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INSTRUMENTS FOR STUDYING WAVE PATTERNS IN INDUCED SEISMOACOUSTIC AND SEISMIC EVENTS

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Abstract: In studying seismoacoustic emissions and induced seismic events it is convenient to use monitoring systems which monitor these events on a continuous basis in real time. Continuous registration provides an overview of the long-term trends of the recorded quantities, and enables us to specify the conditions for selecting recording instruments and optimum technical parameter settings. The paper describes ways of combining digital measuring systems with monitoring recording systems.

Key words: seismoacoustic emission; induced seismicity; pulse rate; seismic monitoring recordings; automatic seismographs

1. INTRODUCTION

The method and instrumental equipment required for experimental research into the failure of rock mass using seismoacoustic and seismic techniques are described. The seismoacoustic instruments were designed to have a constant frequency response in the frequency range of 160 to 200 Hz, the seismic instruments having constant magnification in the 0.5 to 40 Hz frequency range. Both cases involve measuring systems consisting of spaced-out pick-ups, a transmission link and monitoring centre, or formed of autonomous stations operating in real time.

The reliability of instruments operating continuously depends on resistance to adverse weather conditions and other common factors. These include namely high resistivity against mains voltage induction and peak disturbances, maximum attainable input sensitivity (0.2 μV), large dynamic range (120 dB), and low power consumption under a stand-by feed system. The result of these measurements are input data, of the required quantity and quality, for interpreting the dynamics and kinematics of the wave patterns being studied.

The electronic measuring systems used in solving these problems consist of a complex of functional and construction units with maximum possible compatibility with regard to mechanical design, power sources, signal strength and manner of data transmission. The separate functions which these systems provide (i.e. receipt of information at the instrument's input, their processing, control of output devices, and transmission of data for further processing) will be described with the aim of guaranteeing reproducibility of the measurements.

Seismoacoustic measurements are used to monitor critical stress conditions characterized by brittle failure of rocks (Mogi, 1962; Buben and Rudajev, 1974). This method has become widely used in recent decades as one of the effective methods of active non-destructive research. As opposed to methods of passive non-destructive testing, e.g. microscopic gamma-gamma ray, spectral and ultrasonic methods, which disclose failures only within a selected region of limited volume, the method of acoustic emission can be considered an active observation method which can be used to study failures within a larger volume, and also to identify event foci.

From a physical point of view, seismoacoustic pulses at first accompany the spreading of randomly distributed initial microcracks. As the failure develops, these microcracks increase in size, affect each other more and more, and begin to combine. This is reflected in the local distribution of pulses, as well as in their time distribution. Reaching the stage of overall failure is characterized by the beginning of spontaneous combining of microcracks, which can add to the amount of information in the pulse emission development in the final interval before critical failure of the rock (Buben and Rudajev, 1974).

The emission of seismooacoustic pulses is characterized by the following parameters: time and energy distribution, onset times of first or subsequent wave phases, and frequency spectrum.

However, other derived parameters are also used, namely the pulse rate and energy recorded within selected intervals, time-dependent pulse clusters, as well as multichannel records of pulses in selected amplitude classes. Various instruments are used for operational seismoacoustic measurements and recording; they are mostly based on the principle of recording the envelope curves of rectified pulse wave patterns which differ in integration constant values depending on the type of recording instrument (Brož, 1977; Šimáně and Brož, 1979).

For detailed study of individual time-developed pulses it is necessary to record the actual pulse pattern in real time. However, this is technically quite difficult because it involves a record of random events in relatively long time intervals, and the frequency distribution of these pulses in the 160 Hz to 2 kHz frequency range requires adequate recording speed. This practically means that, as regards classical recording equipment, the only device that satisfies these conditions is a continuously recording tape-recorder. Digital recording systems can be used to set up a seismoacoustic recording device with the properties required on the basis of digital storage.

The time-developed pattern of two consecutive seismoacoustic pulses is shown in Fig. 1. The recording was made in the Příbram Uranium Mines directly on tape.

Monitoring the seismoacoustic emission is one of the methods used in monitoring the stability of mine workings, underground engineering structures, the stability of rock slopes, etc. (Šimáně, 1967). Several generations of instruments have already been developed and designed at the Institute of Geotechnics of the Czechoslovak Academy of Sciences (Brož and Fučík, 1976; Brož 1989; Šimáně, 1982) for the

