Stability analysis of surrounding rock mass in underground powerhouse based on octree and catastrophe theory

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ABSTRACT: Based on the underground cavern engineering of the left bank of Shuangjiangkou hydropower station, Octree theory is used to define the indexes of the MS spatial aggregation degree and the deviation values of MS frequency and energy, establishes the relationship with surrounding rock mass instability from three aspects of "time, space and strength". The cusp catastrophe model of the MS spatial aggregation degree and the deviation values of MS frequency and energy is established to quantitatively describe the early warning state of surrounding rock mass instability of underground cavern. The results show that the multi-level tree structure and voxels generated based on Octree theory is higher goodness of MS point set in three-dimensional space. The cusp catastrophe model based on the MS spatial aggregation degree and the deviation values of MS frequency and energy can effectively identify the early warning interval and potential damage area of surrounding rock mass, The warning time zone and potential damage zone quantified by this method are highly consistent with the characteristics of MS precursors with high recognition and field investigation results, which fully proves the rationality and applicability of this method. The research results can provide basis and reference for the early warning of surrounding rock instability in the later excavation of underground powerhouse.

Keywords: Underground caverns; MS monitoring; early warning; Octree theory; Catastrophe theory.

1 INTRODUCTION

Due to the limit of geological conditions and construction types of hydraulic structure, the hydropower powerhouse is generally arranged in the form of underground cavern group. Due to the characteristics of large span, large size and high side wall of underground cavern group, coupled with the influence of various geological structures, various types of surrounding rock and the cavern group effect, large-scale excavation and unloading of underground cavern will lead to a series of engineering rock mass instability disasters, such as surrounding rock deformation and failure [1].

Through precursor information analysis of microseismic (MS) parameters and quantitative inversion calculation, the rock mass damage area is delineated and the fracture source parameters are inverted to predict the macroscopic deformation and failure of rock mass in advance [2]. Dou et al. [3] used acoustic emission and field MS monitoring to put forward a comprehensive warning model of six sensitive indexes of coal rock failure precursor to provide a basis for in-situ mine burst disaster warning.

This paper aims to quantify the early warning state of cavern rock mass instability in underground powerhouse. Due to the large scale of MS data collected in engineering practice, it is difficult to realize real-time monitoring and early warning of cavern surrounding rock mass because of the large computational volume through multiparameter evolutionary analysis, this paper proposes indicators of spatial aggregation and frequency of MS events and energy deviation based on the octree theory, and describe the damage degree of surrounding rocks in ‘time, space, intensity’ .The results show that the instability interval obtained by the early warning model is basically consistent with the spatial and temporal interval of collapse at the site, and the early warning analysis of an approach traffic cave was carried out by using the early warning model. The early warning interval is consistent with the spatial and temporal interval of the surrounding rock deformation at the site and there is no omission, which further verifies the effectiveness of the method.

2 EARLY QUANTITATIVE WARNING METHOD FOR SURROUNDING ROCK

Based on the underground powerhouse system of hydropower station, the project adopts the scheme of parallel arrangement of the main and secondary powerhouse, the main transformer chamber and the tailwater surge chamber. The excavation size of the main and secondary powerhouse is 215.7m×28.3m×68.3m (length × width × height), and the excavation size of the top of the main transformer chamber is 158.26m×19.40m×27.19m. The horizontal buried depth of the underground workshop is about 400~640m, and the vertical buried depth is about 320~500m.

The underground cavern group of hydropower station has a large scale, deep buried depth and high ground stress. The maximum measured value of ground stress test in flat cavern is 37.82MPa. The strength to ground stress ratio of rock mass is low.

2.1 Evolution of original microseismic data

Among the damages at the engineering site, the large scale collapse at the upper arch shoulder of the auxiliary building was the most serious in the early morning of May 17, 2019. The MS monitoring data from April 1, 2019 to June 30, 2019 were extracted and analyzed in view of the massive surrounding rock collapse in the area of Stake 0+120~0+135 upstream of the powerhouse of Hydropower Station in the early morning of May 17, 2019. The activity rate and energy evolution of MS events in the three months before and after surrounding rock collapse are shown in Fig 1 and 2.

