EVALUATION OF ULTRASOUND EMISSION FOCI IN LOADING ROCK SAMPLES

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ABSTRACT
Laboratory experiments proved that during loading of rock samples the migration of ultrasound signals (US) foci occurred in the volume of sample. There is distribution of US foci analysed in this paper. On the base of ultrasonic signals location the segments of higher concentration were determined. For the purpose of the assessment of detailed future part of total rupture the whole volume of the rock sample was divided in eight segments. The experiments were carried out for various loading rate. Detailed analysis, based on the cross-correlation of the foci number in the separate segments, proved that the occurrence of US in the individual segments are mutually influenced. The results indicate that the used correlation method allowed to assess the future part of the total sample fracture.

KEYWORDS: ultrasound emission, rock samples, location, correlation analysis, loading rate, prediction of total rupture

1. INTRODUCTION

When exposing rocks and building structures to loading beyond their critical load point, only a certain part of their volume is disrupted (*Veverka et al., 2000*). Identification of this predisposed part of volume, still before its total destruction, is critical in terms of the possible application of a measure which, taken directly in the exposed section, will be instrumental in lowering the danger of an sudden release of deforming energy (*Zang A. et al., 1998; Zang A. et al. 1996*). The issue of forecasting endangered parts of stressed materials has been examined on the basis of a model approach in laboratory conditions on rock samples, while using ultrasound emissions (*Rudajev et al., 2000*). Under examination were granite samples exposed to uniaxial loading under different loading rate (*Rudajev et. al., 2002; Veverka et al., 2001*). Loading rate was modified in a range of four orders, from 10 minutes (short-term tests) via 100 to 1000 minutes (medium-range tests) up to 10000 minutes (long-term testing). The time of disruption is understood to be a time interval from the outset of loading until the sample´s total disruption. During the experiments, measurements were made of rock deformation (longitudinal and transverse), of the extent and rate of loading and ultrasound emission. This ultrasonic emission, whose sources are fragile microcracks, was recorded by means of a six-channel ultrasonic network. Proceeding from the determination of time differences of the arrivals of the first waves at the individual sensors, ultrasonic foci were localized (*Hirata et al., 1987; Veverka et al., 2000*). The experiments have also determined that in the final phase of disruption the sources of ultrasonic emission tend to cluster into spots of future material disruption. The correlation analysis method was employed to evaluate the development patterns of rock sample disruption (*Rudajev et al., 1996*). This particular method made it possible to determine the actual impact of disruption in the individual parts of rock sample, facilitating evaluation of that part of rock where total disruption occurred.

2. EXPERIMENT

The samples subjected to the experiment had been collected in Vítkov Quarry, part of the Karlovy Vary pluton in the region of Krušné hory (Ore Mts., Czech Republic). The sample is a two-mica granite of medium grain size, with mean grain size 0.35 mm. The rock contains chiefly quartz, potassium spar, plagioclase, muscovite and biotite. The samples had the shape of cylinders, their height was 100 mm and diameter of 50 mm. This particular rock was chosen with a view to its known elastic properties, corroborated by earlier omnidirectional testing of a spherical sample of the rock by ultrasonic waves under omnidirectional pressures ranging from 0 to 400 MPa. It was proved that granite was velocity isotropic even under increased hydrostatic pressure. The maximum dispersion of velocities under atmospheric pressure was 5.4 to 5.7 km/s, and under maximum pressure of 400 MPa it varied within the interval of 6.1 to 6.3 km/s (*Přikryl, 1998; Rudajev et al., 1994*).

