Exploration Geophysics, Remote Sensing and Environment XXVI.2 (2019)

DOI: 10.26345/EGRSE-030-19-203

SEISMO-ACOUSTIC EFFECTS OF FRACTURES IN ROCK SAMPLES

SEISMOAKUSTÍCKÉ PROJEVY PŘI PORUŠOVÁNÍ HORNINOVÝCH VZORKŮ

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Abstract

The submitted contribution describes an original method of studying both linear and pulse loading of the rock environment that can be applied to both borehole cores from any type of prospecting borehole, prepared rock blocks or in-situ measurements. The special instrumentation was developed for monitoring of seismic and seismoacoustic emission originating during loading. The using of this apparatus and developed method processing allowed assessing different effectiveness of both hydraulic fracturing methods and evaluating suitability for industrial applications in the exploitation of geothermal energy through rock heat exchanger methods.

Abstrakt

Předložený příspěvek popisuje originální způsob studia vzniku impulsů porušení horninového prostředí, které lze aplikovat jak pro vrtná jádra, tak upravené skalní bloky nebo i pro měření insitu. Speciální přístrojové vybavení bylo vyvinuto pro sledování emise seismických a seismoacoustických impulsů vznikajících během zatížení hornin. Použití těchto přístrojů je možné použít i při posouzení účinnosti hydraulického štěpení hornin, což je vhodné pro průmyslové aplikace v oblasti využívání geotermální energie prostřednictvím metody podzemního výměníku tepla.

Keywords

hydraulic fracturing, seismoacoustic monitoring, rock macro-sample, seismoacoustic recorder

Klíčová slova

hydraulické porušování, seismoakustický monitoing, horninové makro vzorky, seismoakustický záznamník

1 Introduction

Research on potential sources of geothermal energy has long been familiar with the concept of "HDR" – hot dry rock. This is a medium of less fractured rock that is not saturated by groundwater and has a significant temperature potential for use in obtaining geothermal heat. The existence of constricted, homogeneous, low-permeability rocks logically leads to consideration of their potential for loosening and rendering them permeable (Jiráková et al., 2015). The hydraulic fracturing method has experienced substantial development in this respect; this method employs the geothermal borehole itself to inject liquid with various additives under high pressure to break up the rock in the vicinity of this borehole – this activity is frequently termed simulation of the rock environment/massive. Optimal conditions can be attained by continuous stimulation of the environment between two boreholes. The medium for obtaining geothermal energy is then forced into the first borehole and this medium is collected from the second borehole and transported to the geothermal power/heating plant on the surface, as described by Brož et al. (2014a). In addition, deformation in the range from very small fractures with a size of units of micrometers to global deformation stretching over tens to hundreds of meters, resulting from primary tectonic deformation that is usually present in the considered rock environment at depths of the order of several hundreds to thousands of meters. At these depths, the only possible successful method for determining the properties of the rock environment in relation to the hydraulic pressure depends on either experimental work to obtain rock samples or the method of in-situ monitoring of deformation on the basis of monitoring seismic and seismo-acoustic emissions during the hydraulic experiment (Brož, 2011).

From 2010 to 2014, the STIROMAS (STImulation of ROck MASsif) project dealt with the progressive method of hydraulic fracturing in the Czech Republic. This method was intended to verify the effectiveness of the "pulse" method of hydraulic fracturing, where the working ("fracturing") liquid does not act on the rock environment through constant or linearly increasing pressure but rather, after attaining a certain pressure level, sharp pressure pulses with a frequency of the order or tens of Hz are applied to this liquid. Dramatic development of the fracture system occurs in the stimulated rock even at lower pressure levels than in the linear fracturing method. The research project investigated the actual effectiveness of this pulse method on a wide variety of rock types and for various sample sizes and shapes. Testing of cubic samples with a volume of up to 1 m^3 – “macro-samples" – was an important stage of this research project. An example of instrumentation of the tested rock block by seismo-acoustic recorders is demonstrated on Fig 1. Several metamorphic and igneous rock types (granite, rhyolite, migmatite and amphibolite) and concrete were tested. To assess the different effectiveness of the two above hydraulic fracturing methods, part of the samples were tested by the linear approach and part by the pulse method. In whole, the number of tested samples was more than thirty. The effectiveness of the particular method was derived from the results of the level of fracturing pressure of the individual blocks. Attainment of this level was unambiguous – the tested block suddenly cracked in a fraction of a second, indicated both acoustically and subsequently by the outflow of fracturing liquid from this crack. This phenomenon was later confirmed by the results of seismic and seismo-acoustic monitoring.

In the fracturing test, the samples were prepared so that the pressurized liquid could act directly in the center of the sample (see Fig. 2). Thus a central borehole was made in each cube and this was then pressure-shielded by a glued-in steel tube over most of its length, to prevent undesirable action of the pressurized liquid at the surface of the sample. Only the end part of the borehole in the geometric center of the sample was left unshielded and the fracturing process then necessarily began at this point. For the fracturing test in the framework of the research project, special hydraulic equipment was developed to facilitate pre-selection of the pressure curve of the fracturing liquid and simultaneously enable reading, with high sampling frequency, of various parameters of the whole hydraulic system and especially the pressure in the fracturing liquid and, as appropriate, the flow rate, temperature, etc. An important property of the test hydraulic equipment consists in its ability to create pressure impulses in the working liquid with a selectable amplitude and frequency. The whole system was designed for hydraulic pressures of over 30 MPa.

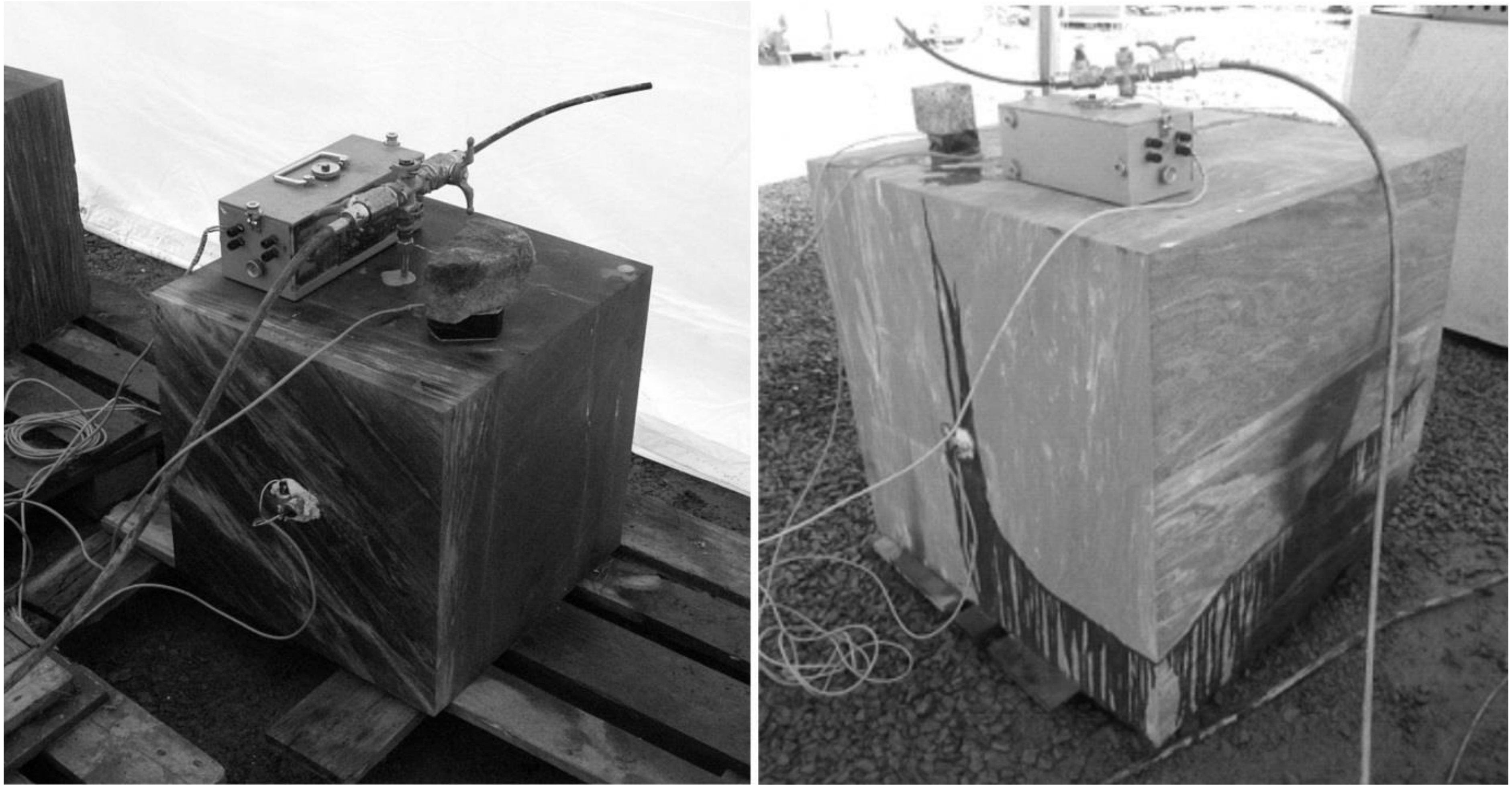

Fig. 1 Example of instrumentation of the tested rock block by seismo-acoustic recorders, to the right is block after hydraulic test with visible pressure fluid outflow

