Comparison study of Excavation Stability using Different Tunnel Excavation Methods

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Abstract. For the safety and efficiency of tunnel construction, optimal schemes for tunnel excavation with different surrounding rock grades should be proposed to provide references for engineering construction. Through 3D numerical simulation, the mechanical properties of the surrounding rock during tunnel construction were studied by 3D numerical simulation. For different surrounding rock grades, three different excavation methods were simulated. A comparative analysis of ground settlement, surrounding rock displacement, and maximum principal stress caused by different construction methods was also performed. The results show that different construction methods have a small impact on the displacement of surrounding rock. When the surrounding rock is of grade I, the maximum vertical displacement of the excavation surface is less than 2 mm. Bench cut method can be used for excavation with fast construction speed. When the surrounding rock is of grade IV, the stratum settlement and excavation surface displacement are large. The Center diagram method can ensure the construction progress and minimize the vertical displacement of surrounding rock. When the surrounding rock is of grade V, the displacement caused by tunnel excavation further increases. The double-side drift method can be adopted to minimize the stratum settlement and surrounding rock displacement.

1. Introduction
Due to the fast urbanization, the cities continue to expand quickly and the demand for safe, convenient, fast, spacious, and comfortable transportation is increasing. In order to relieve the
traffic pressure in the Guangdong-Hong Kong-Macao Greater Bay Area and improve the traffic connection between Guangzhou, Zhongshan, and Zhuhai urban areas to promote economic development, mountain tunnels have to be built in hilly areas with complex strata and poor geological conditions, which brings out new challenges in the engineering construction.

The stress change of the surrounding rock and the settlement of the stratum during tunnel construction are the most important and difficult points in the excavation. At present, the numerical simulation is commonly used for evaluating the stress-train change in the excavation. Based on stress monitoring, Sun et al.[1] used finite element software to simulate the stress state of the tunnel lining structure and calculated the stress state of the support structure under different grades of the surrounding rock. The excavation sequence of the tunnel has an impact on the stability of surrounding rock and the response of the tunnel vault and ground subsidence are different under different excavation sequences[2]. Gao et al.[3] introduced peridynamics into the stability analysis of surrounding rock during tunnel excavation, and simulated the tensile and compression failure characteristics of the surrounding rock. Wang et al.[4] analyzed the internal deformation characteristics of the surrounding rock throughout the whole tunnel excavation process. Yang et al.[5] studied the evolution of surrounding rock damage areas in tunnel excavation. By analyzing the deformation and failure characteristics of surrounding rock under different buried depths, lateral pressure coefficients, excavation methods, and cross-sectional shapes, the evolution process of surrounding rock instability caused by tunnel excavation and unloading was revealed. In addition, the impact of multiple tunnel excavation on surrounding rock was also evaluated[6][7]. In the above research results, the stability of the surrounding rock should be considered when selecting the tunnel excavation method in addition to construction difficulty, economic, and environmental factors. Therefore, it is necessary to carry out a reasonable evaluation of tunnel excavation methods[8][9].

This study aims to analyze the stability of an urban mountain tunnel of the Zhuhai Xingye express project. According to the drilling results, the main rock and soil layers distributed in the survey area of the project site comprise of artificial filling, and the quaternary slope layer, residual layer, and underlying bedrock are made up of granite. Past construction experiences regarding the large-section tunnels in China may not help in this case due to special geological conditions of this project and the rainy weather conditions in Zhuhai. Therefore, it is important to study the optimal excavation method for the specific surrounding rock grade of the tunnel to meet the requirements of tunnel safety and construction efficiency.