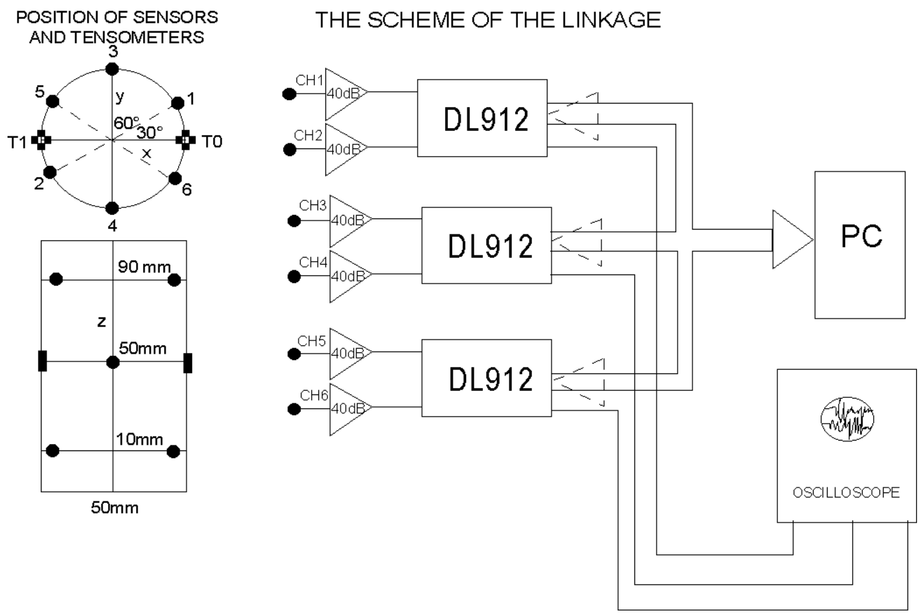


Fig. 1 Wiring diagram

Loading was performed in a lever water press, continuous during the short experiments, with constant increase of acting force (duration of experiments in Table 1 from 10 to 100 minutes), and under incremental increase of load in the long-term experiments (in Table 1 experiments lasting 1,000 and 10000 minutes). The advantage of using a water press lies in its silent operation, while offering long-term loading.

Strain was measured by cross resistance tensometers located in the middle section of the sample on the opposite sides of its cylindrical surface. These resistance tensometers were connected to a measuring bridge which recorded transverse and longitudinal deformations with an accuracy of 1 μm/m.

Ultrasound emission (UE) was monitored by six piezoceramic transducers glued to the cylindrical surface of the sample. The transducers were configured with regard to minimizing errors in locating the foci of the events (Fig. 1). The transducers were placed at three horizontal levels on the surface of the cylindrical sample at heights of 10, 50 and 90 mm from its base. These transducers were connected to a recorder of transient events via a preamplifier with an amplification of 40 dB, and then via an HPIB bas-bar stored in a computer and simultaneously displayed on an oscilloscope screen. The parameters of transforming the signal into digital form were as follows: sampling frequency 2 MHz, 4096 samples/transducer/event and the dynamic range of one sample was 8 bits. The first onset of the waves was determined and the co-ordinates of the foci of the events were calculated later with the aid of a special program developed for this purpose.

3. ULTRASONIC EMISSION PROCESSING - METHOD

3.1. LOCATION OF UE FOCI

The foci of UE events were located by using three different algorithms (*Veverka et al., 2000*). These three algorithms assumed a homogeneous and isotropic medium. The input parameters of the focus location algorithms were the arrival times of P-waves, and the output of the co-ordinates of the focus and, in some cases, the velocity of propagation of the waves through the medium. The numbers of events recorded in the individual experiments are shown in Table 1. Sufficient locations of strong events, selected from all the events to cover the whole course of the experiment uniformly and reliably, were determined.

3.2. CORRELATION ANALYSIS

The rock sample was divided by three mutually perpendicular plains into 8 segments for the purpose of applying the correlation analysis method, for the evaluation of the mutual effect of ultrasonic signals in different parts of the rock sample. Rock samples were cylinder-shaped with a diameter of 5 cm and height of 10 cm. Consequently, the individual areas were formed by segments in the shape of a quarter-cylinder 5 cm high and 2,5 cm in diameter. The order of the individual segments was always numbered in a uniform fashion, namely in the right-handed Cartesian system whose beginning is in the centre of the base, both coordinates x, y of segment No. 1 are negative, segment No. 2´s x coordinate is positive and its y coordinate is negative, segment No. 3´s x coordinate is negative and its y coordinate is positive, segment No. 4 has both coordinates positive, in all the cases

