Numerical Simulation of New Support Structure for High In-situ Stress Tunnel of Sichuan–Tibet Railway

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Abstract. Existing support technology can easily cause the shield machine to jam. A novel ductile support structure is proposed for large deformation tunnels in soft rock along the whole Sichuan–Tibet railway on the basis of the concept of consuming energy of ductile multilevel yielding support. The design of the support structure is to ensure the safety of the shield machine through the large deformation section of soft rock as quickly as possible. In-situ stress data obtained by hydraulic fracturing measurement method were used as boundary conditions of models. The support structure deformation of front shield tunnelling machine and long-term deformation of corrugated steel primary support, steel waist beam and reinforced concrete secondary lining support system were simulated and analysed on FLAC3D software. The variation of the new support structure under the large deformation of soft rock was predicted. Results show that the force path of ductile multilevel yielding support structure is clear. After the excavation of the tunnel and before the application of the concrete lining support, displacement increment of the primary support structure is large. The latter gradually slows down with time, but it still shows an increasing trend. In terms of total displacement distribution, the displacement in the Z direction is obviously larger than that in the X direction, which is consistent with the actual tunnel deformation characteristics. When the tunnel is in operation for 2, 10, 50 and 100 years, stress concentration is found in the arch foot of the assembled supporting system. This condition is mainly manifested as compressive stress after 10 years and tensile stress between 10 and 100 years.

1. Introduction
In the Sichuan–Tibet Railway, which is being planned and built, bridges and tunnels account for more than 80% of the total length of the railway. The total length of the tunnels, including Duomug, Yigong and Sejilashan tunnels and many other long and deep buried tunnels, is approximately 1200 km [1]. When the tunnel passes through the soft rock, the deformation and failure, such as section shrinkage and lining cracking, occur. The deformation of soft rock has the characteristics of large value and fast deformation speed, which is unconducive to the long-term operation of the tunnel. At present, many scholars have conducted many studies on soft rock large deformation in the aspects of deformation mechanical mechanism, support parameters and timing and construction method, which plays a certain guiding role in construction [2].
Taking a tunnel of Sichuan–Tibet railway as an engineering case, the large deformation disaster exists in several sections of the tunnel, posing a serious threat to the construction personnel and equipment [3-4]. In the section of severe deformation, the shield tunnelling machine is extremely easy to cause jamming, thereby seriously delaying the construction progress [5]. The initial support structure of
Sichuan–Tibet line tunnel using traditional anchor shotcrete in the design, construction and other aspects of the drawbacks and problems is considered. A novel concept of tunnel support is proposed. A prefabricated ductile multistage support theory system is established to solve the fast-sealing problem of loose rock with high in-situ stress for ensuring the smooth progress of long-distance tunnel shield construction.

2. Project Summary

2.1. Engineering background
A tunnel of the planned Sichuan–Tibet Railway is located in Kangding City and_Yajiang County, Ganzi Prefecture, Sichuan Province, with a total length of 18,837 m and a maximum burial depth of approximately 1,100 m. The tunnel mainly passes through slates intercalated with sandstone, partially intercalated with carbonaceous sericite and carbonaceous sericite. The surrounding rock is soft. At the buried depth of 805 m, the measured maximum horizontal stress is 44.3 MPa, and the lateral pressure coefficient is as high as 2.1. This tunnel has prominent large deformation problems in the whole line (the highest in-situ stress level for large deformation treatment is 30 MPa at present). The large deformation is predicted to be as long as 9,300 m, accounting for 49%.

2.2. Measurement of in-situ stress
The depth of test section in the stress parameter measurement by hydraulic fracturing refers to the depth from the surface to the centre point of the fracture section. The average length of fracture sections in the test is 0.6 m. In accordance with the fracturing curves of each test section, reasonable fracturing characteristic parameters are selected. In accordance with the corresponding theoretical calculation formula, the principal stress value of the stratum at the simulated position of the tunnel section (805-805.7 m) is as follows.

\[ \sigma_H = 37.28 \text{MPa}; \quad \sigma_h = 22.56 \text{MPa}; \quad \sigma_v = 20.93 \text{MPa} \]

3. Numerical simulation of excavation and support of tunnel

3.1. Establishment of models
Considering the unfavourable situation of the tunnel in the large deformation section, the tunnel with buried depth of 448.56 m was selected as the typical calculation section. The tunnel is 10.54 m in width, 11.54 m in height and 500 m in length. The lithology is mainly sand slate. The tunnel is located in bedding section with high in-situ stress and weak rock mass, and the side wall is easy to produce large deformation after tunnel excavation.

