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Energy monitoring and analysis during deformation of bedded-sandstone: Use of acoustic emission

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ABSTRACT

This paper investigates the mechanical behaviour and energy releasing characteristics of bedded-sandstone with bedding layers in different orientations, under uniaxial compression. Cylindrical sandstone specimens (54 mm diameter and 108 mm height) with bedding layers inclined at angles of 10°, 20°, 35°, 55°, and 83° to the minor principal stress direction, were produced to perform a series of Uniaxial Compressive Strength (UCS) tests. One of the two identical sample sets was fully-saturated with water before testing and the other set was tested under dry conditions. An acoustic emission system was employed in all the testing to monitor the acoustic energy release during the whole deformation process of specimens. From the test results, the critical joint orientation was observed as 55° for both dry and saturated samples and the peak-strength losses due to water were 15.56%, 20.06%, 13.5%, 13.2%, and 13.52% for the bedding orientations 10°, 20°, 35°, 55°, and 83°, respectively. The failure mechanisms for the specimens with bedding layers in 10°, 20° orientations showed splitting type failure, while the specimens with bedding layers in 55°, 83° orientations were failed by sliding along a weaker bedding layer. The failure mechanism for the specimens with bedding layers in 35° orientation showed a mixed failure mode of both splitting and sliding types. Analysis of the acoustic energy, captured from the acoustic emission detection system, revealed that the acoustic energy release is considerably higher in dry specimens than that of the saturated specimens at any bedding orientation. In addition, higher energy release was observed for specimens with bedding layers oriented in shallow angles (which were undergoing splitting type failures), whereas specimens with steeply oriented bedding layers (which were undergoing sliding type failures) showed a comparatively less energy release under both dry and saturated conditions. Moreover, a considerable amount of energy dissipation before the ultimate failure was observed for specimens with bedding layers oriented in shallow angles under both dry and saturated conditions. These results confirm that when rock having bedding layers inclined in shallow angles the failures could be more violent and devastative than the failures of rock with steeply oriented bedding layers.

1. Introduction

Energy-related characterizations of rock can provide important information regarding their mechanical behaviour. Energy releasing characteristics of rock are of great importance in rock blasting designs to maximize the effectiveness of blasting efforts. In addition, understanding the energy releasing intensities during deformation of rock under different stress and hydrogeological conditions is helpful to mitigate the catastrophic consequences of rock slope failures. Despite these crucial implications, the energy releasing characteristics of rock have not been widely studied in the literature.

Rock is an inherently heterogeneous medium due to the presence of discontinuities and rock mechanical behaviour is influenced by various mechanical and geometrical properties of those discontinuities. As such, the energy releasing characteristics during deformation of rock are also influenced by the presence and spatial characteristics of discontinuous features. Many energy-related studies in rock mechanics have mainly considered intact rock behaviour, thus the energy-related mechanisms during the deformation of rock masses (i.e. intact rock with weaker joint planes) is less well-understood. This paper discusses the feasibility of using an Acoustic Emission (AE) system for monitoring energy release during rock deformation and the influences of the orientation of bedding layers and water saturation on energy releasing characteristics and fracturing behaviour of bedded sandstone in uniaxial compression.

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1.1. Energy release and failure of rock

Brittle rock failure is a process involving complex interactions between constituent particles. The traditional stress–strain relationship obtaining from conventional laboratory testing is generally used to characterize the mechanical behaviour of rock (and many other materials). However, it provides only limited information regarding the mechanical response of rock. A better picture of rock behaviour can be obtained by considering the energy-related mechanisms. Several studies in the literature have highlighted the importance of energy-related characterizations in describing mechanical behaviour of rock and some important outcomes of such studies in the literature are discussed below.

When taking the energy conversion into consideration, two important energy-related mechanisms (1) energy dissipation and (2) energy accumulation, that take place upon compression of rock, can be identified. Micro-crack development and consequent plastic deformation before the ultimate failure causes the irrecoverable energy dissipation, while some energy accumulates with the elastic deformation. The accumulated energy is called the strain energy or elastic energy, which is totally reversible until the ultimate failure. Fig. 1 illustrates the two scenarios in the space of stress versus strain.

By testing intact granite, limestone and sandstone samples, Xie et al. [1] showed that the rock damage is caused by the energy dissipation mechanism, which results in strength deterioration, and structural failure of rock is caused by the release of accumulated or stored elastic energy. They used the relationship shown in Eq. (1), to calculate the absorbed energy by unit volume of rock sample, e. They further found a unique relationship between failure modes and absorbed energy while stress–strain curves were not showing any relation with the failure modes.

$$e = \frac{\int FdL - E_s}{V} \tag{1}$$

where $\int FdL$ is the integral of the load (F)–displacement (L) curve, E_s is the elastic energy accumulated in the testing machine and V is the sample volume.

