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SEISMIC MEASUREMENTS ON A ROCK MASSIF SURFACE AT SHORT DISTANCES

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ABSTRACT
Various geotechnical tasks require the knowledge of rock properties, e.g., of elastic moduli, fracture systems, inhomogeneities, etc. Seismic measurements usually provide these parameters. To describe the detailed properties of small rock volumes, it is necessary to use high-frequency signals and suitable registration systems. Seismic measurements are carried out directly on rock surfaces. Although the conditions, under which measurements are carried out, seem to be simple and convenient, practical measurements themselves are often complicated. The various measuring systems, including seismic sources and seismic receivers used for different base lengths, are discussed in this paper.
It was found that, for the repeatability of measurements, the fixing of the sensors with plaster plays most significant role. Repeatability of hammer blow as seismic source is adversely affected namely by signal amplitude triggering. Pencil lead breaking tests with lead 1 and 6 mm in diameter were found as suitable for testing of the high-frequency measuring systems. Measuring directly on the rock massif surface is different compared to exploration seismic measurements. Due to absence of a low-velocity layer it necessary to use a special choice of mutual orientation of sources and receivers. Polarization analysis may be advantageous to identify the arrival of P and S seismic waves. It was also found that the rock massif behaves as a narrow frequency-band pass filter. For exciting frequencies of 0.1 and 1 MHz the transmitted signal displayed the same frequency of 25 kHz at a distance of 1.1 m.

KEYWORDS: repeatability of measurement; velocity measurement; seismic source; seismic P- and S-waves

INTRODUCTION

The purpose of this paper is to evaluate several selected procedures in field seismic measurements when the seismic source-to receiver distance is small (approx. 0.2 – 10 m) and both the source and receivers are located on the surface of a rock massif. Measurements of this type are currently carried out to determine the velocity of propagation of seismic waves in a rock massif in places, where only the rock surface is accessible. Seismic measurements are often used to monitor the changes in the rock massif due to the changes of temperature and stress-strain conditions which can lead to the generation of fractures, changes of permeability of the massif and, in particular, to a decrease in its strength. To monitor these important parameters, it is very convenient to monitor the changes in the propagation velocity of seismic waves, which is a function of the effective elastic moduli of rocks. However, obtaining plausible values depends on evaluating the repeatability of seismic measurements, i.e. the repeatability of seismic energy sources and the possibility of setting the measurement conditions in advance (e.g., the use of a chosen signal frequency in measuring along a chosen length of the measuring base). Since measurements along small distances are involved, great emphasis is put on precise determination of time of the signal source realization, as well as the time of signal arrival to registering sensor.

The paper, therefore, deals with comparing several types of seismic sources from the point of view of frequency content of the signal they generate, the possibility of determining the precise time of emitting the seismic signal, and also gives the basic information about the experience gained with source distance, at which measurements can be made with the tested types of sources.

Attention is also devoted to some problems of monitoring, in particular to the problem of the direction from which seismic waves approach the receiver in an environment with velocity gradient and in the vicinity of a seismic source. When measuring with piezo-ceramic exciters and transducers of P- and S-waves, it is useful to have an idea of the anticipated polarities of the passing seismic waves. Several methods of attaching transducers to the surface of the rock massif are also compared.

PRESENT STATE

In recent years, a number of requests have appeared to monitor the geological medium using geophysical methods in connection namely with plans to build radioactive-waste repositories. The geological environment in the immediate vicinity of underground excavated spaces is affected by the driving process and effects which are associated with the redistribution of stress in the vicinity of the excavation (e.g., Bossart et al., 2002). This medium is referred to as the Excavation Damage Zone (EDZ). To characterise the extent and properties of the EDZ in the vicinity of actually functional underground excavations, it is necessary to make use of mostly non-destructive geophysical research methods. The conditions of measurement directly on the rock massif, and the necessity to achieve high accuracy and repeatability of the measurements indicate that traditional procedures, derived from surface measurements, are insufficient. A number of new findings were drawn from the research carried out in the Mont Terri Underground Rock Laboratory (Bossart and Thury, 2008). Micro-seismic measuring directly on the rock wall, when the measuring base is comparable with in size with the dimensions of the tunnel, are complicated, e.g., by the generation of a strong interference wave (surface, tunnel wave) if the cross-section of the mine adit is circular (e.g. Gridin et al., 2003; Jetchny et al., 2010).

Mareli et al. (2010) reported that it was not simple to achieve repeatability either of the seismic source or of the seismic transducer record. This affects the wave records made during repeated measurements. All waves, which arrive at later times, differ significantly when the measurement is repeated. This is because of a new positioning of the instrument and transducers at the same points of measurement even though the environment has not changed at all. Even if the positions of the transducers are fixed, one must reckon with the significant effect of the actual local conditions of each individual transducer, i.e. the measurement is repeatable at a given point, but different from that at a close point. Mareli et al. (2010) mention the sparker (the source is an electric high-voltage impulse generated under water; source frequency 5 kHz) as a source which guarantees repeatability. As receivers which display the best results on re-mounting (well-defined transmission of energy) they mention hydrophones, i.e. piezo-ceramic pickups placed at the same point in a borehole filled with water. Also Balland and Renaud (2009), e.g., dealt with seismic measurements within a rock massif using boreholes. However, these measurements can no longer be considered as non-destructive methods. The best results, without boreholes, can be achieved with anchored transducers. Mareli et al. (2010) concluded that further technical development was required to arrive at portable transducers with good and repeatable transmission of seismic energy from the rock environment.

In the case of recording seismic waves at longer distances, the seismic source is usually realized by an explosion in boreholes of various depths. For relatively small distances, the borehole depth is about tens of centimetres and the explosive matter is about hundreds of grams (Pandula and Jelšovská, 2008). Boreholes of the first tens of metres deep are used for surveying at longer distances, and the weight of the explosive charge is about hundreds of kilograms (Holub, 2008).