In the outer horse mode of shield tunnelling machine (Figure 1), the prefabricated corrugated segment and polymer filling system is incorporated into the primary support scheme, which has the advantages of high construction efficiency and low cost. The scheme of filling bag and polymer filling material can effectively improve the compactness between the primary support and surrounding rock, and can absorb part of the deformation of surrounding rock. Moderate and severe deformation sections use the outer horse mode. The supporting structure consists of three parts, namely, flexible support structure in front of the shield tunnelling machine, 30 cm-thick C100 precast reinforced concrete segment or corrugated plate, and 30 cm-thick C35 concrete lining (Figure 2).

The rheological characteristics of surrounding rock in the planned tunnel are consistent with the Burgers model. Assuming that the volume variation of rock is elastic and that the rheological properties are mainly caused by deviation stress. The rheological equation of Burgers model under three-dimensional stress states is as follows.

\[ \varepsilon(t) = \frac{\sigma_0}{E_1} + \frac{\sigma_0}{\eta_1} + \frac{\sigma_0}{E_2} \left( 1 - e^{-\frac{t}{\eta_2}} \right), \quad (1) \]

Where \( \sigma_0 \) is a constant stress; \( t \) is the loading time; \( E_1, E_2, \eta_1, \eta_2 \) are Burgers model parameters.
Equivalence of supporting structure. The corrugated plate is equivalent to thin plate to facilitate the simulation and calculation, representing the equivalent bending stiffness and compression stiffness.

\[
E_1 I_1 = E_2 I_2, \quad (2)
\]
\[
E_1 A_1 = E_2 A_2, \quad (3)
\]

where \(E_1, I_1\) and \(A_1\) are the elasticity modulus, inertia moment and the section area of the corrugated plate, respectively; \(E_2, I_2\) and \(A_2\) are the elasticity modulus, inertia moment and the section area of the thin plate, respectively.

![Shield tunneling machine](image1)

**Figure 1.** Special-shaped shield tunnelling machine.

![Multistage support system](image2)

**Figure 2.** Multistage support system.

The inertia moment and area of corrugated plate are determined on the basis of the standard. The corrugated plate is equivalent converted to the thin plate section by using Formulas 1 and 2, and the equivalent elastic modulus and thickness of the thin plate are obtained. The steel waist beam is made of 200 mm × 200 mm × 10 mm square steel pipe. The radius of rotation \(r\), weight per meter \(k\), yield strength \(f_y\) and compression bearing capacity \(F\) are determined.

In the formation structure method model, the stiffness of the square steel pipe is converted into the stiffness of the primary support structure in accordance with the equivalent stiffness. In accordance with the equivalent principle of compressive stiffness, the following formula is used for calculation.

\[
E = E_0 + \frac{S_0 f_y}{S_C}, \quad (4)
\]

where \(E\) is the elastic modulus of primary support after conversion; \(E_0\) is the elastic modulus of the corrugated plate; \(S_0\) is the cross sectional area of the steel pipe on the supporting structure; \(E_C\) is the elastic modulus of the steel tube of the supporting structure; \(S_C\) is the cross sectional area of corrugated sheet with unit length, and the elastic modulus of square steel tube is converted to the corrugated sheet supporting structure.

**Boundary Conditions and Calculation Parameters.** The surrounding rock pressure of the supporting structure in the deep buried tunnel is calculated, and the section is selected to check the primary supporting capacity of corrugated steel. The ground stress in the vertical direction is \(\sigma_v\), and the load in the horizontal direction is 0.4 \(\sigma_v\) in V-level surrounding rock. Considering that the corrugated steel primary support structure is located in the V-level surrounding rock, the primary support assumes 80% of the total surrounding rock pressure, and the arch, wall and side wall loads are calculated.

In accordance with the engineering geological conditions, the physical and mechanical parameters of surrounding rock and supporting structure are shown in Tables 1–3.

