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Moment tensor analysis of acoustic emission for cracking mechanisms in rock with a pre-cut circular hole under uniaxial compression

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ABSTRACT

Acoustic Emission (AE) technique and moment tensor (MT) analysis were both applied to study the spatial–temporal evolution of micro-cracks of coarse-grained granite samples, containing a circular opening, which were subjected to uniaxial compression. The results show that AE locations are in agreement with the macroscopic fractures, observed on the surface of the granite specimens after the end of the experiments. Shear cracks are dominant as the ratio is more than 40% of the total number of events, tension cracks are fewer, since they accounted for more than 30% of the total events, and mixed-mode cracks represent a minimum proportion.

1. Introduction

Acoustic Emissions (AE) technique can continuously monitor the spatial–temporal evolution of micro-cracks and, thus, may reveal the deformation processes as well as the failure mechanisms in rocks under loading. Pioneering works of the AE studies on rocks were performed by Mogi [1] and Scholz [2]. Following these works, a series of achievements has been realized, e.g., the AE location algorithms, the temporal–spatial evolution behaviors of micro-cracks in rock bodies and the change of the AE parameters during rock fracture process [3–9]. In the study of rock mechanics, it is not sufficient only to know where the micro-cracks take place. The deep understanding on the development and propagation of the micro-cracks requires knowledge of their fracture modes. The realization of this objective becomes possible using analysis method of moment tensor (MT) theory. MT inversion is a quite useful and quantitative approach for AE source analysis. In 1971, Gilbert [10] introduced for the first time the concept of the MT in the study of rock failure process. Aki and Richards [11] proposed the eigenvalue formulas of the MT for shear-mode fracture and tensile-mode fracture. Ohtsu [12,13] presented the details of the MT theory for determining the direction, the mode and the volume of cracks, and developed a software package called Simplified Green's Function for Moment Tensor Analysis, SiGMA. Chang and Lee [14] determined that the micro-cracks within a rock under triaxial compression are primarily shear cracks, and their proportions were augmented along with the increase of the confining pressures. Lei et al. [15] found that in coarse-grained granite samples, the overall failure process was dominated by shear cracks, while in fine-grained granite samples tensile cracks dominated in stress states below 80% of

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Nomenclature

M	moment tensor of the AE source model
C_{ap}	Akaike Information Criterion
l_1, l_2	degree of the Auto-Regression model
σ_1^2, σ_2^2	variance of the Auto-Regression model
$G_{ip,q}(\mathbf{x}, \mathbf{y}, t)$	Green's functions
m_{ij}	MT components
$A(\mathbf{x})$	first motion of the AE signal
$S(t)$	source time function of crack motion
Cs	physical coefficient containing sensor sensitivity
X, Y, Z	shear, hydrostatic and deviatoric component of cracks, respectively
$\lambda_{\max}$, λ_{int}, $\lambda_{\min}$	maximum, intermediate and minimum eigenvalues of **M**, respectively
$Ref\,(\mathbf{t}, \mathbf{r})$	reflection coefficient
l	vector of motional directions of the cracks
n	vector of normal directions of the cracks
σ_r	radial stresses
σ_θ	tangential stresses
$\tau_{r\theta}$	shear stresses

the peak stress that was beyond the stress limit at which shear cracks started increasing progressively. Based on the tests of hydro-fracturing with the use of AE techniques, Manthei et al. [16] considered that the directions of the macroscopic fracture surfaces coincide with those of the micro-crack directions according to the MT analysis. In the studies performed by Graham et al. [17] and Charalampidou et al. [18], the polarity method and the MT analysis could both provide similar results in terms of the AE source mechanisms, depending on the classification of the micro-crack types.

Although many significant studies have been performed on the fracturing mechanism of micro-cracks using the MT theory, these studies investigated mainly for solid specimens. In underground engineering structures, such as mines, tunnel and deep-buried underground powerhouse, rock mass stability is influenced by the excavation and apparent stress concentration at the roof and side wall of such structures. The circular openings are cross-sectional structure in underground engineering, whose progressive fracturing processes have been extensively studied by numerical simulation but lack of experiment researches. In the view of the above factors, uniaxial compression experiments have been carried out in coarse-grained granite samples with a circular opening, together with AE monitoring.

2. Experimental procedure

Coarse-grained granite that the grain size is from about 2 mm to 9 mm and is about 5 mm in average, were used in this work. The rock was processed to Cubic, with approximately 300 mm in length, 300 mm in height and 100 mm in width. A circular opening of the size ϕ 60 mm was drilled in middle of the specimen, as shown in Fig. 1. A servo-controlled machine with a maximum loading of 3000 kN, which records the amount of load and the degree of displacement in real time, was used during the uniaxial compression experiments. The Sensor Highway-II (SH-II) system produced by the American Physical Acoustics Corporation (PAC), was used for the AE monitoring. This system uses an 18 bit A/D switching technology that allows instant time waveform recording, whose maximum upper limit amplitude is ±10 V. During the experiments, the loading rate was set to 20 kN/min. In this study, AE signals were amplified by 40 dB, and the amplitude threshold, the sampling frequency, and the sampling length were set at 18 mV, 2.5 MHz and 8192, respectively.

Eight Nano30 type sensors are used to acquire AE signals, of which the operating frequency is 125–750 kHz. Each sensor was equipped with a 1220A-AST type pre-amplifier. During the experiment, the sensors were fixed on the side face of the samples with rubber bands. Vaseline was smeared between the AE sensors and the interfaces of the granite sample to ensure a good coupling. Moreover, plastic sheets were placed between the pressure platens and specimens to reduce friction signals.

As a result of the existence of the prefabricated structure, AE waveforms will exhibit refraction and reflection when they are radiated to the boundary of the circular opening, which can lead to changes in the P-wave onset times and amplitudes of the first motions. In this work, eight sensors were placed in two different arrangements, so as to provide a good coverage while monitoring the AE events. One arrangement involves eight sensors located on the upper part of the rock specimens to study the failure process of the upper half of the rock, as shown in Fig. 1a, while the other arrangement involves the layout on the right side, as shown in Fig. 1b. Before experiment, the P-wave velocities were measured twice for each specimen in horizontal and vertical direction (Table 1). The average of the measured values is used for the location calculations of the AE events. In this paper, the P-wave velocities during rock failure were supposed as constant.