Deformation and failure analysis of surrounding rock mass in deep buried tunnels subjected to excavation

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Abstract: With the rapid development of underground engineering, the construction of hydraulic tunnel is faced with complex geological conditions. Rock burst and deformation have become the bottleneck of engineering construction. The study of deformation and failure mechanisms of surrounding rock mass during the excavation of deep buried tunnel has become important for the field of underground engineering. The traffic tunnel of Shuangjiangkou hydropower station is studied to identify the failure mechanism of surrounding rock mass of deep buried tunnel. We introduced microseismic monitoring technology to delineate potential risk areas and reveal the space-time evolution of microfractures. The failure type of the surrounding rock is determined by source parameters. The relationship between surrounding rock deformation and excavation dynamic response is analyzed based on the geological and microseismic data. The results show that the 3D microseismic visualization model can realize the advanced detection of the internal damage of surrounding rock. The source parameters reveal that tensile failure is the main form of failure in the tunnel surrounding rock. Strong unloading and poor geological conditions are the main factors affecting the stability of surrounding rock mass. The study combines microseismic monitoring with field investigation, and then comprehensively evaluates the stability of the tunnel surrounding rock providing a reference for similar underground engineering.
1. Introduction
The increasing material needs of the people have resulted in higher requirements for energy supply. Various hydropower stations have been built in southwest China to increase energy supply [1]. Due to the different functional needs of water conservation project layout and construction diversion, hydraulic structures are mostly arranged underground. Complex geological conditions exist in underground tunnels and structural planes, such as faults and joints are often developed. Numerous engineering practices show that bad geology has a great influence on the overall stability of surrounding rock mass [2].

At present, the in-situ monitoring of surrounding rock stability of underground caverns mostly adopts conventional methods, such as stress strain and displacement deformation monitoring. These methods can monitor large deformation in the surrounding rock mass reflecting the deformation and mechanical parameter changes in the observed section. However, the traditional monitoring methods are limited in time and space, thus making it difficult to capture the microfracture, the precursor of rock mass failure, before the macroscopic deformation of rock mass. Microseismic (MS) monitoring technology, a highly sensitive, three-dimensional space monitoring technology for rock mass microfracture, not only analyzes the time, location, and magnitude of rockburst events through acoustic waves, but also captures the microfractures that are smaller than the rockbursts in magnitude. Precursor events provide potential possibilities for the prediction of the damage risk of surrounding rock of underground caverns. Many scholars have conducted an in-depth research on MS monitoring technology [3-13].

In seismology, the energy ratio of S-wave to P-wave (Es/Ep), one of the important indices, reflects the failure mechanism of surrounding rock mass. Boatwright and Fletcher [14] found that for fault-slip or shear seismic events, S-wave energy is much greater than P-wave energy, i.e., Es/Ep ≥ 10. Nonshear type failures, such as tensile failure Es/Ep is close to or less than 3 for events induced by changes in volumetric stress. Based on the above understanding, this paper introduces the theory of shear and longitudinal wave energy ratio in seismology into the field of MS monitoring. Taking the traffic tunnel project of Shuangjiangkou Power Station as the background, the energy ratio of transverse and longitudinal waves of MS events in different stages is analyzed, and the deformation and failure forms of surrounding rock are revealed.

2. Research object
In this paper, in line with the Shuangjiangkou entrance traffic tunnel project, a high precision MS monitoring system is established for the construction of a deep underground tunnel to reveal the development law and failure mechanism of surrounding rock damage. The MS monitoring system achieved real-time monitoring of micro-fractures on August 11, 2017 and completed the monitoring task on October 24, 2018. During the monitoring period, the main blasting and excavation support of the traffic tunnel were conducted. Fig. 1 is the actual construction drawing on site.

3. Temporal and spatial distribution characteristics of MS events
MS monitoring technology can delineate the potential risk area of surrounding rock by collecting elastic wave, active noise reduction, and inversion location. By establishing the relationship among the MS activity, construction performance, and the response of geological structure, it helps in evaluating surrounding rock damage and residual stability.