**Table 1.** Physical and mechanical parameters of surrounding rock and supporting structure.

| Materials | Weight | Elasticity | Poisson’s | Cohesion | Internal |
|-----------|--------|------------|-----------|----------|----------|
|           |        |            |           |          |          |

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Table 2. Parameters of anchor.

| Materials                         | Equivalent modulus of elasticity (GPa) | Length (m) | Compressive yield (kN) | Elastic modulus of cement slurry (GPa) | Adhesive strength of cement slurry (MPa) |
|-----------------------------------|----------------------------------------|------------|------------------------|--------------------------------------|----------------------------------------|
| V-level rock                      | 26.5                                   |            |                        |                                      |                                        |
| Q345 Corrugated plate             | 78.5                                   |            |                        |                                      |                                        |
| Steel waist beam                  | 78.5                                   |            |                        |                                      |                                        |
| C100 precast segment              | 25                                     | 50         | 0.22                   |                                      |                                        |
| C35 concrete lining               | 25                                     | 25.2       | 0.3                    |                                      |                                        |
| Feet-lock bolt                    | 23                                     | 210        | 0.3                    |                                      |                                        |

Table 3. Rheological parameters of surrounding rock.

| $E_1$(GPa) | $E_2$(GPa) | $\eta_1$(GPa·d) | $\eta_2$(MPa·d) |
|------------|------------|-----------------|-----------------|
| 6.5        | 118.1      | 340.5           | 67.8            |

3.2. Analysis of numerical simulation results

The span and height of the tunnel are 10.54 m and 11.54 m respectively. In order to eliminate the influence of the boundary effect of the model on the calculation results, the model size is 130 m × 130 m × 10 m, the linear pressure load of 19.34 MPa is overlaid, the horizontal pressure load of 8.37 MPa is loaded, and the vertical constraint is applied at the bottom of the model. The load structure model is adopted, and FLAC3D software is used to calculate and analyse it. The primary support adopts 380 mm × 140 mm × 5 mm corrugated steel plate. A steel waist beam with 200 mm × 200 mm × 10 mm square steel tube with the whole ring is set, and the longitudinal spacing of the steel frame is 1 m. The anchor rod is mortar bolt with diameter of 25 mm, longitudinal spacing of 1.0 m, and ring spacing of 1.0 m. The length of the bolt is 3.0 m, and it is arranged in the form of a plum blossom. Locking anchor rod is arranged at the side wall of the supporting structure. Solid element is adopted in the model surrounding rock. Cable element is adopted for anchor rod. Shell element is used for corrugated plate, steel waist beam and reinforced concrete secondary lining. A grid of radial hexahedral elements is adopted from the opening of the tunnel to the surrounding stratum. TBM tunnel adopts full-section excavation. Each excavation length is 1.5m, and the excavated part adopts empty model to represent the material to be removed or excavated.

**Deformation Prediction of the Front Support Structure of Shield Tunnelling Machine.** The displacement curves of the corrugated steel structure in front of the shield tunnelling machine within 24 h are shown in Figure 3. The displacement of the lining increases continuously as the supporting time continues under the rheology of surrounding rock.

The vault subsidence after 12 h reaches 2.74 cm. The displacement of the arch foot reaches 3.72 cm. The displacement of the sidewall reaches 3.25 cm. After 24 h, the vault subsides to 3.5 cm. The displacement of the arch foot reaches 5.03 cm. The displacement of the sidewall reaches 3.95 cm. The tensile strength of surrounding rock is usually relatively low, and it is easy to fail under the action of tensile stress, especially at the vault position. Because of tunnels during the excavation destroyed the
relative balance of the original rock mass, fabricated corrugated steel structure can timely support. The closed surface and a certain depth of crack rock mass and effectively prevent the individual the loss of the rock. The surface layer and the deep rock mass as a body, prevent the arch of cascading failure of rock mass, the tunnel surrounding rock deformation in a short time increase amplitude is small, Ensure that the shield machine as fast as possible through the soft rock area.

**Figure 3.** Displacement cloud graphs of supporting structure in different deformation times. (a) 4 hours after support; (b) 8 hours after support; (c) 12 hours after support; (d) 16 hours after support; (e) 20 hours after support; and (f) 24 hours after support.

