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MEASUREMENT OF P- AND S-WAVE VELOCITIES IN A ROCK MASSIF AND ITS USE IN ESTIMATING ELASTIC MODULI

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ABSTRACT
The research in question deals with problems of determining seismic P- and S-wave velocities for purposes of computing the elastic constants of a rock massif. This experimental study indicates various ways of measurement and its processing for different geological conditions. The experimental measurements were carried out on the surface of the studied rock massif, on the walls in workings, as well as on the surface in a quarry. The question of seismic pick-ups, geophones or piezo-electric transducers and the number of components required to identify P- and S-waves, is discussed. This is considered in connection with the choice and properties of the impact or piezo-electric seismic source. The result is a number of generalizing recommendations with respect to the measuring technique, inclusive of its use for determining the directional dependence of the elastic moduli.

KEYWORDS: seismic source, seismic waves velocity, elastic constants, geophone, piezo-electric transducer

INTRODUCTION

The joint recording of P- and S-waves appears to be one of the significant ways of determining the mechanical parameters of a rock massif and of improvement the methods of interpretation in seismic exploration. This is a method which is known and has been developed theoretically and practically. Current seismic sources for measuring P-waves are usually also sources of S-waves, hence the possibility of combined measurements of P- and S-waves depends, in the first place, on applying a suitable measuring geometry and, as the case may be, using special pick-ups.

In the case of seismic wave recording at the longer distances, seismic source is usually realized by explosion into boreholes of various depths. For relatively small distances, the borehole depth is about tens of centimetres and explosive is about hundreds of grams (Pandula and Jelšovská, 2008). The boreholes of depth of the first tens of metres are used for investigation in longer distances and weight of charge is about hundreds of kilograms of explosive (Holub, 2008). This experimental study is concerned with problems of determining elastic parameters near by a seismic source by determining P- and S-wave velocities while measuring directly on the surface of a rock body. Three variants of measurement are presented. The first two make use of exciting waves by an impact and recording using 3-component geophones, or using a pair of piezo-sensors. The third variant is based on generating waves and recording them with the aid of piezo-ceramic transducers.

The properties of the individual methods of measurement are discussed with regard to specific geological conditions under which the measurements are carried out. The results of field measurements are also compared with laboratory results.

The advantages of combined P- and S-wave measurements in shallow seismic exploration were already mentioned by Sjøgren (1984). For example, he pointed out that, in the case of metamorphic and igneous rocks, the ratio of velocities v_P/v_S can be used to assess their fracturing by cracks. Dasios et al. (2001) pointed out namely the better resolution of S-wave measurements as compared with P-wave measurements. In general, one may say that the combined P- and S-wave measurements for the purpose of computing dynamic moduli are mainly used in well-logging methods. In agreement with the ISRM (1998) the P- and S-wave velocities can be used to compute the following dynamic moduli: Young's, shear, bulk and Poisson's ratio.

Barton's (2007) monograph deals with the use of P- and S-wave velocity measurements most extensively. This monograph also discusses the relation between dynamic and static moduli of various kinds of rocks.

SEISMIC MEASUREMENTS USING WAVES GENERATED BY IMPACT AND RECORDED BY 3-COMPONENT GEOPHONES

Measurements with 3-component (3C) geophones are used in combination with a seismic-wave impact source usually where the studied rock

