Analysis on the Construction Timing and Stability of Double-layer’s Initial Supports of Soft Rock Tunnel Based on Convergence-Confinement Method

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Abstract. Many tunnels face large soft rock deformation problems in Southeast China. Double-layer’s initial support could effectively solve the problem of large deformation in soft rock tunnels, which can flexibly control the timing and ensure support stability. Combined with the Yuntunbao Tunnel of Chengdu-Lanzhou Railway, the timing and stability of the double-layer’s initial support in soft rock tunnel were studied based on the convergence-confinement method. The ground reaction curve was calculated under different models, and the longitudinal deformation profile was evaluated using numerical simulation. Empirical equations helped to compute the support characteristic curve. The convergence-confinement curve was drawn to discuss the second layer’s initial support timing according to the results mentioned above. After the verification of field data, the effectiveness of numerical simulation was initially verified. The results show that: 1. The ground reaction curve obtained by the H-B model is closer to the engineering reality than the curve obtained by the M-C model. 2. Compared with the bench method, the complete section method is unfavorable to the support, and the support safety factor is lower. 3. The first layer’s initial support should be implemented immediately after excavation, and the second layer’s initial support should be executed when the first layer reaches 70% of its limit deformation.

Keywords: soft rock tunnel, convergence-confinement method, double-layer’s initial support, stability analysis.
1. Introduction

With the gradual advancement in high-speed railway tunnel construction in Southwest China, an increasing number of tunnels face large soft rock deformation. Unlike general tunnels, soft rock tunnels with high geostress have large deformation, deformation rate, and prolonged deformation time [1]. Based on the practice of many large deformation tunnels such as the Lanzhou-Chongqing Railway and the Xining-Chengdu Railway, the double-layer’s initial support has gradually been used to cope with the large deformation tunnels of soft rock with high geostress. The double-layer’s initial support can flexibly control the initial support construction time and soft rock large deformation [2]. In recent years, many scholars have done a lot of research on double-layer’s initial support [2-4]. The research results generally reported that the double-layer’s initial support effectively controls the large deformation, but the support timing of the second layer’s initial support is somewhat lacking.

The convergence-confinement method is often used in surrounding rock stability analysis. It can describe the mechanism of surrounding rock-support interaction, determine the timing of support construction, and study the surrounding rock-support stability, which can guide practical projects. For surrounding rocks, Carranza-Torres C et al. [5] introduced the practical application of the convergence-confinement method in engineering, and the results obtained using Hoek-Brown (H-B) as the yield criterion of rock masses agree with actual data. Cui L et al. [6] proposed an analysis method based on the finite difference method, H-B, and Mohr-Coulomb (M-C) criterion, which can calculate the ground reaction curve and the longitudinal deformation profile under three models. Results showed that the elastoplastic model design is conservative. For support, Su Y et al. [7] constructed a calculation method for the stability coefficient of the supporting structure based on the H-B failure criterion. Through the analysis and comparison of a tunnel case, the method’s effectiveness was initially verified. Many scholars have applied the H-B and M-C models to the convergence-confinement analysis of tunnels. However, in soft rock tunnels with large deformation, the two models’ applicability has not been investigated. Since the convergence-confinement method is less used in soft rock tunnels at present, considering the Yuntunbao Tunnel, this study investigated the applicability of H-B and M-C models to soft rock tunnel and analyzed the influence of two common excavation methods, full section method, and bench method, on the soft rock deformation. And the convergence-confinement principle was used to optimize the timing and estimate the stability coefficient of the double-layer’s initial support in a soft rock tunnel.

2. Methodology

2.1. Convergence-confinement principle

The convergence-confinement method is a theory and method to explain the interaction process between surrounding rocks and support, which can estimate the load and surrounding rock pressure of the support behind the tunnel face. As shown in Figure 1, the support construction will lag behind the tunnel face by a certain distance with the tunnel excavation advancement. Thus, the tunnel face has a control effect on the surrounding rock deformation within a certain range in the direction of the tunnel axis, which is the spatial effect of the tunnel face.