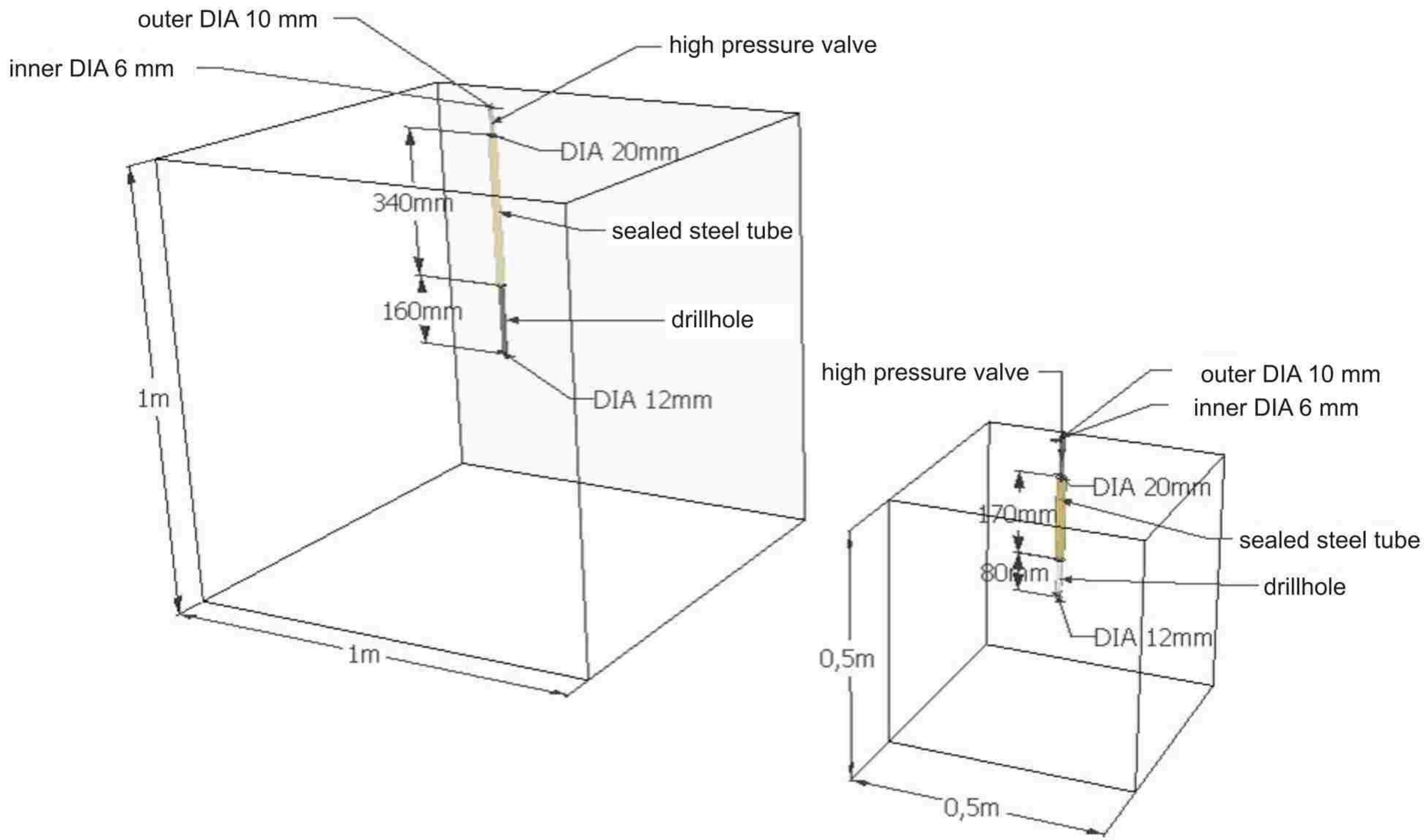

Fig. 2 Scheme of inner instrumentation* of *the tested rock block application of hydraulic pressure

Deformation of macro-samples during test wasn´t measured. All blocks were investigated in detail, so the scheme of outer lines of natural tectonic planes was made. The way of blocks preparation excluded those samples which were damaged by tectonic planes in higher level. It was proved by preliminary hydraulic tests which were done directly in the underground conditions (see Fig. 3) prior to main testing. It means that hydraulic pressure had always had to break through the "virgin" rock material before connecting into some natural fractures contained in the block.

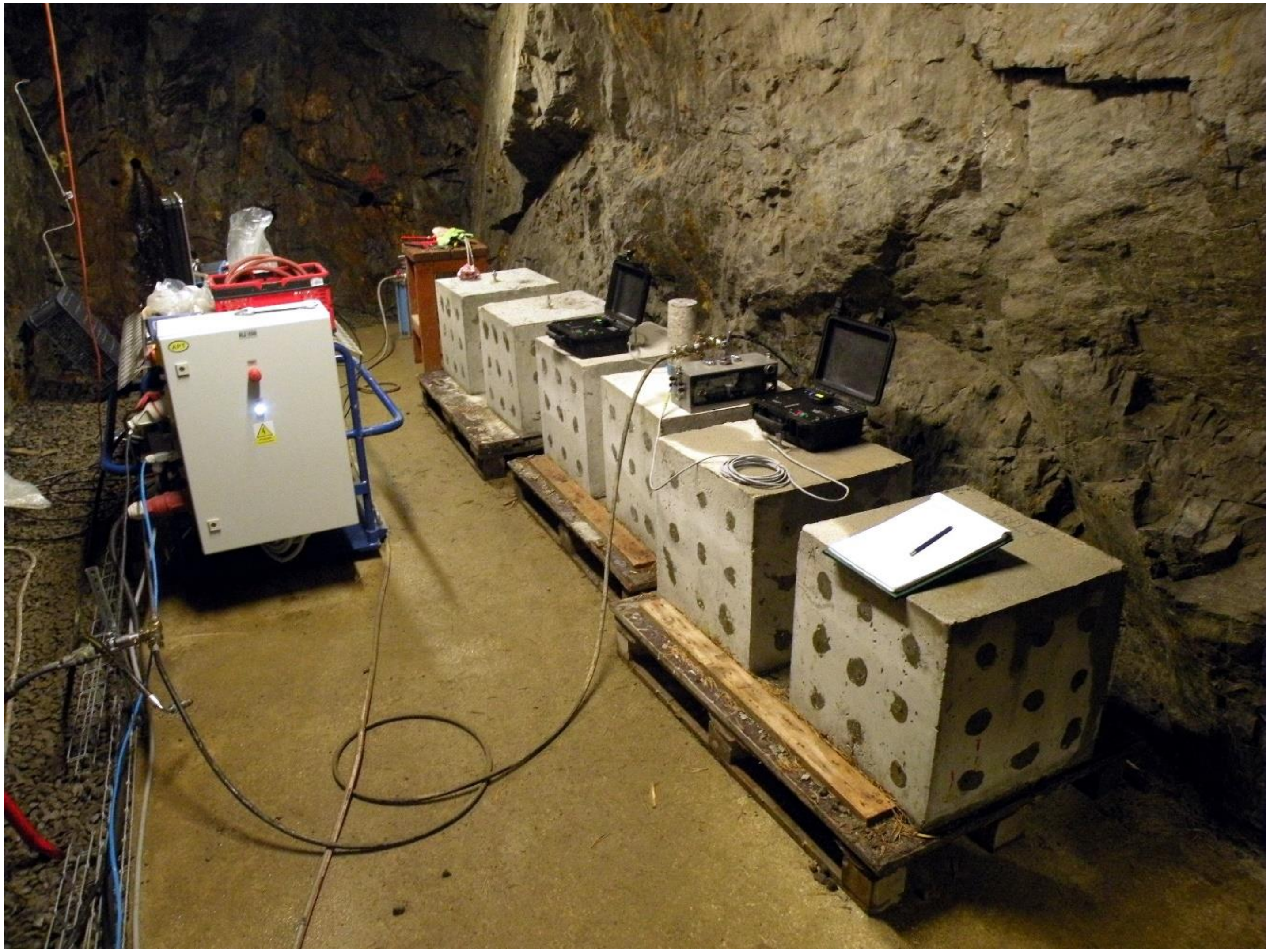

Fig. 3 View into the testing chamber in underground laboratory Josef – several macro-samples prepared to be fractured by special hydraulic tool (standing to the left of the picture)

This article describes the results of acoustic monitoring of the fracturing testing of the above-described macro-samples. The main motivation consisted in the unique opportunity to place acoustic sensors in such large blocks (a substantial part of the samples consisted in ideal cubes with 1 m sides). Obtaining of a detailed record of the acoustic pulse caused by spreading of the newly formed fractures using various different types of sensors makes it possible to attempt to perform various frequency and energy analyses to derive correlation relationships to other determined parameters (primarily geomechanical parameters of the tested rock types).

