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# Damage quantification of intact rocks using acoustic emission energies recorded during uniaxial compression test and discrete element modeling

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ABSTRACT

In this paper, acoustic emission (AE) energies recorded during 73 uniaxial compression tests on weak to very strong rock specimens have been analyzed by looking at the variations in *b*-values, total recorded acoustic energy and the maximum recorded energy for each test.

Using 3D Particle Flow Code (PFC3D), uniaxial compression tests have been conducted on discrete element models of rocks with various strength and stiffness properties. An algorithm has also been used to record the AE data in PFC3D models based on the change in strain energy upon each bond breakage.

The relation between the total released acoustic energy and total consumed energy by the specimens has been studied both for the real data and numerical models and as a result, a linear correlation is suggested between the released AE energy per volume and consumed energy per volume of the intact rocks.

Comparing the recorded acoustic energies in numerical models with real data, suggestions are made for getting realistic AE magnitudes due to bond breakages (cracks) from PFC3D models by proposing a modification on Gutenberg–Richter formula that has been originally proposed for large scale shear induced earthquakes along faults.

Also, using the numerical model, an attempt has been made to quantify the damage to the intact rock by proposing a damage parameter defined as the total crack surface observed during the tests divided by the total crack surface possible based on size of particles.



## 1. Introduction

It is known that the damage process of intact rocks starts with tensile cracks growing parallel to the maximum principal stress until a “critical crack density” is reached and a “process zone” is formed [50,51]. This manifests with reduction in cohesion during development and coalescence of cracks until a dominantly frictional rupture occurs along the formed shear band and the specimen fails [38,41]. A technique to observe the damage process of rocks is acoustic emission (AE) monitoring. Acoustic emission is defined as an elastic wave propagated due to a rapid release of energy within the material [37]. Analyzing the waveforms and using techniques such as Seismic Moment Tensor Inversion (SMTI), source locations as well as the mechanism of events can be identified [30].

There have been many attempts to correlate the observed AE activity with the stress level or different stages of rupture in geomaterials. It is known that there is an overall correlation between the evolution of stress strain curve in rocks and the AE rate [11,51]. Therefore, the simplest technique would be to correlate the number of events with the observed mechanical behavior [31,45,54]. However, it has been suggested that instead of cumulative number of events, the cumulative AE energy would be physically more meaningful [15,49,61].

Although there have been several studies on the AE behavior of granular soils [27,32,33], clays [32,35,57], soft rocks such as Tuff and Shale [1,14,21,42–44,58] and hard rocks mostly granite [9,53,55,62], the literature review reveals that there is an absence of reports on the variations of released energies specially for weak rocks. The main reason is probably the high attenuation of such material and the fact that many events are too small to trigger the sensors. Also, the majority of AE studies in rock materials are devoted to hard rocks while new applications of AE monitoring

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especially in Petroleum engineering require understanding of the release of AE energy in weaker classes of rocks.

Therefore, in this paper a wide range of rocks with different strength and stiffness properties have been studied with the purpose of understanding the relation between the amounts of released acoustic energy with the total consumed energy. Also, using discrete element modeling, an attempt has been made to quantify the amount of damage in terms of crack surface for the materials studied.

## 2. Theory

Any extra energy put into a system, ex. intact rock, which is already in a state of equilibrium, has to somehow dissipate so that the system regains its stable equilibrium by reaching its minimum potential energy. This decrease in potential energy to reach the equilibrium state is achieved by continuous lengthening of cracks passing the rock from unbroken to broken condition [19,18]. The dissipation of energy can be in various forms such as propagation of cracks or acoustic waves.

Fig. 1 shows the stress–deformation curve for an arbitrary rock. The area under the loading curve (solid line), A(ΔOAB), is the extra energy put into the system. Two possible response curves of the rock are shown with dotted lines. The area under these two curves, A(ΔOAE) and A(ΔOAD), would be the energy required to extend the cracks.

If A(ΔOAB) < A(ΔOAD) which is the case for a ductile rock with smaller Young's modulus, the crack will not propagate but it is possible that it undergoes some form of time-dependent weakening due to various phenomena such as flow of fluid to the crack that in turn result in reduction of the energy required to extend the crack (shifting the curve AD toward AB). In this case, although there is no excess energy yet to produce seismicity, the crack can still propagate (aseismic deformation) [13]. If A(ΔOAB) > A(ΔOAE) which is the case for a brittle rock with higher Young's modulus, the excess energy shown as the shaded area contributes to acceleration of cracks and release of seismic energy.

