Possibilities of forecasting of rock sample total fracture by application of correlation analysis of acoustic emission events series

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Abstract

The series of acoustic emission events from loaded rock samples were studied by means of correlation analysis. As characteristic parameters of the correlation functions were chosen: the first values of the autocorrelation coefficients, the number of positive autocorrelation coefficients and the linearity of the autocorrelation function. The increase in the values of the autocorrelation coefficients and the trend to their linear decrease is evidence of increased mutual effect of the individual events on one another, i.e. of the redistribution of stress in the sample. The predictive character of correlation parameters is absolute and they need not be relatively judged in the course of the whole loading process. It was found that the rock is being stressed close to its critical state if the correlation coefficient of the approximation line increases above 0.9, the correlation radius is longer then 20 s, and the value of the first autocorrelation coefficient reaches 0.6 (it is twice more than at the beginning of loading). The experiments were carried out on the various types of rock samples with different structure - sandstone and migmatite. The loading was carried out in a broad range of loading rates and different loading patterns. The nature of the ultrasonic emission originating during short-term test is influenced mainly by the response of the sample to acting force. During long-term test the parameters of ultrasonic emission reflect rheological properties of rocks sample. Results obtained under laboratory conditions could be applied to seismoacoustic investigation of rock burst occurrence.

Introduction

One of the present significant tasks of geomechanics is the assessment of the stress-strain state of rocks, and especially forecasting the occurrence of their extensive brittle fracture.
A number of methods and procedures are used to study deformation processes in rock massif and in forecasting sudden releases of seismic energy (Anifrani et al. 1995, Newman et al. 1995, Sornette and Sammis 1995, Voight 1989). In this contribution, we deal with a laboratory method of assessing the instability of rock samples based ultrasonic emissions from loaded rock samples.
Deformation processes, taking place in-situ, can be modeled by laboratory methods under simplified conditions. To be specific, the system of loading can be chosen, and the reaction of various types of rocks to the loading can be studied. Although a considerable simplification of

actual deformation processes is involved, nevertheless, significant similarity between laboratory experiments and phenomena occurring in the natural environment can be observed. This similarity is in the same manner of seismic energy release, and also in the same form of the distribution functions, e.g., energy-frequency function, time distribution of the after-shock sequence, etc. (Shibazaki & Matsu'ura, 1988). The parameters of these distribution functions are not random, but depend on the physical (material) properties of rocks (e.g., granularity, primary degree of failure) and on the level of stress. The problem of similarity between the sample and natural conditions is in substantially faster changes of the state of stress under laboratory conditions, and also in the finite dimensions of the samples.

The methods of forecasting total failure of rock samples are based on analyzing the distribution of the acoustic emission, and mostly require 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 the changes in the autocorrelation coefficients provide absolute criteria for determining the warning state of sudden failure without comparison with the preceding state.

Correlation analysis of UE sequences

In assessing the UE from a loaded sample using correlation analysis, it is possible to select the time series of the number of UE events, occurring per unit time (acoustic rate). We can start with the simple hypothesis of a loaded rock sample under uniformly increasing load as the model of the failure process of a rock massif. To compare the processes of sample failure state under various loads, we can chose time intervals, corresponding to such load, and perform the autocorrelation analysis within them independently. For comparison of the results of the autocorrelation analysis in different intervals, it is necessary to compute the frequency sequence of UE events so that the mean value of the number of events of all series being compared is the same. This can be done by choosing different lengths of the elementary time steps (sub-intervals), with respect to which the frequency of the events is being computed in the individual loading intervals.

Under low stress, inhomogeneities of the stress field at pre-existing micro-fractures and at the edges of grains are generated only gradually. In these source regions, isolated at the beginning, the strength of the material is exceeded locally and through UE the expansion of existing fractures can be observed, as well as the generation of new micro-fractures. Low values of autocorrelation coefficients are usually observed, indicating a more or less random occurrence of UE events. As the stress increases, also the number of places where the strength has been exceeded grows locally, and the separate fractures or source regions of failure may affect one another. The values of the initial autocorrelation coefficients increase, the interval of correlation increases, and a tendency to order the autocorrelation coefficients along a straight line is usually observed.