2 Materials and methods

2.1 Seismo-acoustic measuring methods

Seismo-acoustic waves are propagated in solid substances as progressing longitudinal and transversal waves. A solid rock environment is a necessary condition for the propagation of seismic waves. The waves are dampened if dislocations are present in this environment. The seismo-acoustic wave motion has the general property of wave motion in space. The wavelength λ is given by the relationship:

$$\lambda = vT \qquad \lambda = \frac{v}{f}$$

where:
λ – wavelength,
v – phase speed,
T – period,
f - wave motion frequency.

The wavelengths of longitudinal waves of seismoacoustic impulses in rocks are in the range from 21 m to 21 mm for frequencies of 16 Hz to 16 kHz. The rate of propagation depends on the kind of rocks, density and temperature of the environment and also on the presence of other substances, such as water vapor and the humidity of the air. In solid substances, it depends on the density and modulus of volumetric elasticity, i.e. described by the Poison number.

Brittle fracturing of the rock leads to redistribution of the tension at a rate corresponding to the velocity of propagation of seismic waves. In general, it can be stated that the mechanism of this fracturing in the rocks need not progress as shattering deformation, but rather can occur as shear motion on previously dislocated or newly formed shear surfaces. In addition to the acting tension, the rheological properties of the rocks, their homogeneity and long-term strength can also contribute substantially to the time distribution of the formation of these deformations.

Manifestations of seismo-acoustic emissions occurring in the rock environment have been known since the middle ages, when release of tension in the rock occurred in underground mining of polymetallic rocks in the area around the ore veins, caused by mined-out areas. These manifestations could be identified by physiological listening at quiet times in these mines. Prof. Mogi (1967) described this method as seismo-acoustic emissions occurring in stressing of the rock. In the last years in the Prague laboratories the investigation of acoustic emission was focused on possibility of assessment of instability of rocks (Rudajev et al. 1996, Rudajev et al. 2000, Vilhelm et al. 2004). The application of prediction methods in situ conditions is described e.g. Číž et al. (1999).

Later it was employed in other fields of engineering in monitoring the manifestations of deformation of structures loaded above the values of their structural strength or in manifestations of the response to blasting work in nearby structures. A comprehensive survey of seismo-acoustic investigations can be found, e.g., in the publication of Lockner et al. (1993). The starting point for the instrumentation for measuring seismo-acoustic impulses was based on utilization of the principle of recording these acoustic manifestations both using microphones and especially utilizing the principle of geodynamic and magneto-electric sensors based on the principle of gramophone pick-ups. These were followed by sensors based on the principle of the piezoelectric effect.

2.2 Instrumentation

Practical application of microseismic and seismo-acoustic measurements is based on knowledge that is generally obtained in measurements on classical rock samples – mostly borehole cores with standard dimensions. For example, this work was performed by Vinciguerra and Dresen (2006) on the example of basalt and granite samples. Special measuring apparatuses have been constructed for experimental work on cores, rock blocks or for work in-situ, which differ especially according to the range of the frequency spectrum of the measurement and length of registration, in dependence on the sensors used in the given frequency bands.

Work on this experiment was performed using a system of a three-component apparatus of the BRS 32 type described in Brož et al. (2014b), permitting both work on rock samples and measurements in-situ. The basic parameter of this apparatus is based on 28-byte dynamics with an input sensitivity of 0.1 uV on each independent sampling channel. The sampling frequency of the apparatus can be selected from 250 Hz to 4 kHz. The basic module of a three-channel field apparatus is constructed on the basis of the above principle of registration of emissions of seismo-acoustic impulses. This basic module can also be used for multi-channel measurement of an elevated number of these dislocated basic modules. The modules are synchronized together by registration of the GPS time signal with the HW second signal. If a universal type of 28-byte A/D converter is employed, the apparatuses can use various types of sensors according to the required sensitivity and frequency range of the measurement. Micro-seismic measurements in the frequency range from 1 Hz to 80 Hz are performed using SM6 electrodynamic geophones with a sensitivity of 28.8 mV/mm/s while seismo-acoustic measurements are carried out using type GPIIIV and GPIIIH sensors with a sensitivity of k = 17mV/mm/s in the frequency band 46 Hz – 2 KHz. Special low-noise three-component preamplifiers with amplification of 40dB and 50dB are included to facilitate recording of these very weak acoustic signals.

The above-described instrumentation was used to perform both detailed analysis of the wave field and record the frequency spectra of the individual seismo-acoustic impulses in three orthogonal directions; the time orders of occurrence of these impulses was monitored in dependence on the course of loading the sample. In studying the time distribution of the emissions of seismo-acoustic impulses, the apparatus also meets the requirement of prolonged continuous registration over several hours to days, so that it is possible to distinguish in the time series of impulses both the location of the beginning of the brittle deformation – called shocks – and, after the actual major deformation, also the third phase in this time series, termed the after-shock sequence. Further statistic monitoring of the time series of impulses then permits determination of the dispersion and other statistic data. It holds in general that these processes are studied in a similar manner and confirmed in the fields of classical seismology in much lower frequency ranges, of the order of units to tens of Hz for

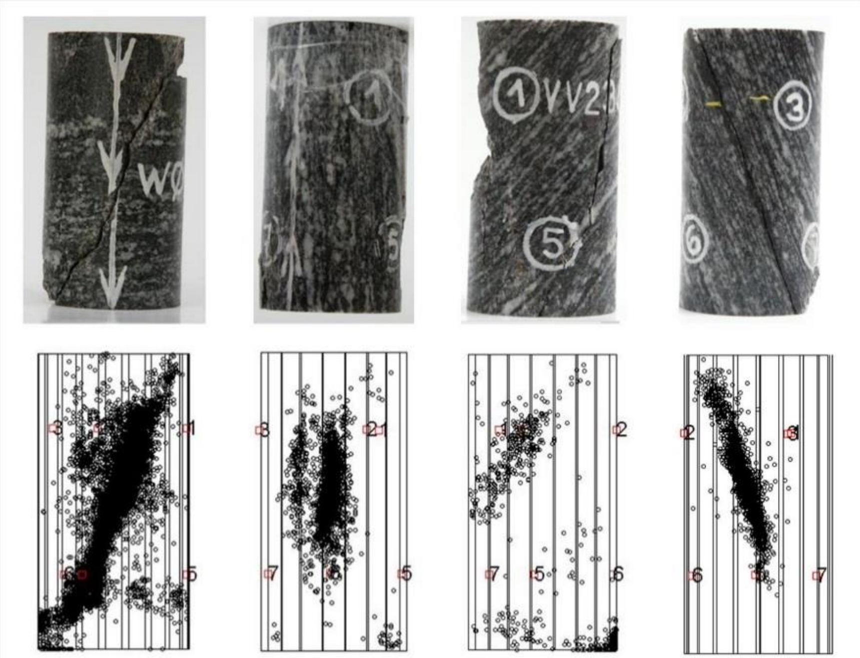

Fig. 4 Location of the focal points of seismo-acoustic impulses in axial loading of a rock – borehole core. Size of cylinbdrical sample: r= 50mm, v=100mm (taken from Petružálek et al. 2008)

large continental tectonic earthquakes and hundreds of Hz for local earthquake areas. However, in relation to the very different geological structural conditions in the individual earthquake areas, it has not yet been possible to use this experience to predict earthquakes.

Another possible means of processing seismo-acoustic data consists in localization of the site of occurrence of the seismo-acoustic impulses. These tasks are based on the use of methodology known from seismology for determining the hypocenters of earthquakes. In contrast to these methods, where a search is performed for the epicenter of one or maximally several dozen phenomena corresponding to the main shock wave, in the field of acoustic emission of impulses it must be expected that deformation of the sample will lead to as many as several hundreds or thousands of these impulses, irradiating their wave forms. In relation to the small dimensions of these samples, the methods for their localization are very demanding on instrumental technology. An example of such an experiment was described by Petružalek (2008). From this work we have taken an illustrative figure (Fig. 4) of the correlation of the spatial distribution of the emissions of seismo-acoustic impulses with actual deformation of the loaded rock sample.

2.3 Instrumentation for measuring brittle deformation on test blocks and in-situ

The experiments on concrete and rock blocks and measurements in-situ were performed using a portable apparatus of the BRS 32 type (Fig. 5, 6), which was used to record the manifestations of the deformation for the entire duration of the hydrological loading. Time synchronization between the individual apparatuses was ensured by receiving the GPS satellite time signal. For measurements in-situ, this time channel is backed-up in the internal time Rt circuit, which is automatically synchronized when the GPS receiver is activated. This approach ensures time synchronization even outside of the area of receiving the GPS signal, i.e. for in-situ measurements underground.