Table 1 Overview of the Parameters and Experiments

Experiment	Intended loading time	Loading time	Number of events		Strength	Mean acoustic velocity	Beginning of the UE events	
No.	[min]	[min]	total	localised	[MPa]	[event/min]	[MPa]	[%]
1	10	16.43	323	225	138.6	30	70	50
2	100	118.17	881	433	120.6	9	60	50
3	1000	1101.57	849	522	133.5	0.8	110	80
4	10000	8018.70	3875	616	102.7	0.4	100	90

Table 2 Number of Localized Signals in Individual Segments

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
10	88	13	33	26	23	17	11	8
100	63	27	172	75	34	19	28	15
1000	106	27	318	40	6	1	23	5
10000	53	36	331	48	55	3	81	9

Table 3 Parameters for Correlation Analysis

	Beginning	Window	$\Delta\sigma$	$N_{sum.}$	$N_{beg.}$	$N_{sum.}$-$N_{beg.}$
	$\%\sigma_{max}$	$\%\sigma_{max}$	%			
10	70	20	1	219	79	140
100	77	15	1	433	90	343
1000	87	6	1	522	20	502
10000	82	10	1	616	100	516

the z-coordinate ranges from 0 to 5. Lying above segment No. 1 is segment No. 5, No. 6 lies above No. 2, No. 7 lies above No. 3 and No. 8 is above No. 4, with the z-coordinate of those segments being in the interval 5-10. For each segment, time sequence of signals whose foci were located within the pertinent segment was set up. This particular method was instrumental in providing 8 time sequences of ultrasonic signals. The actual impact of the occurrence of ultrasonic signals in the individual segments was evaluated by means of mutual correlation of the appropriate sequences. Mutual correlation coefficients are determined on the basis of the following formula:

$$R_{ij}(k) = \frac{\sum_{n=1}^{N}\left[(x_i(n)-\bar{x}_i)(x_j(n+k)-\bar{x}_j)\right]}{\sqrt{\sum_{n=1}^{N}\left[x_i(n)-\bar{x}_i\right]^2 \sum_{n=1}^{N}\left[x_j(n)-\bar{x}_j\right]^2}}$$

where

$x_i(n)$ n-th element of i-th sequence, i.e. sequence belonging to the i-th segment average of the i-th sequence

$x_j(n)$ n-th element of the j-th sequence, i.e. sequence belonging to the j-th segment average of the j-th sequence

$R_{ij}(k)$ mutual correlation between the i-th and j-th sequences

i,j = 1, 2,..., 8

4. MEASURED DATA

The experiments performed on the granite samples have shown that signals do not arise during loading evenly in the entire volume of the sample. Table No. 2 gives the number of signals originating during loading in the individual segments with the exception of the shortest experiment where the highest concentration of signals was found in segment No. 1, while in the other ones the highest concentration was always determined in area No. 3. However, for the purpose of evaluating the mutual impact of the onset of signals in the individual segments, solely signals occurring during loading in excess of 70% σ_{max} were used (See Table No. 3). The signals originating at the onset of loading are primarily concentrated close to the sample´s bases, which may be caused by the contact of the jaw of the press with the sample or by enhanced stress concentration in the vicinity of the sample's loaded surfaces (Hawkes and Mellor, 1970). Table No. 3 contains a column designated onset σ_{max} from which the signals were analysed. The next column marked Window gives the deliberated stress range, i.e. in the first interval in the 10-minute experiment signals originating within the range of 70-90% σ_{max} were evaluated. This particular stress window then kept shifting slidingly with step 1% σ_{max}, i.e. the second interval ranged from 71 to 91% σ_{max} etc. The sliding step is given in the third column of Table No. 3. The fourth column presents the overall number of localized ultrasonic signals from the onset of loading until the sample's total disruption. The next column gives the number of signals originating before the attainment of the stress value from which the signals were analysed, i.e. the number that was not taken into account during the analysis. The last column gives the number of localized signals subjected to analysis.

Sequences of localized signals were constructed for each segment and each stress window by dividing the length of each window into 30 partial subintervals. The number of signals originating in the individual subintervals then makes up time the sequence of the relevant segment. The first two to three mutual correlation coefficients were used for analysis.