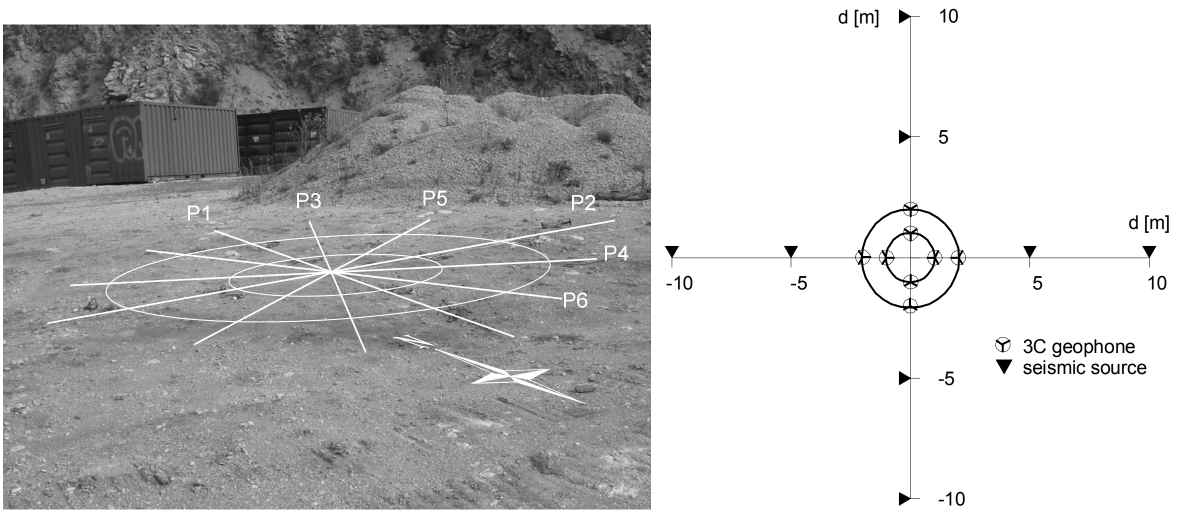

Fig. 1 Measurement setup. The measured profiles (left part) and the measuring array (right part) are shown. The Kostiviarska Quarry.

massif is covered, even if only by a thin layer of weathered rocks or soil. The waves are then greatly attenuated, and the attenuation increases with the wave frequency. Therefore, it is necessary to make use of more energetic sources, e.g., the impact of a hammer weighing 1 kg on a metal plate with an exciting signal frequency of hundreds of Hz. The recording of seismic waves with 3C geophones enables polarization analysis to be used to identify the arrival times of the P- and S-waves. A 3C geophone is formed by three single-component pick-ups, the maximum-sensitivity axes of which form an orthogonal system.

Since measurements over lengths smaller than the wavelength of the generated waves are involved (several metres from the source) one may assume that the displacement vector of the longitudinal wave is pointing towards the focus and the direction of oscillation of the shear wave is perpendicular to the direction to the focus. Under such geometry of particle oscillation, it is not advantageous to orient the orthogonal system of seismic pick-ups radially (i.e. towards the focus), tangentially (perpendicular to the direction towards the source) and vertically, because in case of markedly polarized waves some components would measure very small amplitudes, which would then be responsible for considerable inaccuracies in determining the required arrival times. Therefore, Galperin's configuration was used, in which 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).

The field measurements were carried out on the sub-horizontal surface of one of the benches of the Kostiviarska Quarry near Banská Bystrica (Slovakia). The exploited raw material is argillaceous limestone to marlite of the Krížna nappe of Cretaceous age. This raw material is used for cement production. At the location of measurement the rock was partly covered by soil. Since exploitation was carried out by shooting in boreholes, one may assume that the near-surface rock was fractured due to these winning operations.

The field experiment was carried out as a seismic refraction measurement along profiles with a common centre point. The seismic energy was generated by vertical impact of a hammer, weighing 1 kg, on a metal plate. The prevailing frequencies of the initial phase of the recorded signal were up to 500 Hz. The impact points were located in the centre of the geophone array and then at distances of 5 and 10 m from the centre, to both sides along the separate profiles (if space at the locality allowed). At each impact, measurements were made simultaneously along both profiles, along the profile which, together with the impact points, lay on one straight line and on the profile perpendicular to this straight line. Four 3C geophones were located along each profile at distances of 1 and 2 metres from the common centre of all profiles. After each series of measurements was concluded, the whole measuring system (i.e. both perpendicular profiles) were turned through 30° (Fig. 1). The measurements along the profiles covered the directional dependence through 360° in steps of 30°. A 24-channel seismic Geode system (Geometrix) was used to record the generated waves.

