Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 9, No. 2, 2024

Study on the Deformation Characteristics of Different Excavation Methods for Class V Perimeter Rock Tunnels

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Abstract: Taking a water conservancy project water transfer tunnel as an example, FLAC3D finite element simulation software was used to simulate the excavation and support, and the displacement and distribution of the plastic zone of the tunnel perimeter rock were taken as the analytical indexes, and the simulation of the three excavation methods, namely, the full section method, the half section method and the CD method, was carried out to compare, and to study the characteristics of the deformation of the perimeter rock of the different methods of excavation. The simulation results show that: ① the vertical deformation of the three excavation methods all show that the bottom bulge is larger than the settlement of the vault; ② the full-face method is easy to produce shear damage at the vault, the step method is easy to produce shear damage at the waist of the tunnel, and there is no obvious damage characteristics of the CD method; ③ the CD diaphragm wall method is able to control the vertical deformation of the surrounding rock effectively, and the horizontal displacement will be increased, and joint support measures should be taken at the waist of the tunnel to strengthen the support.

Keywords: Numerical simulation; Excavation method; Envelope deformation; CD method; Soft rock tunnels.

1. Introduction

With the continuous improvement and development of China's tunnel engineering technology, the tunnel construction technology with Xin'ao method as the mainstream is becoming more and more mature. Among them, IV, V weak surrounding rock due to its poor lithology, easy to occur large deformation, improper treatment will bring great potential danger to the construction safety, so the study of large deformation of soft rock tunnels has been a hot topic. Penghua Li[1] analyzed and demonstrated the practical application of CD method of excavation in V type of surrounding rock, and the results showed that the diaphragm wall can effectively solve the problem of excavation in soft rock and improve the construction safety. Zhengbing Xi[2] conducted a simulation study on the excavation method of large-section soft rock tunnels, and found that compared with the step method, the CD method has more uniform stress release and better results. Dan Su [3] carried out optimization study on support measures for loess tunnel and found that over-head support can effectively control deformation and applied in actual projects. Li Xiangqun [4] used MIDAS/GTS NX finite element software to simulate the deformation of tunnel excavation and used different methods for comparative verification. Guo Xiaolong [5] combed and summarized the control technology of large deformation in soft rock tunnels and elaborated on the different control methods.

This paper takes a water tunnel as an example, and uses FLAC3D finite element software to simulate the excavation and support process of three different methods, i.e. full section, step method and CD method, to study the deformation characteristics of the surrounding rock, so as to provide a certain reference for the similar soft rock tunnel projects.

2. Project Overview

The research water transmission tunnel is located in the central region of China, by the field geological survey and drilling experiments and other methods, it is proved that the surrounding rock stratum of the tunnel is mainly composed of mudstone, sandstone, muddy sandstone and other properties of the poor soft rock composition, the rock joints are not developed, closed shape, the structural surface of the straight and smooth, no filling. Mudstone has low strength and is easy to disintegrate and mud off when it meets water; sandstone is poor in rock formation, easy to be crushed by hand, and the local phase changes into sandy mudstone with low strength and easy to be crushed and loosened. The excavation support simulation of the tunnel is carried out by full section, step method and CD method respectively, and the initial support method is reinforcing mesh and shotcrete layer, considering that the actual project has not yet been applied to the secondary lining, so only the initial support is simulated and analyzed.

3. Numerical Simulation

In the reinforcing mesh shotcrete support, the modulus of elasticity of the reinforcing mesh is converted to the concrete calculation parameters based on the principle of equivalence, and the conversion formula is shown in Equation (1).

$$E_c = E_0 + \frac{A_S \times E_S}{A_c} \quad (1)$$

Among them.

E_C - Modulus of elasticity of converted reinforced mesh shotcrete (kpa)

E_0 - modulus of elasticity of initial sprayed plain concrete (kpa)

A_g - Cross-sectional area of reinforcing mesh (m2)

E_S - modulus of elasticity of reinforcing mesh (kpa)

A_C - Cross-sectional area of initial sprayed plain concrete (m2)

According to the tunnel design document, the diameter of the tunnel is 5.0 m. In order to reduce the influence of the boundary effect on the simulation results, the upper, lower and left and right sides of the tunnel are taken as the boundaries of about 5 times the diameter of the tunnel, and the burial depth of the tunnel is about 25 m. The longitudinal direction of the model is taken to be 30 m, and the overall dimensions of the model are 55 m × 30 m × 50 m (X direction × Y direction × Z direction), and the structured mesh is used for the modeling in order to increase the precision and efficiency of the calculations. and efficiency, the establishment of the model is shown in Figure 1, and the simulation calculation parameters are shown in Table 1.