Experiment

Rock samples of migmatite and sandstone from localities in the Czech Republic were studied. The samples were loaded uni-axially. The deformation parameters were measured in the course of the loading: the acting load, and locally, at two measuring points (at half the height) the longitudinal and transverse deformations were measured by two cross strain gauges. The data from the gauges were processed by a Hottinger Baldwin digital multi-channel tensometric bridge. Ultrasonic activity was monitored by 4 broadband ultrasonic emission pick-ups, type WD, produced by the firm PAC. The signals were amplified and recorded by a special PC interface card SF 41. The card enables independent and continuous recording of the ultrasonic emission in the frequency range of

5 kHz to 1.5 MHz. The parameters recorded were: the arrival time of the signal with accuracy as high as 125 nanoseconds, the integral value of the rectified signal (this value is proportional to the energy) and other parameters (Lokajíček & Vlk 1996).
Different loading patterns were used to prove the independence of autocorrelation analysis on the loading regime. With regard to the period of loading until final failure, the experiments can be divided into short-term (tens of minutes) and long-term (more than 10 hours). The sandstone samples were loaded in two loading cycles.

Assessment of the state of stress by autocorrelation analysis

The state of stress of the rock samples were assessed and namely the time of the future total failure was estimated by determining the changes in the parameters of the autocorrelation function of the sequence of emitted ultrasonic signals. For the purpose of assessing the general validity of the conclusions drawn, the effect of the structure on the UE, as well as the effect of the different rates of loading was monitored. For this purpose, short/term tests, lasting minutes, long-term tests, lasting several hours, were run, and cyclic loading was applied.
In all cases the methods of processing were the same and consisted of divided the whole loading period into partial intervals to which autocorrelation analysis of the sequence of emitted UE signals was applied. It was proved experimentally that, under non-cyclic loading, the UE increases roughly once approx. 65% of the samples' compressive strength has been reached. Under cyclic loading, the Kaiser effect was observed, which means that the UE in the second cycle increases only when the pressure exerted on the sample in the first cycle has been achieved.
As an example we show here an experiment on migmatite sample, which took 120 minutes. The acoustic emission under a uniform loading rate of 26 kPa/s is shown in Fig. 1. This figure shows the cumulative curve of the number of events ΣN recorded. The substantial increase of the UE occurred at 4700 s, i.e. when approx. 65% of the samples' compressive strength had been reached. The curve of the cumulative number of events displays an exponential increase, which agrees with previous results (Rudajev et al. 1997).
The autocorrelation analysis was applied in consecutive sub-intervals. An example of the autocorrelation functions, corresponding to seven selected intervals is shown in Fig. 2. The parameters of the autocorrelation functions are in Table 1. The first column of Table 1 shows the beginning of the interval. The second column gives the load in percentage of the compressive strength. The third column contains the correlation coefficient, corresponding to the linear approximation of the autocorrelation function (where applicable). The fourth column shows the duration of the positive autocorrelation coefficients, i.e. the time t at which the approximation line intersects level $R(t_k) = 0$ (correlation radius). The last column gives the value of the first autocorrelation coefficient. In the short-term tests, the value of the first autocorrelation coefficient increases with the load, and the tendency to linear decrease of the correlation function, characterized by the coefficient of correlation, is more pronounced.
Previous experience (Rudajev et al. 1998, 2000) showed that the results of the autocorrelation analysis under rapid loading do not display the unique trends observed in the slow tests. The reason is that the short-term loading experiment involves the immediate reaction of the samples' material to the acting force without the effect of the structure and especially the rheological properties of the rock being manifest.
The loading of sandstone samples was realized in two cycles. In the first loading cycle, a constant loading rate, corresponding to 85% of the compressive strength, was achieved by applying additional load during approx. 2200 s. The sample was kept at this level of the state of stress for

800 s. Thereafter the sample was rapidly unloaded in the course of 600 s. Correlation functions of the recorded sequences of UE events were computed in select intervals. These curves indicate that the parameters of the autocorrelation function display no pronounced trend. The parameters of the autocorrelation function, corresponding to the interval before maximum state of stress was reached in the first cycle, i.e. 18 MPa (87.5% of compressive strength) are given in Table 2.