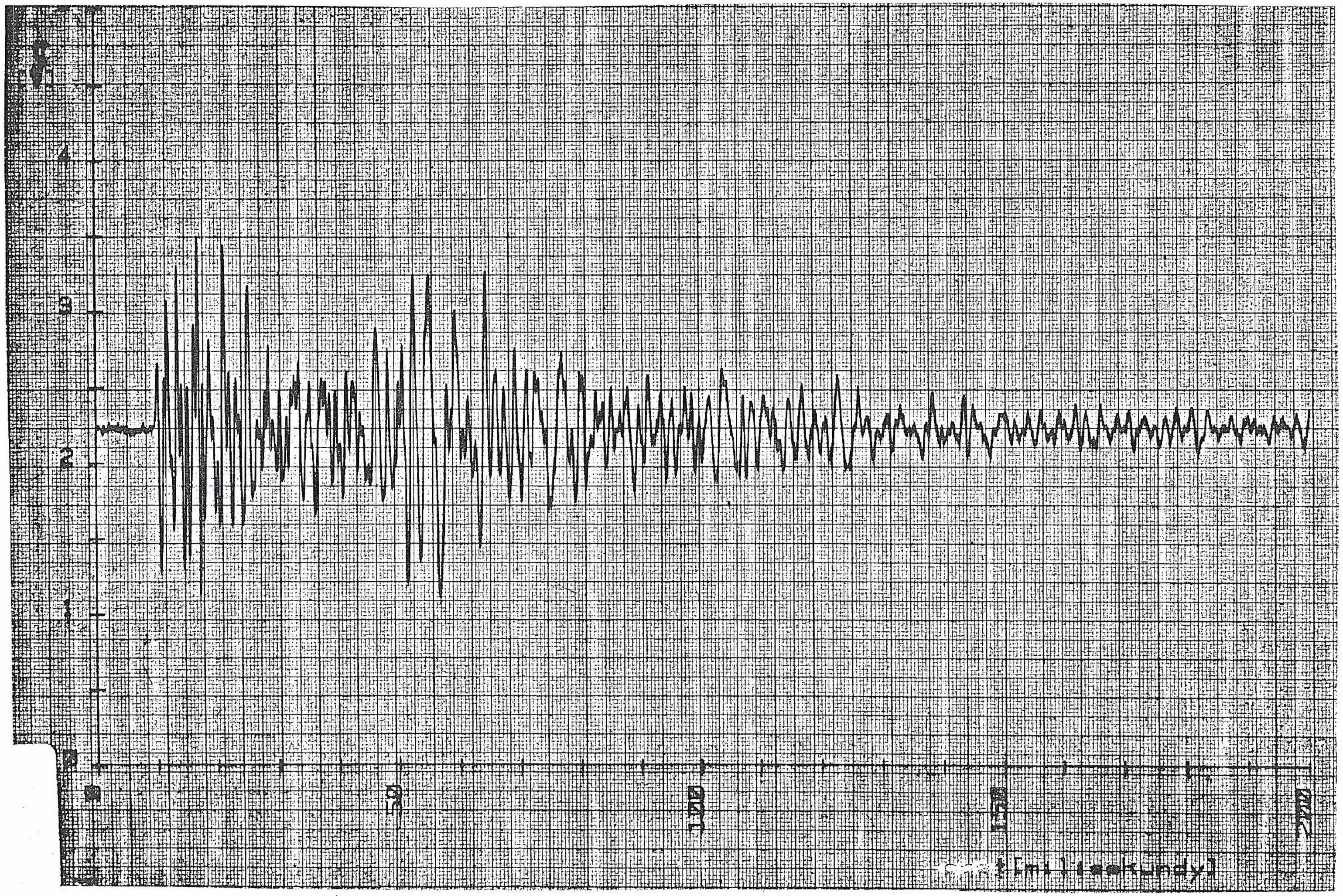

Fig. 1. A pair of seismoacoustic pulses recorded on magnetic tape. y – voltage on the GPIIIH geophone, x – time axis.

purpose of recording the occurrence of seismoacoustic pulses in time together with their amplitudes.

The fundamental condition for obtaining the statistical characteristics of seismoacoustic emission is a sufficiently extensive set of pulses (Mogi, 1962; Brož, 1977). The representativeness of this set depends directly on the quality of the measuring equipment formed from the input sensing circuits, the cable transmission and the digital recording device, designed on the basis of a microcomputer (Brož and Starý, 1982).

Long years of experience with the development, design and operation of a seismoacoustic monitoring system were obtained in the Magnesite Mines in Lubeník (CSFR). The stability of pillars between stopes and stope ceilings has been monitored using the seismoacoustic method for more than five years. The system of recording the seismoacoustic pulse emission used provides for monitoring the time distribution by two eight-channel analogue recording set-ups with simultaneous computer processing of the frequency characteristics of the sets and location of pulse foci. The SAPI 1 computer, which is connected on-line in the measuring channel, evaluates the occurrence rate of pulses in the separate pick-ups at given interpretation intervals and plots their histograms.