5. RESULTS OF THE EXPERIMENTS

Using the same methodology, mutual correlation values of time sequences of the occurrence of localized ultrasonic signals in the individual segments were calculated for all four experiments. These sequences were stipulated for specific stress intervals described by their length, i.e. so-called window, in percentage values of the sample's strength and initial stress value of the individual intervals under analysis. The pertinent software is presented in appendix. The results are presented in the form of tables (Tables Nos. 4-7) whose first line gives sliding intervals in percentage terms of strength limits. The subsequent lines give mutual correlation values of the sequence of ultrasonic signals from active segments (those segments are entered in the first column where the segment in which most ultrasonic signals originated is given by bold figures). The plus sign indicates that disruption in this main segment is affected by the disruption caused by the second considered segment; on the other hand, the minus sign means that the main segment influences the second segment. If no sign is given for mutual correlation values, this implies that disruption occurred in the considered segments concurrently.

SHORT-TERM EXPERIMENTS - 10 MINUTES:

The distribution of the foci of the analysed localized ultrasonic signals is depicted in Fig. 2. This also shows the time dependence of the occurrence of those ultrasonic signals and the course of stress depending on time. Their occurrence is concentrated in segments 1, 3, 4, 5, minimum of signals appeared in segments 7 and 8 (Table No. 2). Disruption originated primarily in segment 5, passing into segment 1 where most signals occurred, while that segment 1 influenced segment 3 (See Table No. 4). Occurrence of the signal in segment 4 did not affect any other segment - mutual correlations $R_{4,i}$ are insignificant. All in all, there was a modest increase of signals during loading.

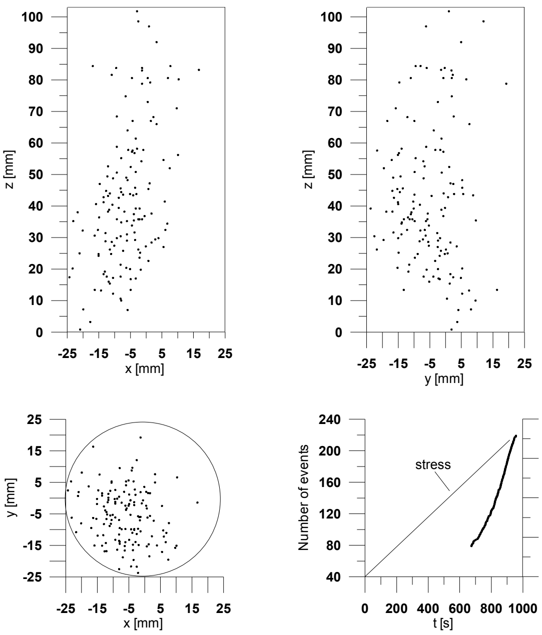


Fig. 2 Experiment 10 minutes

Table 4 Short-term Experiment - 10 minutes, window 20% σ_{max}

Window [% σ_{max}]	70-89	90	91	92	93	94	95	96	97
Correlation									
1-3			+0.41	+0.47	+0.40	+0.33	+0.56	+0.50	
1-5	-0.56		-0.54	-0.60	-0.52	-0.66	-0.50	-0.36	-0.49

