Stability analysis of surrounding rock-supporting system of shallow buried soft rock tunnel based on time effect

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Abstract. In view of the lack of consideration of the time effect parameters of surrounding rock and supporting structure in past research, this paper aims at the surrounding rock deformation characteristics of highway soft rock tunnel, and by introducing the long-term strength of rock and the creep coefficient of sprayed concrete, the surrounding rock and concrete mechanical parameters considering time effect is obtained. This paper uses ANSYS software to establish the finite element model, according to the application of anchors, steel arches and shotcrete support after the excavation without any support and excavation. The simulation results of surrounding rock-support stability after tunnel excavation are obtained. The effects of surrounding rock mechanical parameters and supporting parameters on tunnel deformation and surrounding rock stability under different time effects are studied. The research results can provide useful theoretical suggestions for the safe construction of subsequent soft rock tunnels.

1. Introduction

As an important part of tunnel construction, the stability analysis of tunnel surrounding rock-support system has complex influencing factors, including two factors: surrounding rock system and support system, including rock material characteristics, stress state, steel arch parameters, anchor spray support parameters, etc., and the support time after tunnel excavation plays a key role in the stability of tunnel surrounding rock.

At present, the research on the stability of surrounding rock of soft rock tunnel is mainly through numerical simulation, monitoring measurement, physical simulation and other methods, and the stability of tunnel surrounding rock is analyzed based on the displacement change or stress change of surrounding rock of tunnel. The time effect of surrounding rock stability is mainly studied by Zhou Depei [1] through theoretical analysis and model experiments to study the time effect of surrounding rock deformation pressure on circular tunnel lining. Peng Chao et al [2] has studied the surrounding rock pressure of large section highway tunnel considering time effect. Liu Bo et al. [3] carried out a three-dimensional settlement prediction model for tunnel excavation considering time effect, and derived the three-dimensional surface settlement prediction formula of single tunnel and double tunnel considering time effect, three-dimensional slope rate of surface settlement and the calculation method of three-dimensional curvature. Zuo Qingjun et al. [4] studied the expansion constitutive model of cement-rich slate tunnel surrounding rock based on time effect, and corrected the axial expansion ratio of shale slate under lateral restraint. The relationship between water absorption time and
one-dimensional constitutive relation in the expansion process. He Dongliang et al. [5], Sun Yuanchun et al. [6] have studied the deformation of tunnel surrounding rock considering space-time effect. Yang Junping [7] studied the mechanical behavior of soil tunnel considering space-time effects through physical model tests. Parsapour, D [8] and other semi-analytical solutions for the surrounding rock of expansive rock tunnels with time. Paraskevopoulou, C et al. [9] studied the time effect of tunnel deformation by the convergence constraint method. Some researchers also used the shear strength reduction method in slope and foundation stability analysis to study the stability of tunnel surrounding rock [10,11,12,13].

The above studies have studied the time effect of surrounding rock deformation, but did not consider the time-effect parameters of the supporting structure and surrounding rock. Therefore, the numerical calculation of the parameters of surrounding rock and supporting structure in different time periods is carried out to analyze the stability of tunnel surrounding rock under time effect and provide experience for the timing of shallow buried soft rock tunnel support, according to the two conditions of anchoring, steel arch and shotcrete support after excavation and unsupported excavation.

2. Establish a calculation model

2.1. Project Overview
A soft rock tunnel is a separate double-hole super-large tunnel with a length of 11700m. The left and right longitudinal slopes of the cavern are +1.90%, the axes of the two tunnels are 48.6m apart, the clearance of the left and right tunnels is 10.25m×5.0m, and the maximum buried depth is about 515m. The tunnel area is a structurally denuded Zhongshan geomorphic area with large terrain fluctuations. There are three fracture zones in the tunnel area, the rock mass is broken, and the hole formation conditions are poor. The rock mass in the tunnel area is gray schist, with integrated contact between the groups, flaky structure, mostly thin layer ~ very thin layer, the layer thickness is generally (1~5) cm, the local part is medium thick layer, layer thickness (10~20)cm, the overall appearance of the morphological condition is 66°<30°~40°. The flaky surface is undulating. The continuity is good. The interlayer is displaced. The cementation is serious, and the spacing is generally (1~5) cm can be divided into layered-fragmented structures. The groundwater is mainly bedrock fissure water, which receives vertical infiltration replenishment of atmospheric precipitation, and there is water seepage during tunnel excavation, which is greatly affected by seasonality.

