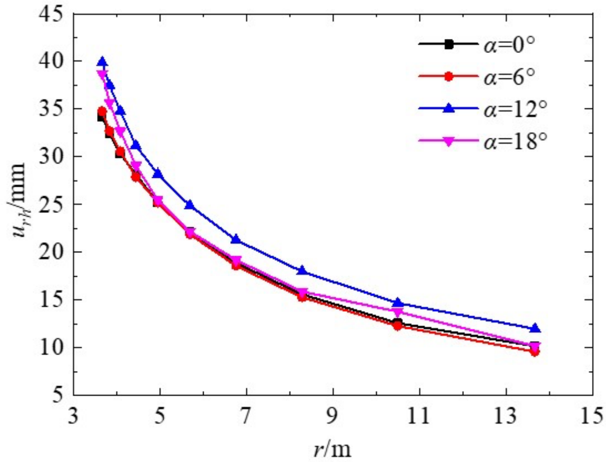
Fig. 10. Effect of *α* on u_{rt}. (a) *H* = 300 m. (b) *H* = 500 m



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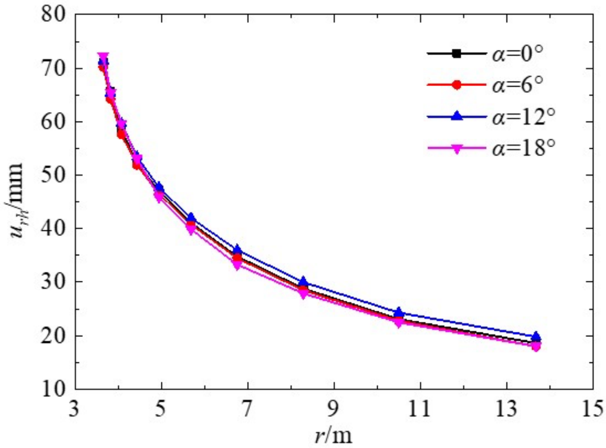

(b)

Fig. 11. Effect of *α* on u_{rh}. (a) *H* = 300 m. (b) *H* = 500 m

5. Conclusions

To determine the changes in the stress, displacement, and plastic zone of the surrounding rock in the vertical section of the TBM inclined shaft after excavation, this study conducted a numerical simulation study using the FLAC3D numerical simulation software. Under the engineering background of an inclined shaft, the effects of *H*, *K*, and *α* on the changes in the stress, displacement, and plastic zone of the surrounding rock at the vault and haunch in the vertical section were substantially discussed. The following conclusions were drawn.

(1) In the vertical section of the TBM inclined shaft, *H* has a significant influence on the stress, displacement, and plastic zone of the surrounding rock at the vault and haunch, especially the displacement of the tunnel wall. With the increase of *H*, it is necessary to enhance the support strength, which can reduce the displacement of the tunnel wall and avoid collapse.

(2) *K* has immense influence on the stress and plastic zone at the vault, but the effect on the stress and plastic zone at the haunch is relatively minor. Meanwhile, the effect of *K* on the displacement at the vault and haunch is large. In practical engineering, the *K* value should be reasonably determined according to the stratum parameters with the change in *H*, which is considerable importance to engineering safety.

(3) Different from the horizontal tunnel, the change in α has immense effects on the stress, displacement, and plastic zone at the vault of the inclined shaft, but the effect on the aforementioned aspects at the haunch is minor. These results indicate that considerable focus should be given to the change in α and relatively appropriate supporting structures should be selected.

This study used the FLAC3D numerical simulation software to study the mechanical change of the surrounding rock in the vertical section of an excavated TBM inclined shaft. Thereafter, changes in the stress, displacement, and plastic zone in the vertical section of the inclined shaft were substantially analyzed. This study provides specific guiding significance to practical engineering construction. However, the stress and deformation of supporting structures were not significantly analyzed. In the follow-up study, detailed numerical simulation and model experiments can be conducted specific to different supporting structures. The objective is to explore the change laws of the mechanical behaviors of the surrounding rock and supporting structures, thereby laying the foundation for selecting engineering supporting schemes.

Acknowledgements

The authors are grateful for the support provided by the Scientific Research Fund of Qingdao Agricultural University (Grant No. 663/1120055).

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