Numerical Analysis of Vertical Deformation of Tunnel Excavation through Ultra-long Broken-Zone

Binbin Xu¹2,3,4*

¹Tianjin Port Engineering Institute Co. Ltd. of CCCC First Harbor Engineering Co. Ltd., Tianjin, 300222, China
²CCCC First Harbor Engineering Co. Ltd., Tianjin, 300461, China
³Key Lab. of Geotechnical Engineering of Tianjin, Tianjin, 300222, China
⁴Key Lab. of Geotechnical Engineering, Ministry of Communication, Tianjin, 300222, China

*Corresponding author’s e-mail: xubinbin@tpei.com.cn

Abstract. In order to simulate the tunnel excavation of super-long broken rock zone, finite element analyses using Plaxis3D are carried out along with the construction, in which the influence of grade of surrounding rock and the excavation method on the deformation of tunnel are specially considered. Before numerical calculation, the parameters are reasonably simplified. The calculation results show that the CD method can efficiently reduce the deformation of rock in the broken zone to keep the stability. In the practical construction, it is recommended that the CD method is preferred when entering the broken zone.

1. Introduction
With the rapid development of domestic economy and traffic construction, the high-level expressway is continuously planned and constructed. Some of the expressways go through the mountain ridge where the fracture rock and the fracture water develop very well and the weight of the soft rock occupies greatly. The necessary conditions to ensure the safety of construction are to control the deformation of surrounding soft rock within proper magnitude efficiently and to evaluate the stability of the broken zone of tunnel and its support structure accurately.

For the construction method of the broken enclosing rock, there are plenty of researches. Yuan and Yang[1] analysed the distribution of displacement field and stress field under three different construction methods to analyse the influence factors on the safety and economy. Huang et al. [2] carried on a series of finite difference simulation for broken-zone tunnel using various construction methods. Wang and Bi [3] summarized the characteristics of stress and strain with different methods. Due to the multiple categories of tunnel enclosing rock and the construction methods, a numerical calculation is carried out using finite element method to analyse the influence of rock stability. Several numerical models are built to observe the detailed displacement and stress[4-7]. The comparison among the excavation method and the rock level is made to guide the practical construction.

2. Engineering profile
The proposed new tunnel is a separated tunnel which includes the left part and the right part. The length of the left part is 2440m and the maximum depth of embedment is 128.85m. The length of the
right part is 2425m and the maximum depth of embedment is 137.81m. The geological condition is mainly structural corrosion erosion landform. The shallow buried depth of the tunnel is 21-24m. The basic quality index (BQI) is about 204.37 and the level of the surrounding rock is classified into V2. The rock is mainly conglomerate with medium-strong cementation. The fracture contains block stone and gravel and its ingredient is limestone and dolostone. The particle size is between 10 and 30cm. The geophysical prospecting results show that it is mainly high-resistance region and the watery property is relatively small. Due to the poor self-stability of rock, the stability of the sidewall is weak. There may be risk of large-scale collapse during the excavation if the support is not proper.

3. Finite element model and calculation parameters
According to the design drawing of the tunnel section, the skeleton line is built using the multiple-line function. The research object is the left part of the tunnel and the classification of the enclosing rock is V2 level, where the CD method is used and the advanced support uses the advanced leading conduit with diameter of 42mm. The skeleton and the calculation model are shown in Figure 1 respectively. The stratum is divided into two layers. The upper layer is filling and the broken zone is located at the lower layer. Considering the boundary effect of the model, the horizontal calculation magnitude is 30m distance to the right and left boundary from the centre of tunnel face. The magnitude in the drilling direction is 50m and the depth is 60m.

![Figure 1. Calculation model](image)

4. Calculation and analysis
In the numerical calculation, there is great influence of the choose of the parameters on the calculation results. The perfect calculation procedure should be the comparison between the calculation and practical monitoring at the initial stage. The continual adjustment of the parameters should be carried out the make the difference between the calculation and the monitoring is very small. Then, the adjusted parameters are used to make further analysis. However, most of the calculation are carried out far before the construction and there is no monitoring data to refer. In order to evaluate the influence factors of construction method and surrounding rock classification on the deformation of the tunnel, the qualitative analyses are carried out and the calculation scheme is listed in Table 1.

