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Technical Note

Fractal analysis of acoustic emission during uniaxial and triaxial loading of rock

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1. Introduction

The acoustic emission (AE) technology has been widely used for site monitoring and forecasting geotechnical hazards or instabilities, such as rockbursts[1–11]. In a broad sense, AE is a phenomenon of transient elastic wave emission due to rapid local energy release of materials. It is a course of stress relaxation during the transition from an unstable high-energy state to a stable low-energy state caused by an uneven stress distribution in the material. Compared with conventional monitoring methods, such as a multipoint displacement meters, AE technology can monitor the internal cracking of surrounding rocks before the failure manifestson the surface of a structure.

Many studies have been carried out on the AE characteristics of rocks. For example, Lockner reviewed the successes and limitations of AE studies as applied to the fracture process in rock with emphasis on the ability to predict rock failure[12]. Application of laboratory AE studies to larger scale problems related to the understanding of earthquake processes was also discussed. Osamu et al. investigated the stochastic process of AE occurrence, event times of AE were measured during steady creep phases under different stress levels[13]. Zhang et al. conducted AE tests on a large gneiss deposit with a sample dimension of up to 1.05 m, studying two different precursor phenomena for predicting the macro-failure of rocks based on AE records, an accelerated release of energy and a sharp increase in the loading and unloading response ratio[14]. Yang et al. conducted AE tests on coal under compression and proposed a method for determining the time to failure[15]. Vilhelm et al. studied the application of self-correlation analysis to interpret and analyze the AE signals of rocks[16]. Moradian et al. analyzed the acoustic characteristics of three different material combinations, rock–concrete, rock–rock, and concrete–concrete, during a direct shear tests. The results indicate that the AE technique is sufficiently accurate to monitor the shear behavior of joints and can thus be used for site monitoring[17]. He et al. investigated the effect of the bedding plane orientation on the rock burst behavior of sandstone using AE events and AE energy to show the damage level and accumulated energy, respectively[18].

Previous studies mainly focused on the AE temporal distribution characteristics but seldom on the three-dimensional AE distribution representing micro-rupture in space due to the uncertainty of location of AE source space caused by reflection and refraction of stress waves as well as the limited sampling frequency of testing equipment. Recently, by virtue of the rapid development of AE equipment and computation techniques, an increasing number of studies on AE spatial distribution tests have been reported[19–30]. For example, Lockner et al. developed a fast-acting axial control system that adjusts the load applied to the sample to maintain a constant acoustic-emission rate, and the post-peak-stress region, in which a macroscopic fault formed in

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the sample, can be studied[31]. Inversion of the arrival-time data provides three-dimensional locations of AE hypocenters, resulting in detailed imaging of fracture nucleation and propagation. Lockner et al. conducted triaxial compression tests on intact samples of granite and sandstone at 50 MPa confining pressure[32]. They aimed at investigating the AE events leading up to fault nucleation in an attempt to observe precursory changes in the locations and amplitudes of these events. Lockner et al. also discussed the experimental evidence related to nucleation and growth of fractures and these observations were used to develop a conceptual model, based on crack interactions, which described the fault nucleation phase[33]. Shah et al. performed unconfined compression experiments on Charcoal granite specimens with the monitoring of acoustic emission[34]. The analysis of interaction between spatial and temporal clustering revealed the size of clusters in both space and time. Meglis et al. carried out uniaxial compression and bi-directional loading tests on large Lac du Bonnet granite samples[19,20]. The micro-cracking and failure mechanism of the granite samples were monitored via AE techniques. Lei and Moura et al. conducted researches on rock AE location and rock failure precursor21–25. Xu et al. performed AE location tests on fine sandstone under a circulating load[26], and the AE time-space evolution characteristics and damage evolution of rocks were analyzed. Graham et al. studied two methods, the polarity method and moment tensor inversion method, for AE source location analysis and classification[27]. Dresen et al. used AE location technology to study the course of crack nucleation, development and evolution by applying three-dimensional uniform pressure on Bentheim sandstone samples with different apertures up to 195 MPa[28]. Ai et al. studied the AE space-time evolution rules and energy releasing characteristics during deformation and the failure process of coal in triaxial and unloaded tests[29,30]. Their studies indicated that the acoustic spatial distribution can track the cracking evolution of rock samples with pre-fabricated cracks or holes.