The following three types of sensors were used for the recording:

- "Vegik" (Russia) vertical seismograph with internal frequency of 0.5 Hz, oscillation rate sensitivity of v = 17 mV/ mm/s and resistance of 47 ohm in the damping spool for aperiodic damping. This seismograph was located either on the deformed block or on the footwall of the rock massive for measurements in-situ. The measurement yields the value of the seismic energy for disintegration of the sample determined from the measured maximum amplitudes of the rate of oscillation of the vertical component. This single-component recording was made by the BRS32 – E apparatus with sampling frequency of 250 Hz.

- A three-component, seismic recorder of the oscillation rate composed of three geophones of the SM6 type (Sensor Nederlanden – Holland) with internal frequency of 4.5 Hz, sensitivity of 28,8 MV/mm/s, working in the 2 Hz – 40 Hz range. The BRS32 – SE recording apparatus worked with a sampling frequency of 250 Hz.
  Three-component seismo-acoustic sensor of the GPIIIH type (Geotest Uhříňov), which worked with an oscillation rate sensitivity of 12.5 mV/mm/s in the 46 Hz to 2 kHz frequency range. A sampling frequency of 2 kHz was adjusted on the BRS32 – SA recording apparatus for recording these signals.

Fig. 5 BRS32 recorder with internal battery and GPS receiver

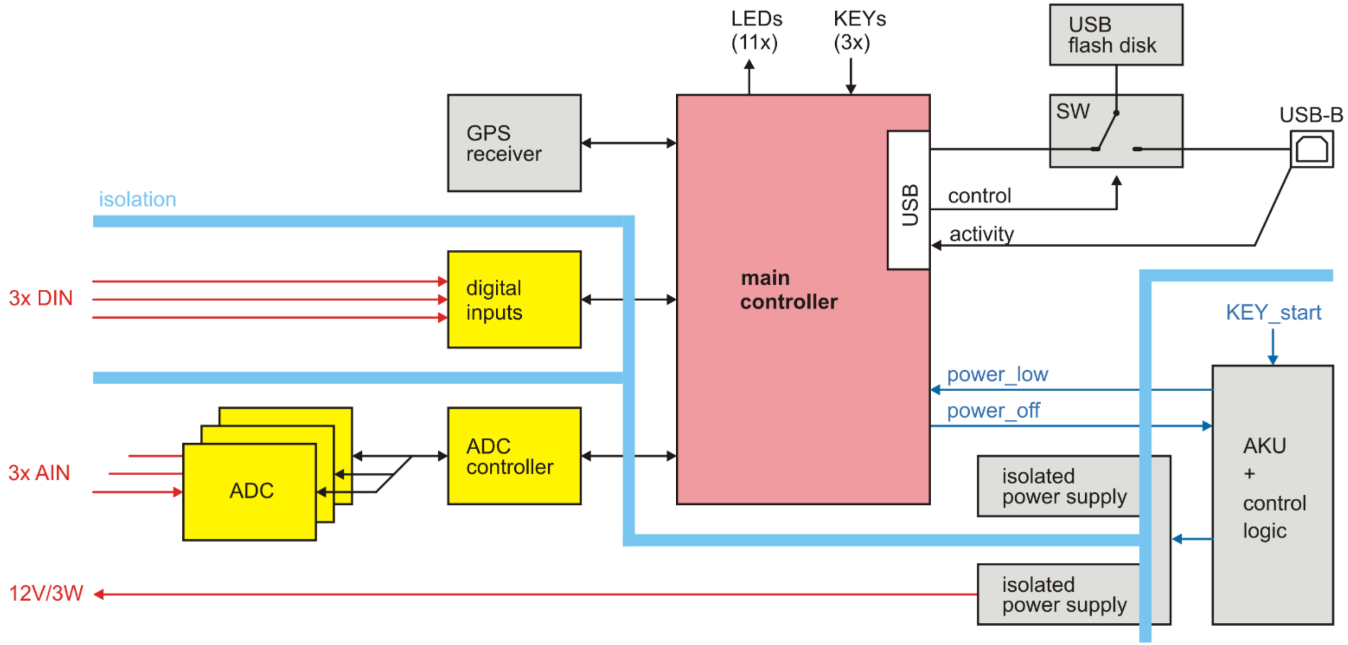

Fig. 6 BRS32 recorder scheme with internal battery and GPS receiver configuration

This is a battery-operated instrument, which can use an internal or external three-component seismic or seismo-acoustic geophone with recording on an internal USB memory with a capacity of up to 32 GB (continuous recording for up to 4 months for sampling at 250 Hz), where programming of the instrument, data transmission and other parameters can be adjusted through an USB interface. The frequency range and dynamic range are dependent on the installed internal geophone and vary from 0.05 Hz to 2 kHz with dynamics of up to 120 dB. The recorder itself has an input dynamic range of greater than 144 dB. After it is turned on, the instrument is automatically connected to the time-date GPS signal, which ensures time synchronization of the data with a precision of 1 us and stores the coordinates of the location of the apparatus at the head of the data file. The instrument works for up to 48 hours on one battery charging. Because of its overall size and simplicity of operation, the apparatus can be used for all applications in measurement of natural and induced seismicity. The instrument is manufactured by Tedia s.r.o. Plzeň. Any type of sensors can be connected to the apparatus without any HW adjustment of the input circuits – its input voltage is converted to a physical quantity on the basis of the value of its constants simply by SW adjustment in the initiation file of the apparatus.

Technical parameters:

- Power supply: 12V Accum. / 7.2 Ah + external battery charger 220V/ 13,4V
- Power voltage sensitivity: 0.0001 mV 2V
- Data transfer: USB 2.0
- Capacity of the USB memory: 32 GB
- Sampling frequency: adjustable – 250, 500, 1000, 2000, 4000 Hz

The recording time is a function of the sampling frequency, battery capacity, memory size and temperature of the surrounding environment. For standard equipment and adjustment, this corresponds to 48 hours for 250 Hz sampling. The original data files are stored in the machine code and are subsequently converted to the ASCII data format during the evaluation. These are data whose the identification heading contains both the sensor parameters and the measuring site parameters; they can be processed by any seismic interpretation program. The data are automatically recorded on the USB memory. In data transmission, these data are first stored in the data banks in the original form and only then are they processed. The processing of the data consists both of visualization of the data and inspection of all the seismic curves in the given time window by an interpreter. The obtained results are compared with the available data on time information of the performed experiment. Selected phenomena are further processed as standard seismograms with wave shapes with the selected time axis and further, e.g., through type and frequency analysis. For completed measurements, it was assumed that there were only very weak phenomena prior to the deformation of the rock and, during the actual deformation, recording of the seismic responses of this hydraulic-mechanical impact.

The following set of figures (Fig. 7 to Fig. 11) depicts examples of seismic phenomena recorded by this apparatus.

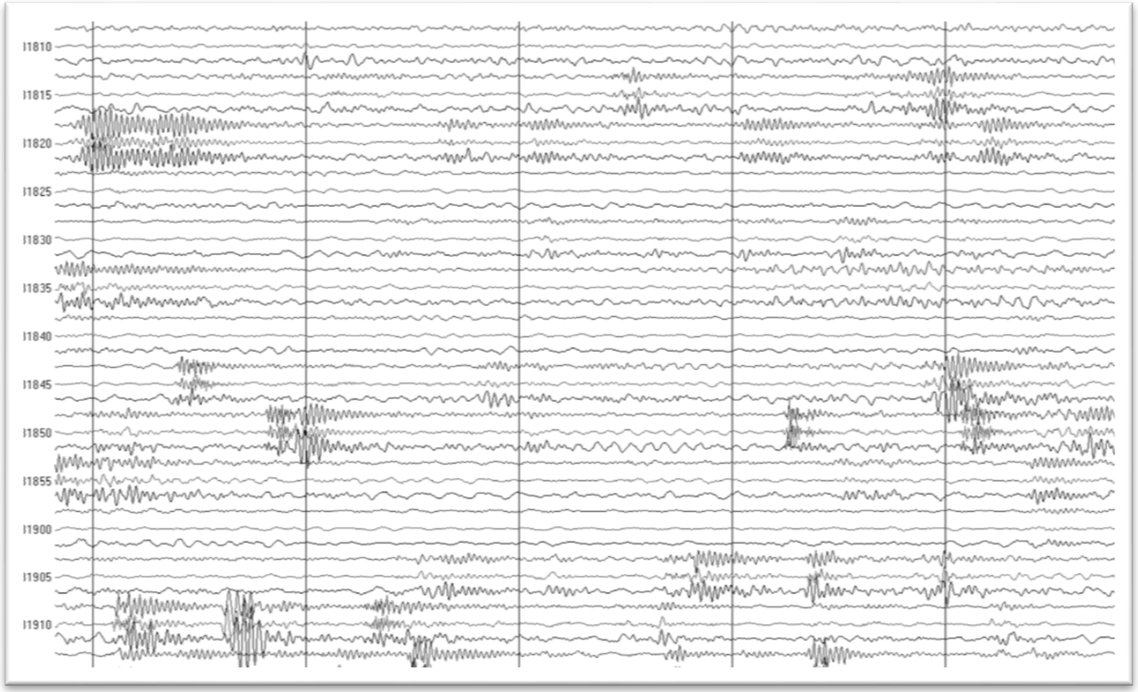

Fig. 7 Regular time recording of seismic impulses in a normal daily regime at the site in-situ containing local seismic noise and impulse phenomena; one line corresponds to 5 s (x-axis time [s]; y - axis Amplitude of signal velocity vibration [mm/s])

