Numerical Ultimate Load Analysis Based Study on Safety Monitoring Reference Value for Tunnels in Weak Rock

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Abstract. It is usually hard to ensure overall stability and construction safety when tunneling in weak rock. Therefore, it is of practical engineering significance to conduct safety monitoring reference value study based on numerical ultimate load analysis by building an equivalent rock model. In this paper we investigate ultimate strains of equivalent rock masses of different classes based on numerical ultimate load analysis by building an equivalent surrounding rock model; examined the deformation reduction factor changes for different classes of surrounding rock by building a plane model for calculation and analysis; established tunnel stability assessment criteria through observation of ultimate shear strain diagrams under different reduction factors; and determined appropriate management measures according to warning levels. Our analyses show (1) under different loads the higher the rock mass classification the smaller its vertical displacement and hence its ultimate strain; (2) the higher the rock mass classification the more susceptible it is to strength, creep and instabilities; (3) Assessment criteria are established by comparing displacement $U$ measured during tunneling with the ultimate displacement $U_0$, i.e. the tunnel is stable if $U < U_0$ and unstable if $U > U_0$.

1. Introduction

In weak rock tunneling deformation, cave-in and other distresses frequently occur and it is hard to maintain overall ground stability and construction safety. To ensure overall stability of rock mass it is necessary to conduct safety monitoring reference value study based on numerical ultimate load analysis by building an equivalent rock model [1-3]. As the design basis, the ultimate load analysis method is applicable to two-dimensional and three-dimensional geotechnical problems. The theoretical basis is the ultimate load analysis theory.

Many researches have conducted extensive research into the numerical ultimate load analysis method and produced substantial results. Zheng Yingren [4, 5] defined the overall plane failure criteria for material based on traditional ultimate load analysis method, applied this method to tunnel stability safety factor and proposed two shear failure safety factors, i.e. overall and local safety factors of tunnel. Through numerical ultimate load analysis from the angle of material ultimate strain Chen Wei et al. [6] proposed equivalent ultimate strain, rock instability failure mode and displacement limit value for hard rock sections and established deformation warning criteria for Milashan Tunnel.
stretches in hard rock. Su Zhongming et al. [7] verified the feasibility of the numerical ultimate load analysis method on tunnels through relevant model test and introduced the method of calculating safety factor for soil tunnels under different conditions using numerical ultimate load analysis to quantify the safety of tunnel at different construction stages. Jia Peng et al. [8] applied RFPA strength reduction factor to tunnel stability assessment to give ultimate load and tunnel safety factor and a visual display of the entire process of rock crack failure and instability. Taking the rock tunnel of Qingdao-Huangdao subsea highway where local fracture zones exist and considering seawater permeability, Wang Zaiquan et al. [9] analyzed the stability of the subsea tunnel rock before and after grouting using FE ultimate load analysis method.

Rock Classes IV and V surrounding a tunnel is typically referred to as weak rock. In this paper we investigate surrounding rock Classes IV and V by building an equivalent computation model, obtaining ultimate strain values of equivalent rock mass of different classes using the numerical ultimate strain analysis method and analyzing changes in vertical displacement of center point of equivalent rock masses under different loads. Then we build a planar model for calculation and analysis and establish tunnel stability assessment criteria through observation of ultimate shear strain diagrams under different reduction factors so as to take appropriate management measures according to warning levels.

2. Study on Ultimate Strain Values of Rock Masses of Different Classes

2.1. Building numerical calculation analysis model

We analyzed ultimate strain values of equivalent rock mass according to mechanical parameters of Classes IV and V rock surrounding a tunnel to obtain the ultimate strain values. We used FLAC3D to simulate uniaxial compression test on equivalent rock mass of Class III using test cubes 150mm×150mm×150mm, applying constraint to the bottom and imposing vertical downward uniformly distributed load to the top with no consideration given to friction at the top.

In analyzing the ultimate strain of equivalent rock mass we applied loads incrementally while monitoring center point displacement. When the center point does not converge under a load level the rock mass fails. This level of load is taken as ultimate load of equivalent rock mass. The strain value at the prior level of load is taken as ultimate strain. Fig. 1(a) and 1(b) respectively displays vertical displacement changes of the center point of equivalent rock masses of Classes IV and V under different loads.

As shown in Figure. 1, when vertical load reaches 1.442MPa in the case of Class IV rock the vertical displacement of center point of equivalent rock mass does not converge and the rock mass fails; when vertical load reaches 0.361MPa in the case Class V rock the vertical displacement of center point of equivalent rock mass does not converge and the rock mass fails; for both classes of rock the strain value at the prior level of load is taken as ultimate strain. The higher the rock class, the smaller the vertical load needed for vertical displacement of equivalent rock mass center point not to
converge and hence the rock mass is prone to failure. Under different loads, the higher the rock class, the smaller its vertical displacement and hence the smaller its ultimate strain.