If the given condition (occurrence of pulses simultaneously in more than five measuring channels) is satisfied, the pulse-focus location program, which measures the time differences between the pulse onsets at the separate pick-ups simultaneously with the pulse amplitudes, is triggered automatically. These values are then printed and serve as the input data for the pulse location programs. At the same time, it is possible to determine approximately the flux density of the pulse energy

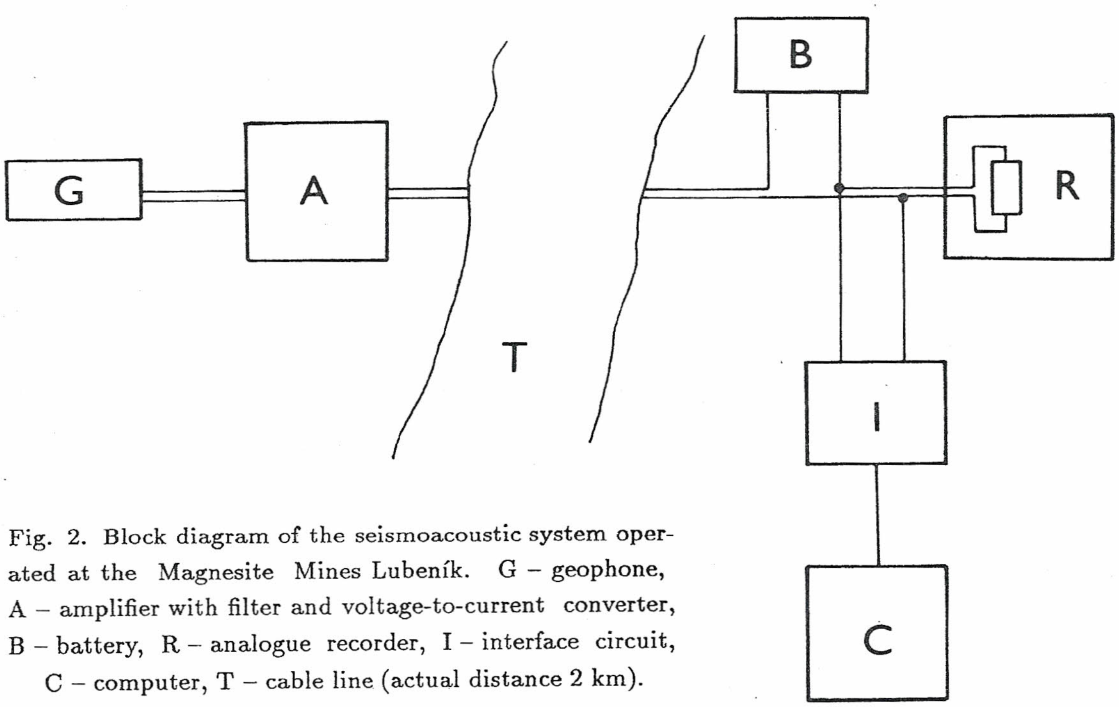

Fig. 2. Block diagram of the seismoacoustic system operated at the Magnesite Mines Lubeník. G – geophone, A – amplifier with filter and voltage-to-current converter, B – battery, R – analogue recorder, I – interface circuit, C – computer, T – cable line (actual distance 2 km).

as the square of the maximum amplitude of oscillation velocity. Another method of interpreting these records is based on their statistical analysis.

The stress condition of the massif and subsequently its stability are assessed by evaluating the occurrence of seismoacoustic pulses, technical information on the progress of the work in the mine, and other methods of observation.

The analogue monitoring system operates continuously and enables the time distribution function of seismoacoustic pulses to be evaluated immediately. This is particularly important during blasting operations which may cause secondary upsetting of the stability of stressed areas in mine workings.

This seismoacoustic monitoring system is operated simultaneously with an automatically triggered seismic device which records not only blasting operation, but also the seismic events it generates. The device records seismic events for an interval of several minutes after the blast, simultaneously with the recording of seismoacoustic pulses in a parallel recording channel which is made at decreased recording speed in the second phase of the recording for a period of 10 to 20 minutes.

A measuring system was designed for this purpose with the aid of the Magnesite Mines Research Centre. The block diagram of the system is shown in Fig. 2. The mine part consists of a seismoacoustic pick-up G (GPIIIH) which is connected to a low-consumption, narrow-band, hybrid amplifier with a gain of 70 dB in the 160 to 2000 Hz frequency range. This amplifier also works as a voltage-to-current converter. Its output, which is common with the battery, is connected to the cable transmission via a surge absorber.

The noise in the cable transmission is suppressed by current transmission with a single signal earth which is common to all measuring cables. In the measuring cell the cable is connected to the processing device which consists of the recording instrument R and computer C. All measuring channels are supplied from a common battery source B. The signals are fed to the computer via the input interface circuit I, consisting of a time window and amplitude discriminator.