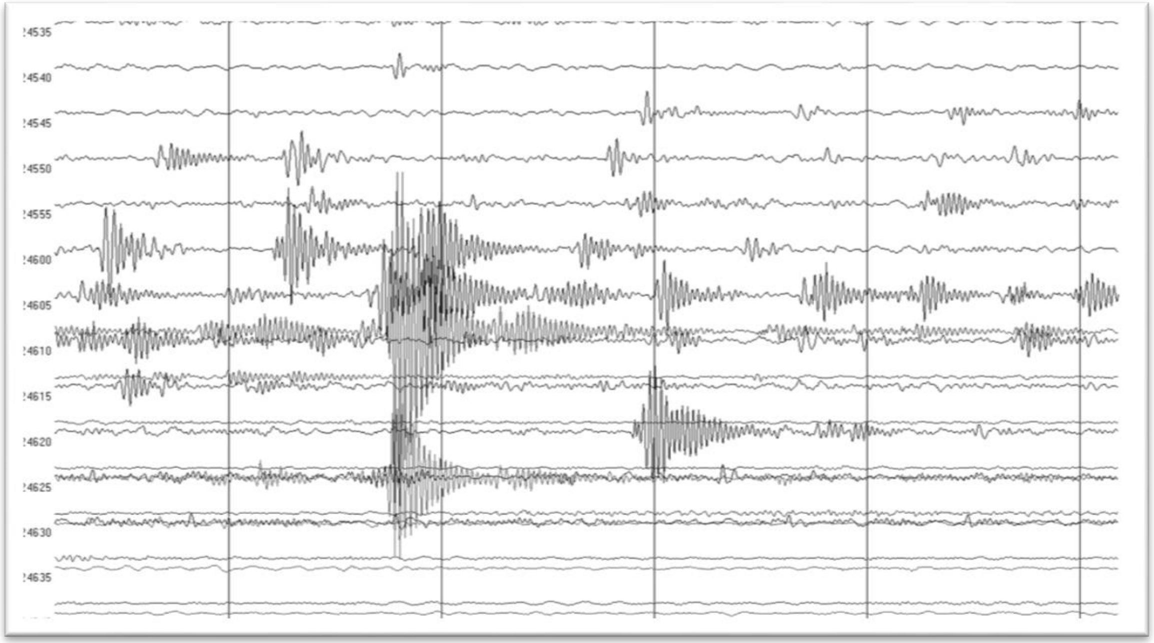

Fig. 8 Two-component recording of seismo-acoustic impulses during loading of the sample (x-axis time [s]; y - axis Amplitude of signal velocity vibration [mm/s])

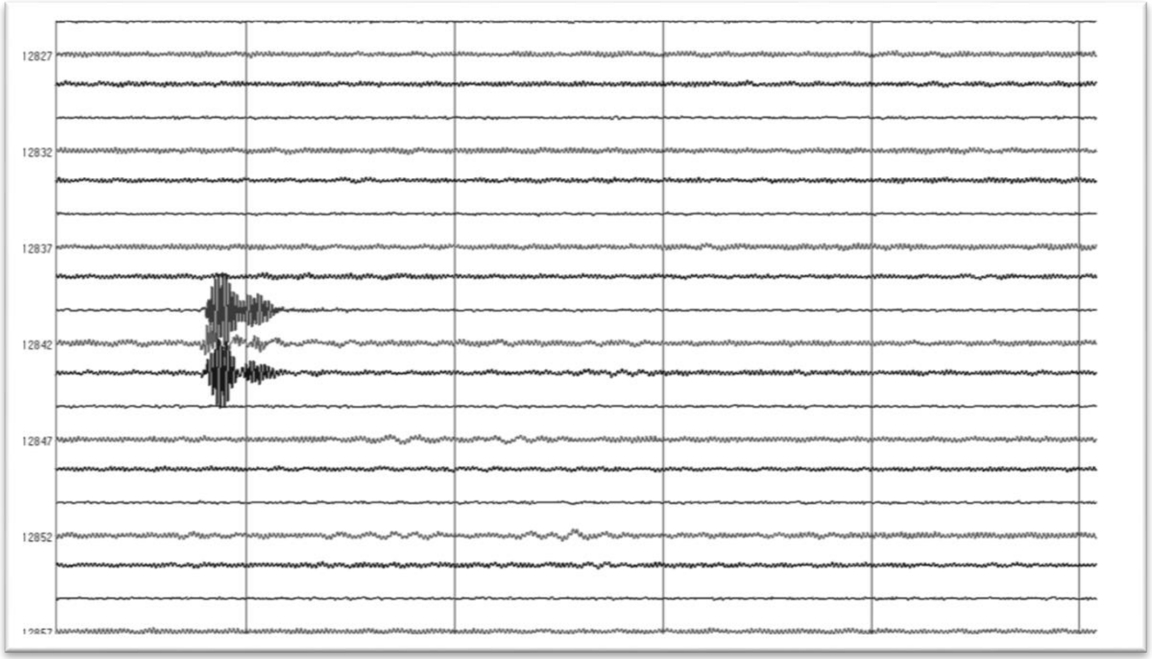

Fig. 9 Recording of the seismic response to a single deformation of the rock block in three components (x-axis time [s]; y - axis Amplitude of signal velocity vibration [mm/s])

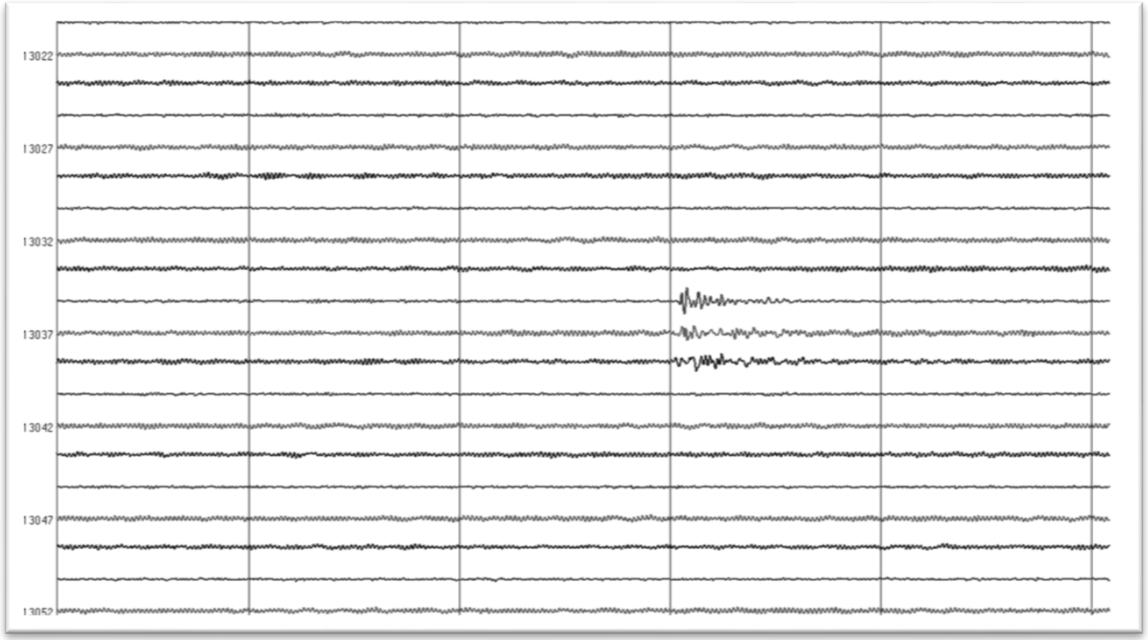

Fig. 10 Recording of a seismic phenomenon on three components for which the distribution of the individual phases of the recorded seismic response to the impact is apparent (x-axis time [s]; y - axis Amplitude of signal velocity vibration [mm/s])