2.2. Model calculation conditions
In the finite element model, the surrounding rock is simulated by PLANE42 unit (planar unit), and the sprayed concrete and steel arch are simulated by BEAM3 unit (beam unit). The anchor is simulated by link1 unit (rod unit), and the bolt, arch and Surrounding rock common node are rigid contact. The calculation uses ANSYS software, the geotechnical material uses the Druck-Prager yield criterion, and the mechanical properties of shotcrete, steel arch and anchor are using the ideal elastic model. In the finite element simulation, the full-section excavation method is used, and the finite element model of the secondary lining is not established without considering the auxiliary measures such as the small pipe and the steel mesh. The established geometric model and finite element unit division are shown in Figure 1.

The longitudinal dimension of the tunnel is small and the cross-sectional dimension is small. For the convenience of calculation, the plane strain problem is considered. The numerical calculation only considers the effect of gravity. The bottom, left and right sides of the calculation range are larger than 5 times of the span of the cave. The upper boundary is taken to the ground, the left and right sides are constrained horizontal displacement, the upper part is the free boundary, the lower part is the fixed constraint, and the gravity stress field is applied. Only the left tunnel is excavated during the calculation.
2.3. Parameter determination

For the stability analysis of the shallow buried soft rock tunnel, only the self-weight stress field of the rock mass is considered. According to the determined rock mass mechanical parameters of the tunnel area, the long-term strength of the rock is introduced into the relevant literature, and the mechanical parameters of the surrounding rock considering the time effect are obtained. The rock mass of the tunnel is soft rock. The mechanical parameters of the surrounding rock involved in the calculation of the time effect of the tunnel rock mass are shown in Table 1.

| Surrounded rock level | Elastic Modulus (MPa) | Uniaxial compressive strength (MPa) | c (MPa) | φ (°) |
|-----------------------|-----------------------|-------------------------------------|--------|------|
| IV                    | 1160.08               | 54.8                                | 0.31   | 24.03|

The mechanical parameters of steel arches and anchors do not take into account the time effect, and directly adopt the physical and mechanical parameters of arches and steel bars in the design specifications of highway tunnels. When the two-dimensional plane strain of the anchor is simulated by the link unit, the effect of the anchor on the rock mass is actually strengthened. Therefore, the elastic modulus of the anchor needs to be reduced. Based on the comparison of a large number of 2D and 3D finite element results, the reduction factor is determined to be 0.85.

2.3.1. Rock mass mechanical parameters at different time. In order to consider the time effect of tunnel surrounding rock deformation and the time effect of tunnel-support system stability, according to the literature research results [10,11,12,13], the long-term strength of rock is introduced and the value is introduced into the generalized Hoek-Brown criterion. The shear strength c of the body and its variation with time (Table 2). The deformation modulus E and RMR of the rock mass under the time effect have the following relationship:

\[ E = 10^{\left(\frac{RMR-10}{40}\right)} \quad (RMR<50) \]  

Table 2. Cohesion and friction angle of rock mass at different times.

| Time(Day) | Cohesion(MPa) | Friction angle | Time(Day) | Cohesion(MPa) | Friction angle |
|-----------|---------------|----------------|-----------|---------------|----------------|
| T=0d      | 0.1616        | 22.3166        | T=7d      | 0.1442        | 20.4858        |
| T=1d      | 0.1585        | 21.9881        | T=14d     | 0.1340        | 19.3616        |
| T=2d      | 0.1555        | 21.6864        | T=28d     | 0.1225        | 18.0574        |
| T=3d      | 0.1529        | 21.4084        |           |               |                |
2.3.2. Mechanical parameters of shotcrete at different time. As a special supporting structure, shotcrete has a time effect that affects the force and deformation of the structure. In this paper, the characteristics of shotcrete strength and equivalent elastic modulus change with time are considered by the creep coefficient of shotcrete. On the basis of the literature [14], the creep coefficient and equivalent elastic modulus of shotcrete in each time period are obtained by taking t=28d are shown in Table 3.

3. Analysis of calculation results
The numerical calculation of the stability of the surrounding rock-support system is carried out according to the application of anchors, steel arches and shotcrete support after no excavation and unsupported excavation, regardless of the stress release of the surrounding rock and the creep effects of geotechnical media.

3.1. Excavation unsupported simulation analysis
Considering the gravity field and the unsupported excavation, the equivalent plastic strain of the surrounding rock of the tunnel when T=0d and T=28d is shown in Fig.2, and the stress release rate of the surrounding rock is not considered at this time. It can be seen from the results in the figure that if no support is applied, the surrounding rock will undergo a large range of plastic yield at the time of excavation (t = 0d), and the maximum radius of the plastic zone and the area of the plastic zone will increase with time. Continuously increasing, the equivalent plastic strain at the arch and the side wall is the largest, which is the most unfavorable position; the plastic zone at the arch shoulder has the largest depth.