An example of the analogue record of the distribution of seismoacoustic pulses

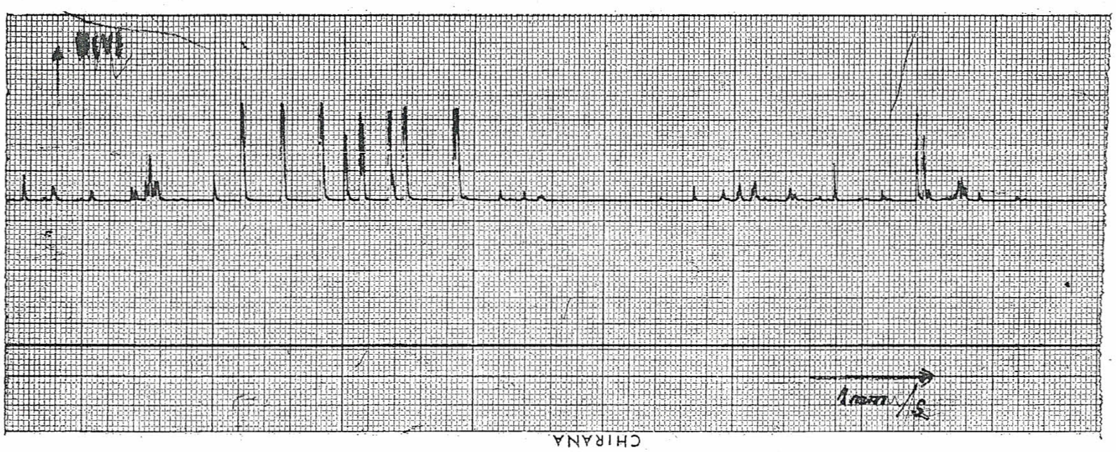

Fig. 3. Example of an analogue record of seismoacoustic pulses.
y – output voltage on geophone, x – time axis.

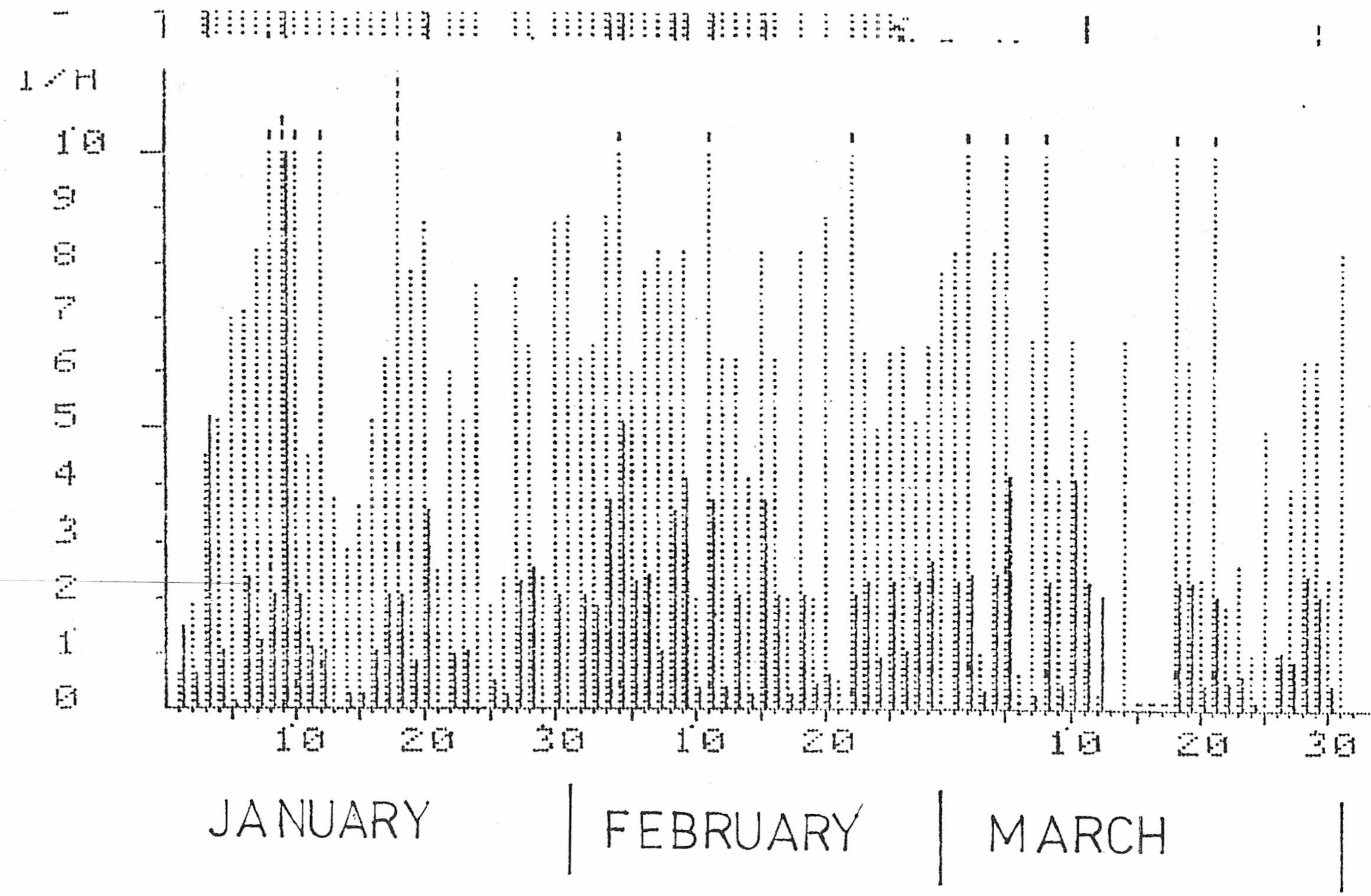

Fig. 4. Computer processing of average daily rate of seismoacoustic pulses on two measuring channels. y – hourly number (pulse/hour), x – time axis.

in time is shown in Fig. 3. An example of the time distribution of pulses by the computer is shown in Fig. 4 in which the average impulse rate values in two measuring channels are shown.