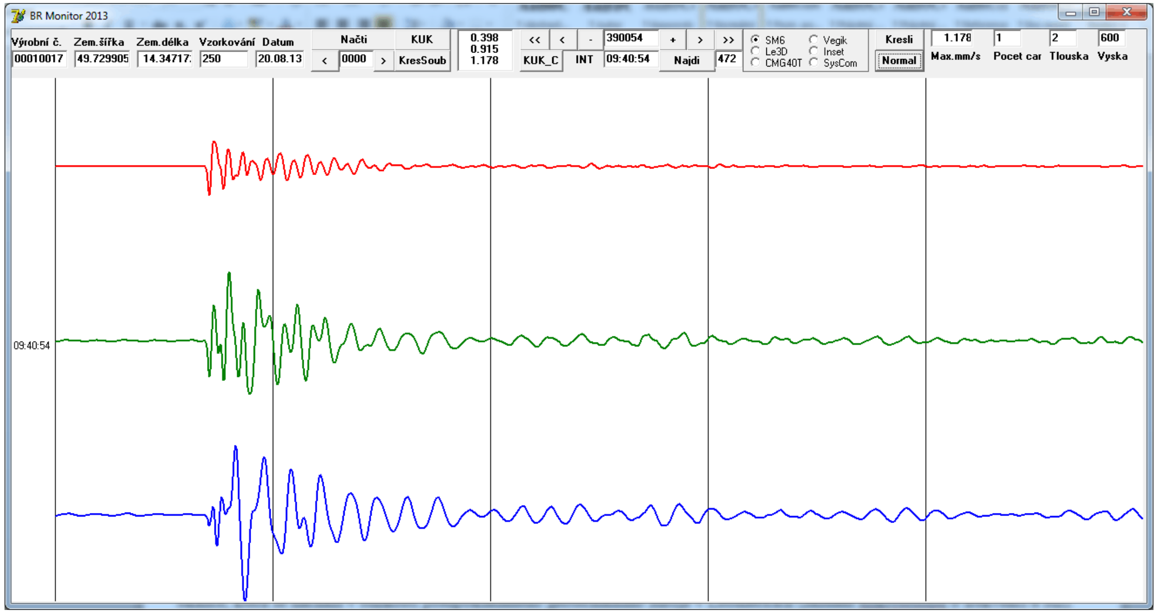

Fig. 11 Detailed shape of the three-component wave recording of the course of the seismic response to deformation of the rock block during hydraulic fracturing (x-axis time [s]; y - axis Amplitude of signal velocity vibration [mm/s])

3 Results

3.1 Finding the impulse in the acoustic recording

The obtained acoustic recordings were subsequently analyzed in the following manner. The first step involved finding the time interval when there was an acoustic manifestation connected with fracturing of the tested rock. The basic guideline for determining the most probable position of the acoustic pulse of the forming fracture on the time axis of the recording consisted in comparing the data from the acoustic monitoring with the data in the pressure recording of the fracturing liquid, which was obtained by the actual fracturing hydraulic equipment. On this equipment, a rapid decrease in pressure in the working circuit was always visible at the moment of formation of the fracture. This is caused by penetration of the fracturing liquid into the newly formed fracture. The fracturing equipment has a reservoir for completion of saturation of the liquid, but the rate of supplementing the pressure is far from being capable of balancing the rate of development of the pressure drop of the fracturing liquid in fracturing of the block (Fig. 12).

The time correlation of the two recordings mostly made it possible to very rapidly find the section with the actual acoustic impulse. An example of recorded acoustic impulse is presented on fig. 11. Thus, the timed velocity recordings of the individual pulses were gradually obtained from the individual tests.

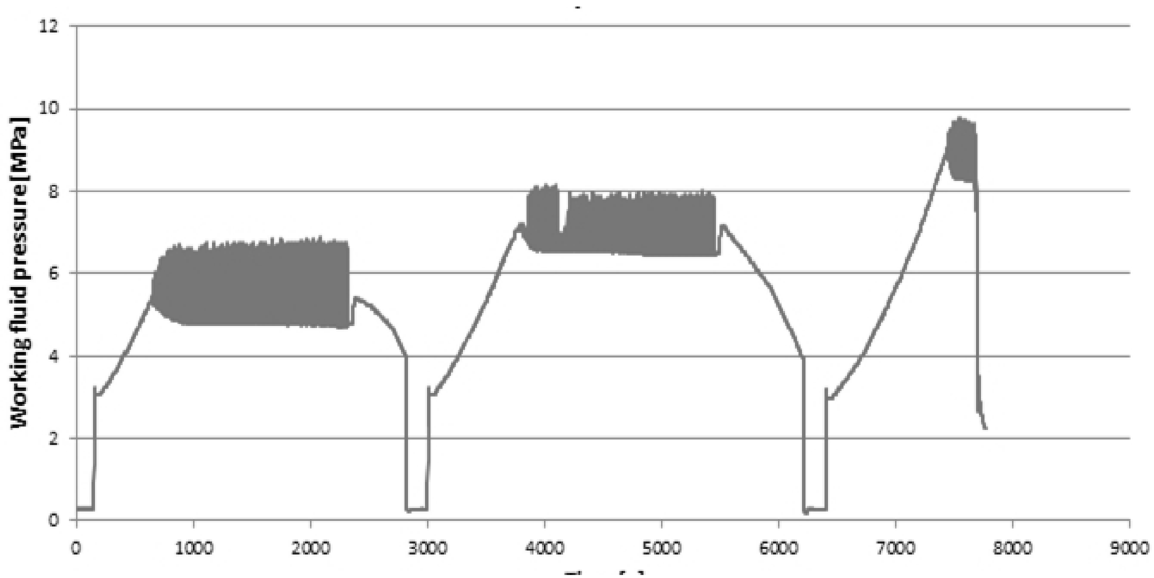

Fig. 12 Typical working pressure curve of the fracturing liquid during the pulse test

3.2 Frequency analysis of the recorded impulses

Subsequently, part of the time recording was analyzed using special software, which enables the use of rapid Fourier transformation to decompose the velocity recording of the impulse into individual frequency components and to determine the energetically highest frequency of the recorded pulse (Fig. 12–14). A substantial part of the recorded pulses had two distinctive frequencies and in this case they were both used for the evaluation. Statistic evaluation of all the obtained distinctive frequencies yielded graph (Fig. 15) on which can be distinguished two frequency extremes at cca **7±2** Hz and 26±3 Hz.

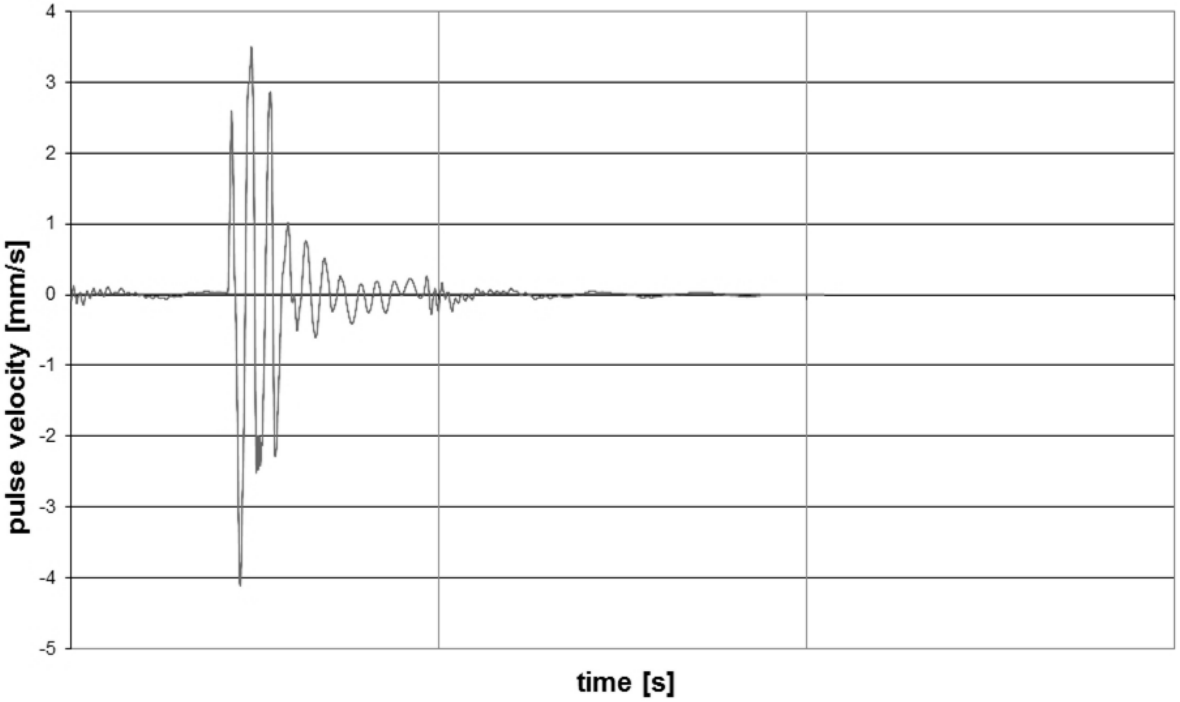

Fig. 13 One-dimensional component of the recorded impulse on deformation of the rock block. The length of time interval is 3 s on the picture

