Reinforcement Analysis of Bifurcated Highway Tunnels with Large Section of Different Surrounding Rock Grades in Tiger Leaping Gorge

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Abstract. In order to analyse the reinforcement effect of tunnels with different surrounding rock grades in Tiger Leaping Gorge, a three-dimensional tunnel model was established. The effects of surrounding rock parameters and bolt supporting on the displacement and tension strain disturbance zone of surrounding rock were explored. The numerical results of tension strain and displacement show that the improvement of surrounding rock stability is limited by reinforcement measures, and the change of tension strain disturbance zone is also small when the rock is intact. However, when the surrounding rock is relatively fragmented, the range of tension-strain disturbance zone and displacement of the cave are very large. After strengthening, the range of tension-strain disturbance zone is reduced by 61.5%. Comparing the displacement of vault and arch waist, it can be seen that the displacement of cave in grade V surrounding rock is larger, the vertical displacement of vault is 3.5 times higher than that of grade IV surrounding rock, and the horizontal displacement of large section in arch waist is 58.63 mm, and it has great influence on the stability of tunnel. The displacement value of vault and arch waist reinforced in grade V rock is similar to that of tunnel without reinforcement in grade IV rock.

1. Introduction
The geological condition of Xiangli expressway in Yunnan Province, China is very complex. There are fault fractured zones and the terrain is relatively steep, and it is the first high-speed underground interchange tunnel in mountainous area in China. The safety of construction has received special attention. The design and support of various sections which include large section, multi-arch tunnel and small spacing tunnel are key factors for tunnel stability. To ensure the project construction succeed, comprehensive analysis is needed.

As the surrounding rock in mountainous areas are various, the classes of surrounding rock in tunnels are closely related to the stress distribution of tunnels. The classes of surrounding rock have a decisive influence on the construction methods and supporting measures of tunnels. At the same time, they are also one of the most important conditions causing tunnel deformation. The stress field in surrounding rock will redistribute after tunnel excavation, so the tunnel excavation method has an important influence on the stress state of surrounding rock, which shows the change of displacement field of surrounding rock from macroscopic point of view. In addition, the deformation of rock mass caused by...
construction has time and space effect, and it was mainly reflected in two aspects: one was time effect of surrounding rock stress released when excavation went forward; the other was the inherent rheological properties of surrounding rock, secondary lining structure and other media [1].

Some researchers use indoor model test method, numerical simulation calculation method, site engineering monitoring and other means to study tunnel excavation support and surrounding rock deformation control. Galli [2] carried out finite element numerical simulation of three-dimensional tunnel construction process, and analysed the interaction of surrounding rock and lining in the construction and excavation process. Through self-developed finite element numerical program, Li [3] analysed the elastic modulus of rock mass, initial stress state and radial displacement of surrounding rock by convergence restraint method; and compared the curves of convergence displacement and longitudinal section displacement of tunnel excavation with that had support structure. The whole process of stress release of surrounding rock can be basically divided into three stages: stress release, stress adjustment and stress stabilization [4]. Guan [5] summarized the control measures of face reinforcement, advance support and foot support of surrounding rock after tunnel construction at home and abroad, according to the stress and deformation characteristics of broken surrounding rock.

In summary, the current researchers usually analysed the stress release and displacement changes in surrounding rock to judge the safety state of surrounding rock. However, there is less research to study the stability of surrounding rock through the change of tension-strain zone. Because the compressive strength of rock is enough, rock generally shows tension, shear or tension-shear failure when external forces lead to rock mass failure. Ding [6] found that the maximum tensile strain criterion can be used to determine the damage area of surrounding rock in tunnel engineering. Therefore, the allowable tension strain of rock around the cave can be obtained by numerical calculation, then we can get the disturbance range of rock mass. The critical tensile strain values for different types of rocks, as shown in Table 1.

| Rock type                        | Critical tensile strain value /‰ |
|----------------------------------|----------------------------------|
| Granite                          | 0.25                             |
| Basalt, Diabase, Gabbro, Dolerite| 0.30                             |
| Quartz conglomerate              | 0.16                             |
| Quartzite, quartz sandstone      | 0.20                             |

In this paper, the disturbance zone of tunnel surrounding rock is determined by taking into account the displacement variation of surrounding rock and the allowable tensile strain value, and the stability analysis of tunnel cave and support is carried out based on the criterion.