The system described represents one of the options of using seismoacoustic monitoring equipment in practice. Transcendent memories, which enable storing sampled pulse patterns in the scratchpad memory, are used in methods which deal with the detailed study of wave patterns or changes of pulse frequency spectra in dependence on the stress of the rock. These special instruments, manufactured by Maurrel of Switzerland, Data Loop of Great Britain, Tektronix of the USA, etc., can be used for short-term experimental measurements. Their use should be considered with regard to the results of the seismoacoustic monitoring system.

The decision on using them should be made after evaluating the empirical statistical criteria of marked increases in pulse rate, or in the clustering of their foci. A certain attempt at a compromise between using monitoring systems and devices with transcendent memories is the following single-purpose microprocessor device (Brož and Starý, 1990).

This is a hybrid digital-analogue system which enables a time record of seismoacoustic pulses, selected by the amplitude criterion, to be made automatically on a six-channel line recorder. The main part of the instrument is a multichannel digital store which is capable of transforming input seismoacoustic pulses in time. The software of the instrument, which is stored in the memory of a single-chip microcomputer, contains procedures start, digitization, sampling and fast data storage in a multichannel memory, all in a fixed algorithm. Once the memory is full (capacity 8 Kbytes per channel), the samples are automatically fed at a slow rate to the recorder which plots the pulses from the six measuring channels. The instrument provides information on the time pattern of the pulses and more accurate onset time data. However, this setup has its limitations in the frequency range. This is defined by the maximum sampling frequency of the converter and sampling theorem. For the eight measuring channels this is 200 Hz.

3. SEISMIC MEASUREMENTS IN THE AREA OF INDUCED SEISMICITY

The assessment of seismic effects induced by local earthquakes and artificial sources is based on the evaluation of the time history of seismic oscillations. Depending on the type of sensors, the records are either velocigrams or accelerograms of soil vibrations. The velocity record is an optimum compromise between the response which is constant for the displacement (seismograph), and the response which is constant for the acceleration (accelerograph). With the same dynamics of the recording device, the velocigraph intercepts almost the tenfold of the amplitude range of seismic oscillations.

A prerequisite for setting up the response of seismic devices is the determination of the level of the seismic noise on the proposed site. Also the maximum expected amplitude and frequency of oscillations are necessary pieces of knowledge. Such information is necessary selecting and constructing measuring devices. The values of displacement amplitudes of stationary noise on selected sites range between 0.001 and 0.005 μm, as a rule within the frequency range of 0.5–20 Hz, which corresponds to maximum values of 0.12–0.6 μm/s for the soil oscillation velocity. Their actual values must be checked by experimental measurements (Rudajev *et al.*, 1979).

The suitability of the observation site is characterized by the ratio between the seismic signal and the noise level. The noise frequency spectrum depends on the quality of the bedrock, where the seismometer is situated. For a seismic site, which is not situated on solid rock, the transfer characteristic of its bedrock should be investigated, because the resonance characteristics of geological structures in the immediate neighbourhood of the seismometer could make themselves felt in seismic signals.

The measuring devices can be divided in two main groups: monitoring devices in continuous operating mode and triggered devices, in which the start of recording is effectuated either manually or automatically following certain criteria.

a) Monitoring devices

The characteristic technical parameters are given by the requirements on recording speed, critical frequency of the system and its dynamics. The classic drum recording devices, used at the observatories of the main teleseismic array, require special structural building measures and permanent attendance. The required technical parameters for the induced seismicity devices are, however, much higher than those that can be fulfilled by photogalvanometric recording. This concerns namely the increase of the recording speed, frequency range and accuracy of time readings. In order to meet these requirements, the signal must be processed electronically, or the digital transformation of recording speed of seismic events should be used.

