Computers and Geotechnics 92 (2017) 1–10

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

A numerical study on cracking processes in limestone by the b-value analysis of acoustic emissions

Qi Zhang, Xiao-Ping Zhang *

The Key Laboratory of Safety for Geotechnical and Structural Engineering of Hubei Province, School of Civil Engineering, Wuhan University, Wuhan 430072, China

ARTICLE INFO

Article history:
Received 3 April 2017
Received in revised form 17 July 2017
Accepted 20 July 2017

Keywords:
Cracking processes
AE amplitude
b-value
Bonded-particle model (BPM)
Moment tensor

ABSTRACT

To better investigate the cracking processes under uniaxial compression, a numerical approach using bonded-particle model (BPM) was adopted to simulate the loading processes and AE events of limestone. To validate the model, a physical experiment with acoustic emission (AE) monitoring was performed. It revealed that the AE parameters in the BPM including crack number and AE event were generally comparable with the AE count and AE hit in the experiments. The b-value of AE does not accurately evaluate the degree of damage in rocks. But it can indicate the different states of damage during cracking processes.

1. Introduction

Rocks subject to external loads produce plastic deformation or form cracks, with rapidly releasing energy in the form of elastic waves [1]. This phenomenon is known as acoustic emission (AE). The modern acoustic emission technology was initially introduced by Kaiser who studied acoustic phenomenon in a tensile test [2]. Nowadays, the AE technique is widely used to study the cracking and failure processes in rocks [3–10]. AE signal parameters, such as AE counts, hits, duration, amplitude, rise time and energy, can allow investigation of the process of crack initiation, propagation and coalescence and interpretation of the failure mechanism of rocks. Fig. 1 shows a typical AE signal of an AE hit. When the AE amplitude reaches a threshold, it records as an AE count. An AE hit generally contains several AE counts. An AE amplitude refers to the peak amplitude of an AE hit. Many researchers use characteristics of acoustic emission to study the progressive mechanisms of rock failure. He et al. [11] studied the characteristics of AE during rock burst process of limestone under true-triaxial unloading conditions. Xiao et al. [12] studied the relationship of acoustic emission characteristics and stress release rate of coal samples in different dynamic destruction stages. Li et al. [13] investigated and analyzed the rock burst mechanism induced within fault–pillars based on acoustic emission characteristics. Fortin et al. [14] adopted three-dimensional (3-D) locations of acoustic emissions to analyze the development of compaction bands in Bleurswiller sandstone. Yang et al. [15] explored the acoustic emission behavior of granite after subjected to different high temperature treatments.

As for numerical methodology, a great number of researchers have focused on developing and validating numerical models to reproduce acoustic emission and capture the progressive mechanical breakdown in rocks. Tang et al. [16,17] initially introduced a numerical code, RFPA (Rock Failure Process Analysis) that was used to study progressive rock failure and damage accumulation during brittle rock failure associated AE. Lisjak et al. [18] described another AE modeling technique based on the combined finite-discrete element method (FEM/DEM), which simulated material failure by explicitly considering fracture nucleation and propagation in the modeling domain. Lattice model, a discrete element method, was developed and used to model the rock failure and earthquake process associated with the AE technique [19,20]. Hazzard & Young [21] developed an AE technique in a bonded-particle model (BPM), which used particle kinetic energy on bond breakage to quantify seismic energy radiated from the source. This method was not accurate enough to calculate the b-value during the cracking processes in rock-like material. An improved method using moment tensor based on change in contact forces on particle contact breakage was used to simulate micro-seismic activity of a mine-by experiment in a crystalline rock [22] and investigate seismic velocity changes in brittle rock due to stress and damage [23]. In the present study, this approach was used to study the relationship between various stages of b-value and the fracture growth

* Corresponding author.
E-mail addresses: swqzhang@163.com (Q. Zhang), jxhkzhang@163.com (X.-P. Zhang).

http://dx.doi.org/10.1016/j.compgeo.2017.07.013
0266-352X/© 2017 Published by Elsevier Ltd.

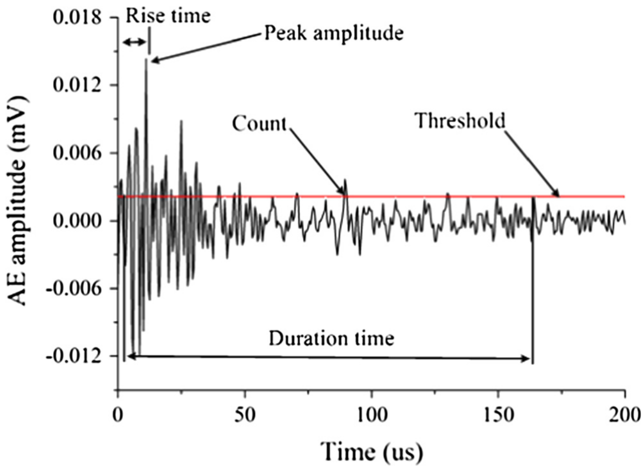

Fig. 1. Parameters of an AE signal.

