Numerical simulation of excavation and support in shallow underground subway tunnel

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Abstract. During excavation of shallow tunnels, it is very important to construct primary support and secondary lining structures to guarantee the stability of tunnel surrounding rock and construction safety. Based on a subway tunnel project, in this study, the typical support and lining model is established by using the finite difference program. Stress characteristics and deformation patterns of the primary support and secondary lining structures are analysed and discussed, and the influencing mechanisms of different tunneling modes on the stress characteristics of the support and lining structures are revealed. The numerical results show that the benching excavation and support can effectively relieve the stress concentration in the primary surrounding rock support of typical subway tunnel project. The secondary lining, which is constructed after the deformations of the tunnel surrounding rock and the primary support tend to be stabilized, can strengthen and protect the tunnel surrounding rock and the primary support structure, bear part of the surrounding rock load, and serve as a safe reserve for the safety of subway tunnel projects.

1. Introduction
With the continuous development of urbanization in China, and the limited urban space aboveground can no longer meet the needs of social and city development. Therefore, extending the development and utilization of urban underground space, and developing underground transport represented by subway have become the most effective measures to relieve urban traffic congestion.

The interaction of the composite lining structure has always been a hot and difficult research issue in the field of subway tunnel engineering. The shallow tunneling method is commonly used for excavating underground cavities that are relatively close to the surface[1-2]. Secondary lining can be worked with advance support to improve and reinforce the surrounding rock with little impact on the surrounding traffic environment, and has recently been widely implemented in urban subway construction [3-6]. Li et al [7] studied the methods for calculating the pressure on the surrounding rock of large-section loess tunnels and the stress characteristics of their lining structures. Ye et al [8] investigated the stress characteristics of segmental lining in shield tunnels during construction.

Based on a typical section of subway tunnel project, the stress characteristics of the primary support and secondary lining structures of the shallow subway tunnel is simulated by using the finite difference program, and the influencing mechanism of different excavation modes on stress field distribution of the support and lining structures is revealed. The results can serve as a reference for similar studies on stress characteristics of support and lining structures and engineering safety control in urban subway tunnel projects.
2. Project overview and modeling

2.1. Project overview
The shallow tunneling method was used in its construction, which was a single-hole single-line horseshoe tunnel (6.2m in height and 5.8m in width) and adopts composite lining. The burial depth of the rail surface is 2.30-13.65m, and its typical section is shown in Figure 1. The numerical simulation analysis of two excavation processes using full-face method and benching method respectively is carried out for the subway tunnel project.

2.2. Numerical Model
The numerical model of subway tunnel, as shown in Figure 2, is established according to the geological conditions and typical geological sections of the subway tunnel project. This model includes 3564 nodes and 1928 units in total. The FLAC3D software is used for tunneling simulation and numerical analysis of the support and lining effects.

2.3. Parameters
According to the engineering geological conditions of subway tunnels and the stratigraphic distribution of the numerical model, the different mechanical parameters of soil-rock mass are shown in Table 1.

| Types of strata                  | Volume weight (kN/m³) | Poisson’s ratio | E₀ value (MPa) | Intensity parameter |
|---------------------------------|-----------------------|-----------------|----------------|--------------------|
| Plain fill                      | 18.60                 | 0.25            | 15             | 27                 |
| Residual gravel cohesive soil   | 18.40                 | 0.30            | 48             | 22                 |
| Completely weathered granite   | 19.00                 | 0.30            | 108            | 26                 |
| Cataclastic intensely weathered | 22.10                 | 0.36            | 902            | 40                 |
| Moderately weathered granite   | 26.30                 | 0.25            | 6137           | 50                 |
| Slightly weathered granite     | 26.40                 | 0.18            | 32956          | 120                |

2.4. Method for simulating tunnel supporting and lining processes
Composite lining structures were used in the tunnel. Figure 3 shows the grid model of the support and lining structures. The secondary lining is simulated by using the material parameters of the reinforced concrete actually used in the construction.

Numerical simulation analysis of the stress field in the primary support structure under the two conditions of full face tunneling and benching tunneling is performed for both the left line and right line. The excavation schedule of the subway tunnel is shown in Figure 4.
3. Analysis of Numerical Simulation Results

3.1. Stress field analysis for primary support

Left line is firstly excavated. After the excavation is finished, the primary support structure is constructed timely. Maximum principal compressive stress field of left line after the completion of primary support is shown in Figure 5, and maximum principle tensile stress field is shown in Figure 6.

As can be seen from Figure 5, the maximum principle compressive stress is mainly distributed in the left and right side walls, and the excavation mode has significant influence on stress characteristics of the primary support. In the full face tunneling mode, the maximum principle compressive stress in the left side wall of the left line is 0.82~3.50 MPa, and the maximum stress in the right side wall is 1.03~2.68 MPa. In the benching tunneling mode, the maximum principle compressive stress in the left side wall of the left line is 0.68~2.30 MPa, and the maximum stress in the right side wall is 0.81~1.89 MPa. It can be seen through comparison that the maximum principle compressive stress in the left side wall of the left line is significantly higher than that in the right side wall; this is mainly because the left side wall, a great part of which is located in residual gravelly cohesive soil, is subjected to larger compressive load. The primary support structure bears most of the unloading load. Compared to the full face tunneling mode, the benching tunneling mode can dissipate the unloading stress to a greater extent, and in this case, the primary support bears significantly less unloading stress with the maximum principal compressive stress reducing by about 34% from 3.50 MPa to 2.30 MPa.

