Deformation and mechanic response of surrounding rock mass during shallow buried large-section tunnel excavation

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Abstract. The stability of underground tunnel is closely related to the stress status of surrounding rock mass. Aiming at a typical large-span hydraulic tunnel, the variation of deformation and stress of rock mass during excavation was investigated. Results show that the peripheral convergence of surrounding rock increases with buried depth, and the crown settlement is more sensitive to depth. The horizontal displacement of surrounding rock decreases with the distance to tunnel side wall and the excavation disturbance is about 2 times of the tunnel width. There are obvious time and spatial effects of displacement because of the existence of working face. The restrain distance is about 1.5 times of tunnel width. The excavation of the tunnel changes the stress status of surrounding rock mass. Stress concentration first forms above the crown of the tunnel and then a continuous stress arc develops around the support. The stress arc is favorable to the stability of tunnel.

1. Introduction

Hydraulic tunnel plays an important role in flood control, hydroelectric generation and many other hydraulic engineering projects. With the development of economy, more and more large-sectional tunnels are needed. The deformation and mechanical behavior of the surrounding rock mass of super large-section tunnel are different to those of small-section tunnel. For shallow buried tunnel, the rock mass is relatively weak, the construction of large-section tunnel may lead to large deformation and result in tunnel collapse. So deformation characteristics and mechanical behavior of the surrounding rock mass need to be carried out to assess the reliability of support structure and assure the tunnel stability.

The common way to investigate the deformation and mechanical characteristics of tunnel is to carry out field monitoring and numerical analysis. Shalabi [1] studied the time-dependent deformation behavior of surrounding rock in squeezing ground. Li et al. [2] analyzed the deformation characteristics of a railway tunnel in loess ground. Galli et al. [3] investigated the deformation of tunnel lining and rock mass during excavation through 3D model. Kontogianni and Stiros [4] carried out geodetic monitoring to study the deformation characteristics during tunnel excavation. Park et al. [5] studied the ground response during tunnel excavation in soft rock mass. Carranza-Torres [6] presented an elasto-plastic solution to estimate the shear strength of tunnel surrounding rock mass. Nuttens et al. [7] carried out
high resolution terrestrial laser to measure tunnel deformation. Jeng et al. [8] studied the deformation of weak sandstone around a tunnel by field measurement. Hsiao et al. [9] investigated the rock deformation in tunnel intersection area by numerical simulation. Scaioni et al. [10] performed a photogrammetric technique to monitor the deformation of tunnel.

Although the deformation and the stress around underground structures have been studied by many researchers, most of them focus on the deep buried traffic tunnel. The publications on shallow buried hydraulic tunnel are not enough. The deformation mechanism of large-span underground excavations is far from being understood. It is important for a desirable support design and excavation safety. Aiming at this, a shallow buried large section hydraulic tunnel in Zhejiang, China was studied in this paper, the stress and deformation characteristics of the surrounding rock mass were discussed in detail.

2. Project information

The proposed tunnel locates in Linhai, Zhejiang Province, eastern China, adjacent to the East China Sea (Fig. 1a). The downtown has a concave terrain surrounded by a circle of mountains. The flood disaster is the main problem that threatens the life of local residents. The proposed tunnel is a constituent part of a flood-control engineering system, which connects the downtown and the Jiaojiang River. The hydraulic tunnel was mainly excavated in Jurassic welded tuff. The tunnel length is 2602m. The buried depth of the tunnel ranges from 5m to 210m. The tunnel section is of rectangle with an arc crown (Fig. 1b). The height of the tunnel is 15.4m and the width is 15.8m. Near the entrance of the tunnel, the overlying rock layer is thin. The rock mass is fractured and moderately weathered. The joint spacing ranges from 0.1m to 0.5m and fills with clay and debris. The rock mass is relatively weak and thus the deformation and stability characteristics of the tunnel in this section needs to be studied.