2. Numerical simulation

2.1. Research object

A section of the mountain tunnel was selected from the geological exploration report and the rocks along the tunnel line are mainly divided into grades I-V with slightly developed junction fissure. The risk of collapse during tunnel excavation depends on the rock condition. To study the influence of surrounding rock grades on the deformation caused by tunnel excavation, surrounding rocks of grades I, IV, and V are selected for the analysis for which the support parameters should be adjusted or steel supports should be set to stabilize the excavation surface. Moreover, the second lining should be made early and monitored carefully.
There are 5 layers for the stratum, including silty clay, fully weathered granite, strongly weathered granite, moderately weathered granite, and slightly weathered granite. In the simulation, the Mohr-Coulomb constitutive model was adopted to calculate silt clay and fully weathered granite while the Hawker Brown constitutive model was used to calculate the strong weathered granite, moderately weathered granite, and the slightly weathered granite. The relative parameters of the stratum were obtained from the geological tests report as shown in Table 1. In the table, $R$ is the unconfined compressive strength measured by laboratory tests.

| Types                  | Thickness (m) | $\gamma$ (kN/m$^3$) | $R$ (Mpa) | $\Phi$ (°) | $c$ (kPa) | $E$ (Gpa) |
|------------------------|---------------|----------------------|-----------|------------|-----------|-----------|
| Silty clay             | 1.83          | 17.0                 | 14.6      | 15.2       | 30.0      | 0.017     |
| Fully weathered granite| 7.07          | 19.2                 | 40.3      | 25.1       | 28.5      | 30.4      |
| Strongly weathered granite | 20.95     | 23.4                 | 42.0      | 28         | 25        | 30.0      |
| Moderately weathered granite | 40.59    | 25.4                 | 38.8      | 43.7       | 26.4      | 60.6      |
| Slightly weathered granite | 61.28     | 26.2                 | 84.9      | 42.9       | 37.7      | 62.0      |

2.2. Numerical model and parameters

The whole process of tunnel excavation and support was simulated by Plaxis 3D finite element software and the construction steps were simulated. The 3D numerical model is shown in Figure 1. The buried depth of the tunnel is approximately 100 m, the cross-section width of the tunnel is 16.03 m, and the height is 9.8 m. The width of the FE model is 200 m, the height of the model is 131.53 m, and the tunnel length is 100 m. For the boundary condition, the bottom of the model is a fixed constraint, the side is a normal displacement constraint, and the upper surface is free. Figure 2 shows the distribution of initial vertical stress condition (Negative indicates compressive stress).

![Figure 1. Three-dimensional finite element model](image1)

![Figure 2. Distribution of initial vertical stress condition.](image2)
Some of the mechanical parameters of the stratum were calculated based on the geological tests report; others were valued empirically according to the references of physical and mechanical parameters of all grades of rock in the “Code for Design of Road Tunnel”[10]. The tunnel lining is made of C35 concrete with the anchor bolt length of 3.5 m, and the spacing of 1.2 m in the horizontal direction and 2 m in the vertical direction. The material parameters for the tunnel lining and bolts used in the numerical simulation are listed in Tables 2 and 3. In the tables, \( \gamma \) is the weight, \( E \) is the elastic modulus, \( d \) is the diameter, \( \mu \) is the Poisson's ratio, and \( T_{\text{top, max}} \) and \( T_{\text{bot, max}} \) are the skin resistances of the rock bolts. Several locations on the excavation surface of the tunnel surrounding rock are selected for analysis as shown in Figure 3.

### Table 2. Parameters of the lining

| \( \gamma \) | Type         | \( E \)   | \( \mu \) |
|------------|--------------|----------|----------|
| Lining     | 22           | Linear and isotropic | 31.5E6   | 0.2       |
| Unit       | kN/m³        | kN/m²    |          |

### Table 3. Parameters of the rock bolts

| \( E \)    | \( d \) | Type  | \( T_{\text{top, max}} \) | \( T_{\text{bot, max}} \) |
|------------|--------|-------|--------------------------|--------------------------|
| Bolt 70E6  | 17     | 0.042 | Linear 158               | 158                      |
| Unit kN/m² | kN/m³  | m     | kN/m³                    | kN/m³                    |