The 3C geophones in Galperin's configuration were always oriented so that pick-up number one pointed towards the common centre point. To simplify the processing, all three-component seismograms were then transformed from the original co-ordinate

Table 1 P- and S-wave velocities determined from field measurements and values of Poisson's constant and Young's modulus. The values of velocities and derived parameters, determined using sources at distances of 5 and 10 m from the centre of the measuring array are given separately (Fig. 1). The Kostiviarska Quarry.

profile azimuth [degree]	v_P [m/s]		v_S [m/s]		v_P/v_S		σ		E [GPa]	
	5m	10m	5m	10m	5m	10m	5m	10m	5m	10m
0	1540	1610	830	890	1.87	1.80	0.30	0.28	4.7	5.4
30	1620		850		1.90		0.31		5.1	
60	1450		850		1.70		0.24		4.8	
90	1410	1400	860	890	1.63	1.57	0.20	0.16	4.7	4.9
120	1680	1950	840	1020	1.99	1.90	0.33	0.31	5.0	7.3
150	1820	2030	1030	1220	1.76	1.67	0.26	0.22	7.2	9.6
Average value							0.28	0.24	5.3	6.8

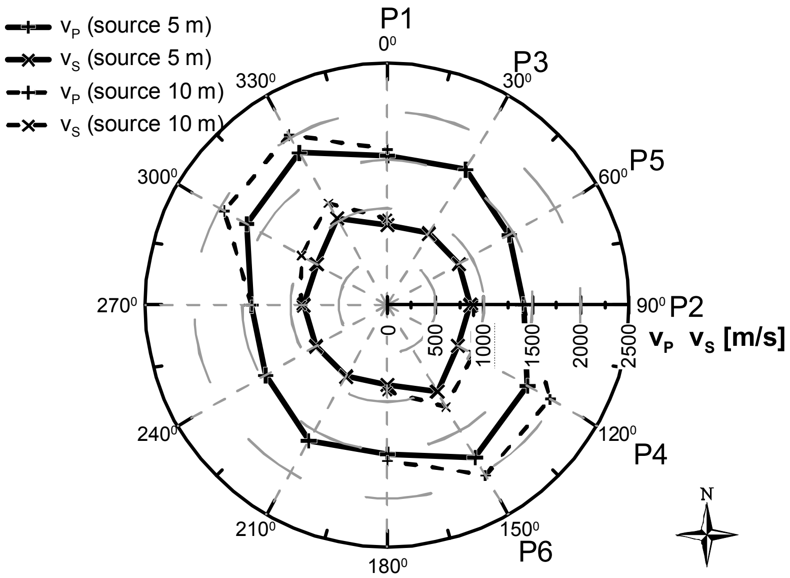

Fig. 2 Diagram of the velocity dependence of P- and S-waves. The Kostiviarska Quarry.

system to yield one vertical and two horizontal seismograms – one radial and one tangential. In this slightly rotated orthogonal system, the positive vertical *z* component was pointing upwards, the positive radial component *r* towards the source and the positive *t* component made up a right-handed Cartesian *r*-*t*-*z* co-ordinate system. The advantage of this transformation is that standard programs can be used for depicting and preliminary analysis, e.g., ReflexW. Rotating the co-ordinate system is advantageous also with regard to the immediate relation between the orientation of the transformed components and the orientation of the vectors of motion due to the P- and S-waves.

The time of P-wave arrival, recorded on *z*-component, was used to determine the velocity of propagation of P-waves along the individual profiles. As a check the observed times were compared with the arrival of the P-wave in the *r*-component. The velocity was determined from the slope of the differential travel-time curve. The velocity for reciprocal travel-time curves from sources at distances of 5 and 10 m from the centre was computed separately. The determined P-wave velocities and their directional dependence are shown in Table 1 and Figure 2.