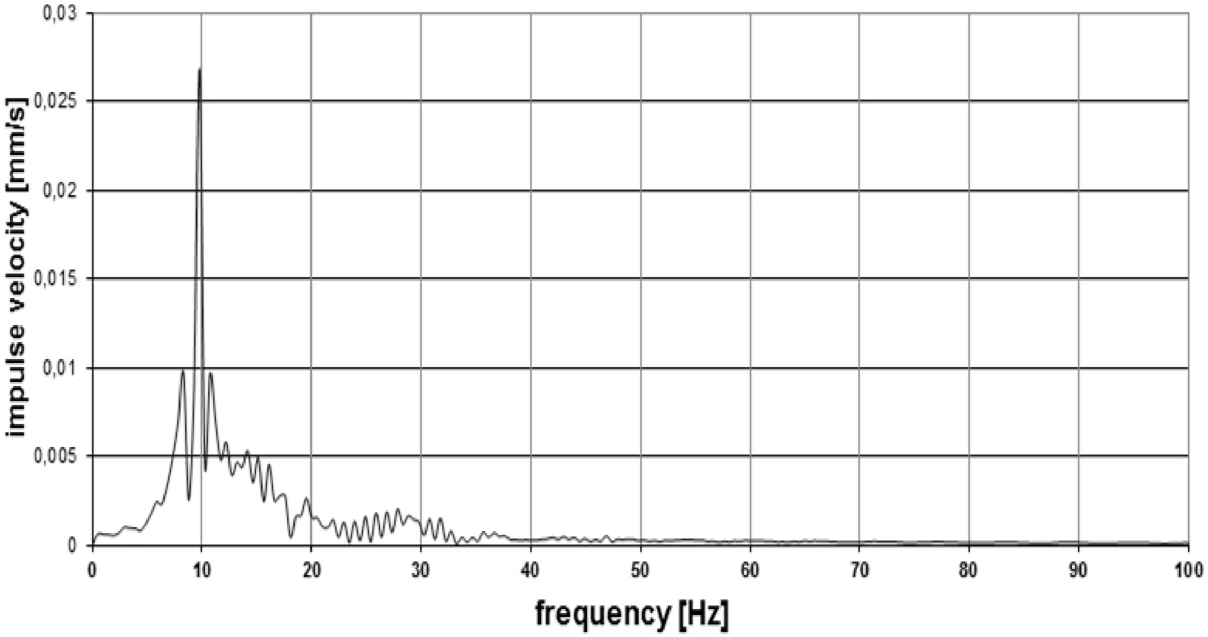

Fig. 14 Frequency spectrum of the seismo-acoustic impulse on the formation of a new fracture

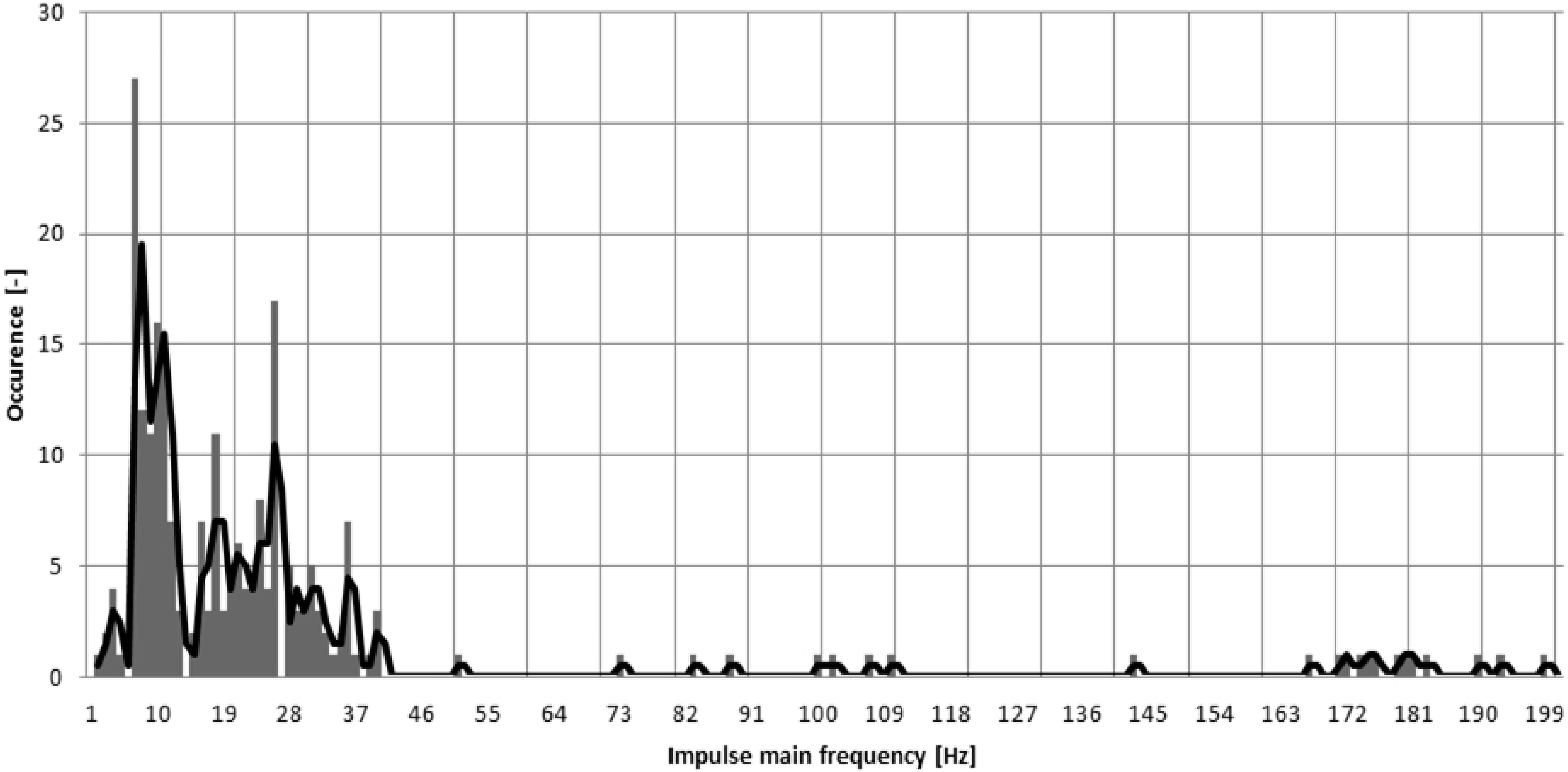

Fig. 15 Statistical evaluation of the main frequencies of all the impulses from the successful fracturing tests (36 tested samples)

3.3 Eliminating the interfering effect of the fracturing equipment

A very interesting separate task in development of the method of acoustic monitoring of fracturing tests consisted in consideration of interfering acoustic effects occurring through connection of the fracturing equipment. The greatest acoustic impact on the acoustic measurement came from the application of pulses to the fracturing liquid in the pulse method of testing macro-samples. In this case, the pulses were clearly visible on the recording, see Fig. 18.

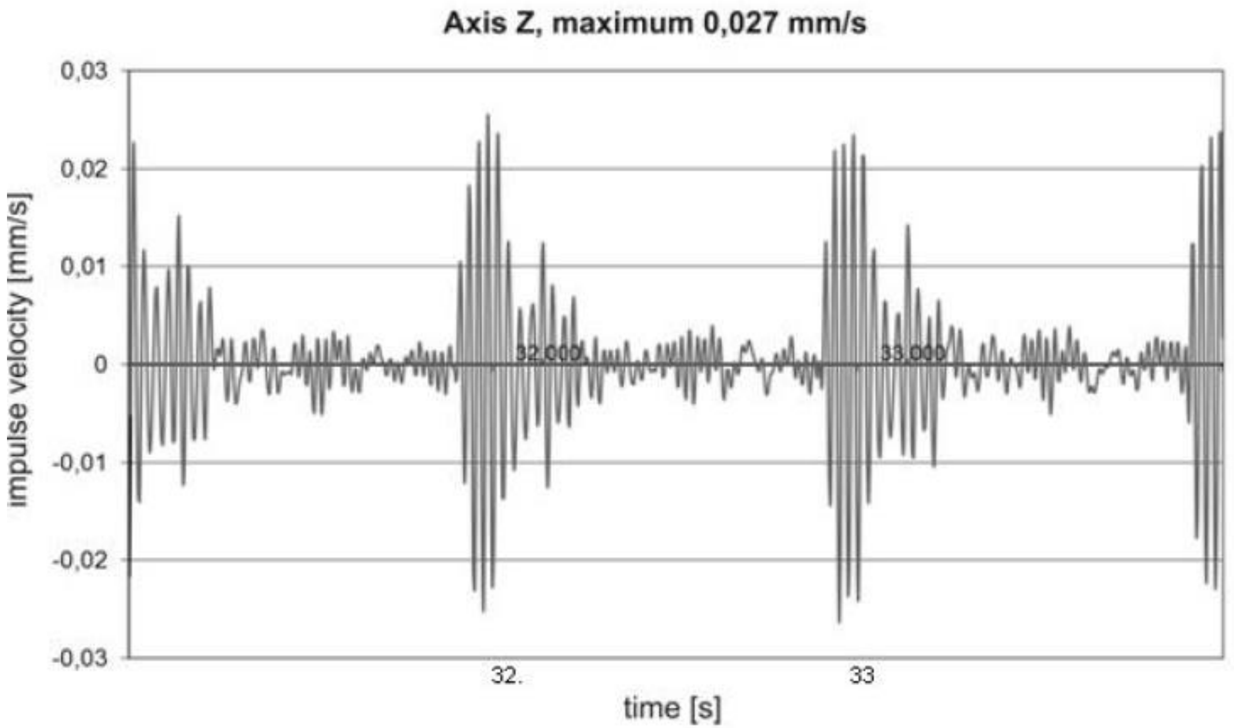

Fig. 16 Seismo-acoustic recording of the effect of the pulsing equipment on the rock block