2. Model building
Abaqus, developed by Dassault SIMULIA, USA, is one of the most advanced large-scale finite element simulation software in the world. It has strong analytical ability, reliable calculation results and a large number of optional material model libraries. It can better simulate the mechanical response of geotechnical materials. Based on the advantages of ABAQUS software, the finite element analysis software ABAQUS is adopted in this study, and the constitutive model of geotechnical materials is Mohr-Coulomb elastoplastic model.

Tensile strain can be used to determine the stability of surrounding rock. Stacey [7] had studied the range of tensile strain of different rocks. However, it is difficult to determine the maximum tensile strain of surrounding rock, which needs further study. At present, according to tension strain calculation method, the ratio of uniaxial tensile strength to elastic modulus and safety factor of rock is defined as the allowable tensile strain value of rock.

| Surrounding rock grade | Elastic modulus E/GPa | Cohesion C/MPa | Internal friction angle $\phi$° | Unit weight $\gamma$/kN/m$^3$ |
|------------------------|-----------------------|----------------|---------------------------------|-------------------------------|
Through field data and research results of relevant scholars, the rock of this project is middle weathered limestone and its’ tensile strength is 1.2 MPa. The safety factor K is 2. The allowable tensile strain value is 0.15%, and the ultimate tensile strain value is 0.3‰. The model area is 200 m high, 200 m wide and 140 m long. In the model, the span of large-section tunnel is 27.46 m and the length is 40 m. For convenience of calculation, the multi-arch and small-spacing part of the tunnel are simplified.

| Grade IV surrounding rock | 4 | 0.5 | 38 | 25 |
|---------------------------|---|-----|----|----|
| Grade V surrounding rock  | 1.3 | 0.15 | 27 | 20 |

3. Results

3.1. Grade IV surrounding rock

It can be seen from the results of stress and strain that the tensile and compressive stresses of surrounding rock do not exceed the limit, so the stability of surrounding rock is mainly controlled by the tensile strain at this time. The calculation of two typical sections of the three-dimensional numerical model are taken from the tensile strain results for analysis. According to current research, the area where the maximum tensile strain exceeds the allowable tensile strain by 0.15 ‰ is determined as the disturbed zone. For convenience, TLG is used to replace Tiger Leaping Gorge.

In Figure 2, when the distance between tunnels is more than 12m, the disturbed area in the middle part of the rock will disappear. The Maximum tensile is 6.13×10⁻⁴, when the distance is less than 6m. It can be seen from Figure 3 that in the large-section tunnel, the distribution rule of allowable tensile strain is similar to that in the multi arch tunnel. There is allowable tensile strain zone at the vault and the arch bottom of the tunnel, but the disturbance zones at the arch shoulder and the arch foot of the tunnel have a large extension range and a trend of continuous expansion, which are the unstable area of the large-section surrounding rock.
In order to consider the influence of grouting, construction steps and lining, the calculation model of lining reinforcement is established. The stress of lining is analysed, and the results are compared with that of unlined tunnel.

The tensile strain of the surrounding rock with bolt and lining supporting is quite different from that in the case of unlined tunnel. The tensile strain in the middle of the rock is smaller than the allowable value when the distance between the tunnels exceeds 10.8m. In Figure 4, when the distance is 10m, the area of the middle part of the rock that is lower than the allowable tensile strain increases, and the tensile strain in the middle part of the rock is close to the allowable tensile strain. The disturbed zones reduce much in Figure 5.