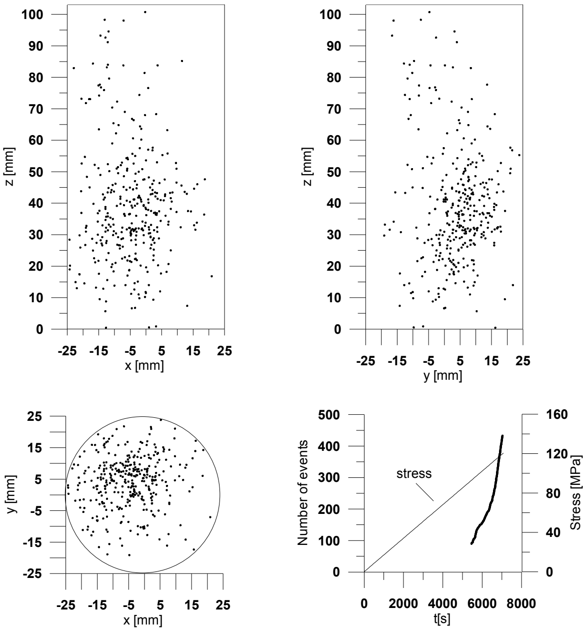


Fig. 3 Experiment 100 minutes

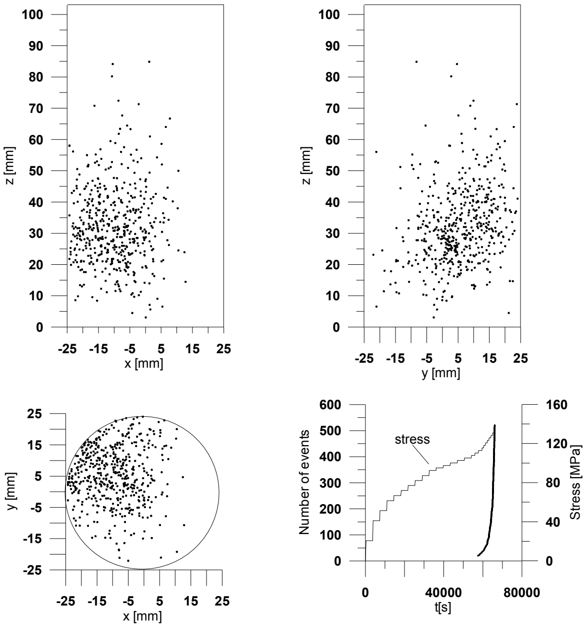


Fig. 4 Experiment 1 000 minutes

Table 5 Medium-term Experiment - 100 minutes, window 15% σ_{max}

Window [% σ_{max}]	77-92	93	94	95	96	97	98	99	100
Correlation									
3-4					+0.65	+0.56	+0.64	+0.52	+0.53

Table 6 Medium-term Experiment - 1000 minutes, window 6% σ_{max}

Window [% σ_{max}]	87-92	93	94	95	96	97	98	99	100
Correlation									
3-1	-0.34	-0.23	-0.37		-0.56	-0.43;0.47	-0.57	+0.65;0.80	-0.62;+0.6

MEDIUM-TERM EXPERIMENTS - 100 MINUTES:

The distribution of the foci of the analysed localized ultrasonic signals is depicted in Fig. 3. This also shows the time dependence of the occurrence of those ultrasonic signals and the course of stress depending on time. Most signals originated in segments 3 and 4 (max. 3), and partly in segment 1. A minimum of signals occurred in segment 6 (Table No. 2). The first more pronounced correlations appeared as late as in intervals 80-95% σ_{max}, solely between segments 3 and 4. In segment 4, signals preceded the occurrence of signals in segment 3 (See Table No. 5). In the last loading phase, disruption continued solely in segment No. 3 where total disruption occurred.

MEDIUM-TERM EXPERIMENTS - 1 000 MINUTES:

The distribution of the foci of the analysed and localized ultrasonic signals is depicted in Fig. 4. This also shows the time dependence of the occurrence of those ultrasonic signals and the course of stress depending on time. Most signals originated in segment 3, in the final stage of disruption also in No. 1, and partly also in segment 4. A minimum of signals originated in segments 5, 6 and 8 (Table No. 2). Segment 3 affected segment 1 almost throughout the testing (up to 95% σ_{max}). In the phase between 96 and 97% σ_{max}, signals originated in segments 1 and 3 independently without mutual impact, in the phase of 98% σ_{max}, segment 3 again influenced segment 1, on the contrary up to 99% σ_{max}, segment 1 affected segment 3. During the last phase, signals originated jointly and randomly, not affecting one another (See Table No. 6). Basically, only the lower part of the sample was disrupted in segments 1 and 3.