The situation was complicated subsequently by the fact that deformation of the samples occurred primarily and quite logically during the pulse phase of the test. The pulse from the formed fracture thus very frequently almost completely disappeared in the velocity acoustic recording of the pulsing itself. In this case, it was found to be very useful to employ fast Fourier transformation because, after separating the recording into the individual frequency components, the recording of the formation of the fracture can be very clearly distinguished from the acoustic effect of the pulsing (Fig 16, 17). The pulsation was manifested primarily in the frequency interval from 30 to 45 Hz (Fig. 15) and at velocities to 0.0005 mm/s. The impulses themselves were mostly in the lower frequencies and mainly exhibited approx. one order of magnitude higher velocities of about 0.005 mm/s. While mixing in the acoustic impulse substantially prevented analysis of the length of its duration and damping character, the above-described procedure permitted performance of frequency analysis with very good results (Fig. 18).

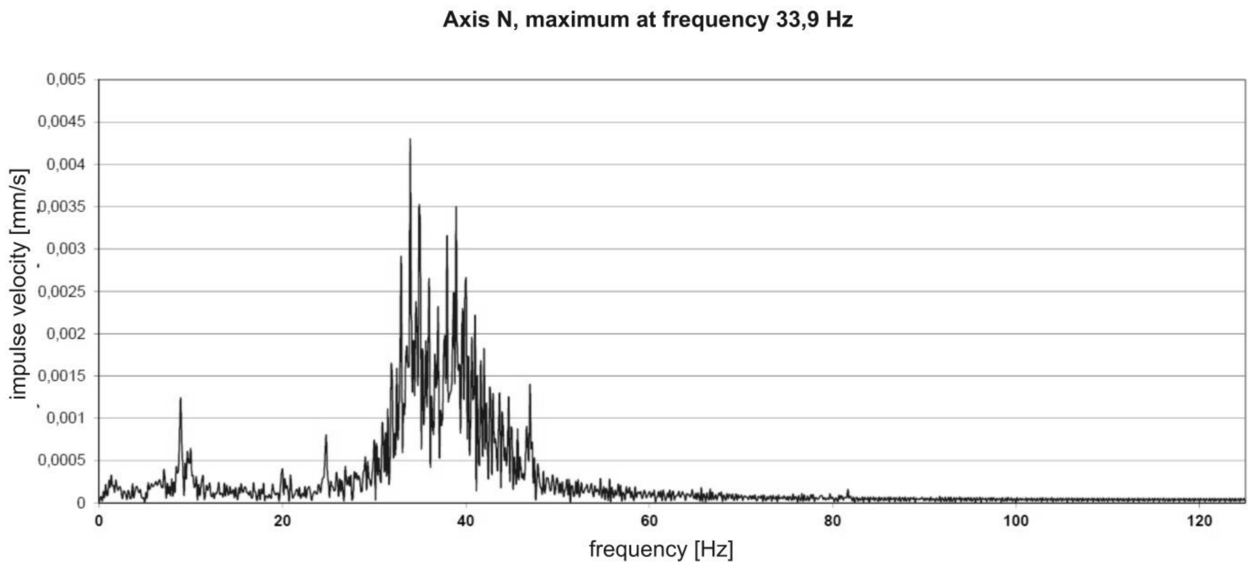

Fig. 17 Frequency spectrum of the seismo-acoustic recording of the working pulsator

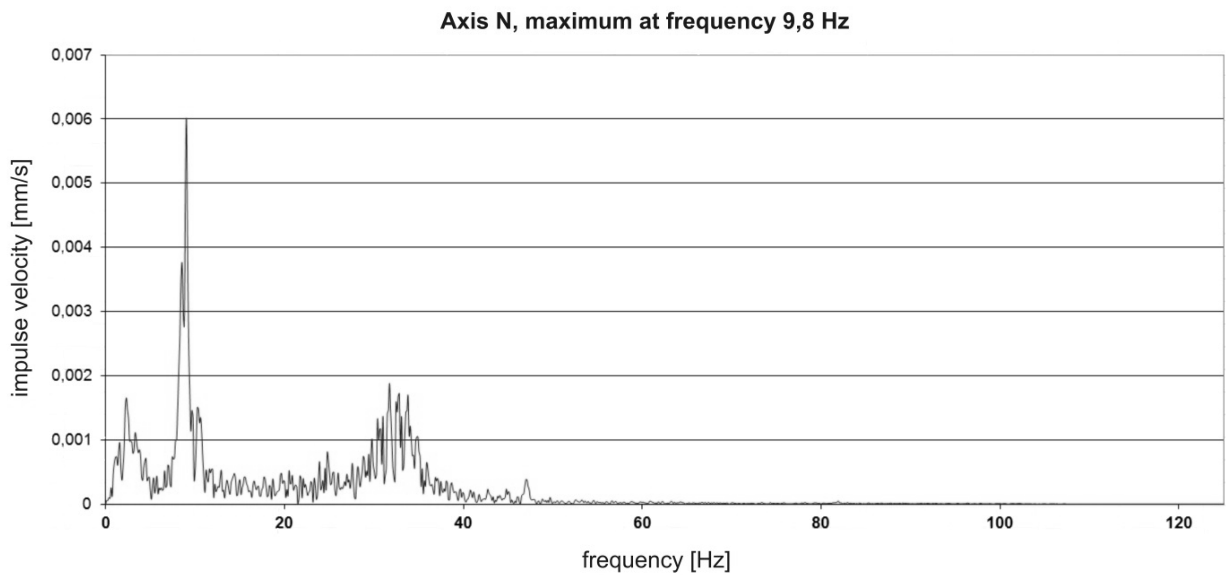

Fig. 18 Frequency spectrum of the seismo-acoustic mixed recording – pulsator and deformation

4 Conclusions

The submitted contribution describes an original method of studying both linear and pulse loading of the rock environment that can be applied to both borehole cores from any type of prospecting borehole, prepared rock blocks or in-situ measurements.

A hydraulic source of linear and pulse loading was constructed for this study, equipped with a control computer for controlling the individual phases of the experiment and providing for on-line outputs about the loading parameters. Simultaneously with this technology, instrumentation was developed and tested in practice for monitoring seismic and seismo-acoustic manifestations during loading and subsequently verification of the methodology for interpretation of these data. The individual measurements were performed on rocks with exact geological and geotechnical descriptions, on the basis of which summary evaluation of the results of these measurements was performed. On the one hand, rocks suitable for hydraulic fracturing were determined and, on the other hand, the difference in the effectiveness for linear and pulse hydraulic fracturing was evaluated. On the basis of this work, it is possible to assess the effectiveness of this method for industrial applications in the exploitation of geothermal energy through rock heat exchanger methods.

Generally developed method enables complex monitoring of course and process of new cracks creation. Origin of crack is accompanying by radiation of elastic waves with acoustic frequencies – acoustic impulse. Processing of complex recorded acoustic data brings detailed information about origin and properties of the rock cracks.

The presented method enables frequency and amplitude analysis of recorded acoustic impulses. By this method are evaluated splitting process and forming of new cracks in rocks. The frequencies (resp. wave lengths) of P-wave are connected with source (focus) dimensions and they are also influenced by rock medium through which the waves propagate. Maximum amplitudes of acoustic signals serve for estimation of splitting energy.

If the monitoring system is equipped by 3D acoustic sensors, then the main direction of radiated energy can be specified. This direction is perpendicular to the plane of new originating crack.

The location of seismo-acoustic impulse source (focus) is based on suitable distribution of acoustic network and on time synchronization of separate sensors. Usually kinematic method is applied. This location method supposes knowledge of velocity model of pertinent medium.

Described seismo-acoustic method is therefore very suitable for monitoring of brittle deformation of rock formation, rock slopes and walls. Technical parameters of developed apparatus and sensors makes possible continuous monitoring of fracturing process of region endangered by rock slope deformations in best way by measurements in equipped boreholes. The best placement would be in area of sliding surface where the creation of new cracks could be presumed. Applied apparatus can be easy supplemented by data long-distance transmission and to evaluate seismo-acoustic data on-line in environment of complex early warning type monitoring system. Authors of the article are in present trying to start new research project which would demonstrate the usage of such monitoring system in some landslide area in Europe.

Acknowledgement

Research project was supported by the Ministry of Industry and Trade of the Czech Republic during the project "Stimulation of rock massif to establish a fracture reservoir for capture of geothermal energy in the hot-dry-rock system" (Grant Number: FR-TI3/523).

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