| Time (Day) | Elastic Modulus (GPa) | Creep Coefficient | Overall Elastic Modulus (GPa) | Time (Day) | Elastic Modulus (GPa) | Creep Coefficient | Overall Elastic Modulus (GPa) |
|------------|-----------------------|------------------|-----------------------------|------------|-----------------------|------------------|-----------------------------|
| 1          | 5.8543                | 1.6021           | 2.2498                      | 15         | 21.649                | 0.66401          | 13.01                        |
| 2          | 9.9029                | 1.4919           | 3.974                       | 16         | 21.828                | 0.62579          | 13.426                       |
| 3          | 12.761                | 1.3896           | 5.3403                      | 17         | 21.982                | 0.58946          | 13.83                        |
| 4          | 14.827                | 1.2971           | 6.4546                      | 18         | 22.116                | 0.55487          | 14.223                       |
| 5          | 16.356                | 1.2135           | 7.389                       | 19         | 22.231                | 0.52188          | 14.608                       |
| 6          | 17.516                | 1.1377           | 8.1938                      | 20         | 22.332                | 0.49037          | 14.984                       |
| 7          | 18.417                | 1.0684           | 8.9039                      | 21         | 22.419                | 0.46023          | 15.353                       |
| 8          | 19.132                | 1.0047           | 9.5436                      | 22         | 22.495                | 0.43138          | 15.715                       |
| 9          | 19.711                | 0.94583          | 10.13                       | 23         | 22.56                 | 0.40373          | 16.072                       |
| 10         | 20.187                | 0.89108          | 10.675                      | 24         | 22.618                | 0.3772           | 16.423                       |
| 11         | 20.583                | 0.83995          | 11.187                      | 25         | 22.667                | 0.35172          | 16.769                       |
| 12         | 20.917                | 0.792            | 11.672                      | 26         | 22.711                | 0.32724          | 17.111                       |
| 13         | 21.20                 | 0.74689          | 12.136                      | 27         | 22.748                | 0.3037           | 17.449                       |
| 14         | 21.441                | 0.70431          | 12.581                      | 28         | 22.781                | 0.28104          | 17.783                       |
Figure 2. Equivalent plastic strain of surrounding rock when excavation unsupported by self-weight stress field. (left: t=0d, right: t=28d)

See Table 4 and Figure 3 for the plastic zone of surrounding rock and the maximum and minimum principal stress of surrounding rock with time t under unsupported conditions. It can be seen that the area of the plastic zone and the maximum depth of the plastic zone continue to increase with time. When T=0d, the tunnel is just excavated, the maximum depth of the plastic zone is 1.95R, the plastic zone area increases by nearly 3 times when T=28d, and the maximum depth reaches 4.97R. With the increase of time, the tunnel gradually appears slightly pulling. Stress, in which the maximum tensile stress occurs in the deep position of the shoulder and the vault, and the maximum compressive stress occurs in the deep part of the side wall.

Table 4. Dimensional plastic zone size and max or min principal stresses of surrounding rock under excavation without self-weight stress field.

| Time  | Plastic zone area M2 | Plastic zone max depth (Rps/R)a | S1max Max tensile stress (MPa) | S3min Max compressive stress (MPa) |
|-------|----------------------|--------------------------------|-------------------------------|-----------------------------------|
| T=0d  | 510.332              | 1.95                           | -                             | 4.84                              |
| T=3d  | 681.618              | 2.54                           | -                             | 4.67                              |
| T=7d  | 952.402              | 3.23                           | -                             | 4.45                              |
| T=14d | 1528.62              | 4.73                           | 0.016                         | 4.27                              |
| T=28d | 1979.22              | 4.97                           | 0.058                         | 4.05                              |

a Rps is the max depth of the tunnel plastic zone, R is the tunnel radius, R=6.3m.

Figure 3. Max principal stress (left) and min principal stress (right) of surrounding rock when excavation is not supported by self-heavy stress field

See Figure 4 for the displacement of the surrounding rock in the x and y directions when the excavation is not supported. The abscissa is the angle, \(\theta=0^\circ\) means the right wall, \(\theta=90^\circ\) means the vault, \(\theta=270^\circ\) means the left wall. As can be seen from the figure, with the increase of time, the
displacement of the surrounding rock x (horizontal direction) and y (vertical direction) of the same point gradually increases.

Figure 4. Displacement of the surrounding rock in the X and Y directions when the excavation is not supported by the self-heavy stress field.

3.2. Simulation analysis of support after excavation

According to Table 2 and Table 3, the strength of the surrounding rock decreases with time, and the strength and equivalent elastic modulus of the shotcrete increase. Then it will inevitably lead to the plastic zone of the surrounding rock after support, the safety factor of the lining, the force of the steel arch and the bolt continuously change with time.

