Deformation and Stability Analysis of Surrounding Rock Mass in Deep Underground Cavern Based on Microseismic monitoring and Numerical Modelling

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Abstract. In the excavation and unloading process of large-scale underground engineering, surrounding rock mass damages such as splitting, rock burst and collapse will often occur, affecting the progress and safety of the project. Correctly identifying and delineating the potential instability and failure area of surrounding rock mass and forecasting in advance can effectively reduce the hidden dangers of engineering safety. In this paper, a comprehensive analysis method combining microseismic (MS) monitoring and numerical simulation is proposed to analyse the effect of structure planes on the stability of surrounding rock mass of underground cavern and predict the deformation. First, numerical simulation is applied to analyse and predict the deformation and stress evolution characteristics of surrounding rock mass. Second, based on the MS monitoring data of the underground powerhouse and field investigation, the temporal and spatial distribution characteristics of MS activity were analysed, and the failure region was revealed and delineated. Finally, the effectiveness of the proposed method is verified by the comparison of MS monitoring results and numerical simulation. The results show that MS events are obviously concentrated in the surrounding rock mass damage area. The failure of spalling and rock-burst in underground powerhouse area is the typical brittle failure under high in-situ stress and low strength-to-stress ratio. In essence, the collapse at the top arch of auxiliary powerhouse is caused by the combined action of high in-situ stress and unfavourable structural plane. The results of MS monitoring and numerical simulation have a good corresponding relationship, and the conclusions provide technical guidance for subsequent construction schemes and support measures.

Key words: Underground cavern; Structurally-controlled deformation; Ms monitoring; Numerical simulation; Stability analysis
1. Introduction

Due to the complex geological conditions and structural characteristics, the surrounding rock mass failure such as slope, splitting, rock-burst and even collapse often occur in the process of large-scale underground cavern excavation, which affect the progress and safety of the project\(^\text{[1-6]}\). Timely and accurate prediction of structural-controlled deformation and failure can provide reasonable technical guidance for underground engineering construction. Numerical simulation method can simulate complex mechanical models and boundary conditions, and is widely used to analyze the stability of surrounding rocks in excavation caverns\(^\text{[7]}\). However, due to the complex geological environment, rock mass structure and in-situ stress characteristics are difficult to grasp, the mechanical parameters are usually difficult to determine, which requires us to combine the on-site monitoring data during the construction period for comprehensive analysis. Microseismic (MS) monitoring technology is a new three-dimensional detection method that can monitor the three-dimensional area of rock mass and obtain the micro-fracture activity, so as to predict the risk area of rock mass\(^\text{[8-14]}\). In this paper, based on the discrete element analysis of surrounding rock mass deformation of underground caverns during construction, combined with on-site MS monitoring data, the deformation characteristics and failure mechanism of rock mass are comprehensively analyzed.

2. Project background

The hydropower project adopts the design scheme of underground powerhouse, with a horizontal buried depth of about 400 m ~ 640 m and a vertical buried depth of about 320 m ~ 500 m. The axes of the three main caverns, the main powerhouse, the main transformer chamber and the tailrace surge chamber, are arranged in parallel according to N10°W. The layout is shown in Figure 1. The rock mass belongs to hard rock and has good integrity. It is dominated by porphyritic biotite potassium feldspar granite, with pegmatite veins locally developed, accounting for about 10.67%. The uniaxial compressive strength of rock is more than 60 Mpa, and the internal acoustic test results show that the wave velocity is generally higher than 5000 m/s. As shown in Figure 2, no large faults were found to pass through in the powerhouse area, and the structural planes were mainly joint fractures (J1, J2, J3, J4, J5) and secondary faults (SPD9-F1, SPD9-F2 and lamprophyre dyke). The surrounding rocks are mainly of type III, and some are of type IV and V. The geo-stress in the underground powerhouse area is high, with the maximum principal stress mainly ranging from 20 to 30 MPa and up to 37.8 2MPa\(^\text{[15]}\).

