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Optimization of the Excavation Scheme for Underground Engineering Based on Energy Release Rate

ZHANG Chengliang

School of Territorial Resource Engineering, Kunming University of Technology, China

zclky78@163.com

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Abstract. Loading and unloading experiments on rock materials have shown that the strength parameters and deformation properties of rocks during unloading were considerable different from those during loading. Therefore, it is reasonable to evaluate the stability of underground engineering during excavation based on the unloading behaviour of rocks, so that the in-situ conditions can be reflected realistically. In this study, unloading behavior of rock mass during excavation considering the geological conditions is modeled for an underground tunnel. The energy release rate, the total amount of released energy and the averaged energy release rate are numerically evaluated and compared for different excavation schemes. Numerical simulations confirm the feasibility of applying the average energy release rate in evaluating the stability of tunnels and optimizing the excavation schemes.

Introduction

Rock materials tend to failure under certain stress states and those failure criteria established purely from the viewpoint of forces and displacements are not generally applicable. A stress-strain relation describes the mechanical state of rocks under a particular range of stress. However, the information about stress state and displacement cannot not be obtained as soon as possible in practical underground engineering, and the application of the stress-strain relationship is generally difficult[1-2]. Several authors, on the other hand, argued that the stress-strain relationship cannot capture the failure behaviors of rocks satisfactorily. The failure modes and the amount of released energy differ from each other for different specimens, although the stress-strain curves are rather similar. In essence, failure of rocks is a phenomenon that can be interpreted as a loss of stable state driven by a certain energy mechanism [3-4]. Rocks are exchanging energy with the external environment during the whole process of loading until instability and failure takes places, either translating the input work into internal elastic strain energy or releasing the internal energy to the environment in a certain manner. In this study, the conservation principle of elastic energy is employed in establishing a numerical model for the simulation of excavation. Different schemes for an underground tunnel are analyzed and compared, with particular attention paid to the energy release rates in different schemes. The stability of the tunnel is evaluated carefully so as to provide useful information for the optimization of the excavation scheme.

Energy analyses for the failure of rock specimens

Energy is not only a fundamental quantity in all physical processes, but also the intrinsic cause of failure of materials. For instance, the failure of rock materials is strongly related to the change of internal energy. If the transfer and translation of energy during deformation process until failure can be clarified, the failure process and the relevant physical mechanism may be understood more comprehensively.

Loading experiments

In a triaxial compression test, the work inputted into the specimen by the apparatus can be expressed as follows [5]: $W = \int F du = AL\int \sigma_1 d\varepsilon_1 = ALK_1$ (1)

Herein,A and L denote the area of cross section and the length of the specimen, K_1 is the work inputted into a unit volume of the specimen. W in Eq. (1) may be mathematically interpreted as the area enclosed by the axial stress - axial strain curve, the abscissa and the ordinate. The unit of K_1 is MJ/m^3, which is essentially accord with the unit of stress, MPa.

In triaxial compression experiments, rock specimens expand horizontally under the axial compression and do work to the confining liquid in the cell. Therefore, the net energy, K_2, stored in the specimen is generally lower than the work inputted vertically [5-7], namely,

$$K_2 = \int_0^{\varepsilon_1} \sigma_1 d\varepsilon_1 + \int_0^{\varepsilon_2} \sigma_2 d\varepsilon_2 + \int_0^{\varepsilon_3} \sigma_3 d\varepsilon_3 = \int_0^{\varepsilon_1} \sigma_1 d\varepsilon_1 + 2\int_0^{\varepsilon_3} \sigma_3 d\varepsilon_3 \tag{2}$$

Unloading experiments

If the axial strain is kept constant after the application of the vertical stress, no additional energy will be inputted vertically during the unloading of confining pressure. The yield and failure of the specimen is purely initiated by releasing the elastic strain energy absorbed previously. The released energy is continuously absorbed by the liquid in the cell during the horizontal expansion of the specimen [6]. Obviously, more energy is released when the confining pressure at failure is lower and less energy is stored finally in the rock specimen, i.e. the higher the deviatoric stress $(\sigma_1 - \sigma_3)$ at failure is, the higher the energy release rate is and the severer the material is damaged and deteriorated. Once the damage zone of the specimen extends to a certain degree, a sudden failure of the specimen will occur.