It was much more difficult to identify the arrival time of the S-wave. The three-component configuration of the recording pick-ups enabled polarization analysis to be used to determine the arrival time of the S-wave. A special program, which enabled the particle motion to be depicted in co-ordinate plane cross-sections and in 3D under general rotation, was prepared for this purpose. To diminish the ambiguity of interpretation, a graph of P- and S- wave travel-time curves was available for the given position of the seismic source in recording the S-wave arrivals. The determined times were used to compute

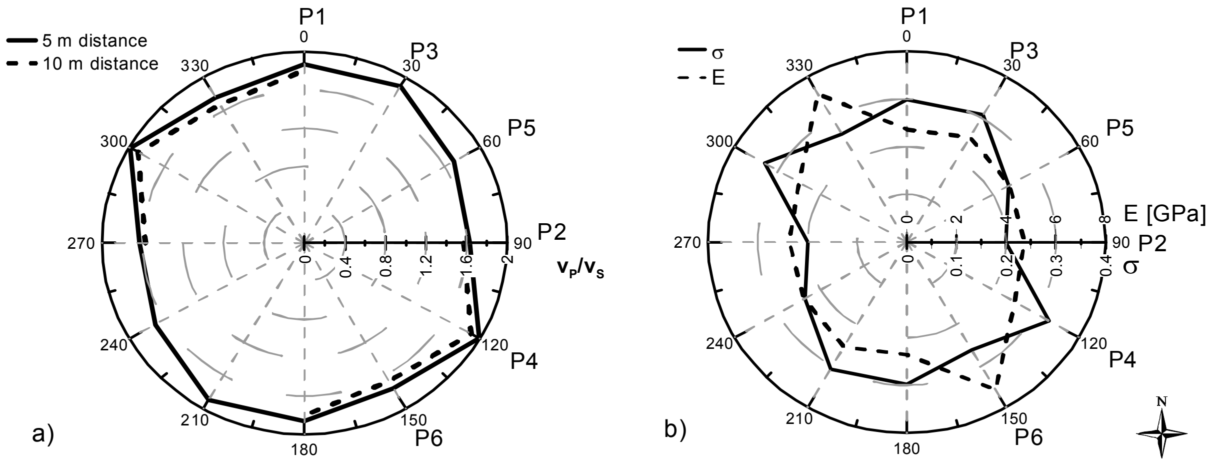

Fig. 3 a) Directional dependence of ratio v_P / v_S of the velocities of P- and S-waves.
b) Directional dependence of Poisson's ratio σ and Young's modulus E. All quantities correspond to measurements along the 5-metre base. The Kostiviarska Quarry.

velocities v_P and v_S, and their ratio was displayed in the course of picking. The complex seismic trace analysis was realized as another auxiliary parameter for the reduced *z, r* and *t* seismograms. The arrival of the S-wave is typically reflected in the increase of the instantaneous amplitude of the z-component. The resultant directional dependence of the S-wave velocity is illustrated in Figure 2; the numerical values are given in Table 1. The table indicates that the P- and S-wave velocities measured at a larger distance are approximately 10 % higher, which is also reflected in the higher values of Young's modulus, which is 28% larger at 10 m than at 5 m. On the contrary, Poisson's ratio displays a decrease of about 13 %.

The measurements made proved that the medium was considerably anisotropic in terms of velocity for P- and for S-waves. Figure 3a shows the directional dependence of the velocity ratio v_P / v_S. The directional dependence of the velocity ratio v_P / v_S is, most probably, a combination of the effect of the layered structure of the rock and its deformation (see, e.g., Přikryl et al., 2004).

The combined determination of the P- and S-wave velocities enables seismic elasticity moduli to be determined, given the density. The density was determined from collected samples. Young's modulus E and Poisson's ratio σ were computed using the following relations (e.g., Barton, 2007):

$$\mathrm{E} = \rho\, v_S^2 \frac{(v_P/v_S)^2 - 4}{(v_P/v_S)^2 - 1} \qquad \sigma = \frac{1}{2}\frac{(v_P/v_S)^2 - 2}{(v_P/v_S)^2 - 1}$$

where ρ is the bulk density. Table 1 shows the values of the moduli. They are also plotted in Figure 3b to provide a better idea of their directional dependence.

Although the anisotropy of the medium cannot be described only by two elastic constants, nevertheless, the anisotropy of mechanical properties is frequently assessed in a first approximation on the basis of only two moduli, determined in the direction of the maximum and minimum velocities.