Table 1. Parameters of the autocorrelation analysis for the migmatite sample (Figs 1, 2)

beginning of interval	load σ	coefficient of correlation r	correlation radius	$R(t_1)$
sec	(% of strength)		sec	
5900	81			-0.09
6100	84			-0.04
6300	87			0.12
6500	90			0.09
6700	92	0.47	10	0.09
6900	95	0.87	> 10	0.45
7100	98	0.91	> 10	0.64

The second loading cycle lasted 1100 s and ended with total failure of the sample. At the beginning of this cycle, a loading rate of 2 MPa/min was applied up to a load of 16 MPa (480 s from the beginning of loading). Further load was added until total failure at the rate of 0.5 MPa/min. The maximum load in the first cycle (18 MPa) was achieved after 720 s from the beginning of loading.
The loading interval, from the beginning of the second cycle to time 750 s, is affected by the Kaiser effect, i.e. the number of UE events is relatively small and the autocorrelation functions do not provide information about the relation between the load and the UE. Table 2 gives the parameters of the autocorrelation functions for intervals in second cycle.

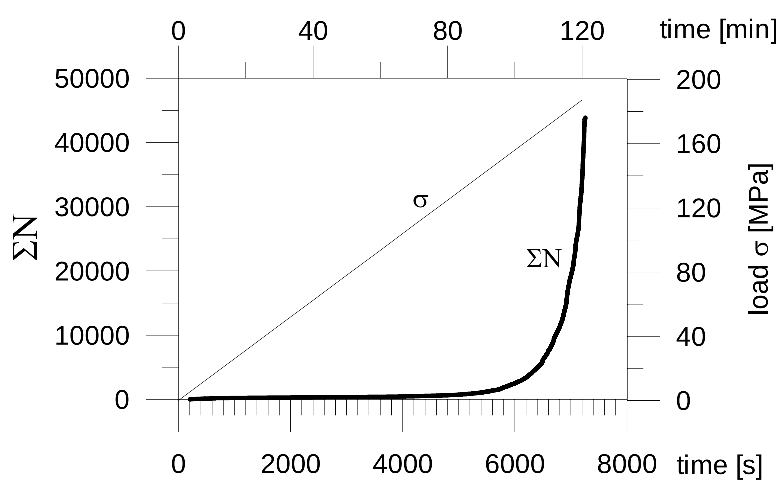

Fig.1 *Loading test, migmatite rock sample. Increase in cumulative number of events ΣN (thick line) with time (load σ) – thin line.*