![Fig.1 Site construction drawing.](image)

(a) Drill holes for explosives  (b) Transport basting surrounding rock mass

(c) Bolt support  (d) Surrounding rock mass failure

3.1 Temporal distribution characteristics of MS

Due to the complex construction environment, there are mechanical vibration effects, such as current interference, blasting disturbance, and bolt drilling, etc. After eliminating invalid events caused by similar effects, a total of 1,952 effective MS events were collected, as shown in Fig. 2. It can be seen from Fig. 2 that the distribution of MS events during the monitoring period is uneven over time, showing a wave-like undulating and gradually decreasing manifestation. The key red elliptical boxes mark the 4 main time periods for MS accumulation: (A) September 28 to October 23, 2017; (B) November 24 to December 10, 2017; (C) January 5 to January 10, 2018; (D) March 23 to April 4 2018.

The four MS aggregation periods are mainly affected by bad geological conditions and strong unloading construction, inducing microfracture and rock aggregation, deteriorating the strength of surrounding rock, and increasing the risk of surrounding rock stability.
3.2 Spatial distribution of MS

MS events are the direct reflection of internal damage of surrounding rock. Therefore, the spatial aggregation state and migration law of MS events can be used to identify and delineate the potential risk area of surrounding rock mass.

Fig. 3 is the MS event space diagram of the traffic tunnel at the factory entrance. It can be seen from the figure that the whole three-dimensional space model mainly contains four damage accumulation areas, namely (I) K0 + 885 ~K0 + 792, (II) K0 + 708M ~K0 + 605, (III) K0 + 571~K0 + 486, and (IV) K0 + 428 ~K0 + 356. The stress is redistributed during excavation unloading and the circumfluence stress concentration around the tunnel leads to the aggravation of surrounding rock fracture, especially in the vicinity of bad geological structures, which is consistent with the spatial and temporal distribution characteristics of the actual MS events.

4. Ratio of S-wave energy to P-wave energy

The elastic wave collected by the MS monitoring system contains abundant source parameter information, which can effectively reveal the failure characteristics of rock and understand the
damage evolution mechanism inside surrounding rock from the microscopic perspective. Therefore, it is very important to study the seismic source parameters in blasting excavation to reveal the damage mechanism of surrounding rock mass.

As an important source parameter, the ratio of S-wave energy to P-wave energy ($Es/Ep$) can reveal the source failure mechanism in which S-wave energy and P-wave energy can be calculated by the following formula:

$$E = 4\pi r c^3 \frac{J_s}{F_c^2}$$

(1)

where $\rho$ represents the density of the rock (kg/m$^3$), $r$ represents the distance between the sensor and the MS source (m), $c$ represents the wave speed (m/s), $F_c$ represents the empirical coefficient of seismic wave radiation type. When the focal mechanism is unknown, the average root-mean-square radiation coefficient on the focal point is usually taken as $F_\alpha = 0.52$ (P-wave) and $F_\beta = 0.63$ (S-wave); $J_c$ represents the integral of the particle movement velocity.

During the excavation of the traffic tunnel in the factory, the energy ratio of the main damage areas was calculated for the four main damage areas, (I), (II), (III), and (IV). It can be seen from Fig.4 that 38% of the MS events $Es/Ep < 3$, and for only 28% of MS events $Es/Ep > 10$ in area (I) indicating that the surrounding rock in this area is dominated by tensile-shear composite failure. The number of MS events with $Es/Ep < 3$ accounted for 42% of the total, and the number of MS events with $Es/Ep > 10$ accounted for 20% of the total, indicating that the tensile failure of the surrounding rock is dominated in area (II). For 37% of the MS events, $Es/Ep < 3$, and for only 18% of the MS events, $Es/Ep > 10$, indicating that the surrounding rock in area (III) is mainly tensile-shear failure, followed by tensile failure. For 38% of MS events, $Es/Ep < 3$, and 40% of MS events, $3 < Es/Ep < 10$ indicating that the area (IV) is dominated by tensile-shear composite damage.
Fig. 4 Distribution characteristics of $E_s/E_p$ values in typical intervals. (a) damage area I, (b) damage area II, (c) damage area III, and (d) damage area IV

5. Conclusion
In essence, $E_s/E_p$ represents the ratio of shear wave energy to longitudinal wave energy in the surrounding rock damage caused by external disturbance. The natural undisturbed surrounding rock mass is in equilibrium state under the action of in-situ stress. When the unstable geological conditions are excited by blasting, the surrounding rock stress is adjusted, and the MS activity is induced. During this process, the MS monitoring system calculates the $E_s/E_p$ value. According to the range of $E_s/E_p$ value, the damage form of surrounding rock is determined. The research team revealed that poor geological structure and stress concentration caused by strong unloading are the main causes of microfracture of surrounding rock, and summarized that the damage of surrounding rock is mainly tensile failure.

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