under uniaxial compression. To validate the numerical approach, a physical experiment and numerical simulation for limestone were carried out to present a quantitative comparison of acoustic emission characteristics in different load stages. For the b-value, it is defined as the log-linear slope of the AE cumulative frequency-magnitude distribution. The equation is as follows:

$$\log_{10}N = a - bM \tag{1}$$

where M is the magnitude of the event, and N is the cumulative number of events with magnitude greater than M; a is an empirical constant; b is the gradient. This equation is also called Gutenberg-Richter formula. In case of the AE technique, the Gutenberg-Richter relationship is modified as:

$$\log_{10}N = a - b(A_{dB}/20) \tag{2}$$

where A_{dB} is the peak amplitude of AE hit and N is the cumulative number of AE events with amplitude greater than $A_{dB}/20$; The Richter magnitude of the event is a logarithmic scale of instrumentally measured amplitude, while AE amplitudes recorded in dB are divided by 20 to produce the same form of the relation [24]. a is an empirical constant; b is the b-value of AE. b represents the percentage of low amplitude events in comparison to high amplitude events. A large b-value represents a larger proportion of low amplitude events, and vice versa.

2. AE Simulations in the BPM

The bonded-particle model (BPM) simulates rock and soil as a dense packing of circular particles in 2D or spherical particles in 3D. The breakage of a bond between particles forms a micro-crack. The initiation, propagation and coalescence of the micro-cracks form macroscopic fracture zones when loads are applied. The model can realistically simulate most of the rock behavior, e.g., fracturing, cracking processes under uniaxial, biaxial or triaxial compression, dilation and post-peak softening [25]. It had been demonstrated that the BPM had the capacity to study cracking processes in intact rocks or rock-like material with flaws [26–34]. In addition, acoustic emission (AE) also can be simulated in the BPM. The initiation of micro-cracks is associated with releasing strain energy, and the bond breakages form AE events [21]. The energy released by bond breakages, in the form of seismic waves, produces further cracking activity by increasing local stresses. The force changes at contacts around the source particles on either side of the micro-crack were used to calculate the moment tensor of an AE event. The scalar moment tensor was used to measure the AE magnitude [22,35]. If bond breakages occur close in time and space, the cracks are considered as belonging to the same AE event. Hazzard et al. [22] adopted Silver's method to compute the scalar moment tensor:

$$M_0 = \left(\frac{\sum_{j=1}^{3} m_j^2}{2}\right) \tag{3}$$

where m_j is j th eigenvalue of the moment tensor matrix. This model is the simplest model without the decomposition moment tensor. The moment magnitude corresponding to an event can be obtained from the scalar moment:

$$M_w = \frac{2}{3}\log M_0 - 6 \tag{4}$$

Bowers and Hudson [36] decomposed the moment tensor into an isometric tensor and a deviatoric tensor:

$$M = \mathrm{m}^{ISO} + \mathrm{m}^{Deviatoric} \tag{5}$$

where $\mathrm{m}^{ISO} = (\mathrm{m}_1 + \mathrm{m}_2 + \mathrm{m}_3)/3$ and $\mathrm{m}^{Deviatoric} = \mathrm{m}_j - \mathrm{m}^{ISO}$, ($j$ = 1, 2, 3). The isometric part (M_I) and deviatoric part were defined to be [37]:

$$M_I = |\mathrm{m}^{ISO}| \tag{6}$$

$$M_D = \max(|\mathrm{m}^{Deviatoric}|; \quad j = 1, 2, 3) \tag{7}$$

The isometric part indicates the change in volume due to explosion or implosion. The deviatoric part reveals the shear displacement. The scalar moment tensor was defined as

$$M_0 = M_I + M_D \tag{8}$$

For the pure double couple source, Eqs. (3) and (8) yield the same moment M_0. The advantages of Bowers's method were decomposition moments for dilatational and shear mechanisms at the source [36]. These two mechanisms are usually accompanied by different physical processes. In terms of the source, the moment tensor matrix (M) is usually assumed to be double couple source. For shallow sources, M is interpreted as a simple shear displacement model. The Bowers's method may be more reasonable for failure mechanisms in rock mechanics. To better compare these two methods, the simulation results of AE events obtained by two different methods were presented.

3. Experimental study

3.1. Material and specimen

The uniaxial compressive tests of limestone were conducted in the laboratory of Wuhan University, China. The samples were obtained from the site of the transferring water project from Songhua River to Changchun city in Jilin province, China. The samples were cut and polished carefully into cylindrical specimens with Φ50 mm × H100 mm. To reduce the influence of the end effect, the loading platens and ends of the specimen were coated in grease during the experimental tests. The average P-wave velocity and density were 2900 m/s and 2.50 g/cm^3, respectively. The testing equipment consisted of RMT-301 rock mechanics testing system with a servo-hydraulic loading frame and PCI-2 AE system with an 18-bit A/D and frequency response of 3 kHz–3 MHz. The axial strain and lateral strain are measured by four displacement sensors under uniaxial compression as shown in Fig. 2. The loading rate was controlled at 0.002 mm/s during the whole loading process.