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Technical Note

Identification of early-warning key point for rockmass instability using acoustic emission/microseismic activity monitoring

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1. Introduction

Rockmass is a complex elastoplastic geological body. Under external loads, macroscopic failure is produced through cracks within a variety of micro-crack formations. In the process of rockmass instability, it is accompanied with crystal dislocation, crystals slip, elastoplastic deformation, crack initiation, and propagation until instability occurs. Simultaneously, energy is released in the form of stress waves. Stress wave techniques, such as acoustic emission (AE) and microseismic (MS) monitoring, have been used for many decades to study the fracturing behavior of rocky materials. AE uses transient waves emitted by the initiation and propagation of cracks when a material is under stress [1]. In the 1930s, Obert and Duvall discovered AE event activity from the internal structure of rock under pressure; explosive AE events were monitored in the Amick copper mine in 1940 to predict the advent of rockburst [2]. This phenomenon shows that the physical and mechanical properties of rock material itself are closely related to the loading process and mechanism. AE phenomena vary with the nature of the rock material and loading methods.

Regarding AE activity rate characteristics throughout the entire process of rock failure, several researchers have focused on rock compression, tension, shear and fracture testing [3–7]. These researchers intensively studied the relationship between stress, strain, and AE parameters before rock peak intensity. Several studies reported the characteristics of the relatively quiet period of AE before rock failure [8–10]. The characteristics of MS events activity rate and *b*-value change of rockmass instability was successfully obtained through 6 stope collapses in deep mining [11]. A few reports have analyzed the characteristics of the relationship between the activity rate of MS events, apparent volume (AV), and other parameters in the process of rockmass instability [12–14]. However, in this study, this method has been applied and verified in the field. This Research, based on precursor characteristics data obtained from laboratory tests and field monitoring, has identified the early-warning key point of rockmass instability.

2. Experimental setup

2.1. Laboratory testing system

The AE characteristics were tested throughout the rock rupture process by an MTS815 hydraulic servo rock mechanics test system (MTS System Co., Eden Prairie, USA) and an SAMOS system PCI AE instrument (PAC Co., New Jersey, USA) in the laboratory. The loading method utilized axial strain control, and the loading rate was 2×10^{-6} mm/mm s^{-1}. The sampling interval was set as 50 ms for the AE monitoring, the frequency was 0.1–10 kHz, and the acoustic signal trigger level was 3.6–4.5 mV. The increment of AE (IAE) events refers to the AE event increment data obtained from 5 s of continuous monitoring during the compressive test, as shown in Table 1. The precursor's information characteristics were obtained by uniaxial testing.

2.2. Field testing system

In August 2007, a digital 24-channel MS monitoring system (ISSI Co., South African) consisting of gwelve sensors and 4 QS seismic data acquisition instruments was established to monitor the MS events in deep mining. The MS monitoring system routinely manufactures two kinds of geophones, with natural frequencies of 4.5 Hz and 14 Hz. The 4.5 Hz geophone has a usable

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Table 1
Test results of stress and increment of AE (IAE) events before peak strength.