Apart from seismic methods, geoelectrical resistivity methods are frequently applied. For example, also resistivity tomography with stable locating of electrodes is used to study the development of EDZs (Gibert et al., 2006). In that case it was moreover found the resistivity changes are strongly controlled by the local tectonics and by the bedding in the sedimentary rock formation. This was confirmed also by measuring the anisotropy of electric conductivity, carried out on a substantially more detailed scale directly at the end-face of an Opalinus clay gallery of the Mont Terri Underground Rock Laboratory mentioned above (Nicollin et al., 2010).

LOCALITIES OF MEASUREMENTS AND SEISMIC RECORDERS

The experiences, described in this paper, summarize the knowledge gained from the measurements made under various geological conditions in a number of localities. These conditions included both plutonic magmatic rocks and sedimentary and metamorphic rocks.

The measurements on bodies of granitoid rocks with confining texture were carried out in the locality of the Prosečnice Quarry near the Sázava River (quartz diorite of the Bohemian pluton) and in the locality of Bedřichov near Liberec (underground gallery in the granite of the Krkonoše-Jizera pluton).

The measurements on ultrabasic rocks were carried out in the peridotite Balmuccia Massif in the Ivrea zone (northern Italy) which represents sub-crustal lithospheric mantle material.

The measurements on sedimentary rocks were made in the locality of the Chýnice Quarry near Prague (bedded Devonian limestone of the Barrandien area) and in the locality of the Kostiviarska Quarry near Banská Bystrica (Slovakia – argillaceous limestone to marlite of the Križná nappe of Cretaceous age).

The measurements on metamorphic rocks are represented by the measurements on magnezite in the Lubenik Mine (Slovakia) originated by metasomatism of originally carbonate rocks of Carboniferous age.

The basic recording instruments used in field measurements were the Geode seismograph and DSO 1024A oscilloscope. The engineering Geode seismograph (by Geometrix) has 24 channels and uses a 24-bit A/D converter. Its maximum sampling frequency is 20 kHz. The DSO1024A oscilloscope (by Agilent) has four channels and its maximum sampling

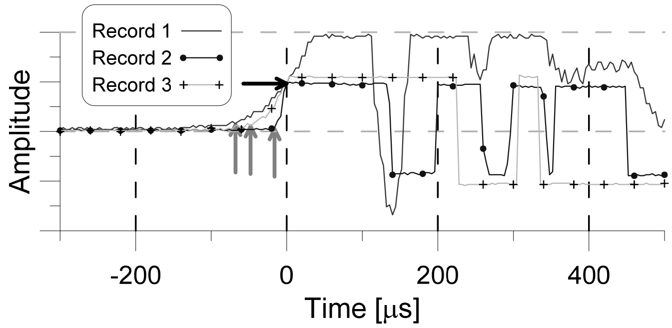

Fig. 1 Example of three records of signals from an accelerometer, fixed to the hammer, of three repeated impacts. The amplitudes of the records have been normalized to the amplitude set for starting the record (indicated by horizontal arrow); the triggering time corresponds to time 0 s in all cases. The vertical arrows indicate the different times of the first growth of the signal amplitude, corresponding to the first contact of the hammer with the rock for the particular impact.

frequency is 2 GHz. It is equipped with an 8-bit A/D converter. To improve the signal-to-noise ratio and dynamic range, both devices enable averaging of repeated records.

SEISMIC SOURCES AND TRIGGERING

As regards seismic measurements over small distances between source and receiver, in an interval of about 0.2 to 10 m, the most usual type of seismic source is the impact of a hammer on a plate. In measuring over distances up to approx. 0.5 m, one usually employs piezo-ceramic exciters, which allow the use of higher signal frequencies than hammer impacts display. An original method of exciting a high-frequency seismic signal was tested: the breaking of a thick writing lead.

HAMMER SEISMIC SOURCE

The use of the hammer impact as a seismic source is a very ordinary method, and one frequently used in surface shallow seismic exploration. In measuring on a cover layer (usually soil, less frequently sand, etc.) it is necessary to apply the hammer blow to a metal or plastic strike plate to achieve rapid deceleration of the hammer and thus also a larger and shorter effect of the acting source force. It is common knowledge that seismograms, recorded during repeated impacts on a single spot, are very similar. It is, therefore, possible to sum the seismograms of repeated impacts and thus increase the energy of the seismic source and improve the signal-to-noise ratio. Measurements made directly on the surface of a rock massif may be carried out without the plate, but it has been found that the separate impacts are frequently less similar than in case of the impact on a strike plate lying on the cover layer. On the uneven and heterogeneous surface of a rock massif, the conditions of the separate impacts may differ significantly. If the rock is not strong enough due to weathering or fracturing, the individual impacts may further break the rock, which in turn changes the conditions of exciting energy. Usually, on an uneven surface of the rock, one is unable to repeat the positioning of the plate reliably, which would otherwise help to stabilize the source conditions at least in part.

To increase the accuracy of determining the position of the point of impact, it is convenient to use a small strike plate. It is usually more reliable to place the strike plate at the desired distance from the measuring set-up only roughly, and to determine the actual point of impact by measuring the distance. On the uneven surface of a rock massif, it is more convenient to adjust the detailed position of the source with regard to the place where the plate can be placed more stably.

The time-of-flight of seismic wave over the distance about 0.5 m in rock material is significantly shorter than times measured during ordinary surface shallow refraction measurement. Therefore, increase demands on the accuracy of time determination. First of all high accuracy of triggering is required. Figure 1 shows a record of acceleration measured by triggering accelerometer placed on the hammer. Three different consecutive strikes have significantly different time course of the acceleration. Because of triggering by signal level, all three relatively distinct signals have a common point, determined by the set switching level and corresponding to the zero time (marked by a horizontal arrow in the figure). The time differences between the separate records, however, indicate that determining the time is not accurate and, simultaneously, show that, if the energy is increased by summing impacts, the summed signal may become significantly distorted with regard to its real shape due to different delays.