![Figure 1. (a) Location map of the project (b) Dimension of the tunnel section](image)

3. Numerical modeling

The three-dimensional numerical model of the hydraulic tunnel was established using Flac3D. The geometric model of the tunnel is shown in Fig. 2. The lateral boundaries are 50m to tunnel central line and the bottom boundary is 65m to the tunnel floor. The upper boundary is the natural ground surface. The extent of the model along the longitudinal axis is about 90m with a buried depth of 5m to 60m. The slope angle of the ground is about 30 degree along and 10 degree perpendicular to the longitudinal axis. The model was discretized using hexahedron element. Total 21300 elements and 23653 nodes were included in the model. The displacement boundary conditions were as follows: for the bottom boundary, both vertical and horizontal displacements were fixed, and for the lateral boundaries, the horizontal displacement was fixed.

The surrounding rock mass is moderately weathered tuff. The rock mass was modeled using an elasto-plastic model with Mohr-Coulomb failure criterion. The primary lining of the tunnel was the steel arc and shotcrete combined with grouting bolt. The lining and bolt were modeled using linearly elastic model. The physical and mechanical parameters of the rock mass and supporting structure obtained from laboratory tests are given in Table 1.
Table 1. Physical and mechanical parameters of the rock mass and supporting structure

| Material | Young’s modulus (GPa) | Poisson’s ratio | Friction angle(°) | Cohesion (MPa) | Density (kg/m²) |
|----------|-----------------------|----------------|------------------|---------------|-----------------|
| Tuff     | 2                     | 0.35           | 32               | 0.5           | 2400            |
| Lining   | 22                    | 0.25           | /                | /             | 2300            |
| Bolt     | 45                    | 0.15           | /                | /             | 7800            |

Figure 2. Numerical modeling and grid

The tunnel was excavated in three steps by drilling and blasting. First, the upper arc crown was excavated and then the lower rectangle part was excavated sequentially in two layers. Each step has a drilling length of 3m. The supporting structure was placed immediately after the excavation. The stage excavation process was modeled in this paper to simulate the deformation and mechanic behavior of the surrounding rock mass.

4. Numerical results

4.1. Displacement along tunnel axis

Fig. 3 shows the simulated crown settlement and horizontal convergence along the tunnel axis. The measured data are also showed in this figure. It can be seen that the modeled data agree well with the measured values, which validate the correctness of the numerical modeling. Fig.3 indicates that the deformation of the rock mass increases with the buried depth. The crown settlement increases nearly linearly with the buried depth, from 3.6mm (with a buried depth of 5.0m) to 9.4mm (with a buried depth of 59m). The maximum horizontal convergence of the side walls shows a decelerated growth trend with the buried depth. The convergence increase sharply from 3.2mm (with a buried depth of 5.0m) to 4.5mm (with a buried depth of 20.0m), and then slowly to 7.7m (with a buried depth of 59.0m). So it can be concluded that the crown settlement is more sensitive to the buried depth.
4.2. Displacement perpendicular to tunnel axis
The excavation of the tunnel surely has a disturbance to surrounding rock mass. In order to investigate the influence of tunnel excavation on rock mass deformation, the maximum horizontal displacement perpendicular to tunnel axis is illustrated in Fig. 4. It can be seen that the maximum horizontal convergence occurs at the middle level of the side wall and decreases with the increase of the distance to side wall. The maximum horizontal displacement is about 2.4mm when buried depth is 20m and reaches to 3.6mm when buried depth is about 49m. The horizontal displacement of surrounding rock mass is approaching to zero when horizontal distance exceeds 30m, which means that the influence range of the tunnel excavation is about 2 times of the tunnel width.