LONG-TERM EXPERIMENTS – 10 000 MINUTES:

The distribution of the foci of the analysed localized ultrasonic signals is depicted in Fig. 5. This also shows the time dependence of the occurrence of those ultrasonic signals and the course of stress depending on time. A markedly higher number of signals originated in segment 3, other active segments being segment 7, and segments 1, 2, 4, 5. Virtually undisrupted were segments 6 and 8. The initial interval was in the range of 82 - 91% σ_{max}. During the first six intervals, i.e. up to the interval of 87 - 96 % σ_{max}, signals originating in segment 7 were preceded by signals from segment No. 3. However, in most other active segments disruption occurs practically concurrently, as illustrated in Table No. 7. In the final phase of disruption, i.e. in intervals where stress reached 97, 98 and 99% σ_{max}, mutual correlation of signals originating in the individual segments is virtually negligible. However, concurrent disruption occurs in segments 1, 2 and 3 during the last interval. It was precisely in this lower part of the sample where macroscopically observable disruption occurred.

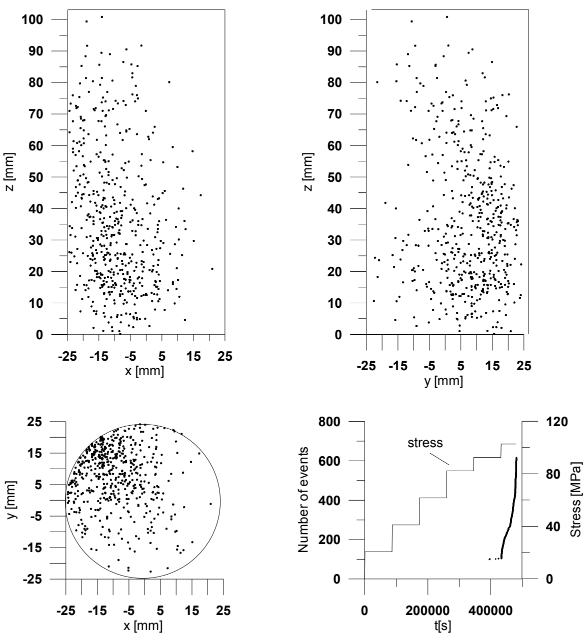


Fig. 5 Experiment 10 000 minutes

Table 7 Long-term Experiment - 10000 minutes, window 10% σ_{max}

Window [% σ_{max}]	82-91	92	93	94	95	96	97	98	99	100
Correlation										
3-1	0.78									0.84
3-2	0.66									0.83
3-4	0.94	0.82	-0.72	-0.59	-0.58	-0.6;+0.54		0.54		0.92
3-5	0.93	0.91	+0.65;0.7;-0.7	-0.66	0.65					
3-7	0.84;+0.85	0.8	+0.71	+0.58	+0.61	+0.59				

6. CONCLUSION

SHORT-TERM TESTS:

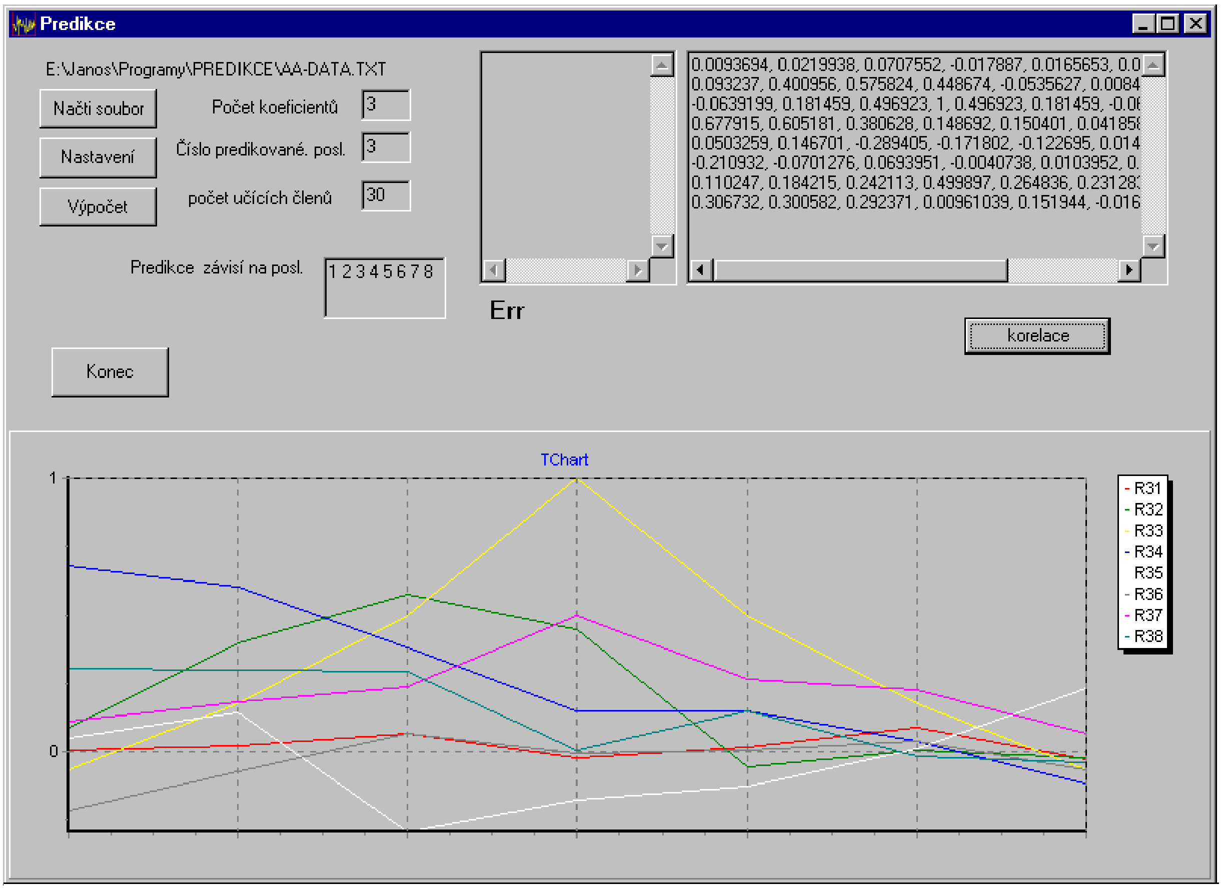
Signals occur virtually in the entire volume of the sample not affecting one another. The overall number of signals is relatively small, which corresponds to the fact that rock reacts solely to the acting force without its structure coming into play. No reological processes originate.

MEDIUM-RANGE TESTS:

The impact of rock structure is manifested as late as in medium- and long-term testing, i.e. with loading lasting for 100 minutes and longer. The first major correlations appeared during the loading of up to 95% σ_{max}. A maximum number of signals was concentrated in a single segment, namely in No. 3. Those signals from No. 3 were preceded by signals from the neighbouring segment 4. This particular correlation disappeared in the last stage of loading (99 - 100% σ_{max}), with signals originating independently with maximum occurrence in segment 3 where total disruption occurred.

LONG-TERM EXPERIMENTS:

Signals begin to occur more prominently as from the pressure of 90% σ_{max}. The occurrence of signals is concentrated into a single segment. The loading stage of 91 - 96% displayed an increased mutual correlation of the occurrence of signals in this segment, with signals originating in the segment above. However,



Glossary:
načti soubor = load file, Počet koeficientů = No. of coefficients
nastavení = set up, Číslo predikované posl. = number of predicted series
Výpočet = calculation, počet učících členů = No. of training elements
Predikce závisí na posl. = prediction depends on series
korelace = correlation
Konec = close the window

Fig. 6 Software used for evaluation of UE data

this particular concentration disappeared with the pressure of 97% σ_{max} and higher. Signals originated spontaneously primarily in the segment where total disruption occurred.

The performed experiments have shown that by means of mutual correlation of time sequences of signals it is possible to evaluate the actual course of disruption in rock samples as well as impact of the onset of signals in various parts of the volume of rock sample in dependence on the state of stress. It has been established that the reological properties of rocks and their structure tend to affect the onset of signals, especially during longer lasting experiments.

APPENDIX

For the processing of data the special software was developed including:

- Formatting of date and their saving in the memory
- Creating of UE sequences with demanding parameters (the number of elements, the window length)
- Cross-correlation analysis
- Display of results

Illustration of software is presented in Fig. 6.

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