If there is uncertainty in the delay of triggering the signals, it is not convenient to sum the signals

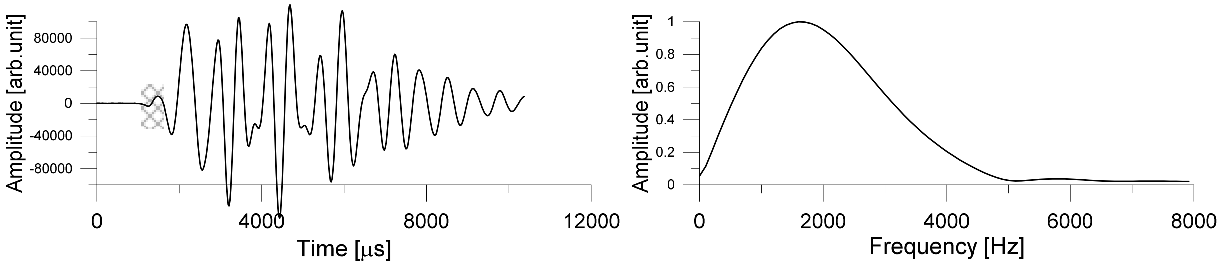

Fig. 2 Left: Example of signal recorded on the surface of a rock massif at a distance of 10 m from the point of impact of a 1-kg hammer. The marked part of the signal corresponds to a frequency of 1.6 kHz. Right: frequency spectrum calculated from marked part of the signal.

from the repeated impacts, but it is better to make several repeated records and, based on their similarity, to eliminate the effect of the trigger delay. By adding signals with different, although small delays, the time of the first onset becomes smeared and substantial deterioration of the legibility of later arrivals occurs. For obtaining well legible records, it is necessary to set the amplification suitably with a view to the monitored part of the signal (different amplifications can be selected for P- and S-wave arrivals).

If the trigger delay is uncertain, the observed times-of-flight cannot be used directly to calculate the velocity, but the velocity may be determined only from the slope of the travel-time curve. This depends on the agreement between the apparent and real velocity. This means that the seismic wave must propagate from the source to the receiver along the surface of the studied environment. This condition is satisfied well, if the measurements are being made over small distances in an environment, in which the velocity does not increase significantly with depth. Practically this corresponds to an environment without manifestations of the EDZ. The increase of velocity with depth may usually be reliably excluded, if there is a larger number of points on the travel-time curve and these display linear dependence of time on distance. In determining the velocity in this manner, it is necessary that the travel-time curve be formed only of records corresponding to one common realization of the seismic source.

The hammer, as the seismic source applied directly to the rock massif, is characterized by a relatively high frequency of the seismic signal as compared to the case in which the energy is generated on the Earth's surface with a cover layer. Whereas ordinary refraction measurements on a cover layer display signal frequencies in the interval of about 20 to 100 Hz, on the surface of a rock massif the frequency of a signal, travelling over distances of 0.2 to 10 m, is in the units and tens of kHz. This is associated with frequency-dependent attenuation, on the one hand, and with the weight of the impacting hammer, on the other. With shallow seismic refraction measurements up to distances of around 100 m, the hammers used weigh about 5 kg, whereas with measurements over shorter distances (the length of the measuring base does not exceed 10 m) directly on the rock massif a lighter hammer weighing up to about 0.5 kg is sufficient. Hammers of smaller weight do generate a weaker signal, which can be recorded only at a small distance; however, the signal has a significantly higher frequency. This may be convenient in particular cases, because the wave length of seismic waves should also be related to the length of the measuring base. To be able to use a seismic wave to determine the travel time of a seismic wave over the length of the measuring base, it is necessary that the measurement take place at a distance from the source, at which the shape of the wave is already stable and its phase velocity can be determined. This distance is usually estimated at about two wave lengths. If the P-wave velocity is 7000 m/s and the frequency 2 kHz, the wave length equals 3.5 m. If the frequency is 40 kHz, the wave length is only 0.175 m. In the former case the velocity can be measured without a problem over a distance greater than 7 m, in the latter case already from 0.3 m. Figure 2 shows the example of a seismic wave recorded at a distance of 10 m from the point of impact of a 1-kg hammer. The recorded signal displays a frequency of 1.6 kHz.

PIEZO-CERAMIC SEISMIC SOURCE

The disadvantage of the impact source is the little possibility of controlling the frequency of the measured signal. On the contrary, the frequency should be easy to choose with piezo-ceramic transducers as the source of seismic waves. The duration of the exciting high-voltage pulse and the choice of the piezo-ceramic transducer with regard to its resonance frequency (the natural frequency is determined by the thickness/dimension of the piezo-ceramic element) allow the frequency of the transmitted seismic wave to be affected. The frequency can thus be chosen within a relatively broad interval. Transducers with natural frequencies of 100 kHz, 500 kHz and 1 MHz were tested in this study. Piezo- ceramic transducers for generating P- and S-waves were tested.

In the case of this type of source, the time of emitting the seismic wave may be derived from the time of the maximum of the exciting electric pulse.

The delay of the mechanical motion behind the electric excitation can best be determined by calibrating the whole measuring chain on a model homogeneous material. By measuring the travel time over several distances between the source and receiver a linear travel-time curve can be obtained. The time, which corresponds to the extrapolation of the travel-time curve at zero distance from the source, corresponds to the total delay in the measuring channel. This value of the delay should be subtracted from the observed times. As an example: the time lag for the Olympus S-wave transducer V153-RB with a resonance frequency of 1 MHz was 160 ns for a P-wave and 740 ns for an S-wave.

Piezo-ceramic transducers usually have a flat base which, e.g., with the 100kHz S-sensor Olympus V1548, is circular and 25 mm in diameter. To achieve optimum energy transmission, the bottom of the transducer should make good contact with the surface of the material with the whole area of its base. This can be easily achieved under laboratory conditions, in which the surface of a rock sample may be smoothed to a plane. Moreover, to improve contact, acoustic couplants are used; for recording and generating S-waves, couplants of very high viscosity are used (referred to as normal incidence shear couplants). However, the contact conditions in situ on the surface of an uneven and fractured rock massif are much less favourable. The direct contact between the transducer and the rock is only a point-contact. Materials, which can easily fill in the surface roughness and enable over-all contact, are therefore used to improve the contact conditions. Plasticine or plaster are used, e.g., for this purpose. The advantage of plasticine is that it requires no time to set and the measurement can take place immediately after attaching the transducer. Under favourable conditions, the plasticine is able to hold the transducer even on a vertical wall. Repeated experiments with fixing a transducer to the same place with plasticine, however, have shown that the conditions are poorly repeatable and the transducer is often spontaneously released. In comparison with plaster the signal becomes significantly attenuated.