The elastic energy accumulation in the testing machine is also a major issue to be encountered in this way of calculating the energy release [2,3]. According to Kwasniewski et al. [4], higher values of the ratio of elastic energy to dissipated energy can create a ‘shock’ at the failure of the rock. They stated that if the value of the ratio is more than five, coal specimens generate a strong to violent shock at the failure. Wang and Park [5] suggested a method to predict rock bursts based on analysis of strain energy in intact granite and numerical simulations.

Therefore, clearly the fracture development behaviour of rock-like brittle materials upon loading is directly associated with their energy releasing characteristics during deformation. Nevertheless, vast majority of the previous studies that investigated the fracturing behaviour of rock by experimenting on various intact rock types have not considered the energy releasing behaviour during the deformation (see [6–9]).

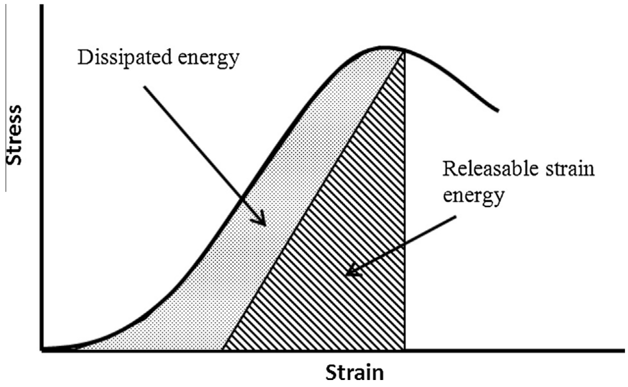

Fig. 1. Dissipated energy and releasable strain energy on stress–strain space.

1.2. Acoustic Emission (AE) technique to characterize rock failure

Acoustic emission is generally referred to the elastic waves emitted by materials undergoing microscopic changes of stress state and the waveform of an acoustic emission from a propagating crack carries information regarding the location, growth distance, velocity and orientation of the crack [10]. The emitting elastic waves are basically generated with the micro-crack development and their propagation. As Miller and McIntire [11] and Ohtsu [12] explained, an AE activity is attributed to the rapid release of energy in a material and that energy release can be related with the energy content of the AE signal. In addition, the true energy is directly proportional to the area under the AE waveform. Therefore, Eq. (2) can be used to calculate that energy [11]:

$$E_i = \int_{t_0}^{t_1} V_i(t)^2 dt \tag{2}$$

where E_i is the energy and V_i is the recorded voltage of channel i (t_0 is the starting time of the voltage transient record and t_1 is the ending time of the voltage transient record).

The definitions of different terminologies pertinent to acoustic emission waveforms are outlined in Adrian [13] and comprehensively illustrated in Roberts and Talebzadeh [14] (Fig. 2).

AE activities can be captured using AE sensors that can then convert those mechanical signals from testing materials to pre-amplified electrical signals and finally to a post amplified AE count after a proper filtration process. In general, ’AE count’ is referred to the number of times an AE signal amplitude exceeds a specified threshold value (Fig. 2). AE method has been widely used to

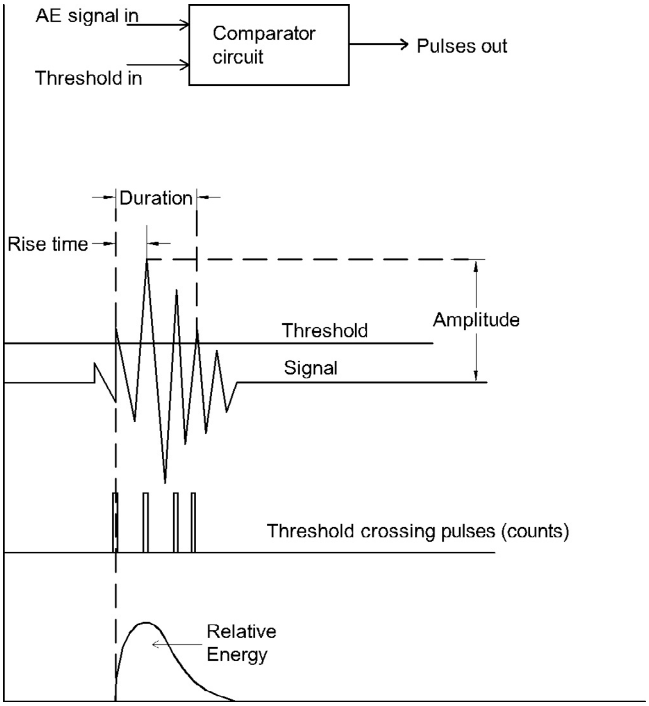

Fig. 2. Definitions of different parameters of an AE signal (after [14], page 696, Fig. 1).