Surrounding rock support conditions after excavation: C25 shotcrete thickness is 25cm, steel arch frame is H175 steel, arch frame is 0.6m axial distance along the tunnel, anchor length is 3m, and 15 anchors are arranged along the tunnel radial direction.

The plastic zone range of the surrounding rock and the surrounding rock stress state at T=28d after tunnel excavation support are shown in Figure 5. Comparing Figure 5a and Figure 2b, it can be seen that the plastic zone range, the plastic zone area and the maximum depth of the plastic zone of the surrounding rock are all reduced after the support is applied. After the support is applied, the position of the side wall and the shoulder of the surrounding rock is plastically yielded, and the maximum depth is about 0.6-0.7 times. There is stress concentration at the arch. There is no tensile stress in the hole.

Figure 5. Stress state of surrounding rock after support under self-weight stress field(T=28d), (a) Plastic zone; (b) Max principal stress S1; (c) Min principal stress S3

The stability analysis results of the surrounding rock-support of the tunnel at different times after support (Table 5) show that the strength of the surrounding rock decreases with time, although the strength of the lining increases, but the plastic zone area and plasticity of the tunnel the maximum depth R_p of the zone continues to increase. This indicates that the decrease of the strength of the surrounding rock of the tunnel has a great influence on the stability, and the stability and safety of the
tunnel decrease with time. Secondly, with the increase of time, the axial stress of steel arch and anchor has a tendency to decrease, and the safety factor of initial construction is also reduced. This is because in the early stage of shotcrete, it’s strength is low, and steel arches play the main support. With the increase of the strength of the shotcrete, the surrounding rock load is jointly undertaken by the combined support system such as shotcrete and steel arch. The axial stress of the steel arch and the anchor is reduced. The surrounding rock load of the lining is increased. And, the safety factor of the lining is reduced.

Table 5. Tunnel surrounding rock-support stability results with time-dependent of self-weight field.

| Time | Surrounding rock | Lining safety factor(K) | Steel arch axial stress (MPa) | Anchor axial stress (MPa) |
|------|------------------|-------------------------|-----------------------------|--------------------------|
|      | Area_{ps} | Upper part R_{ps}/R | Lower part R_{ps}/R | S1max | S3min | max | min | ave | max | ave | max | ave |
| 0d   | 129.23/9 | 0.606 | 0.395 | -0.12 | 5.56 | 2.56 | 0.84 | 1.43 | 399 | 266 | 248 | 103 |
| 3d   | 132.13/9 | 0.606 | 0.565 | -0.15 | 5.58 | 1.84 | 0.72 | 1.14 | 356 | 247 | 218 | 89.0 |
| 7d   | 146.21/2 | 0.606 | 0.629 | -0.20 | 5.83 | 1.69 | 0.74 | 1.12 | 318 | 229 | 193 | 76.5 |
| 14d  | 160.40/1 | 0.612 | 0.629 | -0.24 | 5.77 | 1.64 | 0.79 | 1.13 | 288 | 215 | 175 | 69.3 |
| 28d  | 187.13/1 | 0.812 | 0.907 | -0.29 | 5.70 | 1.52 | 0.79 | 1.07 | 255 | 196 | 155 | 61.1 |

*S1max is negative number means no tensile stress.

The safety factor analysis of the initial shotcrete of the tunnel at different time periods is known (Figure 6). As time increases, the safety factor at the same position gradually decreases. The left and right side walls of the tunnel have the lowest safety factor, and the crown and the inverting arch have the highest safety factor. It indicates that the left and right walls of the tunnel are the most unfavorable locations for the initial construction.

Figure 6. Safety factor of tunnel lining with time under the action of self-heavy stress field.

4. Conclusions
Through the finite element analysis of the stability of the surrounding rock-support structure of the
shallow tunnel and the finite element simulation analysis of the surrounding rock-support stability under two different working conditions, we can get the following conclusion:

Introduce the long-term strength of the rock and obtain the mechanical parameters of the surrounding rock considering the time effect. According to the creep coefficient of shotcrete, considering the characteristics of the strength and equivalent elastic modulus of shotcrete with time, the creep coefficient and equivalent elastic modulus of shotcrete at different times are obtained.

Under the condition of only considering the gravity field, the stability of the shallow buried soft rock tunnel is the maximum equivalent plastic strain at the arch and side wall of the tunnel when the excavation is not supported, especially the depth of the plastic zone at the arch shoulder is the largest. When excavation is not supported, it is necessary to pay attention to prevent large deformation.

After the excavation is applied, the plastic zone area of the surrounding rock and the maximum depth of the plastic zone are reduced, while the left and right side walls of the lining have the lowest safety factor. With the increase of time, the plastic zone area and the maximum depth of the plastic zone of the surrounding rock continue to increase, and the stability and safety of the surrounding rock gradually decrease.

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