The more laborious fixing of acoustic transducers to the surfaces of rock outcrops with plaster has proved much more convenient. The soft plaster does not form an unnecessarily thick contact layer, has the ability of filling in all unevenness at the point of contact and, after hardening, the contact is mechanically resistant and, in comparison with plasticine, the transmission of elastic waves is significantly better. The disadvantage of the procedure is the longer time required even if fast-hardening plaster is used, which requires several minutes to set.

As regards distance, at which piezo-ceramic exciters can be used for time-of-flight measurement, it was found that this was within the interval of 0.2 to 2 m. The real distance then depends also on the actual geological conditions and on the seismic noise at the place of measurement. Experiments performed on various rock materials also indicated that the presence of cracks may in some cases attenuate seismic waves to such an extent that they can only be recorded up to a distance of no more than 0.5 m, whereas without the crack the signal could be recorded even at distance exceeding 2 m. Since manufacturers of piezo-ceramic exciters usually recommend that the exciting voltage be chosen in the prescribed optimum range, in proportion to the thickness of the ceramic material, there is not much scope for changing the exciter energy by increasing the voltage.

LEAD BREAKING SEISMIC SOURCE

An exciting technique for testing monitoring systems was designed and tested using breaking lead. The idea of this seismic source derives from the practical monitoring of material fatigue. Acoustic emission events are localized when the origination of fatigue cracks are detected. The monitoring system monitors the condition of the stressed material on a long-term basis, and even if no damage occurs, it is necessary to have a device available for checking that the monitoring is operative. To simulate the acoustic emission, breaking a 0.5 mm pencil lead on the surface of the material being studied, is used. In the case of testing machinery components, tens of centimetres in dimension, which are made, e.g., of metal, breaking the lead is a sufficiently strong source, which emits a signal, whose frequency is close to the frequency of events of origination of fatigue cracks. In the case of breaking lead on the surface of a rock massif, lead 1 and 6 mm in diameter was used. It was found that 1-mm lead is the source of waves with a frequency of 150 kHz. This is a relatively weak source; in the case of unweathered rock, the measurement could be made at a distance just over 0.5 m. The recorded seismogram displays a relatively weak P-wave and a significantly stronger S-wave (see Fig. 3). The thicker lead (6 mm) produced a stronger wave. We were unable to record the wave image in the close vicinity of breaking the thick lead without distortion (cutting off the signal maxima). The recorded P-wave displayed a frequency of about 80 kHz for the thick and thin lead at a distance of about 0.5 m. Breaking the lead is not too convenient if a system is required of accurate and repeatable triggering of the record. To start the recording, one can use a transducer in the immediate vicinity of the place where the lead was broken, which provides uncertainty in the triggering level of the signal and in the accuracy of the distance between the receiver and the breaking lead. To determine the velocity, therefore, the only possibility is to make use of determining the apparent velocity on the travel-time curve. Breaking the lead appears to be, in the first instance, a simple alternative of realizing a high-frequency seismic source, which can be used to test the functioning of the measuring part of the device for high-frequency sounding with the aid of P- and S-waves.

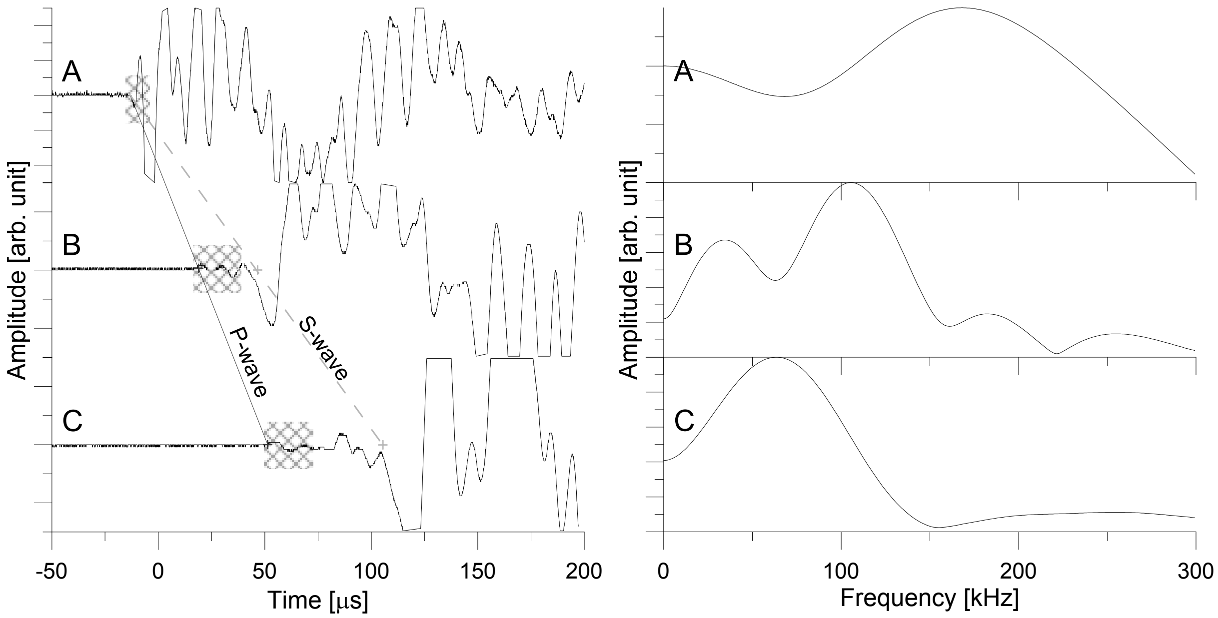

Fig. 3 Thin pencil lead breaking test. Source close to A (600 kHz sensor), dominant frequency at the beginning of signal (marked) about 150 kHz. B and C are 100 kHz sensors, distance from source 26 and 52 cm. P- and S-wave arrival times marked by linear time-distance curves. Seismograms clipped, left part. Frequency spectra (right part) calculated from selected part of signals.

