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Application of autocorrelation analysis for interpreting acoustic emission in rock

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Abstract

The statistical properties of acoustic emission from rock samples were studied as a function of applied uniaxial load. It was found that the parameters of the autocorrelation function of the acoustic emission event series change significantly near failure. An increase in the values of the autocorrelation coefficients and a tendency to a linear decrease with time were observed. We propose that the increasing autocorrelation of the acoustic emission series is an evidence of the increased affect that the individual acoustic emission sources have on one another. This mutual effect of acoustic events arises as a result of the redistribution of stress in the sample during the fracturing process at higher loads (more than 95% of ultimate strength). The results support the possibility of using autocorrelation analysis as a failure warning sign or even to predict the sample's total failure. Different rock materials and various loading patterns were used to generalise the results obtained.

Keywords: Compression; Deformation; Fractures; Laboratory measurement; Microseismicity; Rock fracture; Seismic-event rates; Statistical methods

1. Introduction

The assessment of the stress–strain state of rocks, and especially forecasting the occurrence of extensive brittle fracturing, is currently one of the significant objectives of geomechanics. The results of relevant experiments are of importance in the evaluation of underground opening stability and predicting induced seismic phenomena [1,2].

A number of methods and procedures, often based on seismic or other geological and geophysical data, have been used to study deformation processes in bodies of rock and in forecasting sudden releases of seismic energy [3–6]. The fracturing process can be studied on different scales. Szwedzicki [7], for example, showed that based on macroscopic analysis rock sample failure mechanism can be assessed (tension, shear or coupling of tension and shear). A microscopic approach was applied, for example, in real-time scanning electron microscope observations [8], Kawakata et al. [9] employed X-ray computer tomography, Wulff et al. [10] and Couvreur et al. [11] studied the attenuation of P- and S-waves, and Wei et al. [12] studied strong stress fluctuations. The rock behaviour and fracturing can be studied also by means of numerical modelling [13–15]. Liu et al. [16] showed that numerical tests can evaluate the process of rock samples fracturing by determination of the crack nucleation and initiation, and can differentiate between stable and unstable crack propagation. Based on changes in the time series of quantities studied, precursors of sudden failures may be identified. However, the identification of these precursors depends on the analysis of long-term measurements, that is, on determining the basic trend of these quantities and finding anomalous behaviour conditions, which can be interpreted as precursors. In this paper, we deal with a laboratory method of assessing the instability of rock samples based on monitoring and interpreting acoustic emissions (AE; discrete, burst-type signals [17], referred also as ultrasonic emission, since the frequency content of signals exceeds 100 kHz).

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Deformation processes, taking place in situ, can be modelled by laboratory methods under simplified conditions. Specifically, the system of stress (uni-, bi- or triaxial), the rate of loading, etc., can be chosen, and the responses of various types of rocks to loading can be studied. Although a considerable simplification of the actual deformation processes is involved, significant similarity between laboratory experiments and phenomena occurring in the natural environment can be observed. This similarity applies not only to the manner of seismic energy release (even though the dimensions of microfailures in samples are of the order of millimetres, whereas in mining tremor foci they are 10^4 times larger [18]) but also to the form of the distribution functions, for example, energy–frequency functions, after-shock sequence distribution relations, etc. [19,20]. The parameters of these distribution functions are not random, but depend on the physical (material) properties of rock (for example, granularity and primary degree of failure) and on the level of stress. The problem of similarity between the sample and in situ conditions lies in the substantially faster changes in the state of stress under laboratory conditions, and in the finite dimensions of the samples.

Time series of seismic events or AE events may be analysed using methods of statistical physics, aiming at predicting the time of failure. This approach is based on assuming that an earthquake corresponds to a critical point, but the stress state of the rock mass can approach, or move away from this critical point.

Seismicity can be described using the framework of self-organized criticality, which was originally derived from cellular-automaton models [21]. This concept produces power-law frequency–size statistics similar to the Gutenberg–Richter relationship [22]. This relation seems to be stable as long as the external driving force remains constant. If some energy loss is introduced, the model acquires a memory and this leads to seismic cycles [14,23].

The methods of forecasting total failure of rock samples are based on analysing the distribution of the AE, and mostly involve comparing these distributions under various loads. The results of the experiments we conducted and the study of time series, based on the application of autocorrelation analysis, indicate, however, that changes in the autocorrelation coefficients provide absolute criteria for determining the approaching state of sudden failure which does not require comparison with the overall preceding fracturing process. The results of locating acoustic pulses, in particular the migration and clustering of microfailure foci, can also be used to forecast total failure, as well as energy release analysis and especially the energy–frequency distribution and the pulse frequency as a function of load (or time).

2. Brief overview of methods and interpretation of acoustic emission

The forecast of a sudden release of seismic energy (whether severe earthquake, strong induced event—mining tremor, or failure of a loaded sample) consists of three parts: (1) forecasting the place, (2) the time of origin and (3) the seismic energy released. Forecasting the place is based on locating the places of failure, their migration and clustering in space. In the end, this also contributes to forecasting the time. The estimate of the failure time is based on seismic energy release analysis, the energy–frequency distribution, analysis of shock sequences, and on the autocorrelation properties of time sequences of occurrence of seismic events. All these parameters are function of the stress–strain condition of the rock mass, or sample.

The location of foci of AE sources is based on multichannel recordings of acoustic events. To determine the four unknown parameters of the focus (that is, the focus coordinates x_0, y_0, z_0 and time t_0), at least four sensors are required in the case of known P-wave's velocity propagation [24]. This velocity may also be used to assess the deformation of the sample and its failure state; such information can also be derived from the attenuation of energy [10]. For the purpose of locating the source of emissions, however, velocity variations are important [25]. Location methods serve to determine the most fractured parts of the rock sample. Correlation analysis can provide a quantitative measure of the migration of foci during the failure process [26,27]. The spatial distribution of foci can also be classified in the terms of fractal dimension D [28,29]. According to Lockner and Byerlee [30], the decrease of D from a value close to 3 (applicable to a uniform distribution of foci in space) indicates a change in the spatial distribution of foci and possible creation of fractures. Zang et al. [31], however, reported that the decrease of parameter D neither characterize the nature of any precursor to total sample failure in any of the types of rock they studied nor for the various methods of loading.

Monitoring the AE from loaded rock samples also makes it possible to determine the AE event energy. It is frequently assumed [17,32,33] that the magnitude–frequency distribution of emissions may be described by the Gutenberg–Richter relationship, well known from earthquake research [22]. This relation can be expressed as

$$\log N(M) = a - bM, \tag{1}$$

where $N(M)$ is the number of earthquakes with magnitude M or greater and variables a and b are the parameters of the distribution. In the first approximation, seismic magnitude M is proportional to the logarithm of energy E of seismic events and Eq. (1) can be rearranged as

$$\log(N_i) = A - \gamma \log(\mathrm{E}_i), \tag{2}$$

where N_i is the number of events within energy interval $E_i \pm \Delta E$ and A and γ are the parameters of the distribution [34].

However, it has been shown that this distribution is valid only over a restricted energy range. Holt et al. [35] showed for tests on pressure vessel steels that the AE energy is determined by the particle size together with the applied