Figure 3. Locations of the measured points at excavation surface of the tunnel

2.3. Simulation process

The study of tunnel construction was performed by finite element software Plaxis 3D. The tunnel excavation process was simulated based on the actual construction process. The displacement and stress in the specific locations were obtained and analyzed. To consider the influence of rock grades, the simulation was performed as follows:

1. The stratum was established and the geomechanical parameters were assigned, the initial stratum stress was calculated by the K0 method, the tunnel structure was created, the corresponding structural attributes were entered, the tunnel excavation were simulated through the life and death control unit, calculations and results were processed, and the influence of different excavation methods on the stress and displacement of surrounding rock and stratum settlement was analyzed.
(2) Changing the grade of surrounding rock, the simulation of the above process was repeated, the different construction methods were prepared, and reasonable construction suggestions were provided for different grades of the surrounding rock.

Because the tunnel is an underground structure with large longitudinal size and small transverse section size, the round length of excavation is set at 5 m in the study, the impact of excavation round length on construction was not considered in the present study. Center diagram (CD) method, double-side drift method, and bench cut method were simulated, respectively under the same rock condition considering the influence of construction methods. The difference between the three construction methods is shown in Figure 4.

![Figure 4. Illustration of different construction methods](image)

3. Result analysis

3.1. Displacement and stress of surrounding rock of grade I

The buried depth of the tunnel is approximately 100 m, the bottom of the tunnel is located in the slightly weathered granite, and the top layer of the stratum comprises of silt clay. As shown in Figure 5 (a), the settlement changes of the ground surface on both sides of the tunnel axis were almost the same for different construction methods. The settlement changes of each stratum layer on the upper part of the tunnel along the central axis are shown in Figure 5 (b). For the surrounding rock of grade I, the surface settlement and stratum settlement along the central axis of the tunnel constructed by CD, double-side drift, and bench cut methods showed similar values. The maximum value of the surface settlement above the tunnel vault was −0.36 mm, while the maximum settlement on the central axis of tunnel at the tunnel vault was −1.73 mm.

Tunnel excavation and support construction might disturb the surrounding rock, destroy the original structure of the rock mass, and influence the stress-strain state of the surrounding rock. The vertical displacement and maximum principal stress at selected points (Figure 3) around the tunnel are shown in Figure 6. There is no obvious difference in the displacement and stress of the surrounding rock between the three construction methods. The maximum vertical displacement of the surrounding rock was 1.41 mm, which appeared at the bottom of the arch (node 3), and the minimum vertical displacement was −1.73 mm, which appeared at the top of the arch (node M). The monitoring data was in good agreement with the simulated values, making it reasonable to use this numerical method to analyze the tunnel excavation. The difference in the maximum principal stress, i.e., the compressive stress caused by the three construction methods at selected points of the surrounding rock was observed. The maximum
The principal stress of the surrounding rock at the toe of arch was larger than that at the arch crown and arch bottom, indicating that the surrounding rock at the toe of arch bore the largest pressure.

![Diagram showing ground surface subsidence and settlement along the central axis.](image1)

(a) Ground surface subsidence  
(b) Settlement along the central axis

**Figure 5.** The stratum displacement of surrounding rock of grade I

![Diagram showing vertical displacement and maximum principal stress.](image2)

(a) Vertical displacement of surrounding rock  
(b) Maximum principal stress of surrounding rock