Based on the above conceptual analysis, rock mass initially at the in-situ stress state may suffer a sudden decrease of stress and the stored energy will be released during this process. If no timely protection measures are taken to prevent the deterioration of the stress state, additional deformation will develop at the same time of energy releasing and the stability of the underground engineering may not be sustained.

Numerical simulation of the excavation scheme for a typical underground engineering

As one of 52 secondary roads in Yunnan province, the road from Weixi to Deqin is a long and costly one that is rather difficult to construct. The road passes through Weixi and Deqin, and will be constructed along the Lancang River. It will serve as an important route to enter Tibet from Yunnan, and will resolve the problem of traffic interruption that may occur during the snowy seasons. In this engineering, The Yanziya tunnel with a designed length of 1120 meters is a key project located at Badi town, Weixi County. The tunnel is built within relatively uniform pyroxenite rock mass near the left bank of Langcang River. The surrounding rocks are moderately and slightly weathered and can be classified mostly as III, IV and V grades. The hardness of the rocks is high, within which the velocity of longitudinal waves ranges from 2350 to 3100 m/s. However, the surrounding rock mass is abundant in crannies and the stability of which is weak.

The physical and mechanical parameters are evaluated based on unloading experiments. Reference is also made to the results obtained from geophysical detections and geological investigations. Table 1 gives the parameters of the dolerite under consideration.

Tab1 Parameters of the dolerite

Density (kg/m^3)	2360	Cohesion (MPa)	2.38
Elastic modlus (GPa)	16	Friction angle (º)	42
Poisson ratio	0.31	Tensile strength	1.75

In this study, elastoplastic analysis is carried out for the simulation of excavation. In particular, the yield criterion proposed by Drucker and Prager [7-9] is used due to its capability of considering the influence of intermediate principle stress on the yield and failure behavior. Drucker-Prager criterion could be interpreted as an extension of Mohr-Coulomb criterion and Mises criterion and it is capable of reflecting the failure property of rock materials more realistically. The criterion reads:

$$f = \alpha I_1 + \sqrt{J_2} - K = 0 \tag{3}$$

in which, $\alpha = \frac{2\sin\varphi}{\sqrt{3}(3-\sin\varphi)}$ and $K = \frac{6C\cos\varphi}{\sqrt{3}(3-\sin\varphi)}$; c and φ denote the cohesion and friction angle of materials, respectively.

Failure may also occur in rocks with low tensile strength. In this case, the following restrictions should be fulfilled:

1) For initial tensile failure: $F = \sigma_i - R_t^{'} \le 0$, ($i$=1, 2, 3) (4)

2) For successive tensile failure: $F = \sigma_i \le 0$, (i=1,2,3) (5)

In Eq. (4) and Eq. (5) σ_i denote the principle stresses, $R_t^{'}$ is the equivalent tensile strength of rocks that can be evaluated via $R_t^{'} = \sigma_0 + R_t$. Herein, σ_0 is the initial in-situ stresses and R_t is the tensile strength of rocks. The use of Eq. (5) allows the consideration of 'softening' behaviors after the initial tensile failure. Once a rock element cracks under tension, a portion of the stress will be transferred to other elements. This process of stress redistribution will not cease until the requirement Eq. (5) is satisfied.

Generally, stresses and strains follow a nonlinear relationship that could be expressed incrementally, i.e. $\{d\sigma\} = \{D_{ep}^{t}\}\{d\varepsilon\}$ (6) Herein, $\{D_{ep}^{t}\}$ is the elastoplastic matrix.

The initial stress states and the boundary conditions are two prerequisites for numerical simulations. In this study, the vertical stress p and the horizontal stress q are evaluated based on geological investigations and in-situ measurements, i.e. p=10.56MPa and q=12.15MPa. The truncating boundaries are restricted from vertical and horizontal displacement. After the prescribing of boundary conditions, the equilibrium equations are numerically solved so as to obtain the initial stress states before excavation.

The height and width of Yanziya tunnel is 7.99 meters and 11.04 meters, respectively. Considering the maneuverability of construction, four schemes were designed, i.e. (I) the height of the upper bench is 4.52 meters and the height-span ratio is 0.4; (II) the height of the upper bench is 5.52 meters and the height-span ratio is 0.5; (III) the height of the upper step is 6.52 meters and the height-span ratio is 0.6; (IV) full face excavation with a height of 7.99 meters and a width of 11.04 meters. For schemes (I) to (III), the excavation length is 3 meters. Figure 1 shows the illustration of the designed schemes.