![Figure 1. The process of tunnel excavation and support construction at three different moments (T0, T1 and T2).](image-url)
At T0, the monitoring section is located in front of the tunnel face. Due to the excavation of the tunnel ahead, the surrounding rock around the monitoring section is disturbed, causing a certain displacement and releasing a part of the stress. At T1, when the tunnel was excavated to the monitoring section, the pressure on the surrounding rock of the section was quickly released, resulting in large deformation. But due to the spatial effect of the tunnel face, the deformation of the surrounding rock could not reach the maximum \( u_m \). At T2, the tunnel face is far away from the monitoring section, such that the spatial effect of the tunnel face is reduced. The surrounding rock and the support jointly bore the pressure of the surrounding rock and reached equilibrium. The displacement stabilizes and reaches the maximum \( u_m \). Figure 1 shows that determining the load and pressure of the surrounding rock requires analyzing the load-deformation characteristics of the surrounding rock and determining the location of the support. Therefore, as shown in Figure 2 and Figure 3, the three basic components required by the convergence-confinement method are: 1. the Longitudinal Deformation Profile (LDP); 2. The ground reaction curve (GRC); and 3. the Supporting Characteristic Curve (SCC). In Figure 2 and Figure 3, \( u_0 \) is the initial displacement of the wall; \( u_{equ} \) is the balance displacement of the rock and support; \( u_m \) is the ultimate displacement of the wall; \( L \) is the lag distance of support construction; \( P_0 \) is the original stress of surrounding rock; \( P_{max} \) is the maximum pressure support can reach; \( P_{equ} \) is the balance pressure of the rock and support.

![Figure 2. The Longitudinal Deformation Profile.](image)

![Figure 3. The Ground Reaction Curve and the Supporting Characteristic Curve.](image)

2.2. Correction of GRC considering bolts

The bolts can help the surrounding rock to attain its self-stability. In the convergence-confinement method, the bolts are regarded as an independent support unit to resist surrounding rock deformation. With further study on the mechanism of bolts, it was gradually discovered that bolts are not passive load-bearing but achieve a common load-bearing effect by improving the physical and mechanical properties of the rock mass. Its mechanism of action includes [8-10]:

- An artificial pressure-bearing arch is formed around the tunnel to strengthen the surrounding rock and reduce the deformation of the surrounding rock.
- Improve the elastic modulus, cohesion, and internal friction angle of the rock mass within the bolt area.
- In large deformation tunnels of soft rocks, energy-absorbing bolts can absorb the deformation energy of surrounding rock.

Figure 4 is the calculation model of the bolt action. \( \sigma_v \) is vertical geostress and \( \sigma_h \) is horizontal geostress. In this study, when computing the GRC of the Yuntunbao Tunnel, equation (1) is used to consider the reinforcement effect of bolts on the surrounding rock [10].

\[
E_b = E + \frac{(E_c - E) \cdot \pi \cdot R^2}{S_t \cdot S_b}
\]  

(1)
Where: \(E_b\) is the elastic modulus of the surrounding rock in the reinforcement area; \(E\) is the elastic modulus of the original rock; \(E_c\) is the elastic modulus of bolts; \(R\) is the radius of the tunnel; \(S_l\) and \(S_b\) are the circumferential and longitudinal spacings, respectively.

The calculation radius \(R\) of the non-circular section can be inferred from equation (2), which has greater adaptability and accuracy for the horseshoe-shaped section [7].

\[
R = \frac{(h + b)}{4}
\]  

(2)

Where: \(h\) and \(b\) are respectively the height and the width of the tunnel.