**Deformation Prediction of Corrugated Steel, Steel Waist Beam and Reinforced Concrete.** After 2, 10, 50 and 100 years of tunnel operation, the displacement curves of the corrugated plate and steel waist beam in the Z and X directions are shown in Figure 4. The displacement curves of the reinforced concrete structure in the Z and X directions are shown in Figure 5. The displacement of the assembled structure has different changes in different periods due to the rheology of surrounding rock for a long time under high in-situ stress. After running for 2, 10, 50 and 100 years, the maximum displacement of the arch of the prefabricated structure system is 4.82, 8.08, 11.56 and 13.6 cm, respectively. The maximum horizontal displacement of the arch foot is 5.69, 3.95, 11.63 and 18.4 cm. At the beginning, the primary function of the secondary lining is to set it as the safety reserve of the structure. The initial displacement of the structure is small, but the creep of surrounding rock gradually increases the stress of the secondary lining. If the bearing capacity is exceeded, the structure becomes unstable or destroyed. The maximum vertical displacement of the arch of the concrete lining structure is 4.83 cm, and the maximum horizontal displacement of the arch foot is 5.84 mm. After running for
10, 50 and 100 years, the maximum vertical displacement of the arch is 7.71, 11.6, and 13.65 cm, respectively. The maximum horizontal displacement of the arch foot is 2.80, 11.64 and 18.44 cm. The deformation of secondary lining is smaller than that of segment structure due to the strong resistance of corrugated steel support system to the creep deformation of surrounding rock.

Figure 4. Displacement cloud graphs of corrugated plate and steel waist beam supporting structure. (a) displacement in the Z direction after 2 years; (b) displacement in the X direction after 2 years; (c) displacement in the Z direction after 10 years; (d) displacement in the X direction after 10 years; (e) displacement in the Z direction after 50 years; f) displacement in the X direction after 50 years; (g) displacement in the Z direction after 100 years; and (h) displacement in the X direction after 100 years.
Figure 5. Displacement cloud graphs of reinforced concrete structure. (a) displacement in the Z direction after 2 years; (b) displacement in the X direction after 2 years; (c) displacement in the Z direction after 10 years; (d) displacement in the X direction after 10 years; (e) displacement in the Z direction after 50 years; (f) displacement in the X direction after 50 years; (g) displacement in the Z direction after 100 years; and (h) displacement in the X direction after 100 years.

The displacement of the supporting structure after the calculation includes two aspects: one is the displacement generated by the supporting structure during the excavation of the surrounding rock of the tunnel in the early stage; the other is the displacement generated by the rheology of the structure in the whole process. Under the long-term action, the stress redistribution of the surrounding rock lining due to rheological properties makes the deformation of the supporting structure increase continuously,
and the secondary lining bears more and more stresses, while the deformation also increases continuously, and finally gradually tends to be stable.

4. Conclusion
The variation of the large deformation supporting structure of rock mass during shield construction of a tunnel on Sichuan–Tibet Railway is analysed and discussed through numerical calculation. The key findings are as follows:

1. In the middle and severe large deformation section of the tunnel, the primary support of corrugated steel in front of the shield tunnelling machine can timely support the surrounding rock with large deformation. The calculation and analysis show that the deformation rate of surrounding rock is greatly reduced, reducing the risk of the shield tunnelling machine being stuck frequently in bad geological conditions to a certain extent.

2. Combined with the geological data, the mechanical characteristics of the supporting system of corrugated steel, steel waist beam and concrete lining are analysed. The displacement of the supporting structure decreases obviously under the rheology of surrounding rock after the steel waist beam replaces the concrete segment. The high polymer material filled in time behind the corrugated steel and steel waist girder support system can play a buffer and energy absorption role. This process forms the coupling resistance support system, which has a better adaptability to the large deformation of surrounding rock under the rheology.

3. In the middle and serious large deformation section, the corrugated steel and steel waist girder support system is adopted. In case of large deformation before the secondary lining is applied, the stiffness of the structure can be improved by timely compounding the distance between waist girder support and longitudinal support. This process can avoid the problem of difficult repair of segment shearing dislocation.

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