4.3. Spatial effect of deformation
Fig. 5 illustrates the crown settlement and side wall convergence near the working face. The buried depths of the working face are 25m (30m from tunnel entrance) and 35m (50m from the tunnel entrance) respectively. The working face has an obvious restraint on peripheral displacement of rock mass. The influence distance is about half tunnel width for crown settlement and is about tunnel width for horizontal convergence. Within this range, rock mass displacement increases with the distance to working face. It can also be seen from Fig. 3b that the buried depth also has influence on the restraint effect of working face. The restraint range increases with the buried depth. For the section with a buried depth of 35m, the influence distance of working face on rock mass displacement is about a tunnel width for crown settlement and 1.5 times of tunnel width for horizontal convergence.
It can also be observed that the excavation of the tunnel has a certain influence on the surrounding rock ahead of the working face. The surrounding rock ahead of the working face has a little displacement under the disturbance of excavation. The displacement and the disturbance range also increase with buried depth of the tunnel. The displacement is about 2.5mm and 3.0mm on working faces with buried depths of 25m and 37m respectively and decreases with distance ahead of the working face. When the distance to the working face is more than 1.5 times of tunnel width, the surrounding rock ahead of the working face is nearly no disturbance.

**Figure 5.** The surrounding rock mass displacement near the working face with buried depth of 25m (a) and 37m (b)

Fig. 6 illustrates the variation of surrounding rock displacement with distance to working face. It shows that both the crown settlement and horizontal convergence increase with the distance to working face. The slope of the curve near the working face increases with the buried depth, which means that the displacement has a large increment with the distance. The displacement of the surrounding rock is nearly stable when the distance to working face reaches about 30m with a buried depth of 15m. While for the cross section with a buried depth of 35m, the displacement does not level off even the distance extends to 40m. The distance is beyond the range of working face restraint, proving that the deformation of the rock mass has a time effect. The stress in the surrounding rock mass relieves slowly with time, resulting in an increase of plastic deformation.

**Figure 6.** Variation of crown settlement (a) and horizontal convergence (b) with distance to working face

4.4. **Time effect of deformation**

The rock mass displacement over time was given in Fig. 7. It can be seen that the curves exhibit a typical concave shape. The time-displacement curves can be divided into three stages: the rapid increment stage, gentle increment stage and nearly stable stage. The rapid increment stage is about 15 days for 14m.
buried section and 25 days for 35m buried section, which means that the buried depth also has influence on time effect of the surrounding rock mass. We can also observe that the step excavation method also has an obvious effect on the deformation during the rapid increment stage. The displacement has a sudden increment after the excavation of the bottom layer. After the rapid increment stage, the displacement increases smoothly with time and then levels off.

Figure 7. Variation of crown settlement (a) and horizontal convergence (b) with distance to working face

4.5. Stress distribution during excavation

Fig.8 and Fig.9 give the redistribution of principal stress around the tunnel during tunnel excavation. The concentration of stress for different buried depths is similar. The concentration of the stress for deep buried section is more obvious. The maximum principle stress concentrates over the tunnel after the excavation of the upper step. Then the concentration zone extends to the outside of the side wall when the middle step was removed. Finally, stress arch develops at the lateral sides and above the tunnel. The concentration zone is about half of the tunnel width and the distribution of stress approaching to a natural state beyond this distance. The maximum redistribution stress near the tunnel is about 7.5MPa for buried depth of 20m and 8.6 for buried depth of 40m.

Figure 8. Concentration of maximum principle stress around tunnel section with buried depth of 20m (Unit: MPa)
5. Conclusion
For the shallow buried tunnel, the displacement of surrounding rock mass increases with the buried depth. The horizontal displacement of the side rock tends to be stable when the buried depth is deeper than 30m.

The deformation of surrounding rock mass shows both spatial and time effect. The working face has obviously spatial effect on the deformation of surrounding rock mass. Within the range of 2 times of tunnel width, the displacement of the surrounding rock is restrained by the working face. Beyond the restraint range, the deformation of the surrounding increases smoothly with time until reaches a stable state. The excavation of tunnel also has a disturbance on the rock ahead of the working face, leading to a small displacement in the rock mass ahead of the working face. The disturbance range is no more than 2 times of tunnel width.

The excavation of the tunnel leads to the stress redistribution of surrounding rock mass. A continuous stress arc forms around the preliminary support after the excavation, which is beneficial to tunnel stability.

Acknowledgments
The authors greatly appreciate the support provided by the Zhejiang Province Science and Technology Plan Projects (No: RB1710; RB1709).

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Figure 9. Concentration of maximum principle stress around tunnel section with buried depth of 40m (Unit: MPa)
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