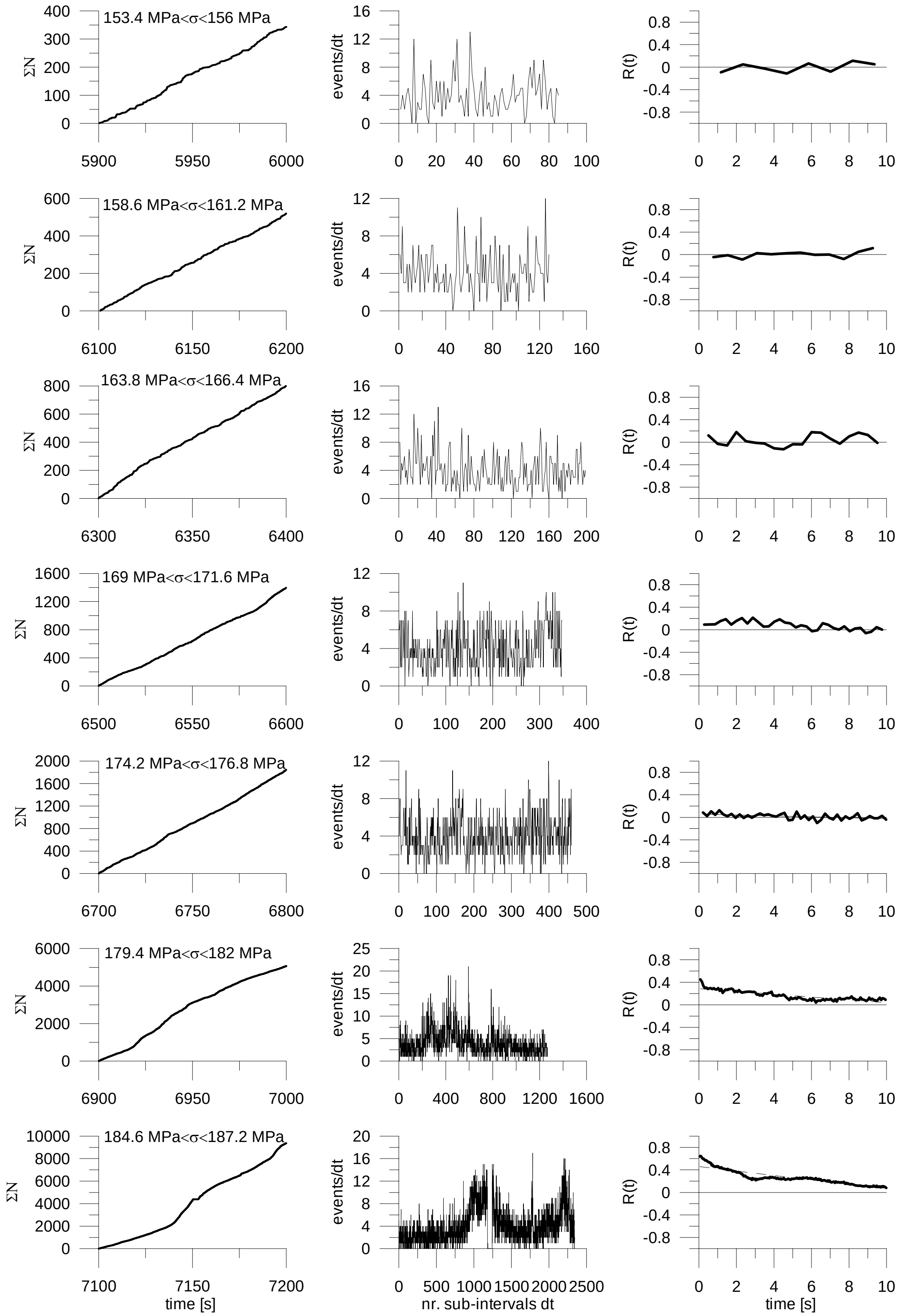

Fig. 2. *Autocorrelation analysis of UE from loaded rock sample in Fig. 1. First column – cumulative number of events in 100 s intervals. Second column – transformed series of UE events; the length dt of sub-intervals corresponds to average value of 3 events. Third column – autocorrelation coefficients.*

Table 2. Parameters of the autocorrelation analysis for the cyclically loaded sandstone sample

beginning of interval	load σ	coefficient of correlation r	correlation radius	$R(t_1)$
sec	(% of strength)		sec	
		1st cycle		
2000	79.4	0.78	16	0.33
		2nd cycle		
800	88.9	0.97	13	0.55
900	92.9	0.99	9	0.64
939	94.4	0.98	16	0.63

Conclusion

The experiments concentrated on assessing the possibility of prediction the time of total failure of rock samples under uni-axial pressure by the means of autocorrelation analysis of the sequences of UE events recorded.

It was found that, under loading with rate 26kPa/s of samples, the emission of ultrasonic signals increases once the load at the level of 65% of compressive strength is exceeded. The autocorrelation analysis of UE can only be applied after this load has been achieved.

The principal parameters of the autocorrelation function considered were the first values of the autocorrelation coefficients $R(t_1)$, the number of positive autocorrelation coefficients (correlation radius) and the tendency of the autocorrelation function to depend linearly on time. This trend is expressed quantitatively in terms of the correlation coefficient of the approximation line.

The value of the correlation coefficient r of the approximation line increases significantly after the load has reached 90% compressive strength, i.e. the autocorrelation function is nearly linear. The value of the first autocorrelation coefficient $R(t_1)$ also increases. Under cyclic loading, it was found that the autocorrelation method could be applied to a number of UE events in the second cycle only after the maximum load from the first cycle had been achieved. The actual case mentioned involved the short-term cyclic test. The time from the beginning of loading in the second cycle until final failure amounted to 20 min.

The increase in the values of the autocorrelation coefficients and the tendency to their linear decrease is evidence of increased effect the individual signals have on one another, i.e. of the redistribution of stress in the sample which occurs after stronger UE events have been generated.

The conclusion drawn from testing the samples may be useful in field measurements connected with research into rockbursts, in which the seismoacoustic method is used.

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