MONITORING

An important part of the whole measuring system is the method of recording high-frequency seismic waves and precise recording of the time of arrival of the separate phases. That is why various types of sensors were tested: electro-dynamic geophones and piezo-electric transducers. The effect of various ways of fixing the sensors to the surface of the rock massif was also studied.

If the recording base is longer than one metre, a high-frequency source (e.g., a piezo-ceramic transducer) should not be used because of the high degree of attenuation of high-frequency seismic waves. On these bases it is more suitable to excite the seismic signal with an impact source, when the frequency of the seismic waves does not exceed units of kHz. Electro-dynamic geophones can then be used to record the signal. Their advantage is that they are ordinary robust sensors suitable for field work. The electric signal from these geophones can be transmitted without amplification by a multi-wire seismic cable to a seismograph, where it is digitized and recorded.

The principal difference between measuring at a short distance (units of metres) directly on the surface of a rock massif and measuring at a long distance (tens of metres) with a cover layer is the direction from which the seismic waves arrive at the sensor. In measuring at a larger distance from the source in an environment with a low-velocity cover, the rays bend so that they arrive at the sensors practically vertically. That is why vertical geophones are used practically exclusively in seismic exploration with the aid of P-waves, and horizontal geophones are suitable for exploration with the aid of S-waves. The vertical velocity gradient, which causes the bending of rays, is usually considerable. In the surface low-velocity layer the velocity of P-waves is usually between 300 and 500 m/s, and already at a depth of 10 m one can frequently encounter partly weathered rock, in which the P-wave velocity may be as much as 2000 to 4000 m/s. The situation is, of course, different on the surface of the rock massif. With the exception of an extremely weathered medium we usually encounter much smaller decreases of velocity in quarries or underground workings, but frequently also in natural outcrops. This decrease in velocity at the surface of a rock massif is caused by unloading, fracturing due to mining, generation of cracks, etc., and rarely achieves the first tens of per cent in comparison with intact rock.

Near the sensor, the bending of the rays by the velocity gradient is frequently emphasized due to the size of the measuring base. If the measuring base is long, there is indeed much more scope for the shortest "source – sensor" join in a velocity inhomogeneous medium to differ from the seismic ray which propagates along the path of shortest time. However, if the measuring base is short, the seismic wave usually arrives at the sensor only slightly diverted from the direction towards the seismic source. This phenomenon is commonly observed also in shallow seismic refraction survey, in which very small P-wave amplitudes, but much stronger S-waves are recorded

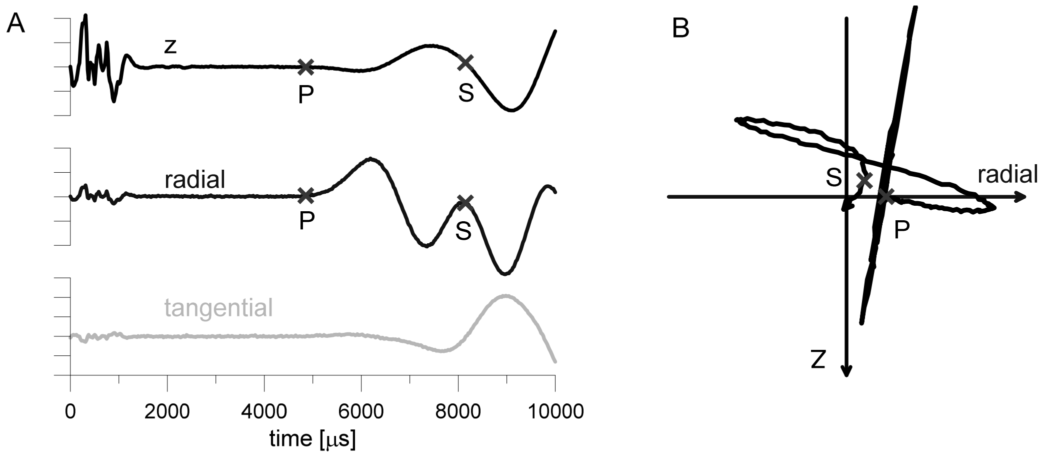

Fig. 4 Example of a three-component record of an electro-dynamic geophone (A) and particle-motion analysis (B). The surface impact measurement, the source – receiver distance 10 m. In graph B, the P-wave, which arrives practically horizontally from the source, can be clearly identified from the direction of arrival. In the vertical component z, the arrival of the P-wave is poorly detectable. The arrival of the S-wave is reflected as a change in the direction of motion to the direction perpendicular to the P-wave. Separate seismograms A do not allow clear identification of the S-wave. The signals have been normalized.

by the vertical geophone in the immediate vicinity of the point where the seismic energy is generated by a vertical impact of a hammer (distance about 1 – 2 m). Indeed, the seismic wave does not travel along the vertical, but practically horizontally along the surface. The vertical geophone thus receives P-wave poorly, but the S-wave well. A similar phenomenon was observed also in measuring on the wall of an underground gallery in an intact granite massif (locality Bedřichov, Czech Republic, see Jirků, 2011). Steel anchors, fixed with concrete to the lateral wall of the gallery, to which the authors fixed the vertical geophones with rubber bands so that the geophones were in vertical positions and the sensitivity axes were parallel with respect to the gallery wall, were used for repeated seismic measurements. The seismic energy was generated by a hammer impacting the gallery wall perpendicularly. Their repeated measurements could not be evaluated, because the first onsets of seismic waves were in all cases significantly distorted by seismic noise, which was probably the result of unsuitable mutual orientation of the geophones' sensitivity axes and the direction of arrival of the P-waves, propagating practically along the gallery wall. Interference waves at the later times dominated significantly on the records. The identification of S-waves was problematic.