3. Study on Safety Monitoring Reference Value for Tunnels in Different Classes of Rock

3.1. Building calculation model
Based on stratigraphic method we built a planar model for calculation and analysis using FLAC3D program, taking 3-5 tunnel diameters around the tunnel perimeter for deep tunnel to dimensions of 100m (W) * 100m (H) * 1m (L). We adopted displacement constraint boundary conditions at the front, rear, left, right and bottom sides of the model and applied a load of 2.0MPa to the top of the model to simulate rock load. According to design data both Class IV and V rock sections are constructed by full-face method. In this calculation two-bench method is adopted. The calculation model is displayed in Figure 2.

![Numerical calculation analysis model](image)

Figure 2. Numerical calculation analysis model.

3.2. Analysis of calculation results
Figure 3(a) and 3(b) display rock deformation vs. strength reduction factor for Classes IV and V rock respectively. We obtained ultimate vault settlement and surrounding convergence values of surrounding rock, and vault settlement and surrounding convergence-1 and convergence-2 values at different strength reduction factors. As shown in Figure 3 deformations of different classes of rock vary roughly in a consistent manner as strength reduction factor changes; ultimate values of vault settlement and surrounding convergence change in two distinct stages, i.e. slow growth stage and abrupt rise stage; ultimate values of vault settlement and surrounding convergence grow slowly until the strength reduction factor reaches 2.1 for Class IV rock and 1.1 for Class V rock. The higher the rock mass classification the more susceptible it is to strength, creep and instabilities.

![Rock deformation vs. strength reduction factor](image)

(a) Class IV rock
(b) Class V rock

Figure 3. Rock deformation vs. strength reduction factor.

As shown in Figure 4 displays diagrams of ultimate shear strain of Class IV rock at different reduction factors and Fig. 5 shows diagrams of ultimate shear strain of Class V rock.
Comparison of Fig. 4 and 5 suggests different classes of rock tend to deform in the same manner at different reduction factors, i.e. sidewalls are prone to local failure which propagates to arch wall resulting in overall failure. Class IV rock has a stability safety factor of 1.4 and Class V rock 0.6, suggesting higher class rock makes the tunnel more susceptible to overall failure.

4. Conclusions
The occurrence and development of tunnel structure displacement is dynamic reflections of the mechanical behavior of the tunnel structure. No matter how complex the tunnel loading mechanism is,
its response to various effects can be represented by its perimeter displacement. It is a visual and feasible method to understand mechanical behavior of a tunnel through observation of perimeter displacement. Tunnel stability should also be represented by the evolvement of perimeter displacement.

As can be seen in the diagrams of ultimate shear strains of surrounding rock, rock failure follows local sidewall failure and subsequent propagation to arch wall leading to overall failure; and higher class rock makes the tunnel more susceptible to overall failure.

To assess tunnel stability assessment criteria are established by comparing displacement $U$ measured during tunneling with the ultimate displacement $U_0$, i.e. the tunnel is stable if $U < U_0$ and unstable if $U > U_0$. To ensure safe construction of tunnels the early warning approach is taken by establishing three warning levels at 1/3, 2/3 of ultimate displacement value and the ultimate displacement value so as to take appropriate management measures according to the warning level, as shown in Table 1.

Table 1. Early warning criteria and construction management measures for safety monitoring during construction of a tunnel

| Class number | Hazard level   | Displacement (mm)                      | Management level                                      |
|--------------|----------------|----------------------------------------|-------------------------------------------------------|
|              |                | Arch settlement | Surrounding convergence |                                                          |
| V            | Unstable       | $U > 197$ | $U > 280$ | I - suspend construction activity and develop a special plan |
|              | Hazardous      | $130 < U \leq 197$ | $186 < U \leq 280$ |                                                          |
|              | Abnormal       | $65 \leq U \leq 130$ | $93 \leq U \leq 186$ | II - Reinforce surrounding rock or support measures. |
|              | Normal         | $U < 65$ | $U < 93$ | III - Normal construction may proceed. |
|              | Unstable       | $U > 76$ | $U > 134$ | I - suspend construction activity and develop a special plan |
|              | Hazardous      | $50 \leq U \leq 76$ | $90 \leq U \leq 135$ |                                                          |
| IV           | Abnormal       | $25 \leq U \leq 50$ | $45 \leq U \leq 90$ | II - Reinforce surrounding rock or support measures. |
|              | Normal         | $U < 25$ | $U < 45$ | III - Normal construction may proceed. |

**Acknowledgments**

The authors would like to express their appreciation to the special project of national key research and development plan (2017YFC0805305), the National Natural Science Foundation of China (41601574), the scientific research project of Tibet autonomous region (2016XZ01G31), the science and technology program of Tibet autonomous region (XZ201801-GB-07), and the Chongqing Science, the technology Innovation Leading Talent Support Program (CSTCCXLJRC201715) and the project of Chengde science and Technology Bureau (201706A074) for providing funding for this research.

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