| Elastic modulus/excavation method | CD method | three-step method |
|-----------------------------------|-----------|------------------|
| 600MPa Case 1                     | Case 2    |                  |
| 100MPa Case 3                     | Case 4    |                  |
For the sake of saving space, only the distribution of settlement of the left part of the tunnel is shown in Figure 2 and the settlement of the right part is similar to that. As the excavation of the tunnel keeps on, there is obvious settlement on the top of the tunnel and uplift on the bottom of the tunnel. Due to the asymmetry of the CD support method, the maximum settlement and uplift is not located at the centre of the tunnel axial line, which is different from the three-step method. The maximum settlement for four schemes are 6.67mm, 10.4mm, 35.05mm, 64.6mm respectively. The maximum uplift for four schemes are 7.44mm, 10.2mm, 35.3mm, 59.2mm respectively. When the elastic modulus of the enclosing rock is designated 600MPa, which obeys the relative code, the maximum settlement is 6.67mm and 10.4mm for CD method and three-step method, and the maximum uplift is 7.44mm and 10.2mm for CD method and three-step method respectively. Compared to the deformation of the three-step method, the maximum settlement of CD method reduces as large as 56% and the maximum uplift decreases about 37%. It is recommended that CD method is used to decrease the deformation of enclosing rock during excavation effectively and to keep the stability of the rock.

During the practical excavation construction, CD method can be used when the tunnel is excavated at the initial stage. Meanwhile, the deformation of the tunnel should be monitored closely and the monitoring data should be compared with the numerical calculation results to evaluate whether it is necessary to change the excavation method. Considering the stable extent of the practical enclosing rock is much bad, the elastic modulus of 100MPa that is close to the elastic modulus of the dense sand is employed and the deformation using two methods are also calculated. The maximum settlement is 35.05mm and 64.6mm for CD method and three-step method, and the maximum uplift is 35.3mm and 59.2mm for CD method and three-step method respectively. The maximum settlement and uplift of CD method reduce as large as 84% and 68% respectively compared with that of three-step method. It can also be concluded that as the elastic modulus of the enclosing rock decreases, the reduction extent of the maximum deformation of CD method also increase compared with three-step method.
(c) Case 2  
(d) Case 4  
Figure 2. Comparison of settlement for four schemes

Table 2. Maximum settlement (mm)

| $E$ (MPa) | Excavation method | CD method | Three-step method |
|-----------|-------------------|-----------|------------------|
| 600       |                   | 6.67      | 10.4             |
| 100       |                   | 35.05     | 64.6             |

Table 3. Maximum uplift (mm)

| $E$ (MPa) | Excavation method | CD method | Three-step method |
|-----------|-------------------|-----------|------------------|
| 600       |                   | 7.44      | 10.2             |
| 100       |                   | 35.3      | 59.2             |

5. Conclusions
The paper carried out a series of numerical calculation to evaluate the excavation method and elastic modulus of enclosing rock on the deformation of the ultra-long broken-zone tunnel. The conclusions are as follows:

1. During the numerical analysis of stability and deformation of tunnel excavation, the calculation parameters should be simplified to some extent to improve the calculation efficiency.

2. When the elastic modulus of enclosing rock is 600MPa, the maximum settlement is 6.67mm and 10.4mm and the maximum uplift is 7.44mm and 10.2mm. Compared to the deformation of the three-step method, the maximum settlement of CD method reduces as large as 56% and the maximum uplift decreases about 37%.

3. When the elastic modulus of enclosing rock is 100MPa, the maximum settlement is 35.05mm and 64.6mm and the maximum uplift is 35.3mm and 59.2mm. The maximum settlement and uplift of CD method reduce as large as 84% and 68% respectively compared with that of three-step method.

4. It is recommended that CD method is used to decrease the deformation of enclosing rock during excavation effectively and to keep the stability of the rock. During the practical excavation construction, CD method can be used when the tunnel is excavated at the initial stage.

References
[1] Yuan Jiwei, Yang Jianhua, Guo Wenbing. (2007) Determination on loose range of surrounding rock of soft rock entry underbolting-net support[C]. New Progress of Mining Construction,
[2] Huang Chenglin, Luo Xuedong, Lv Qiaoseng. (2011) Soft rock tunnel excavation on deformation of the numerical simulation [J], Railway Engineering, 11: 35-38.
[3] Wang Weifeng, Bi Junli. (2007) Construction project optimizing of soft rock and shallow buried tunnel[J], Rock and Soil Mechanics, Supp. 28, 10.

[4] Code for Design of Road Tunnel (JTGD70-2004)

[5] Sun Changyu, Gong Bining. (2006) Stability analysis for rocky slope based on contact algorithm of ADINA[J], Journal of Water Resources and Architectural Engineering, 4: 26-30.

[6] Huangpu Ming, Kong Heng, Wang Mengshu, Yao Haibo, (2005) Effect of keeping core soil on stability of tunnel working face[J], Chinese Journal of Rock Mechanics & Engineering, 3: 521-525.

[7] Liu Jun, Kong Xianjing. (2007) Numerical simulation of behavior of jointed rock masses during tunneling and lining of tunnels[J]. Rock and Soil Mechanics, 28 (2) : 321-326.