Numerical Evaluation of Tunnel Stability with Two-line Excavation by Plaxis3D

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Abstract. Before the excavation of the tunnel, it is very necessary to evaluate the stability of the tunnel especially for the ultra-long broken zone. The CD method and the three-step method are the potential construction method. The calculation parameters are simplified to improve the calculation efficiency and precision. The results show that the CD method can decrease the deformation of the enclosing rock significantly. During the practical excavation construction, CD method can be used when the tunnel is excavated at the initial stage.

1. Background
The mechanical properties of the soft rock are mainly: 1) due to the development of the fracture in the enclosing rock, the structure surface distributes randomly and there is no obvious direction therefore to some extent the fractural soft rock can be regarded as homogeneous isotropic continuum; 2) the entire compressive strength of broken enclosing rock is relatively low and the stability of the tunnel is very weak after excavation. The methods for stability analysis of enclosing rock of highway tunnel are listed in Table 1. 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.

| Method                | Advantage                      | Applicable condition        |
|-----------------------|--------------------------------|-----------------------------|
| analytical method     | High precision, rapid analysis | for circle tunnel           |
| FEM                   | easy to apply, abundant results| for elastic, elasto-plastic |
| discontinuous deformation | integrated block theory         | for discontinuous problem  |
| DEM                   | simple principle, plenty results | for interaction between rock |
|-----------------------|---------------------------------|-----------------------------|
| B(block)EM            | few unknown, high precision     | for rock with fracture       |
| FLAC 3D               | rapid solving                   | for discontinuous           |
| B(boundary)EM         | low solving dimension           | low requirement of PC       |
| block-spring method   | represent deformation rules      | for stability of joint rock |
| engineering geological analogy | low requirement of geological exploration | for large-scale underground cavern group |
| model test method     | close to practical case         | for important engineering   |
| uncertainty method    | consider the discreteness       | for large uncertainty       |

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**

3.1. **Finite element model of left part**

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.

After the tunnel excavation, with the continuous advance of excavation face, the deformation amount of surrounding rock gradually increases and relaxes. At the beginning, the deformation rate is faster. The construction of arch shed and initial support formed by pre-support has supporting effect on surrounding rock, which makes the support structure and surrounding rock deform together and restricts the development of harmful deformation of surrounding rock. Finally, the deformation rate of surrounding rock slows down and tends to be stable. It tends to be stable. Therefore, under the same stratum and geological conditions, the convergence deformation of surrounding rock reflects to a certain extent the stability of surrounding rock and support capacity. The larger the convergence deformation of surrounding rock is, the faster the speed is, the greater the impact on the stability of surrounding rock is, the more unstable the surrounding rock is.

3.2. **Calculation parameters**

Due to the random and complexity of the physical and mechanical properties of the geological materials, it is very difficult to simulate the mechanical characteristics of geological materials completely and to construct numerically according to the practical construction. Therefore, in this
calculation some simplification and suitable assumption are made in the determination of rock parameters to make the results more reasonable.

1) material of enclosing material
The enclosing rock is assumed to be ideal elasto-plastic and the Mohr-Column model is used as the constitutive model. The broken zone is simplified as uniform and homogeneous material ignoring the joint and fracture. Considering the level of V2, according to the suggestion of Code for design on tunnel of highway (JTGD70-2004) [4] the elastic modulus of enclosing rock, the poison ratio, the bulk density, the cohesive strength and the internal friction angle are 0.6GPa, 0.35, 20kN/m\(^3\), 0.1MPa and 20 degree.

2) simulation of reinforced circle by ductule casting paddle timbering
Because the diameter size of the ductule is very small, if it is simulated actually in the calculation the unconverging results may be obtained in the numerical simulation. Therefore, the ductule and the rock reinforced by the ductule casting are usually regarded as a uniform and single geological material. The solid element is employed. The longitude length is still 50m and the thickness of the reinforced circle is 50cm. The equivalent elastic modulus of the reinforced circle can be determined by the following equation [5, 6]:

\[
E = E_0 + \Delta E = E_0 + \frac{S_g E_g}{S_r} \quad (1)
\]

Here, \(E\) represents the equivalent elastic modulus (MPa), \(E_0\) is the elastic modulus of the original enclosing rock (MPa), \(S_g\) is the area of the cross section of the steel pipeline (m\(^2\)), \(E_g\) is the elastic modulus of the steel pipeline (MPa), \(S_r\) is the cross-section area of the rock circle (MPa). According to the material using in the engineering, \(\Delta E\) is around 1500MPa. Therefore, the parameters of the reinforced circle by ductule casting paddle timbering are depth of 0.5m, elastic modulus of 2.1GPa, poison ratio of 0.35, bulk density of 21kN/m\(^3\), cohesive strength of 0.1MPa and internal friction angle of 20 degree.

3) simulation of anchor rod
The equivalent principle of the anchor rod is different according to its various function [7]. The injecting slurry anchor rod has the function of tension and squoosh to enhance the property of the enclosing rock. There is nearly no variation of the internal frictional angle by the anchor while the cohesive strength of the enclosing rock installed by the anchor rod can be increased obviously, which is given by Equation (2):

\[
C = \beta C_0 = \left(1 + \frac{\eta \tau S_m}{9.8 ab} \times 10^4\right) C_0 \quad (2)
\]

Here, \(\beta\) is the amplified coefficient, \(C_0\) is the cohesive strength of the enclosing rock without the anchor rod (MPa), \(\tau\) is the cohesive strength of the anchor rod (MPa), \(S_m\) is the area of the anchor rod, \(a\) and \(b\) are the longitude and horizontal interval (m), \(\eta\) is the empirical coefficient between 2 and 5. According to the practical parameters, the depth, elastic modulus, poison ratio, bulk density, cohesive strength and internal frictional angle of the enclosing rock reinforced by anchor rod are 4.5m, 0.6GPa, 0.35, 21kN/m\(^3\), 0.11414MPa and 20 degree.

4) sprayed concrete and grille type steel truss
The plate element is used to simulation the preliminary support of the sprayed concrete and it is regarded to be linear elastic. The parameters of the sprayed concrete are of 0.26m depth, 22kN/m\(^3\) bulk density, 29GPa elastic modulus, 0.15 poison ratio according to the Code for design on tunnel of highway (JTGD70-2004). The effect of the grille type steel truss is incorporated into the sprayed concrete equivalently by increasing its mechanical index and in the numerical calculation there is no element for the grille type steel truss.

5) secondary lining concrete
The secondary lining concrete is simulated by solid element and its parameters are of 0.6m depth, 23kN/m\(^3\) bulk density, 29.5GPa elastic modulus, 0.15 poison ratio respectively.
4. Calculation and analysis

In order to evaluate the influence of excavation of double-line tunnel simultaneously, the finite element model of the double-line tunnel is established. The distribution of the settlement and the horizontal displacement of double-line tunnel employing three-step method is calculated respectively, as shown in Figure 1. In the calculation, the elastic modulus of the enclosing rock is 600MPa. As can be seen, when the tunnel of the left part and the right part is excavated, the maximum settlement at the top of the tunnel is 12.7mm and the maximum uplift at the bottom of the tunnel is 9.75mm, which is 22% larger than that of the single tunnel. The maximum horizontal displacement at the side of the tunnel is 7.8mm which is 33% larger than that of single tunnel.

![Figure 1. Deformation of double-line tunnel](image)

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 conclusion 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 left and the right part of the tunnel is excavated, the maximum settlement is 12.7mm and the maximum uplift is 9.75mm, and the maximum horizontal displacement is 7.8mm.
3. 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.

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