**Figure 4.** Calculation model of bolt support.

**Figure 5.** Double-layer support curve.

### 2.3. Double-layer support curve

As shown in Figure 5, the deformation of the soft rock tunnel is significant, and there is no clear convergence in the no support. Apply the first layer’s initial support at point A. If the second layer’s initial support is not added, the direction of the support curve may be as shown by the dotted line; that is, support failure occurs. Suppose the second layer’s initial support is applied at point B to increase the support stiffness. In that case, it can be combined with the first layer’s initial support to undergo combined deformation and then balance with the surrounding rock.

### 2.4. Spatial effect of the tunnel face

As shown in Figure 1 and Figure 2, the spatial effect of the tunnel face is impacted the control of the surrounding rock deformation, expressed as the starting point \((u_0)\) of the SCC, and \(u_0\) depends on the lag distance of the support construction. Many researchers have proposed several empirical equations based on measured data, such as the equation (3) fitted by Carranza-Torres C et al. [5], Vlachopoulos N [11], and Chen F et al. [12] used a field data to verify the rationality of the equation. Therefore, this article intends to combine this equation with the measured deformation of the Yuntunbao Tunnel to obtain the initial radial displacement \(u_0\), and to compare and verify the result with the numerical simulation.

\[
\frac{u}{u_m} = \left[1 + e^{-1.1\frac{X}{1+R}}\right]^{1.7}
\]  

(3)

### 2.5. Calculation of support stability coefficient

According to the general definition of the stability factor, the safety factor is the ratio of the structural resistance to the supporting load [6,11], as shown in equation (4). When the second layer is applied for the double-layer’s initial support, it forms a complete network with the first layer. Therefore, its stability coefficient can be obtained from the convergence-confinement curve, as shown in Figure 3, where \(F_s\) is the coefficient of support. In equation (4), \(u\) is the convergence of the wall, and \(X\) is the distance of the unsupported tunnel section from the tunnel face.

\[
F_s = \frac{P_{\text{max}}}{P_{\text{equ}}}
\]  

(4)
3. Case study

3.1. Project overview
Yuntunbao Tunnel is located in Songpan County, Sichuan Province, with a total length of 22,923.436 m. It is a double-track combined tunnel with a maximum buried depth of about 780 m and a minimum of about 12 m. The tunnel crossing area is dominated by grade IV and grade V surrounding rocks, with a small part of grade III surrounding rocks. The tunnel has undergone large deformations in many places since its construction. The observation section selected in this study is D5K232+140 ~ D5K232+200, with a buried depth of about 435 m. This section is a grade V surrounding rock with a rock strength of 5 ~ 15 MPa. The lithology is mainly composed of slate intercalated with sandstone and phyllite. The surrounding rock is broken, and rocky particles with joints and fissures developed. The section’s shape is horseshoe-like, with an excavation section dimension of is 11.4 m high and 13.2 m wide. The bench method is adopted for excavation. According to equation (2), the equivalent circle radius $R=6.15$ m. Shotcrete and steel sets are used as the main load-bearing structure, and steel mesh is added to prevent block loss.

3.2. Calculation of ground characteristic curve
After the tunnel excavation, the original rock stress field is redistributed, and the influence range of the secondary stress is generally within 3 to 5 times the radius of the tunnel. To obtain better simulation results, the model size is taken as five times the radius of the tunnel. This paper uses the plane strain model to calculate the GRC. The width and height are 30 m and 60 m. The boundary conditions are fixed at the bottom, symmetrical on the left, and normal for the right and upper. Thus, tunnel excavation is three-dimensional,

$$F_j = \left(1 - \sum_{j}^{n} k_j \right) P_0$$

(5)

Where: $F_j$ is the support load applied in step $j$; $P_0$ is the original rock stress; $n$ is the total calculation step; $k_j$ is the load released in step $j$.