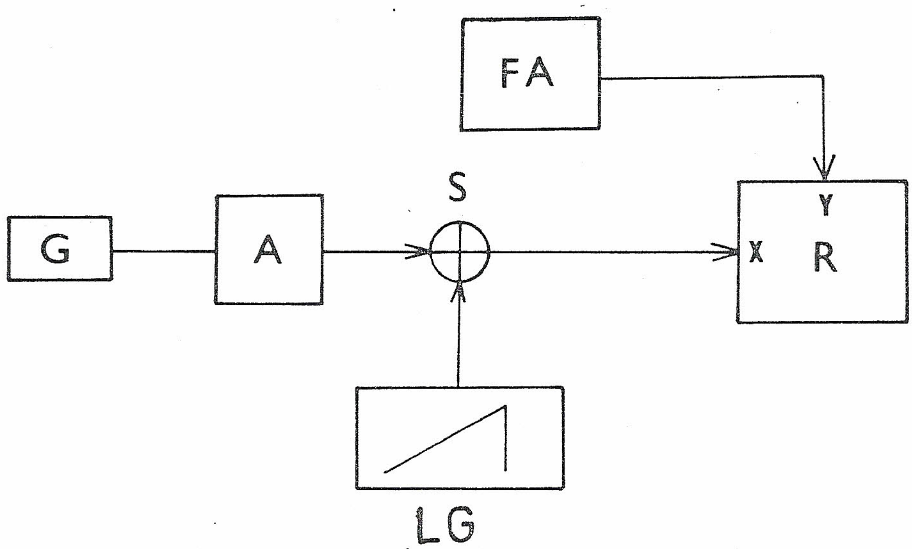

Fig. 5. Block diagram of the seismic monitoring device with the Z 144 line recorder (Metra Blansko). G – seismometer, A – amplifier, S – summing circuit, FA – ferrite rod antenna, R – recorder, LG – line voltage generator.

The monitoring recording provides a continuous record of the phenomena with a minimum speed of 12 cm/min, with the record dynamics exceeding 20 dB, and with a well defined time basis (Rudajev and Buben, 1964). The construction of these devices is based on the principle of drum recorders (Buben and Charbula, 1988), or computer printer and plotters are used.

The monitoring system, designed and constructed at the Institute of Geotechnics, uses the industrially manufactured line recorders. These are mechanically modified and equipped with electronics. The block diagram is shown in Fig. 5. The recording is based on summing the seismic signal with the linearly increasing voltage causing the advance of the recording pen in the direction of the X-coordinate.

The chart is driven by a crystal-controlled motor in the t-coordinate. The oscillator synchronizing is controlled by the carrier frequency and second marks of the time station DCF 77, received by an active ferrite rod antenna. The starting point of recording is commented with complete time information, and during the recording time the minute marks are recorded on the recording track. Recording can be operated with a spare battery supply or a 6 V accumulator with supply current of 160 mA. A ball-point pen is used for recording. The changing interval of recording paper loops can be adjusted within 12–48 hours, depending on the feed rate. An example of records from seismic station KMW in Karlovy Vary is shown in Fig. 6.

Another type of monitoring systems are the devices using personal computers and their peripheral circuits. The computer's processor unit, which can be equipped with, for example, a single-chip 8-bit processor, controls the sampling of the seismic signal in the input analogue-to-digital converter and provides the records of signal sequence in real time on a digital coordinate recorder. This procedure includes the assessment of the sensitivity of the input analogue-to-digital converter. The time information and the system synchronization is derived from the second marks of radio station DCF 77. These marks, which are introduced into the computer's digital input gate, are used to synchronize the data record in the way that each line of the record begins exactly with the start of the minute period, and the recording time on each line can be 1 to 5 minutes. The decoded time information is inscribed in the record in one-hour intervals. If the signal amplitude exceeds the device's adjusted range, the change of the amplification of the digitally controlled input amplifier is made automatically and this operation is mentioned in the record.

The computer monitoring device may be used wih any computer that enables the mentioned peripheries to be connected. Its activity depends on the software, where the requirement of automatic starting of the system in the case of power supply break must be respected, together with recording of time of the new start of recording. Further, tests of peripheries operating round-the-clock should be provided. Our setup consists of a SAPI 1 computer, analogue-to-digital converter and intelligent plotter LP 4540 (Laboratorní přístroje, CSFR), enabling recording to be made on paper rolls of 30m length.

The automatically triggered digital seismic devices with simultaneous monitoring records can also be ranged among computer-based monitoring devices. For example, this system is used in the central station of the telemetric system Lennartz