In the course of the described measurements made directly on the rock massif, one usually finds that the seismic wave arrives at the sensor practically along the surface of the rock massif, and the sensor, whose maximum sensitivity axis is perpendicular to the this surface, thus poorly records the P-wave. However the orientation of the sensor is suitable for recording S-waves. Hence, for recording P- and S-waves, it is in this case suitable to use either a two-component or three-component geophone. Within the scope of the experiments we carried out, we verified that the three-component geophone together with particle-motion analysis is, in some cases, able to identify clearly the arrival of P- and S-waves, whereas this is not possible from the record of a single component (Fig. 4).

The particle-motion analysis requires the sensitivity and frequency response of all components to be identical. If a common three-component sensor with one vertical and two horizontal components is used, the records may become slightly distorted due to the different responses of the vertical component and horizontal components. This is due to their different mechanical construction and the ensuing different responses (amplitude frequency response and phase frequency response). A simple procedure, which enables the same responses to be achieved for all components, even if ordinary geophones are used, is Galperin's configuration. In this configuration, the maximum-sensitivity axes of the separate geophones form an orthogonal system, but all of them make the same angle of 35° 20" with the horizontal plane (Gamburcev and Galperin, 1954; Galperin, 1955; Steeples et al., 1995). This can be used to an advantage, e.g., if the purpose of the measurements is to determine the elastic constants of the rock medium (Živor et al., 2011).

The same problem, i.e. the direction of arrival of a wave does not agree with the maximum-sensitivity axis of the sensors, can also be encountered if piezo-ceramic sensors are used. Piezo-ceramic sensors do not usually have a clear-cut directional characteristic as compared to geophones. Nevertheless, even in this

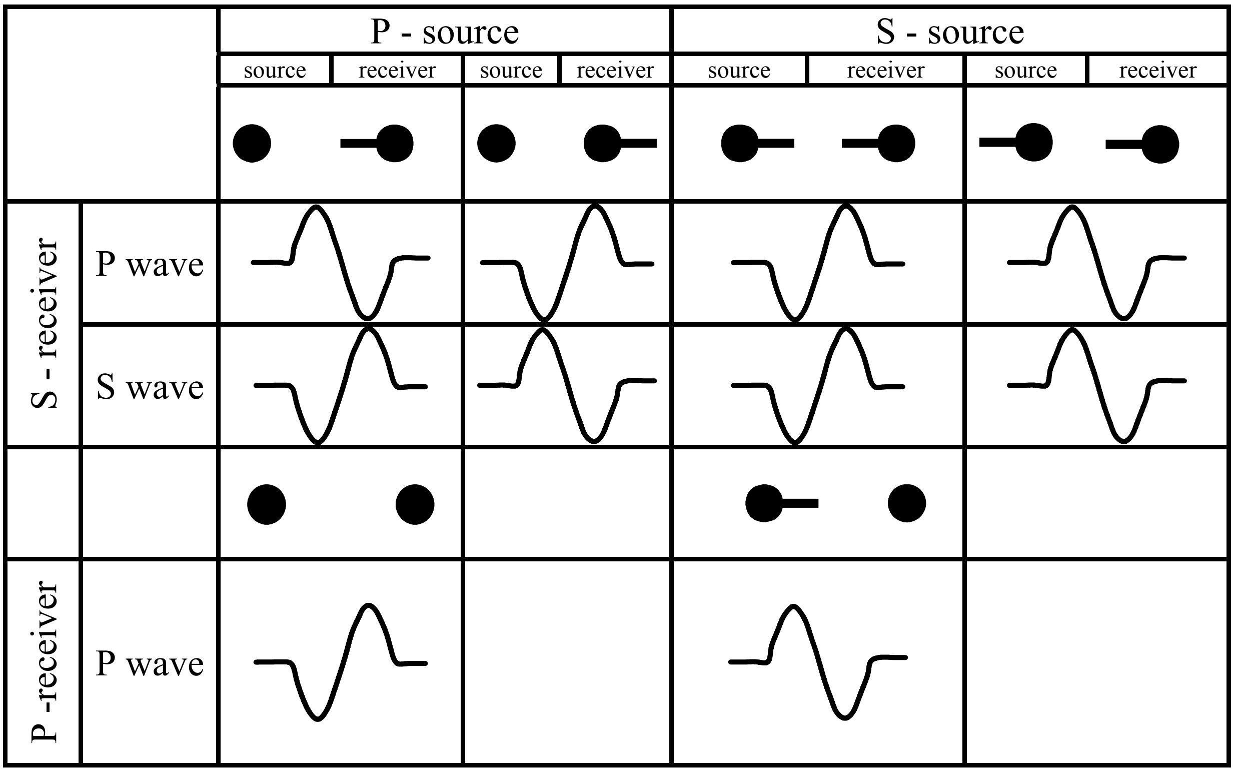

Fig. 5 Overview of combinations of P- and S-wave transducers (source/receiver). The symbols and indicate the different polarizations of the source/receiver of S-waves, the symbol stands for the source/receiver of P-waves. The symbolic harmonic signal indicates schematically the polarity of the first onset of the P- and S-wave for the given combination and polarity of the source/receiver.

case one observes that a P-wave, propagating along the measured surface of a medium, displays lower amplitude than an S-wave. The difference in the size of the amplitudes is, moreover, frequently an impediment in determining the times of arrival of both waves on a single seismogram. This occurs because digital oscilloscopes with a high sampling frequency, which, however, are usually equipped only with an 8-bit A/D converter, are used for recording high-frequency seismograms. The difference between using electro-dynamic geophones and piezo-ceramic sensors is also in that piezo-ceramic transducers of different technical design are used to record P- and S-waves. These sensors thus differ in amplitude frequency response, as well as in delay, which affects the measurement of the time of arrival of elastic waves, e.g., due to the construction of the protective cover of the sensors. A couple of P- and S-wave sensors cannot usually be considered as a single point of measurement. This is due to their non-negligible size as compared to that of the measuring base, and also the usual dimensions of inhomogeneities of rock material. If separate P- and S-wave piezo-ceramic sensors are used, therefore, applying particle-motion analysis cannot be generally recommended.