The finite element software COMSOL is used to calculate GRC according to the model in Figure 4. Combined with the surrounding rock conditions of the Yuntunbao Tunnel and the figures given by Hoek [13], Carranza-Torres C [14], and Zhong Y et al. [2], the surrounding rock parameters used in the simulation calculation can be determined as shown in Table 1 and 2. The GRC obtained by the H-B model and M-C model is shown in Figure 6.

| Table 1. Physical and mechanical parameters of surrounding rock. |
|---------------------------------------------------------------|
| parameter name       | Elastic modulus (GPa) | Poisson’s ratio | Density (kN/m$^3$) | Internal friction angle(deg) | Cohesion (MPa) |
| Parameter value      | 1.6                  | 0.3            | 2400              | 30                          | 0.2            |

| Table 2. H-B constants of surrounding rock. |
|---------------------------------------------|
| parameter name               | Intact rock H-B constant mi | Geological strength index GSI | Disturbance factor D | UCS $\sigma_c$(MPa) | Integrity s |
| Parameter value               | 10                       | 40                          | 0.2                 | 15                    | 0.5         |
3.3. Calculation of support characteristic curve

It is assumed that the two layers of the initial support parameters are the same. The thickness of the shotcrete is 27 cm, and the steel arch is HW200 full ring. According to reference [15], the SCC of the double-layer’s initial support of the Yuntunbao Tunnel can be computed. In this table, \( u_{in,j} \) is the displacement of the wall when support is constructed; \( u_{el,j} \) is the elastic displacement of support; \( u_{max,j} \) is the ultimate displacement support can reach.

| Support type   | \( K \) (MPa/m) | \( P_{max} \) (MPa) | \( u_{el,j} - u_{in,j} \) (mm) | \( u_{max,j} - u_{el,j} \) (mm) |
|---------------|-----------------|---------------------|--------------------------------|---------------------------------|
| shotcrete     | 177.47          | 0.64                | 3.59                           | 55.4                            |
| steel sets    | 59.60           | 0.41                | 6.90                           | 151                             |

3.4. Determination of initial radial displacement

The field data shows the displacement time history curve of the dome displacement of the monitoring section D5K232+140 in Figure 7. Using MatDEM discrete element software to execute three-dimensional numerical simulations of tunnel excavation, the stratum model has length, width, and height of 60, 60, 60 m, particle radius of 0.15~0.72 m, and a total of 137 309 particles. The numerical simulation results are shown in Figure 8.

Figure 7 shows that the deformation of the Yuntunbao Tunnel lasted for a long time and gradually stabilized after three months. The surrounding rock has a large amount of deformation, and the maximum displacement of the monitored section reached 486.0 mm, which are typically large deformation characteristics of soft rock tunnels. Since the first layer of initial support was applied immediately after excavation, \( \chi = 0 \) in equation (3), the displacement release rate is 0.31, and the initial radial displacement \( u_0 = 150.7 \) mm. The initial displacement value obtained by numerical simulation is about 133 mm, close to the displacement value of 150.7 mm obtained by equation (3), and the error is 11.7%.
Figure 7. The Displacement time history curve.

Figure 8. The Longitudinal Deformation Profile.

4. Result analysis and discussion

Figure 9 shows the convergence-confined curve of the Yuntunbao Tunnel for the M-C model and H-B model. Figure 10 shows the convergence-confined curve of the Yuntunbao Tunnel for different excavation methods.

Figure 9. Convergence-confined curve for different methods.

Figure 10. Convergence-confined curve for different excavation methods.

In the SCC of Figure 9 and 10, ABCD is the first layer of initial support, AB is the elastic deformation of shotcrete and steel sets. At point B, the shotcrete enters the plastic state, and at point C, the steel sets enter the plastic state. The second layer of initial support is applied at point D, the shotcrete enters the plastic state at point E, the second layer of steel sets enters the plastic state at point F, and the maximum deformation is reached at point G.