Fig. 1 is a simplified demonstration of how ductility contributes to the extent of AE energy with the rock being loaded elastically until point A and seismic energy released during the unloading after point A. In practice, AE events have been observed as early as the crack initiation strength (∼40–60% of the peak strength) is reached [7,5].

## 3. Description of the material and experiment

"Intact rock" in engineering terms is referred to the rocks with no significant fractures [22]. In order to understand how the intact rocks responds acoustically, a large database of laboratory tests reported by CANMET conducted as a part of low and intermediate level radioactive waste Deep Geologic Repository (DGR) design for the Ontario Power Generation (OPG) is analyzed in this paper. The repository is located within the sedimentary bedrock beneath the Bruce site near Kincardine, Ontario at about 660 m depth [16]. The Precambrian Granite basement of the site at 860 m is overlain by flat lying Palaeozoic age dolostone, shale and limestone sedimentary rocks. A review of the geomechanical properties of the rocks in DGR excavations is presented by Lam et al. [34].

A total number of 73 uniaxial tests were conducted on specimens of shale, limestone and dolostone rocks with acoustic emissions being monitored during the tests. Although an abrupt shift in stress–strain curves has been observed for some specimens indicating the existence of planes of weakness that caused failure [16] and questioning the "intact" nature of them, due to the small size of laboratory specimens, it is assumed that the majority of

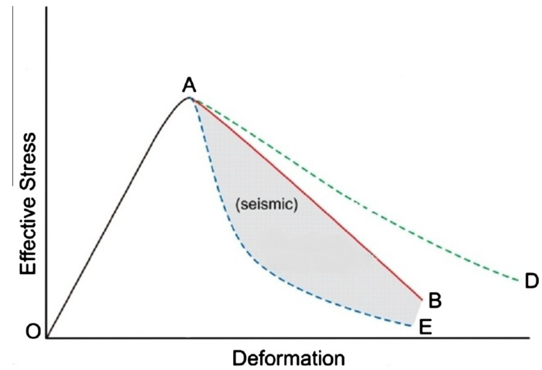


**Fig. 1.** Schematic load–deformation curve for an intact rock. OAE and OAD curves are response curves for a brittle and ductile rock, respectively. Shaded area is the excess energy released as acoustic emission (modified after [13]).

specimens have been intact and therefore the observed AE response would belong to the intact rock. According to the results, several rock units were identified based on ASTM D5878 [2]. The rocks have also been classified according to ISRM classification [4] (Fig. 2). The classifications are summarized in Table 1.

The specimens showed a wide range of compressive strengths from 1 to 200 MPa and Young's moduli from 0.5 to 60 GPa as shown in Fig. 3.

The specimens had an average length and diameter of 176 mm and 74 mm, respectively. The loading in uniaxial compression tests was conducted in stress controlled manner to imminent failure at the rate of 0.75 MPa/s based on ASTM D7012 [3]. The AE recording system consisted of 12 transducer channels, 16 bit, 10 MHz, 40 dB preamplification, 60 dB gain, high and low pass filters and source location software. Two arrays of 3 piezoelectric sensors were mounted on the outer surface at the top and bottom halves of each specimen. The sensors on each array were 120° apart.

AEWin software was used to record the AE data in the lab. Since the outputs of this software will be used for analyses in the next sections, it is necessary to describe what the recorded energies by AEWin signify. The reported energies by CANMET are "Absolute Energy". This energy is based on the sum of squared voltage readings divided by a token resistance $R$, as explained by Pollock [46] and shown in Eq. (1):

$$U = \frac{1}{R}\sum_{FTC}^{PDT} V_i^2 \cdot \Delta t \tag{1}$$

where $R$ is equal to 10 kΩ representing the input impedance of the preamplifier, FTC stands for "First Threshold Crossing" and PDT stands for "Peak Definition Time". The energies were reported in attojoules (aJ = $10^{-18}$ J). This "Absolute Energy" is a good feature to deal with larger signals resulting from burst type emissions [46].

Although since the events have a very high frequency and it is likely that there has been spreading/attenuation even on the small scale of tested specimens, due to lack of source location data, in this research it is assumed that the energy is non-dispersive and therefore, the energies recorded at the sensors are equal to the released energies at the source. Thus, without any further corrections to consider signal loss due to attenuation, having the released energy, magnitude of an AE event can be calculated by the empirical Eq. (2) [52]:

$$M_e = \frac{2}{3}\log E - 3.2 \tag{2}$$

where $E$ is the energy in Joules.