For registering with piezo-ceramic sensors, we also use piezo-ceramic transducers, excited by high-frequency pulses, as sources of seismic energy. This is the way to excite a signal of sufficiently high frequency, which corresponds to the sensors frequency response. This enables one to combine excitation and recording with generators and sensors of P- and S-waves. One can use a combination of the source and receiver of the same type of waves, as well as of a different type. In the course of the field experiments we carried out, we found that all combinations allow joint recording of P- and S-waves, however, thanks to different sensitivities of P- and S-wave sensors the resulting records may also differ substantially in the ratio of amplitudes of P- and S-waves. The use of polarity schemes of the transmitted and recorded signals in Figure 5 proved to be convenient with regard to easier orientation in analysing records using various combinations of P- and S-wave transducers.

FIXING SENSORS

The experiments carried out proved the experience of Marelli et al. (2010) that the manner of contact of the sensors with the environment affects the quality of transmission of seismic energy and has a principal effect on repeatability. In our case, we had to solve the problem of reliable fixing of sensors during field measurements to the surface of a rock massif. It was, therefore, out of the question to use plugs cemented into drilled holes, or to use hydrophones to measure in a borehole under the surface of groundwater, as recommended by Marelli et al. (2010). Several variants of fixing the sensors, which could be easily and quickly applied in the field, were tested. The first variant was fixing with plasticine, the advantage of which is easy and quick execution; the sensor is ready for measurement immediately after being pressed to the massif, and plasticine holds the sensor even on a vertical wall. The plasticine, however, must be well pressed, so that at least some part of the sensor is in contact with the rock. The experiments we conducted, however, showed that with this method of fixing sensors, only part of the seismic energy is transmitted and the contact conditions change with time spontaneously, usually deteriorating the coupling rapidly. The sensor can be pressed to the rock by hand during the measurement repeatedly, but any such manipulation leads to a low-frequency shift of the signal. Since it is practically always necessary to improve the signal-to-noise ratio by adding up repeated measurements, any low-frequency disturbance will degrade the resultant average signal.

The variant in which the metal plate for the sensor is fixed with plasticine to the rock was also tested. A rubber element was made on the metal plate to fix the piezo-ceramic transducer itself. The advantage of this set-up should have been the possibility of pressing the plasticine with a considerably larger force than can be applied to the transducer body. This should have a standardizing effect on the coupling conditions with the rock. Acoustic coupling paste was applied to the contact between the transducer and the flat plate, which again standardized the conditions. However, the field experiment showed that not even this arrangement improved the contact conditions. Not even applying plaster to the plates improved the transmission of the signal substantially. The advantage of applying plaster for many plates in advance is that the application and hardening of the plaster takes place before the measurement and does not delay the measurement itself. However, even in this case it was proved that the stability of the sensors on the plates could not be guaranteed in the field, and the signal continued to be significantly attenuated. The higher attenuation is apparently associated with the larger dimensions of the underlying metal plate as compared to the sensor itself. On the uneven rock surface below the plate, the thin layer of plaster has to be thicker than if the sensors themselves are fixed with plaster.

The only universal method of fixing proved to be direct plastering of the sensors to the rock massif. Adequately soft fast hardening plaster ensured relatively easy fixing of the sensors, using a very thin layer of plaster. This fixing is sufficiently reliable to hold the sensor even on a vertical rock wall. Fixing the sensors with plaster is stable even over longer periods of measurement, and provides the possibility of repeating the measurements. The disadvantage is the laboriousness and the slow process of measuring, if more sensors are not available, which could be fixed in place in advance. Plaster can be used with piezo-ceramic sensors, as well as standard geophones (Vilhelm et al., 2010).

In measurements, in which the sensors are fixed with plaster, the sensors are placed in positions at distances, which have been measured in advance, however, after the plaster has hardened, it is necessary to measure the real accurate distances between the transmitters and receivers.

One of the most important conclusions drawn from the experiments conducted was that the frequency content of the recorded waves was very narrow and determined, in the first place, by the attenuation characteristics of the medium. It was found that the rock massif has a pronounced ability to pass a wave well only in a narrow frequency band. Experiments with high-frequency piezo-ceramic sources of different exciting frequencies have proved that the recorded waves remain practically unaffected by the source frequency. An example of this conclusion is shown in Figure 6. The figure enables one to compare records made using piezo-ceramic transducers with a resonance frequency of 100 kHz and 1 MHz as sources of seismic energy. As a check two sensors (with resonance frequencies of 100 kHz and 1 MHz) were used for the record. Both the sensors were placed immediately next to one another, at a distance of 1.1 m from the source. The recorded seismograms show that the signals coming from the 100 kHz and 1 MHz sources have practically the same frequency content of the signal arriving in the first onset. The measurement was conducted on a weathered block of ultrabasic rock. The dominant frequency of the signal in the first onset is approximately 25 kHz. The records made by the 100-kHz and 1-MHz receivers are also similar. The 1-MHz sensor record displays smaller amplitudes and is affected more by noise as compared with the 100-kHz sensor record. In this particular case, the 100-kHz sensor is closer in frequency to the frequency of the recorded signal.

If we compare the soundings carried out at one point using piezo-ceramic exciters and a hammer, the records will differ significantly in frequency. In the case mentioned above sounding of the weathered block of ultrabasic rock, it was observed that the prevailing frequency of the signal produced by the impact of a hammer was about 4 kHz, whereas the signal excited by the piezo-ceramic transducer displayed a frequency of the first onset about 25 kHz.