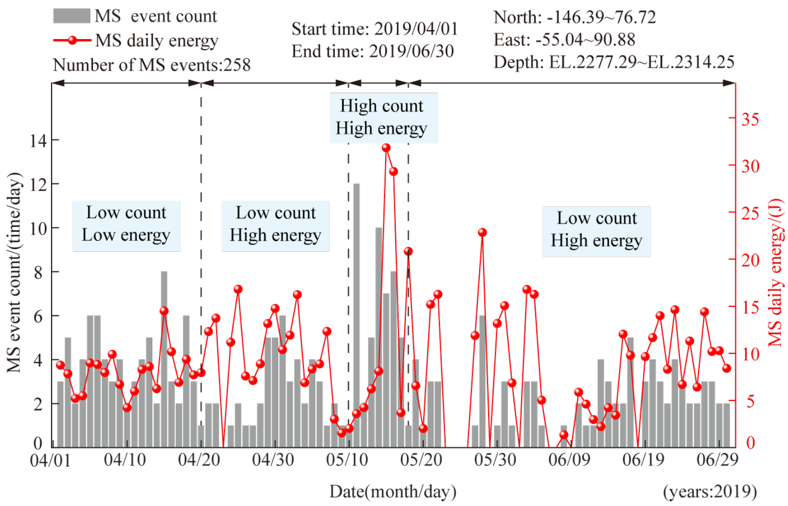

Figure 1. The temporal evolution of MS events frequency and Correction energy.

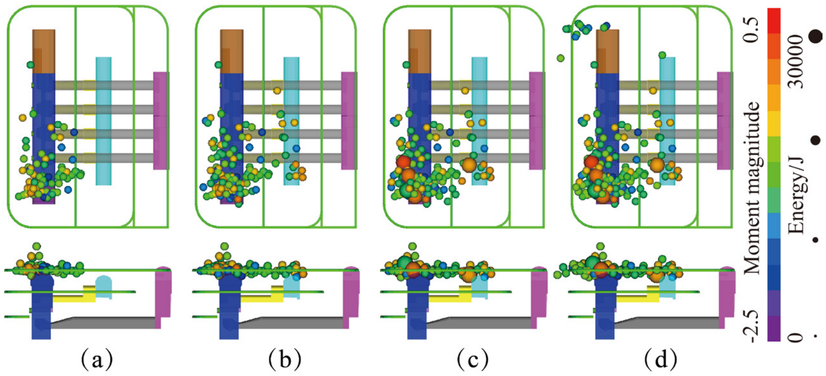

Figure 2 Stages of spatial distribution of MS events (a) the first stage (2019.04.01-2019.04.20), (b) the second stage (2019.04.20-2019.05.10), (c) the third stage (2019.05.11-2019.05.18), (d) the fourth stage (2019.05.18-2019.06.30)

Figure 2 (a) At this stage, the frequency of MS events is at a low level, the number of MS events is maintained between 1 and 8 per day, and the energy released by MS events is low. The overall performance of MS events is "low frequency and low energy", which means that the surrounding rock remains in a relatively stable state. Combined with the field construction and Figure 4, it can be seen that the spatial aggregation of MS events is relatively dispersed, and a small number of MS events gather in clusters in the excavation area of the workshop, indicating discrete fracture extension in the study area. The fracture of rock mass expands steadily and no large fracture is found.

Figure 2 (b) In this stage, the MS event frequency was still at a low level, but the energy released by MS events increased compared with that in stage Ⅰ, and many high-energy events occurred. The maximum daily average energy increased to 4315J, indicating that the energy stored in the rock mass began to be gradually released. Many cracks, including large ones, can be seen in the roadway walls, and the onset of fracture coalesce and rock mass failure can be predicted. As can be seen from Figure 4, the spatial aggregation of MS events is enhanced, and MS events gradually converge at horizontal 0+120~0+135.

Figure 2 (c) As blasting excavation resumed on May 11, the frequency of MS events increased sharply and remained at a relatively high level, with the average daily frequency being 1.84 times and 2.50 times of the first two stages, respectively. The total daily energy released was 5.39 times and 5.97 times of the first two stages. As shown in FIG. 4, MS events formed at this stage were further aggregated, and the degree of fracture propagation and coalesce increased until the surrounding rock collapsed on a large scale on May 17, and the macro cracks further expanded. The characteristics of MS events at this stage are high frequency, high energy and high aggregation.