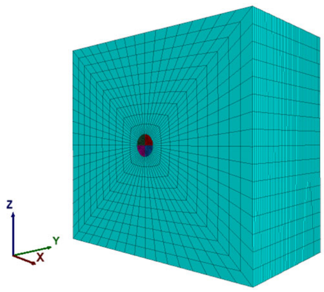


Figure 1. Simulation calculation model

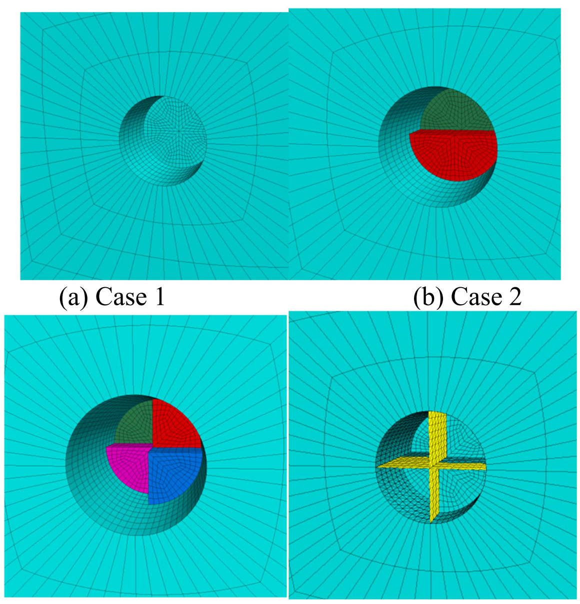
Table 1. Calculated parameters for tunnel simulation

Analog material	bulk modulus E/MPa	Shear modulus E/MPa	Angle of internal friction φ/(°)	Viscosity c/kPa	Heaviness γ/(kN/m3)
perimeter rock	6.7	2.2	30	18	1.80 x 104
tunnel lining	1.81 x 104	1.30 x 104	/	/	2.38 x 104

Assuming that the rock mass is isotropic, the Mohr-Coulomb criterion, an ideal elasto-plastic intrinsic model, is used to describe the intrinsic relationship of the rock mass. In the simulation calculation, the null model is used to simulate the excavation, and the shell unit is used to simulate the initial support, which is applied immediately after the excavation. The excavation support simulation is carried out for different excavation methods, and compared and analyzed to simulate the working condition design, which is shown in Table 2. The schematic diagram of the excavation process is shown in Figure 2.

Table 2. Simulated working condition design

Simulated working conditions	Excavation method	Excavation footage/m	excavation process
Condition 1	full-scale excavation	2	/
Condition 2	up-and-down stepping stone method (math.)	2	Excavate 1 part (upper step) first, 2 parts (lower step) lagged by one foot, then excavate synchronously
Condition 3	CD method	2	Excavate in four parts, excavate part 1 first, parts 2 and 3 lag behind it by one foot to synchronize the excavation, and part 4 lag behind it by two feet to synchronize the excavation.



(a) Case 1 (b) Case 2

(c) Case 3 (d) Partition wall in CD method

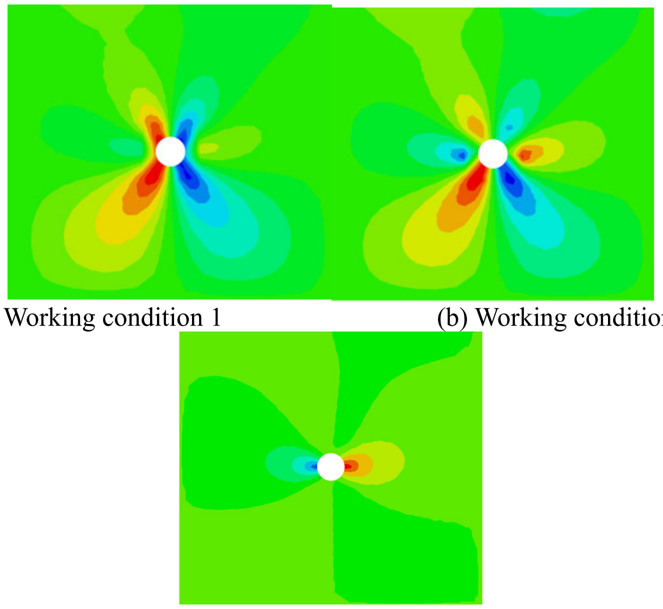
Figure 2. Schematic diagram of the excavation process

4. Analysis of Simulation Results

In order to avoid the influence of boundary effect, the middle part of the model (at Y=15m) is selected as the monitoring section, and the deformation characteristics of the surrounding rock under different excavation methods are compared and analyzed from two perspectives of displacement and plastic zone.