4.1. Suitability of models

The GRC obtained by the two models can reach a deformation of hundreds of millimeters for soft rock tunnels, which is in line with the typical large deformation characteristics of soft rock tunnels. As shown in Figure 9, when the same load is released, the deformation of the M-C model is greater than that of the H-B model. Combined with the double-layer’s initial support curve, the second layer’s initial support enters a plastic state when the SCC and the GRC of M-C models intersect. The support structure has no safety surplus, and the surrounding rock pressure is relatively high. The M-C model only considers the stress-strain relationship and yield conditions of the rock mass, and does not describe the nature of the rock mass itself, which does not meet the actual situation in soft rock tunnel. Compared with the M-C model, the H-B model employs the geological strength index system of the rock mass. Therefore, it can holistically describe the original rock state and mechanical properties of the rock mass. The H-B model...
is used to describe the characteristics of the surrounding rock in this study, which is closely in line with the actual data of the Yuntunbao Tunnel.

4.2. Influence of excavation method on support stability
In Yuntunbao Tunnel, the bench method was used in most sections, and the full section method was used in a few sections with better surrounding rock conditions. As shown in Figure 10, compared with the bench method, the surrounding rock deformation and support increase when the full section method is adopted, and the support is less safe. The balancing force on the support can reach 2.1 MPa when using the full section method, but the maximum pressure can only reach 1.5 MPa, according to field data records. Therefore, if the full section method is used in poor surrounding rock conditions, the stability of the support will be significantly reduced, with likely damage to the support as the result of large surrounding rock pressure.

4.3. Optimization of support timing and stability analysis
According to the convergence-confined curve and equation (4), Table 5 gives the corresponding balance force and support safety coefficient for the second layer at different support opportunities and \( u_{lim} \) is the ultimate deformation of the first layer. From Table 5, for support, the timing of the second layer determines the balancing force and deformation of the support. The earlier the second layer is constructed, the greater the corresponding support bearing capacity, the smaller the deformation of the support, and the smaller the safety coefficient of the support. When the second layer’s construction is delayed, the greater the tunnel convergence. When the tunnel convergence exceeds the limit deformation of the first layer, the first layer will be destroyed. Therefore, the timing of the second layer should not be too early or too late.

| Table 4. Balance force and safety coefficient of support at different support opportunities. |
|---------------------------------------------------------------|
| support position | \( 0.3u_{lim} \) | \( 0.5u_{lim} \) | \( 0.7u_{lim} \) | \( 0.9u_{lim} \) |
| \( P_{equ} \) (MPa) | 1.72 | 1.63 | 1.55 | 1.47 |
| \( F_s \) | 1.22 | 1.29 | 1.35 | 1.43 |

For rock slopes, the stability factor specified in the code is not less than 1.3. To ensure the safety of the first layer’s initial support, it is not recommended to implement the second layer’s initial support at \( 0.9u_{lim} \) when the first layer’s initial support is about to be destroyed. When the second layer’s initial support is implemented at \( 0.5u_{lim} \) or less, the surrounding rock pressure is relatively high, and the support safety factor is relatively small and less than 1.3. Therefore, the second layer’s initial support should be implemented at about 70% of the ultimate deformation of the first layer’s initial support. As a result, the stability factor of the supporting structure reaches 1.35, and the initial support is relatively safe, but it should be strengthened at the weak position. According to field data records, the maximum contact pressure between the support and the surrounding rock can reach about 1.5 MPa, which is close to the result of the convergence-confined curve, and the support stability coefficient obtained by the convergence-confined method is safer.

5. Conclusion
In this study, the convergence-confined method is used to evaluate the stability of the double-layer’s initial support of the Yuntunbao Tunnel, and the following conclusions can be made:

- The ground reaction curve obtained by the H-B model is closer to the engineering reality than the curve obtained by the M-C model.
- Compared with the bench method, the full section method is more unfavorable to the support, and the support safety factor is lower. The stability evaluation of the support can provide a certain reference for the actual project.
- The double-layer’s initial support in soft rock tunnels can effectively solve the problem of large
deformation. The first layer’s initial support should be implemented immediately after excavation, closed into a ring to improve the force state. The second layer’s initial support location is preferably at about 70% of the ultimate deformation of the first layer’s initial support.

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