### 3.2. Grade IV surrounding rock

The analysis and establishment process of the model are the same as that of grade IV surrounding rock. The Mohr Coulomb strength of the geotechnical material is changed to grade V surrounding rock, and the simulation analysis is carried out. The tensile strain results are as follows: It can be seen that there is a disturbed area in the vault, the arch waist and the middle rock of the tunnel. Different from the IV surrounding rock, the tensile strain at the middle of the middle part begins to be smaller than the allowable value when the distance between the two bifurcated tunnels exceeds 30m. In Figure 6, the disturbance zones at the arch shoulder and the arch foot of the tunnel are much larger than those in Figure 2. In Figure 7, There are connected disturbed areas in the arch crown. The value of tensile strain area is large at the arch waist. It is dangerous for large-section surrounding rock.
Figure 6. Allowable tensile strain boundary at clear distance of 10m of unlined tunnel. (TLG grade V rock)

Figure 7. Allowable tensile strain boundary at large section of unlined tunnel. (TLG grade V rock)

The model simulation is similar with that in IV rock, the results of lined tunnel are as follows:

Figure 8. Allowable tensile strain boundary at clear distance of 10m of lined tunnel. (TLG grade V rock)

Figure 9. Allowable tensile strain boundary at large section of lined tunnel. (TLG grade V rock)

In Figure 8, with bolt and lining structure, the tensile strain at the middle of the rock is smaller than the allowable value of the tensile strain when the distance between the two bifurcated tunnels exceeds 15.65m. However, the distance is 30m without bolt and lining. In Figure 9, the breakthrough phenomenon of disturbed area in the vault disappears, and the scope of disturbed area is greatly reduced. When the grade of surrounding rock is poor, bolting and lining support can effectively change the stress state of surrounding rock, and make the surrounding rock from a broken state to a complete state.

3.3. Displacement analysis of grade IV&V surrounding rock in TLG

In order to study the settlement of the vault at different sections, the vertical displacement of the vault and the horizontal displacement of the arch waist of the IV&V grade surrounding rocks are analysed.

From the displacement in Figure 10, it can be seen that bolting and secondary lining support play an important role in grade V rock, and the overall reduction of vault subsidence of surrounding rock is very obvious with the reduction 58.45%, and the overall reduction of vault subsidence is 30.23% in grade IV rock. In grade IV rock, with the increase of the longitudinal distance, the value of the vault settlement firstly reduces, then keeps basically the same after 40m, but the vault settlement of the multi arch tunnel section slightly rises to about 29.13mm. In grade V rock, the vertical displacement is similar.

In Figure 11, the horizontal displacement of the arch waist from the large-section tunnel to the bifurcated tunnel all keeps 3 mm. Compared with that without lining, the horizontal displacement of the arch waist reduces by 66.67%, in grade IV rock. And, in grade V rock, the horizontal displacement of the arch waist from the large-section tunnel to the bifurcated tunnel all keep at 8 mm. Compared with that without lining, the horizontal displacement of the arch waist reduces by 80%. However, the horizontal displacement of the arch waist in both grade IV& V rock changes a little.
4. Conclusions

1) The vertical displacement is controlled by different excavation sections in grade IV rock. The vault subsidence of the separated tunnel is 80% of that of the large section tunnel, but the horizontal displacement is less affected by the excavation section. However, in grade V rock, the vertical displacement and horizontal displacement are controlled by the form of tunnel excavation section.

2) When support measures are taken for both grade IV&V surrounding rock, the vertical displacements of the both tunnels are related to the form of the sections. The vertical displacement of the separated tunnel is lower than that of the large section area, while the horizontal displacement is smaller at different tunnel sections, which is not controlled by the form of the sections.

3) The displacement exceeding the allowable value in the surrounding rock are greatly reduced in grade V rock with bolting and lining support. The vertical displacement of the vault and the horizontal displacement value of the arch waist are similar to those without bolting and lining in grade IV rock.

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