As can be seen from Figure 6, the principle tensile stress is mainly distributed in top and bottom arch, with the largest principle tensile stress observed in bottom arch. Similarly, the excavation mode also has a significant influence on principle tensile stress distribution of primary support. In the full face tunneling mode, the maximum principle tensile stress of left line is 1.70 MPa, while the maximum principle tensile stress is 1.03 MPa in the benching tunneling mode, reducing by about 39.4%. Thus, the stress concentration in top and bottom arch is alleviated effectively.
After the completion of the left line, the right line is excavated. The primary support structure is constructed timely after the completion of the right line. The maximum principal compressive stress field of the right-line tunnel after the completion of the primary support is shown in Figure 7, and the maximum principle tensile stress field is shown in Figure 8.

As indicated by the section, most of the right line is located in completely weathered granite, and a small part is located in moderately weathered granite. Compared with the left line that is located in residual gravelly cohesive soil, the right line surrounding rock bears part of the unloading stress, thus reducing the maximum principle compressive stress. In the full face tunneling mode, the maximum principle compressive stress of the right line is 2.16MPa, located in the upper part of the left side wall. In the benching tunneling mode, the stress concentration in the primary support structure of the right line is relatively reduced, and the maximum principal compressive stress, located in the lower part of the right side wall, reduces by 18% to 1.77MPa.

As can be seen from Figure 8, in the full face tunneling mode, the principle tensile stress is mainly distributed in the left half of the top arch, and the maximum principle tensile stress is 1.13MPa; in the
benching tunneling mode, the maximum principal tensile stress reduces by about 26.8% to 0.80MPa. Similarly, the stress concentration in the top arch and bottom arch is alleviated effectively.

3.2. Stress field analysis for secondary lining

Secondary lining following primary support refers to a cast concrete or reinforced concrete lining that is applied on the inner side of primary support during tunnel construction, and together with primary support, constitutes a composite lining structure. Generally, secondary lining is constructed after the deformations of the tunnel surrounding rock and primary support tend to be stabilized. To learn about the stress characteristics of the tunnel after the secondary lining, the numerical calculation and analysis of the stress field distribution in the tunnel after secondary lining, which is excavated by the benching method, was carried out. The numerical calculation results are shown in Figure 9 and Figure 10.

As can be seen from Figure 9 (principal stress distribution of the left line after secondary lining), compared to Figure 5(b) and Figure 6(b), most of the secondary lining is not subjected to both compressive and tensile stresses, but it plays an effective role in alleviating compressive stress concentration in the primary support, with the maximum principal compressive stress reducing from 2.30MPa to 1.80MPa; similarly, it also has some alleviative effect on the principal tensile stress zone, reducing the maximum principal tensile stress from 1.03MPa to 0.54MPa.

![Figure 9. Principal stress distribution of the left line after secondary lining.](image)

As can be seen from Figure 10 (principal stress distribution of the right line after secondary lining), compared to Figure 7(b) and Figure 8(b), most of the secondary lining is not subjected to both compressive and tensile stresses as well, but it plays an effective role in alleviating compressive stress concentration in the primary support, with the maximum principal compressive stress reducing from 1.77MPa to 1.51MPa; similarly, it also has some alleviative effect on the principal tensile stress zone, reducing the maximum principal tensile stress from 0.80MPa to 0.70MPa.

According to the above analysis, it can be concluded that the secondary lining of subway tunnels can optimize the waterproofing and drainage system along the line, make the appearance look better, and facilitate the installation of communication, lighting and monitoring facilities. In addition, it can
also strengthen and protect the tunnel surrounding rock and primary support structures, bear part of the surrounding rock load, and thus effectively ensure the safety and stability of the tunnel.

4. Conclusions
The calculation results of the primary support of the tunnel project show that there are large stress concentration zones in the top arch, left and right side walls, and corners of the primary support. Excavation modes have a significant impact on stress characteristics of the primary support of the tunnel, and benching excavation and stepwise supporting and lining can effectively alleviate the stress concentration in the primary support of the typical subway tunnel project.

As indicated by the calculation results, the secondary lining, which is constructed after the deformations of the tunnel surrounding rock and the primary support tend to be stabilized, can optimize the waterproofing and drainage system along the line, make the appearance look better, and facilitate the installation of communication, lighting and monitoring facilities. In addition, it can also strengthen and protect the tunnel surrounding rock and primary support structures, bear part of the surrounding rock load. It can serve as a safe reserve for the safety of tunnel projects.

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