**Figure 6.** The displacement and principal stress of surrounding rock of grade I

3.2. Displacement and stress of surrounding rock of grade IV

For the grade IV surrounding rock, the surface settlement and change of soil settlement at the central axis caused by the three construction methods are shown in Figure 7. The settlement of the ground surface and the stratum layer at the central axis caused by tunnel excavation was greater than that of the grade I surrounding rock with obvious difference between the settlement caused by the bench cut method and the other two methods. The bench cut method caused larger ground surface settlement but smaller settlement at the central axis compared with the other two construction methods, indicating that excavation using the bench cut method could restrain tunnel settlement at the excavation surface but had a great influence on the disturbance of the upper stratum layers.
The vertical displacement and maximum principal stress of surrounding rock at the selected points are shown in Figure 8. To compare the effect of the construction method with surrounding rock of different grades more intuitively, the steel arch frame was not set in the numerical simulation but the actual construction to control the deformation of the surrounding rock, causing much larger simulated vertical displacement than the monitoring data. The vertical displacement of the surrounding rock caused by the bench cut method had poor symmetry and greater vertical displacement value than the other two construction methods because of the lack of temporary support in bench cut method construction, leading to a higher stress release rate of the surrounding rock. The maximum principal stress at the arch waist (between node 1&2) caused by the bench cut method was higher than that of the CD and the double-side drift methods. Meanwhile, the difference of the vertical displacement and stress of the surrounding rock at selected points between CD method and double-side drift method was very small.

3.3. Displacement and stress of surrounding rock of grade V

For grade V surrounding rock, the surface settlement and the change of the soil settlement along the central axis excavated by the three construction methods are shown in Figure 9. The influence of tunnel excavation on the upper strata further increased. The surface settlement
value was large in the middle part and small at the two ends. The settlement excavated by the bench cut method was the largest, while the settlement excavated by the double-side drift method was the smallest. But the settlement at the central axis caused by the bench cut method was smaller than that of the other two methods, and the settlement changes along the central axis were almost the same for the CD method and the double-side drift method as shown in Figure 9 (b). The settlement increased linearly in silt clay, fully weathered granite, and strongly weathered granite layers for all methods. After entering the moderately weathered granite rock layer, the stratum settlement increased significantly. The settlement caused by tunnel excavation mainly occurred in the slightly weathered granite where the tunnel was located.

![Figure 9. The stratum displacement of surrounding rock of grade V](image)

The vertical displacement and maximum principal stress of surrounding rock at the selected points are shown in Figure 10. As mentioned above, a steel arch was set in the actual construction, and the grouting reinforcement was performed for the grade V surrounding rock, which resulted in the simulated value much larger than the actual measured value. For the bench cut method, the vertical displacement of the surrounding rock increased significantly with large stress at the arch waist (node 1). The difference in the vertical displacement of surrounding rock was much smaller than the difference in ground settlement caused by the three construction methods. On the other hand, small differences were observed among the three construction methods in terms of the maximum principal stresses of the vault, arch toe, and arch bottom. The largest value of the stress appeared at the waist during the bench cut method.

![Figure 10. The displacement and principal stress of surrounding rock of grade V](image)
4. Conclusion
The mechanical properties of the surrounding rock during tunnel construction were studied by 3D numerical simulation. For different surrounding rock grades, three different excavation methods, namely, the CD method, the double-side drift method, and the bench cut method were simulated. A comparative analysis of ground settlement, surrounding rock displacement, and maximum principal stress caused by different construction methods was also conducted. Considering the safety and construction efficiency of tunnel construction, the following conclusions were obtained:

(1) With the increasing grade of surrounding rock, the ground settlement and vertical displacement of the surrounding rock caused by tunnel excavation increased, while the maximum principal stress decreased.

(2) For the grade I surrounding rock, the difference in surface settlement and vertical displacement of surrounding rock in each layer caused by the three construction methods was very small. The deformation trend was similar, and the maximum principal stress of surrounding rock was almost the same. Therefore, the bench cut method with simple construction process and fast tunnel construction speed could be used to carry out tunnel construction.

(3) For the grade IV surrounding rock, the stratum displacement, vertical displacement, and maximum principal stress of the surrounding rock at the arch waist caused by the bench cut method were significantly greater than those of the other two construction methods. Using bench cut method caused greater disturbance to the surrounding rock, with a small impact from the CD and double-side drift methods. It is advisable to use CD method for construction, because of small cross-section displacement and fast construction speed.

(4) For grade V surrounding rock, the stratum settlement caused by bench cut method was the largest, and the stratum settlement caused by the double-side drift method was the smallest. Due to the poor stability of grade V rock, the double-side drift method should be used for construction to minimize settlement.

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