The depth of the tunnel is 434 meters and the transverse distance between the tunnel and the mountain slope is 185 meters. Since the zones of rock mass disturbed by excavation are generally limited within 3~5 times the radius of the tunnel, the length, height and width of the truncated model is 66, 50 and 50 meters, respectively. The rock mass is discretized with 100800 hexahedral elements with 105213 nodes totally. Figure 2 shows the finite element model, in which blue zones represent the surrounding rock mass and other colors mark the bottom boundary of each excavation scheme.

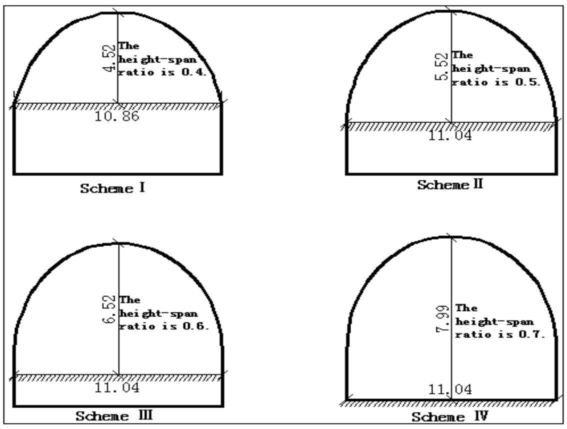


Fig.1 Illustration of the excavation schemes

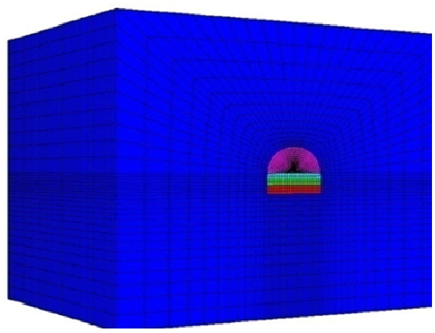


Fig. 2 Finite element model of the tunnel

Results and analysis

Excavation disturbs the surrounding rock mass and alters the initial equilibrium state. The rocks displace towards the cavity previously excavated and results in stress redistribution within the surrounding rock mass. Once the newly attained stresses exceed the limit, relaxed plastic zones will be formed near the tunnel. With the increase of the longitudinal distance from the excavation face, the stress changes from a uniaxial or biaxial state to a triaxial state and the strength condition gradually approaches that of original rocks under natural state. Therefore, the zone near the excavation face is the weakest and most prone to lose its stability. Generally, different stress states correspond to different limitations of the energy reserved. When the strain energy at the new stress states exceeds the limitations, rocks tend to release the energy until a sudden failure occurs. During this process, the released energy can be calculated via the following equations:

$$LERR_i = NE_{i\max} - NE_{i\min} \tag{7}$$

$$ERR = \sum_{i=1}^{n} LERR_i \tag{8}$$

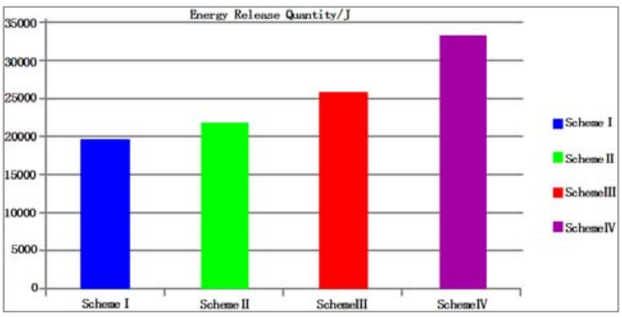
Herein, $LERR_i$ denotes the energy release rate of element i; $NE_{i\max}$ and $NE_{i\min}$ are the maximal and minimal energy density before and after the brittle failure of element i, respectively; ERR is the total amount of released energy; V_i denotes the volume of element i. In equation (7), the energy density NE can be expressed as follows:

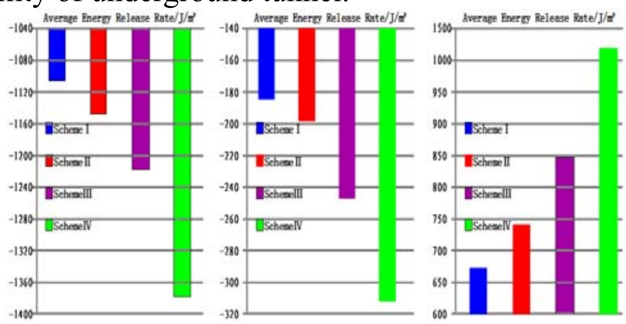
$$NE = [\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\mu(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_1\sigma_3)/2E] \tag{9}$$

In which σ_1, σ_2 and σ_3 are principle stresses at the state of maximal strain energy; E and μ are elastic modulus and poison ratio, respectively. Herein, the effect of unloading on the deformation parameters of rock mass has been taken into account.

In the numerical simulations, three layers of elements (referred to as the first, second and third layer towards the excavation direction) were removed during each excavation step, and the amount of released energy is generally different in different schemes. The multiplication of the energy release rate and the volume of an element give the change of energy, of which a negative value indicates energy releasing and a positive value indicates energy absorbing. The sum of the energy over all elements gives the total amount of released energy from the excavated rock mass. Figure 3 shows the released energy from the first layer of elements in the four designed excavation schemes.

It can be seen from Figure 3 that the released energy from the top of the arch increases nonlinearly with the increase of excavation height. In scheme I and scheme II the amount of released energy differs slightly (19400 J and 21624 J). However, the energy released in scheme III and scheme IV increases considerably compared with the first two schemes. This can be explained by less degree of boundary restriction and larger extent of unloading in the latter two schemes. In underground engineering, the damage and deterioration of rock mass become severe with the increase of released energy. As a result, the potential risk of losing stability also increases, vise versa. The numerical results indicate that scheme I is better than scheme II and scheme II is evidently better than scheme III and scheme IV. In practical engineering, stepwise excavation with a limited excavation height is beneficial for the stability of underground tunnel.





a First Circle b Second Circle c Third Circle

Fig.3 The released energy from the top of the tunnel Fig.4 The average energy release rate in different schemes

The average energy release rate can be evaluated by the quotient of the total amount of energy over the volume of rock mass excavated. Figure 4 shows the comparison of the average energy release rate in the four considered schemes. It is evident that the average energy release rate from the first layer is the highest among the three layers, and the release rate from the second layer decreases considerably to 13 ~ 26 percentage of that from the first layer. On the other hand, accumulation of strain energy is found in the third layer. In addition, the amount of accumulated energy increases remarkably with the increase of the height-span ratio. Therefore, it can be inferred that the area of unloading zones increases nonlinearly with the volume of excavated rock mass so that the energy released in scheme III and scheme IV increase evidently compared with that in scheme I and scheme II. These again indicate that the exaction height should be taken into consideration as well as the progress of excavation so as to sustain the stability of the tunnel.

In underground engineering, large amount of energy will be released during excavation in different forms such as rock burst in some extreme cases. The introduction of energy release rate in this paper provides an effective parameter to evaluate the feasibility of excavation schemes. It also serves as a useful objective function for the optimization of excavation schemes. In particular, the stability of the tunnel can be sustained and the failure of which can be avoided by adjusting the excavation plans so as to maximally reduce the energy release rate.

Conclusions

Four excavation schemes were numerically simulated for the Yanziya tunnel. The energy release rate as well as the amount of released energy from the excavated elements was calculated for each scheme. Comparing the results obtained in each scheme, the following conclusions can be obtained:

1) The energy release rate, the total amount of released energy and the volume of plastic zones are lower in scheme (I) than those in other schemes, indicating that scheme (I) is safer than others. In practical engineering, stepwise excavation with a limited excavation length ensures a lower speed of unloading, so that it is an effective way to sustain the stability of the surrounding rock mass. Contrarily, full face excavation should be avoided.

2) The amount of released energy in scheme II is almost the same as that in scheme I, both of which are considerably lower than that in scheme III and scheme IV. This can be explained by the limited unloading and insufficient energy releasing since the upper benches are smaller compared with the two latter schemes.

3) The use of local energy release rate provides important information for the precise distinguishing of energy absorbing zones and energy releasing zones. The deformation characteristics and the failure mechanism can also be analyzed based on this quantity. This would be significant for the design of supporting systems and reinforcement measures.

4) It is feasible to apply the energy release rate in comparing and optimizing excavation schemes for underground engineering.

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