Serial number	Monitoring items	Monitoring data										Rock properties
1	Stress/MPa	60	65	68	71	79	83	90	94	***96***	89	Beresitization granite
	IAE events	5	7	8	10	8	7	1	1	***5***	7	
2	Stress/MPa	70	73	78	86	92	99	107	***110***	98	85	
	IAE events	9	10	12	13	15	2	1	***7***	12	13	
3	Stress/MPa	66	65	71	72	75	76	82	84	***85***	78	
	IAE events	7	8	9	8	11	3	1	4	***6***	12	
4	Stress/MPa	68	72	73	78	83	92	99	***103***	81	78	
	IAE events	9	12	10	13	15	2	3	***11***	13	15	
5	Stress/MPa	53	58	65	68	71	75	81	86	***87***	82	
	IAE events	4	7	9	11	9	1	1	2	***9***	12	
6	Stress/MPa	58	62	67	71	76	81	86	***88***	78	71	Argillaceous limestone
	IAE events	5	7	7	5	0	1	2	***4***	10	9	
7	Stress/MPa	42	48	53	59	61	66	67	***69***	61	57	
	IAE events	7	9	12	6	0	2	1	***5***	9	9	
8	Stress/MPa	52	58	62	68	71	75	82	87	***89***	83	
	IAE events	7	9	8	2	1	0	1	3	***7***	10	
9	Stress/MPa	48	51	57	60	65	72	76	79	***82***	76	
	IAE events	7	13	11	8	6	1	0	2	***6***	8	
10	Stress/MPa	57	59	63	61	66	69	76	***78***	75	69	
	IAE events	12	8	2	0	1	1	5	***7***	15	10	
11	Stress/MPa	25	29	34	33	35	40	43	***44***	39	35	Coarse crystalline dolomite
	IAE events	5	7	7	6	2	1	0	***4***	6	7	
12	Stress/MPa	20	21	25	26	28	31	35	37	***38***	32	
	IAE events	7	6	8	5	2	0	1	3	***5***	5	
13	Stress/MPa	24	27	29	32	34	38	39	***41***	37	35	
	IAE events	6	5	1	1	0	1	4	***4***	8	5	
14	Stress/MPa	9	11	12	15	16	20	23	25	***26***	21	
	IAE events	4	5	7	8	4	1	0	2	***5***	8	
15	Stress/MPa	13	16	18	17	20	22	23	***25***	21	16	
	IAE events	5	8	9	5	3	1	1	***6***	8	5	
16	Stress/MPa	10	15	19	21	25	28	29	***31***	27	24	
	IAE events	5	7	9	5	1	0	4	***4***	8	9	
17	Stress/MPa	8	9	10	12	15	16	19	21	***22***	17	
	IAE events	5	7	9	9	5	1	1	2	***5***	5	
18	Stress/MPa	16	21	24	28	31	32	33	***35***	33	29	
	IAE events	7	6	5	2	0	1	6	***8***	6	7	

Notes:

- The test results in Table 1 are only partial data.
- The monitoring data in Table 1 are peak strength portion in the whole monitoring process.
- The shaded ranges are the AE quiet period.
- The italics and overstriking digitals are the peak strength and IAE.

frequency bandwidth of between 3 Hz and 2000 Hz but must be installed to within two degrees of its pre-set orientation with respect to the vertical. The 14 Hz geophone is omni-directional and can be installed at any angle, with a usable frequency bandwidth of between 8 Hz (− 3 dB point) and 2000 Hz. The transmission distance of signal is 20–250 m from sensors to QS box and the distance is 650–1100 m from QS box to underground central communication hub. The positional accuracy of system is 8.804 m, 0.315 m and 3.233 m by three artificial seismic sources [15].

The monitoring system was designed, installed, debugged, tested, and subjected to data processing by Wang [16–18] and Wu [19]. The system was applied to predict rockmass instability in deep mining under complex geological conditions to identify the early-warning key point of rockmass rupture.

3. Theoretical bases

In light of the static stress drop as a parameter of the source model, the AV was introduced by mine seismology experts to describe the source model using focal volume parameters. The AV scales the volume of rockmass with coseismic inelastic strain of an order of apparent stress over rigidity [20–22]. The AV is less model dependent than the source volume, and is a scalar. The cumulative apparent volume (CAV) curve can then be expressed as:

$$m = \log(A/T) + C \tag{1}$$

$$M = 10^{(3/2)(m+6.1)} \tag{2}$$

$$\sigma_A = GE/M \tag{3}$$

$$V_A = M/(c_3\sigma_A) = M^2/(c_3 GE) \tag{4}$$

where m is the magnitude; A/T is the maximum displacement over the associated period in the P- or S-wave group; C is a correction for path effects, site response, and source region. The correlation factor C is used to adjust the value of seismic magnitude by the MS monitoring system, it is related to system bates geological structure and rock condition. In this MS monitoring system, C is equal to zero through a few times tests in this mine; M is the seismic moments; σ_A is the apparent stress; G is the stiffness modulus; E is the radiated seismic energies; V_A is the AV; and c_3 is a scaling factor ($c_3 \approx 2$).

The slope of the CAV curve sensitively reflects changes in the strain rate. Accelerating deformation over a period of time is an indication of unstable rockmass deformation. Larger events stand out as jumps in the cumulative curve without distorting the scale, as is the case for cumulative seismic energies or moments. In

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