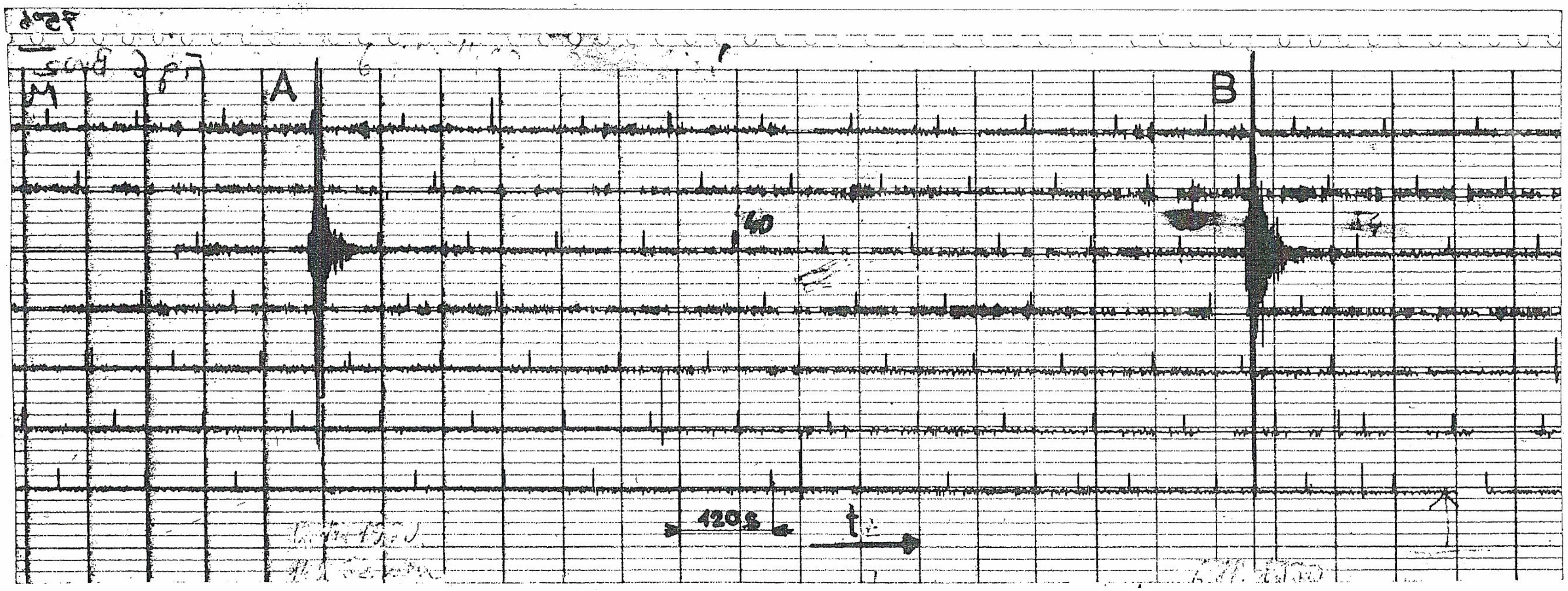

Fig. 6. Examples of two seismic events recorded by the monitoring device in Mine Jiří. t – time axis, y – output voltage of the seismometer.
A: 1990-11-06-14:32:00; B: 1990-11-06-14:52:00.

Electronic (Germany). The recording drum for the selected component of the seismic signal can be connected to the output of a mixer, which provides the decoding of individual seismic stations. The record is synchronized with the time signal of radio station DCF 77.

Seismic monitoring is sometimes required also for self-contained automatic devices without such technical equipment. For example, for switching devices of MARS 88 type (Lennartz Electronic), the peripheral monitoring recording using some internal functions of this device was designed and constructed. The digitally processed signal is reconstructed, by an additional inverse converter, into an analogue signal and is led out, within the selected dynamic range, together with the internal start signal to the device's output. Time signal DCF 77 is tapped from the external receiver in the form of second marks. The block diagram of the device, using a line analogue recorder, is shown in Fig. 7.

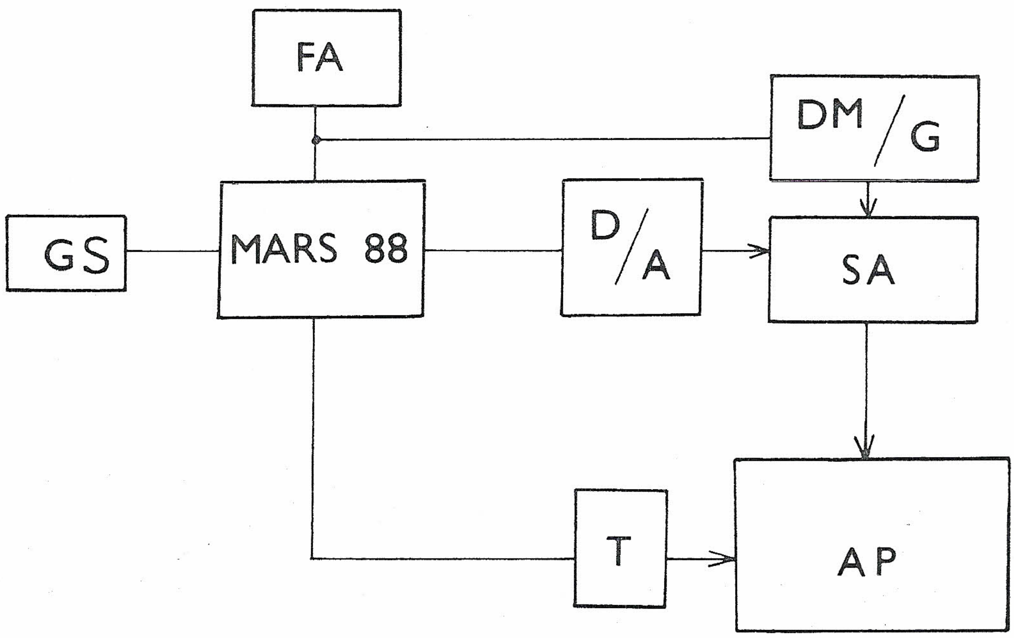

Fig. 7. Block diagram of the monitoring system with the digital processing device MARS 88 (Lennartz Electronic). GS – seismic pick-up, FA – ferrite rod antenna, DM/G – decoder of minute marks and the saw-tooth voltage generator, DA – digital-to-analogue converter, SA – summing amplifier, T – invertor of the triggering pulse, AP – line analogue recorder.