Figure 2 (d) corresponds to the stress adjustment period of surrounding rock. It can be seen that from May 11 to 17, 2019, MS events were frequently active, the daily number of MS events maintained at a high level, and energy released by MS events produced a surge phenomenon until the large-scale collapse of surrounding rock on May 17. After the 17th, the frequency of MS events returned to the normal level, and the energy accumulation curve gradually flattened. In general, the MS activity will enter a relatively "active period" before the large deformation of surrounding rock.

2.2 Octree theory and potential function construction

Octree theory is a kind of tree-like data structure used to describe three-dimensional space. Octree structure is a directional graph with root node by subdivision of 3D geometrical entities, each individual element has the same time and space complexity.

In this paper, the octree adopts the threshold of the number of sample points in the voxel to perform recursive division. When each MS event is captured by the MS monitoring system, the cumulative MS events are divided into the octree to obtain each voxel with corresponding number, and the relevant parameters of the MS events in the voxel are recorded in each voxel. The parameter evolution of each step of the voxel was analyzed, and the potential function representing the damage degree of surrounding rock was constructed. The damage warning of surrounding rock was carried out through the evolution analysis of the potential function. According to the three elements of MS event: time, space and intensity, the precursor indexes of MS events can be divided into time series indexes, space indexes and intensity indexes, and the spatial, temporal and intensity potential functions of surrounding rock damage degree can be constructed respectively.

In order to quantitatively represent the concentration degree of mine earthquake events in spatial distribution, based on octree theory, this paper generates a tree-like irregular grid structure through the spatial connectivity of MS point clouds during the construction period of plant. The clustering degree of MS events is reflected through the three dimensional network of MS data in octree network. The higher the degree of MS events in a certain region, the greater the possibility of instability failure of surrounding rock in the region, otherwise, the more complete the surrounding rock.

$$Q_1 = \sum_{i=1}^{n} d_i N(b_i) \tag{1}$$

where, Q_1 is the time series of spatial aggregation degree of MS events, b_i is the number corresponding to voxel i, d_i is the division level corresponding to voxel b_i, and $N(b_i)$ is the number of MS events contained in the voxel numbered b_i。

The spatial aggregation degree, time frequency and energy of MS events comprehensively reflect the damage degree of surrounding rock. Due to the different frequency of daily MS events, the energy released by single-day MS events also varies greatly[4].

The increase of MS frequency and energy both indicate the enhancement of MS activity. In order to quantitatively reflect the frequency and energy concentration of MS series, this paper takes the time series, MS frequency and daily released energy as one dimension respectively, thus forming a three-dimensional space. The original single information, such as the one-dimensional change of MS frequency over time, has been changed into the change of spatial distance between data points in three-dimensional space caused by the joint action of time, frequency and energy. In this paper, MS time, frequency and daily energy release are respectively taken as X, Y and Z axes of three-dimensional space. Octree division of the three - dimensional space point set is carried out.

According to the above analysis, before the deformation and failure of surrounding rock, the frequency of MS events and released energy parameters are different from those during the stability of surrounding rock, showing the deviation of data points in three-dimensional space. Octree algorithm is an algorithm for space division of 3D data points. When the iterative threshold is set to 1, every data point generated in the 3D space will be partitioned into voxels by Octree structure. If a data point is spatially deviated from the rest of the data, the volume of the voxel occupied by this data point is also much larger than that occupied by the rest of the data for the volume of the re-subdivided voxel. Therefore, based on the octree theory, this paper puts forward the frequency of MS events and energy deviation degree to analyze the frequency and energy evolution law before and after surrounding rock instability failure:

$$Q_2 = \sum_{i=1}^{n} V_i \tag{2}$$

3 PREDICTION METHOD OF SURROUNDING ROCK DEFORMATION IN UNDERGROUND CAVERN BASED ON CATASTROPHE THEORY

Rock mass will release elastic energy in the form of elastic wave when it breaks under external disturbance. A large amount of fracture information can be extracted from microseismic signals, so as to interpret the failure mechanism of rock mass and determine the local or global stable state of rock mass. Therefore, there is a close correlation between the parameter evolution process of MS events and the change of rock mass state.