Although fundamental researches on AE have been performed in the last decades as described above, AE is one of the few technical disciplines in which theoretical study[35,36] lags behind engineering practice, as a theoretical understanding of the AE mechanism and testing standard are far from maturity. The monitored AE data comprise a massive amount of information related to damage evolution of the surrounding rocks, but investigation of dynamic disasters according to the AE spatial–temporal distribution parameters and migration characteristics remains difficult. Thus, systematic AE tests and research are necessary to unravel the relationship between AE parameters and rock failure during the complete rock damage process.

Ever since Mandelbrot initiated the concept of fractals, the theory has been received increasing attention from scientists and technicians in various fields[37,38]. The theory of fractals is based on the concept of self-similarity or self-affinity, and it provides a powerful nonlinear theory to solve chaotic and irregular problems that appear to be disordered, unsystematic, scattered and fragmented. Some researchers reported that fractal dimensional reduction of the AE signals can be used to predict rock instability 39–43. However, present research mainly focuses on the temporal or spatial distribution fractal dimension of AE during the loading of rocks[32,39,42–44], the associated studies of the spatial–temporal fractal dimension is rarely reported, especially during the triaxial loading of rocks.

In this paper, advanced AE testing equipment is employed to perform both uniaxial and triaxial compression tests on granite samples. The real-time evolutions of AE spatial–temporal distribution were obtained; both fractal characteristics of the spatial and temporal distribution of AE are revealed.

2. Experimental description

2.1. Experimental facilities

The MTS815 Flex Test GT mechanical test system and PCI-2 AE system manufactured by the Physical Acoustic Corporation (PAC) were used for this study. Real-time monitoring of AE spatial–temporal distribution can be realized simultaneously during the loading process. The maximum axial loading capacity of the MTS815 Flex Test GT mechanical test system is 4600 kN, and the maximum confining pressure that can be applied is 140 MPa. The range of bandwidth frequencies of the PCI-2 AE system is 1 kHz–3 MHz. The maximum signal amplitude is 100 dB, and the dynamic range is more than 85 dB. Real-time AE characteristic parameter acquisition, waveform acquisition and analysis can be carried out simultaneously. Graphical image display and storage of the real-time liner location, surface location and spatial location during crack development in the sample (i.e. migration track of AE source) can be carried out during the test.

2.2. Experimental materials

The testing granite, biotite monzogranite, was collected from underground caverns of a hydropower station in Southwest China. It is composed of coarse grains with varying sizes of quartz (grey), potassium feldspar (flesh pink), anorthose (off-white) and biotite (black). The samples were prepared as standard cylinders with a length of 100 mm and a diameter of 50 mm. The real size and the strength of the samples are shown in Table 1.

2.3. Experimental methods

Both uniaxial compression and triaxial compression tests were conducted in conjunction with the real-time monitoring of the AE spatial–temporal distribution. The uniaxial compression tests were conducted on four granite rock samples. The triaxial compression tests were conducted on five samples with the confining pressures set to be 10, 20, 40, 60, and 80 MPa.The rock samples were collected from the same rock block to minimize the sampling variations.

In the tests, the longitudinal and transverse deformations of rocks were measured by a longitudinal extensometer and a circumferential extensometer, respectively, and the axial load was measured by an axial force sensor. Six or eight AE sensors were used to monitor AE spatial–temporal distribution in real time in uniaxial and triaxial tests, respectively. The type of AE sensors is micro30 and its frequency is 100–400 kHz. To ensure good coupling, vaseline was applied to the contact positions between the rock samples and AE sensors; to reduce boundary effects, Teflon was applied between the test sample and upper/lower pressure heads. The AE threshold was set to 40 dB. The schematic drawing of arrangement of AE sensors is shown in Fig. 1. To check and ensure the location resolution of the AE events, we conducted pencil lead fracture tests before experiments. The location resolution in this test is about 4 mm.

3. Fractal dimension calculation of the AE spatial–temporal distribution

3.1. Fractal dimension of the AE temporal distribution

The fractal dimension is a key characteristic parameter to describe fractal structures. It can provide a quantitative description of the complexity of the internal structure of a substance. The correlation dimension is an important fractal dimension widely