DISCUSSION

We have tested the field time-of-flight measurements realized directly on the surface of the rock massif with the aid of high-frequency signals. The experiments we have carried out have proved that though these measurements are routine, it is necessary

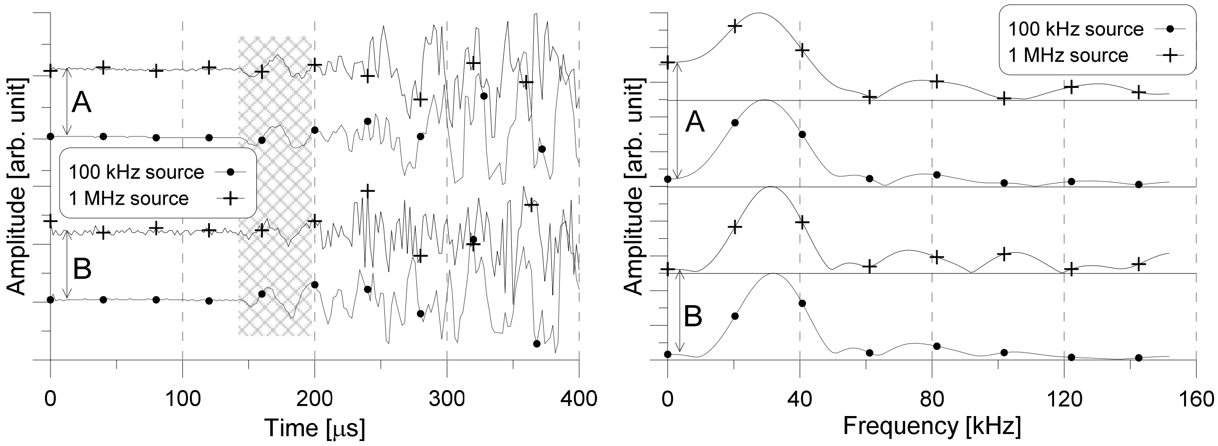

Fig. 6 Left: Example of records of waves for different source frequencies (the source were a piezo-ceramic transducers, natural frequencies 100 kHz and 1 MHz). The record was made at a distance of 1.1 m. Records A made by a 100-kHz piezo-ceramic transducer, records B by a 1-MHz transducer. The similarity in the pair of records A and pair of records B indicates that the filtration properties of the medium have a decisive effect on the frequency content of the recorded signal. The signals have been normalized. Right: Corresponding frequency spectra, calculated from selected part of records.

to devote appropriate attention to the conditions under which they are conducted.

For testing the dispersive properties of a fractured rock medium (e.g., Vilhelm et al., 2010, 2011) time-of-flight measurement at a number of different frequencies would prove exceptionally convenient. It would thus be possible to determine the dispersion curve and from it, e.g., the properties of fracturing of the massif by a system of parallel cracks with a given stiffness (e.g., Pyrak-Nolte et al., 1990). It is usually difficult and unreliable to determine the dispersion curve by analyzing signals with a broad spectrum in case of measurements at short distances. This is due to the short duration of the separate wave groups in comparison with the wave length, small dynamic range of the records of high-frequency measurement and usually non-negligible level of noise. The determination of the dispersion curve using several sources of different frequencies could, therefore, provide considerably more reliable conclusions. However, the frequency-dependent attenuation does not allow measurement using signals with arbitrarily chosen frequency content. The transmission properties of the rock massif in combination with the tested procedure time-of-flight measurements (method of fixing transducers to the rock massif) cause the rock massif to transmit preferentially elastic waves only of a certain frequency. In the case of ultrabasic rocks, e.g., it was found that seismic transmitters with frequencies of 100 kHz and 1 MHz yield seismograms with a predominant frequency of 25 kHz for a more weathered medium, 32 kHz for a less weathered medium, and about 80 kHz for a intact rock, for comparable distances of about 0.5 to 1 m from the source. If a 1-MHz exciter is used, the recorded signal displays, of course, significantly weaker amplitudes than in case of the 100-kHz source.

The same frequency of the recorded signal was observed when the breaking lead was used as the source of seismic energy. In the close vicinity of this source, breaking the lead appeared to be the source of a signal, whose frequency was about 150 kHz, for the 1-mm as well as 6-mm thick lead. That is why the resultant frequency of the sounding signal is close to that of the experiments with the piezo-ceramic transducer with a natural frequency of 100 kHz.

On the contrary, when a hammer is used, a significantly lower frequency of the transmitted signal was observed. For example, for weathered ultrabasic rocks, a frequency of 4 kHz was observed, whereas the signal along the same measuring base had a frequency of 25 kHz if the waves were generated by a high-frequency source or by breaking a pencil lead. This is apparently associated with the frequency bands of the signals excited by hammer impact and by a piezo-ceramic transducer do not overlap and, therefore, no filtration can lead to the same frequency content.

CONCLUSION

The result of the conducted experiments is the methodical recommendation to carry out the seismic measurements directly on the surface of the rock massif with using various seismic sources: hammer (1-2 kHz) and piezo-ceramic transducers (100 kHz, 1 MHz) at distances of about 0.2 to 10 m.

It was found that, to achieve repeatability of measurements, a significant role is played by the manner of fixing sensors and possibly also the seismic sources on the surface of the rock massif. The most reliable method, suitable for field measurements, proved to be fixing the sensors and possibly also the sources with plaster.

The use of the hammer for this type of measurement causes complications as regards the source repeatability. Attention must be devoted namely to the system of triggering with the aid of the amplitude of the signal from the sensor directly attached to the hammer. A considerably higher repeatability can be achieved by using piezo-ceramic transducers as sources of seismic energy with frequency of the order of hundreds of kHz and units of MHz. To test the system of high-frequency recording, pencil lead breaking tests can be used an advantage. The frequency of this source is close to that of the piezo-ceramic transducers, but technically its realization is incomparably simpler. For real measurements using the time-of-flight measurement, however, this source is unsuitable, namely due to the problematic determination of the time of origin of the signal.

In measuring directly on the surface of the rock massif, one must take into account the different geometry of propagation of rays as compared to surface measurements with a low-velocity layer. This yields the recommendations for the choice of orientation of sources and receivers. The manner of propagation of seismic waves also affects the anticipated polarities of the arrivals of waves on the records of various types of receivers. In some cases it may be advantageous to use polarization analysis to identify the arrival of seismic waves.

The most important conclusion is the finding that, in time-of-flight measurement of a rock, one usually encounters attenuation which is significantly frequency- dependent. It was found that, given the said system of measurement, the medium behaves as a very narrow frequency-band pass filter. For exciting frequencies of 0.1 and 1 MHz the transmitted signal displayed practically the same frequency already at a distance of 1.1 m.

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