The entire set contains a decoder of minute marks with a binary divider and digital generator of saw-tooth voltage G. This circuit generates the saw-tooth voltage with periods of 1, 2 or 4 minutes, which is added, in a summing amplifier, to the analogue seismic input signal. At the same time, the internal start signal of the device is fed into summing amplifier SA. This signal is modified into a short pulse of inverse polarity and is used for identifying the phenomena, inscribed at the same time in the digital memory of the MARS 88 device. At the start of recording, the exact time data are inscribed by manual manipulation. The quality of this information is continuously maintained by the decoder of minute marks. When checking the device, a time checking record can also be effectuated. The analogue line recorder works with chart paper in rolls, so that, according to the rate of feed in the y-axis, the records can be taken for several days without attendance.

b) Triggered seismic devices

For recording the seismic events with known or expected (at a certain time) occurrence time moment, we do not encounter any problems, provided the device operates with the required dynamics and frequency range. However, a different method of measuring must be developed for an automatically triggered system which should provide the selection of signals to be recorded according to certain criteria. The basic problems to be evaluated by the system concern the exceeding of the seismic noise level by the seismic signal (Buben and Brož, 1982).

Although it is evident that the study of seismic event onsets is of fundamental importance for their evaluation, the self-triggered devices do not offer any possibility of doing it in real time. Therefore, a buffer memory enabling the non-causal decisions about the usefulness of the signal to be taken, must be introduced in the system.

The decision criteria can formulated, according to technical and program capacities of the devices, on the basis of algorithms which take account of some of the following properties of seismic signals: First of all, it is the signal amplitude and its time development, its frequency spectrum and expected polarity of its onsets in seismic components. Further parameters may concern the signal duration, its shape, coincidence with other seismic events or certain signals in both the positive and negative sense. The system can also incorporate certain time linkages both between individual components and for preferential start triggering.

The prevailing part of intelligent digital devices uses the STA/LTA criterion (Short Time Average/Long Time Average). The STA/LTA values are determined as arithmetic mean values of amplitudes in selected frequency and time bands. Practical experience in applying this criterion has motivated the design engineers to involve further additional parameters in their devices, such as, for example, the number of signal samples used to calculate the values of LTA and STA, determination of the constant level which is being added to LTA, different setting of parameters on individual components, or of different weights assigned to individual components.

Very important information can be obtained from long-time recording, when the automatically recorded signals from self-triggered devices are compared with events recorded by continuously monitoring stations. In automatic devices there appear short disturbance pulses, probably caused by indefinable reactions of digital systems to various types of industrial (man-made) interference. However, much more important is the confirmed information that some seismic events are not recorded at all.

For seismic observations at the localities of nuclear power plants, it is necessary to register also phenomena with very low amplitude values. In such a case a simple amplitude criterion of triggering seems to be more suitable than the STA/LTA standard criterion. This amplitude value is calculated from the admissible value of earthquake magnitude. A consequence of applying the amplitude criterion is the probability of a large number of triggerings of the seismic device.

In order to cope with this problem, a very thorough analysis of the seismic signals and disturbing phenomena should be made at the seismic station. On the basis of long-term monitoring by means of digital devices with high dynamics and sampling frequency, it should be possible, by computer analysis of signals, to formulate additional criteria for the amplitude level of triggering (coincidence with a distant sensor, definition of the time interval of exceeding the threshold value, comparison of phase-shifted signals, etc.).

4. CONCLUSION

In geophysical measurements, the development of electronic and computer-based measuring systems has resulted in higher accuracy, resolution and dynamics. Along with that, however, the processing of very large data sets (a single event recorded at five stations can occupy up to 0.1 Mbyte of memory) imposes enormous requirements on large computer working memories and on materials for data storage.

The discussed and exemplified combinations of digital devices with simpler analogue systems make it possible to investigate the seismoacoustic and seismic processes in real time, improve the quality of data sets and, above all, modify their size. The further development of seismic measuring devices is aimed at the application of intelligent processors, which enable, by locating the devices nearer to the foci of events, to solve the problems of event recongition. The records from our monitoring equipment have yielded fundamental data for the construction of such devices.

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PŘÍSTROJOVÁ TECHNIKA PRO STUDIUM VLNOVÝCH PRŮBĚHŮ SEISMOAKUSTIKY A SEISMIKY INDUKOVANÝCH JEVŮ

Milan Brož

Při sledování seismoakustické emise a indukovaných seismických dějů je vhodné předběžné použití monitorovacích systémů, které tyto děje sledují nepřetržitě v reálném čase. Nepřetržitá registrace umožňuje získat přehled o dlouhodobém časovém trendu měřených veličin, a tím i upřesnit požadavky na výběr měřicích aparatur a optimálních nastavení technických parametrů. V příspěvku jsou popsány možnosti kombinací číslicových měřicích systemů s monitorovacími registracemi a uvedeny příklady řešení.

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