3.1 Cusp mutation theory

During the excavation of the lower caviar, the rock mass changes from the original three-way stress state to the bidirectional and unidirectional stress state, and the stress is constantly concentrated. With the birth, expansion and penetration of cracks, the rock mass surface shows the surrounding rock deformation phenomena such as splicing and spalling, and the surrounding rock enters the plastic deformation stage. The process is nonlinear and discontinuous. The abrupt change theory is a method that can deal with nonlinear and discontinuity without considering the internal mechanism [5].

Based on the Q_1 and Q_2 time series of microseismic events, a cusp catastrophe model is constructed to analyze the daily equilibrium state. Q_1 and Q_2 are one-dimensional time series respectively. Taking the time-space aggregation degree Q_1 of microseismic as an example, let the mapping relationship between Q_1 and time be $Q_1(t)=f(t)$, expand by Taylor formula, and retain the fifth power term to obtain the following equation[6].

$$Q_1(t)=f(t)=a_0+\sum_{i=1}^{5}a_i=a_0+a_1t+a_2t^2+a_3t^3+a_4t^4+a_5t^5 \quad (3)$$

In the equation, Q_1(0=0), that is, at the beginning of data traversal, there is no microseismic event gathering in space, so a_0=0. Through the Tschirnhaus change and t=x-(a_4/5a_5), Equation 3 can be changed into the standard form of equation[7]:

$$Q_1'(t)=5a_5x^4+(3a_3-\frac{6a_4^2}{5a_5})x^2+(\frac{56a_4^3}{25a_5^2}-\frac{6a_2a_3}{5a_5}+2a_2)x+(\frac{a_4^4}{25a_5^3}+\frac{3a_3a_4^2}{25a_5^2}-\frac{2a_2a_4}{5a_5}+a_1) \quad (4)$$

$$u=3a_3-\frac{6a_4^2}{5a_5}, \quad v=\frac{56a_4^3}{25a_5^2}-\frac{6a_2a_3}{5a_5}+2a_2 \quad (6)$$

Bifurcation set theory according to the mutation theory, told the daily microseismic events through the quantitative stability judgment on the Q_1 and Q_2 time series: when ∇< 0, the space, time and energy of microseismic events suddenly change, and the surrounding rock of underground caverns is in an unstable state, which is manifested as local instability of surrounding rock on a macro level. When ∇= 0, the surrounding rock is in the critical damage condition, the small changes will cause the surrounding rock control variables system equilibrium state of change; When∇> 0, the surrounding rock system is in a stable state. The abrupt change model evaluation results of microseismic events Q_1 and Q_2 are taken as the two evaluation basis, and the risk grade expression of the comprehensive early-warning model is obtained by comprehensive analysis of the two evaluation results through the risk matrix. The comprehensive evaluation matrix of rock mass instability risk grade based on the risk matrix method is shown in Table 1.

Table.1 Comprehensive early warning model evaluation matrix.

level of risk	$\nabla > 0$	$\nabla = 0$	$\nabla < 0$
$\nabla > 0$	stable	Relatively stable	I warning
$\nabla = 0$	Relatively stable	Critical warning	II warning
$\nabla < 0$	I warning	II warning	III warning

The quantitative results of surrounding rock stability show the abrupt change characteristic values of Q_1 and Q_2 microseismic events in Table 2 (taking the abrupt change characteristic values of the second and third stages of microseismic events as examples). On May 11, 2019, the characteristic values of Q_1 and Q_2 of the microseismic event both jumped and quickly turned negative, and the comprehensive warning level was III. It was not until May 19, 2019 that the abrupt characteristic values of Q_1 and Q_2 of the microseismic event gradually increased and returned to the stage, indicating that the local surrounding rock system of the cav was seriously affected by the excavation disturbance at this stage. Local instability slip may occur in the surrounding rock system of the cavern, and each voxel divided on the three-dimensional coordinate space of microseismic events is assigned a comprehensive risk abrupt warning level based on microseismic Q_1 and Q_2. When the time series of daily microseismic events Q_1 and Q_2 is passed over, the warning level of each voxel also changes accordingly. When the risk level of the voxel reaches level Ⅰ, the voxel number of early warning can be quickly located through the octree tree structure, and the corresponding location of the potential instability area of surrounding rock can be given.