(1) Displacement results analysis

The horizontal and vertical convergent deformation cloud diagrams of the tunnel surrounding rock under the three working conditions are shown in Figures 3 and 4. The maximum horizontal and vertical deformation of the monitoring section is shown in Table 3.

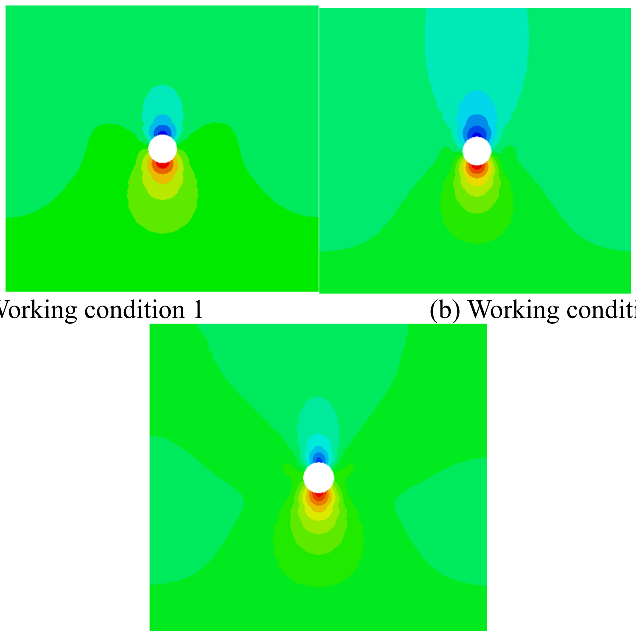


(a) Working condition 1　　(b) Working condition 2

(c) Case 3

Figure 3. Horizontal deformation cloud diagram of surrounding rock for each working condition

From the analysis of Fig. 3, it can be seen that the deformation of surrounding rock under working condition 1 is mainly concentrated in both sides of the arch shoulder and the bottom of the tunnel, with the maximum horizontal convergence value of about 32.2 mm; under working condition 2, there are large deformations in the bottom of the tunnel, both sides of the arch shoulder and the arch girdle, and the maximum horizontal convergence value occurs in the bottom of the tunnel, with a value of about 54.7 mm; under working condition 3, the horizontal convergence deformation is concentrated in the arch girdle, with the maximum convergence deformation of about 102.3 mm. Under condition 3, the horizontal convergence deformation is concentrated in the arch waist area, and the maximum convergence deformation is about 102.3 mm.



(a) Working condition 1　　(b) Working condition 2

(c) Case 3

Figure 4. Vertical deformation cloud diagram of surrounding rock for each working condition

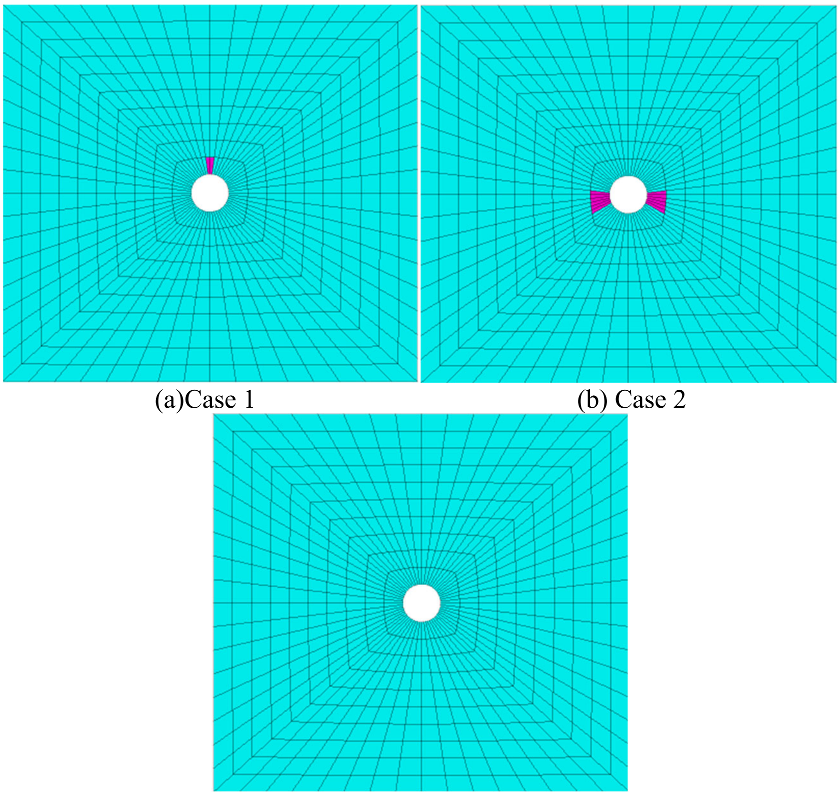
From the analysis in Fig. 4, it can be seen that the vertical deformations under the three working conditions are concentrated in the arch top and bottom. Under working condition 1, the maximum convergence value of the settlement of the arch is about 92.33 mm, and the deformation of the bottom bulge is about 110.89 mm; under working condition 2, the maximum convergence value of the settlement of the arch is about 140.26 mm, and the deformation of the bottom bulge is about 190.50 mm; under working condition 3, the maximum convergence value of the settlement of the arch is about 61.01 mm, and the deformation of the bottom bulge is about 85.83 mm.