![Figure 1. Layout of underground caverns.](image-url)
3. Numerical Simulation and MS Monitoring

3.1. Implementation of the Numerical Model

In this paper, 3DEC (3Dimension Distinct Element Code) program is used to simulate and analyze the layered excavation of underground powerhouse. Built-in Coulomb model is used for the intact rock and Coulomb-slip joint material model is used for the discontinuity. The normal displacement constraint condition is applied around the model and the trapezoidal distributed force is applied on the model element as tectonic stress on the basis of the gravity stress. According to the actual sequence of excavating the middle drift first and then excavating both sides, the excavation of the first bench of underground powerhouse is simulated at first. Compared with the monitoring data, the constitutive model and parameters are proved to be reasonable. Then, according to the construction scheme, the simulation calculation is carried out for the subsequent layered excavation of the caverns, and the results are in good agreement with the actual measurement results of the caverns.

3.2. MS monitoring system

The MS monitoring system produced by ESG (Engineering Seismology Group) in Canada was used, and ten sensors with a sensitivity of 25 V/g were installed, which can cover crown, upstream, and downstream regions of the main powerhouse and the middle wall between the main powerhouse and main transformer chamber. The sensors transformed the elastic wave signals of rock fracture into electrical signals, which were processed layer by layer and then transmitted to the data analysis and processing center. A CEEMD-CS-ST denoise method based on Complete Ensemble Empirical Mode Decomposition (CEEMD), Compressed Sensing (CS) and Soft-thresholding (ST) is used to reduce the non-stationary noise of MS signals. Furthermore, on-site rock mass wave velocity tests and fixed point blasting tests were carried out to verify the positioning accuracy of the MS monitoring system. Compared with the actual coordinates, the positioning error of the final result was less than 5m, which meet the accuracy requirements.

4. Results and Interpretation

As shown in the Fig.3, there is a steeply inclined structural plane-lamprophyre dyke developed in the upstream side of the auxiliary powerhouse, which is filled with weak clay, so the rock is relatively weak. After the excavation of the middle drift, the structural plane of the upstream side is exposed and opens to the excavation face after losing the original bearing layer. The integrity of the already broken
rock mass deteriorates further, and a large-scale collapse occurs under the action of excavation. In the subsequent excavation, attention should be paid to the systematic support of the surrounding rock mass at the exposed position of the structural plane in time to avoid the damage to personnel and equipment.

The MS monitoring system was introduced to monitor the micro-fracture activity in the rock mass in real time. It can be seen from Fig.4 that after the excavation of the first bench of the powerhouse, MS events were mainly concentrated in three areas, namely the upstream arch shoulder of the auxiliary powerhouse, the upstream arch shoulder of the main powerhouse and the top arch section of the installation room. The surrounding rock mass on both sides of the lamprophyre dyke continuously dislocation along the structural plane, resulting in shear deformation, and finally collapsed under the action of excavation and unloading. Therefore, after the excavation of the first bench of the powerhouse, the area with the largest deformation of surrounding rocks was Zone I. Lamprophyre dyke and faults intersected and cut into unstable blocks near the surrounding rock mass on the upstream sidewall of the workshop, and the rock mass was relatively broken. The blasting construction broke the original stress balance, accelerated the displacement of the structural plane, resulting in large deformation of the upstream sidewall of the powerhouse (Zone II). In Zone III, a large number of gently inclined joints and cracks were densely distributed. In the process of excavation of the upper arch downstream of the powerhouse, the phenomenon of rock mass falling occurred. By comparing with the numerical simulation results, we can see that the deformation of surrounding rock mass was relatively large in the places where MS events obviously gather, and most of them were affected by structural planes, which indicated that the numerical simulation results were in good agreement with the MS monitoring results.
Figure 4. Results comparison between numerical simulation and MS monitoring. (a) and (b): Planform view; (c) and (d): Front view.

Fig. 5 shows the activity rate and cumulative energy release of MS events in two months before and after the auxiliary powerhouse collapse. Notably, the number of MS events in a single day doubled in the days leading up to the collapse, the activity rate increased sharply, and the cumulative energy release curve increased in a step-like manner. This can be regarded as an early warning signal of surrounding rock mass deformation, which successfully predicts the subsequent collapse of rock mass and avoids casualties and equipment damage.
5. Conclusions

(1) The collapse of surrounding rock mass in upstream of auxiliary powerhouse is a compound failure dominated by structural planes under high in-situ stress.

(2) The activity rate of MS events increases suddenly, releasing a large amount of energy and gathering locally, which can be regarded as the warning information of surrounding rock mass deformation.

(3) The results of numerical simulation and MS monitoring are in good correspondence, which proves that the comprehensive analysis method combining the two methods is reasonable and effective.

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