Table.2 Evaluation results of surrounding rock mass stability early warning model.

Day	∇_1 (Q_1)	∇_2 (Q_2)	Level of risk	Day	∇_1 (Q_1)	∇_2 (Q_2)	Level of risk
5.3	3.70E+13	4.60E+16	stable	5.13	-5.83E+16	-3.89E+18	Ⅲ arning
5.4	1.16E+10	3.29E+16	stable	5.14	-3.74E+14	-1.55E+18	Ⅲ arning
5.5	3.20E+12	2.01E+16	stable	5.15	-2.03E+14	-4.64E+17	Ⅲ arning
5.6	3.73E+15	1.01E+16	stable	5.16	-2.14E+16	-4.55E+16	Ⅲ arning
5.7	9.47E+14	4.07E+15	stable	5.17	9.93E+12	7.36E+15	stable
5.8	1.03E+15	9.96E+14	stable	5.18	2.99E+10	-1.36E+14	Ⅰ warning
5.9	1.16E+15	5.37E+13	stable	5.19	1.38E+16	3.03E+17	stable
5.10	1.23E+15	9.11E+13	stable	5.20	2.13E+15	1.17E+18	stable

4 CONCLUSION

In this paper, two efficient precursor indicators of perimeter rock instability are proposed based on the octree theory, and the following conclusions are obtained by using the time series of spatial aggregation and frequency of MS events and energy deviation based on the octree, quantitative analysis of the early warning state of perimeter rock instability using the cusp mutation model, and consistency checks of MS event precursor parameters.

(1) the octree theory has efficient computational efficiency, based on the theory of octree generated multi-level tree structure and voxel in three dimensional space time point has good joint degrees, by traversing the space of daily MS events, based on the theory of octree generated multi-level tree structure division level can obtain seismic event space aggregation degree.

(2) in instability of surrounding rock damage process, based on the seismic spatial concentration and frequency deviation, energy will be the cusp catastrophic model, can effectively identify surrounding rock instability of early warning and the potential damage of surrounding rock band, the quantitative method of early warning time zones and potential damage zone and the recognition of high seismic precursory characteristics, field survey results are highly consistent, The rationality and applicability of this method are fully proved.

REFERENCES

ASTM D 7012-10. 2010. *Standard test method for compressive strength and elastic moduli of intact rock core specimens under varying states of stress and temperatures*. American Society for Testing and Materials:

Dai F, Li B, et al. *Deformation forecasting and stability analysis of large-scale underground powerhouse caverns from microseismic monitoring*. International Journal of Rock Mechanics & Mining Sciences, 2016, 86: 269-281.

Dou L M, Feng L F, CAI Wu, et al. Seismo-acoustic precursor identification and comprehensive warning model for the catastrophic failure process of coal and rock Journal of Mining and Safety Engineering, 2020, 37(05): 960-968+976.

Li H B, Liu M C, Xing W B, et al. *Failure Mechanisms and Evolution Assessment of the Excavation Damaged Zones in a Large-Scale and Deeply Buried Underground Powerhouse*. Rock Mechanics and Rock Engineering, 2017, 50(7): 1883-1900.

Zhao Y, Zhang J W, Yuan S F. *Safety Evaluation for Stability of Underground Powerhouse Surrounding Rock Based on Catastrophe Theory*. Journal of Rock Mechanics and Engineering, 2014, 33(S2): 3973-3978.

Zhao Y L, Peng Q Y, Wan W, et al. *Safety evaluation for stability of underground powerhouse surrounding rock based on catastrophe theory*. International Journal of Mining Science and Technology, 2014, 24(06): 737-745.

Zhou Zihan, Chen Zhonghui, Zhang Lingfan, et al. *Energy principle based catastrophe study of slope stability in open-pit excavation*. Rock and Soil Mechanics, 2019, 40(12): 4881-4889.