Table 3. Maximum convergence displacement of the monitored section

Excavation method	Condition 1	Condition 2	Condition 3
Horizontal maximum convergence deformation /mm	32.2	54.7	102.3
Settlement deformation of the vault /mm	92.33	140.26	61.01
Bottom bulge deformation /mm	110.89	190.50	85.83

As can be seen from Table 3, the horizontal convergence deformation of surrounding rock increases about 70% and 87% from Case 1 to Case 2 and Case 3, which is due to the fact that the horizontal stress concentration is easy to be generated at the foot of the excavated rock body in the division excavation, and when the excavation footage is larger, the palm face and the step are easy to be destabilized, resulting in the increase of the local horizontal deformation. The amount of arch settlement from large to small is Case 2＞Case 1＞Case 3, and the vertical displacement bottom bulge is larger than the arch settlement under the three conditions, and the arch settlement is the largest under Case 2; the bottom bulge deformation is Case 2＞Case 1＞Case 3, and the deformation under Case 2 increases about 72% compared with that under Case 1, mainly due to the fact that the lower step is a horizontal surface, which is poor in resisting the vertical deformation, thus generating a larger bulge deformation in the middle; Case 3＞Case 3, the deformation in the middle of the rock body increases about 72% compared to that under Case 1. The deformation of working condition 3 is reduced by about 23% and 55% compared with working condition 1 and 2 respectively. In the excavation of CD partition wall method, the rock body is a small part each time, which reduces the loosening of the rock body and stress redistribution, and the partition wall can limit the deformation of the rock body to a certain extent, so the deformation is smaller.

(2) Plastic Zone Analysis



(a)Case 1 (b) Case 2

(c) Case 3

Figure 5. Distribution of plastic zone of surrounding rock with different excavation scales

Table 4. Distribution of plastic zones in different excavation methods

working condition	1	2	3
Plastic zone area /m2	4	24	0
distribution location	a dome	arch one's back on either side	/

From Fig. 5 and Table 4, it can be seen that under working condition 1, the plastic zone is concentrated in the arch top, and the surrounding rock at the arch top produces shear damage, with an area of plastic zone of about 4 m2 ; under working condition 2, the plastic zone is concentrated in the arch waist of both sides of the tunnel, about 1.5-2 m from the bottom of the tunnel, and it is a localized shear damage, with an area of about 24 m2 , which can be seen that the excavation of the step method is due to the concentration of stress on the two sides of the steps, which leads to the release of deformation in this place, producing larger deformation; under working condition 3, there is no significant deformation due to the restraining effect of temporary diaphragm wall. It can be seen that the step excavation method releases the deformation here due to the stress concentration at the two sides of the step, which produces large deformation; under the condition of working condition 3, due to the restraining effect of the temporary diaphragm wall, there is no obvious plastic zone.

5. Conclusion

In this paper, using FLAC3D numerical simulation software, the excavation support of a water conveyance tunnel under three different excavation methods, namely full section, step method and CD method, was studied and analyzed, and the conclusions are as follows:

Under the three excavation methods, the vertical displacement deformation of the tunnel is shown as bottom bulge＞ vault settlement, among which, the upper and lower step excavation is easy to be destabilized and deformed on the upper step palm surface due to the weaker lower step plane, and the vault settlement and bottom bulge deformation are the largest.

From the analysis of plastic zone, the step method produces shear damage in the perimeter rock at the arch waist position on both sides of the tunnel, the full section method is easy to produce shear damage at the top of the arch, and the CD method has no obvious plastic zone.

Overall analysis shows that the CD method can effectively control the vertical deformation of the surrounding rock, but the surrounding rock at the arch waist on both sides of the tunnel is prone to large horizontal deformation, which can be constrained by additional anchors and other joint support measures for the horizontal displacement of the surrounding rock.

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