At the locality in question, the Kostiviarska Quarry, a number of samples were collected and served to determine the average bulk density and the velocity of ultrasonic waves under laboratory conditions. The density was determined using the method of double weighing, on the one hand, and weighing samples of regular shapes, on the other. Both methods yielded practically the same value of bulk density: ρ = 2.66 g cm^{-3}. The velocities of longitudinal and shear waves in three mutually perpendicular directions were determined by sounding a sample, right parallelepiped in shape. Ultrasonic transducers with a natural frequency of 1 MHz were used for the sounding. The velocity of propagation of longitudinal and shear waves in the plane parallel with the stratification display practically no directional dependence. The velocity values measured perpendicular to the stratification are lower than those measured along the stratification (see Table 2). In this particular case one can expect the values across the stratification to correspond to the minimum velocities (v_{min}) and the values measured along the stratification to correspond to the maximum velocities (v_{max}) of the longitudinal and shear elastic waves. These values enabled anisotropy coefficient k to be determined using the relation:

$$k\,[\%] = [(v_{max} - v_{min})/v_{mean}]*100$$

where v_{mean} is the mean value determined from both velocities v_{max} and v_{min}. The values of the anisotropy coefficient of longitudinal and shear waves, given in Table 2, are practically the same.

Table 2 Velocity of P- and S-waves determined on the sample. Derived values of Poisson's ratio σ and Young's modulus E. The Kostiviarska Quarry.

	v_P [m/s]	v_S [m/s]	σ	E [GPa]
perpendicular to layering (v_{min})	5230	2790	0.302	53.8
parallel with layering (v_{max})	5960	3220	0.294	71.3
anisotropy k [%]	13	14		

The comparison of field and laboratory measurements indicates that the values of Young's modulus from laboratory measurements are higher in orders of magnitude than those from the field. This difference is associated with the different degree of deformation of the studied rock medium, as well as with the different wavelength of the seismic and ultrasonic waves and, therefore, with the effect various structural systems have on their parameters. Laboratory measurements yield higher values of velocities and moduli, because the test sample used is less fractured. In the case of the Kostiviarska Quarry, the difference between the velocities and corresponding moduli observed agrees with the expected marked fracturing of the rock material in the field, which occurs as a result of exploitation using blasting. Such fracturing, however, is not substantiated by the values of the v_P / v_S ratio determined in the field: according to Barton (2007) values around 1.7 correspond to a medium with low porosity (the value of the v_P / v_S ratio close to $\sqrt{3}$ yields Poisson's ratio $\sigma = 0.25$). One may thus assume that, in the field, the pore space is filled with a clayey component, the presence of which decreases the velocity of P-waves in limestone, and simultaneously causes Poisson's constant to increase as compared to the case of a free pore space.

The anisotropy coefficient, determined under laboratory conditions, characterizes the degree of velocity anisotropy in space. However, the field measurements were planar, and the anisotropy coefficient for velocity values determined in the field (Table 1) refers only to the anisotropy in the plane. Hence, laboratory and field anisotropy cannot be compared directly. Nevertheless, it is interesting that the P-wave anisotropy coefficients determined in the field are 26 % and 36 % for measurements at 5 and 10 m distance, and 24 % and 32 %, respectively, for S-wave coefficients. If determined in space, the values of the anisotropy coefficient could be even higher as compared with the value obtained from measurements in the plane. The high value of the anisotropy coefficient in the field is probably connected with the fracturing of the rock massif mentioned above, which the laboratory sample is unable to reflect. Since the measurements at a distance of 10 m encompass a larger volume of the medium, they also reach to a larger depth. One may thus assume that the degree of fracturing diminishes with depth (the velocities measured at a distance of 10 m are higher than those measured at 5 m), but the fracturing in the predisposed direction is accentuated (higher anisotropy coefficient at a distance of 10 m). For all measurements, laboratory and field alike, the anisotropy coefficient for a particular measurement comes out practically the same for P- and S-waves.

USE OF SEISMIC WAVES GENERATED BY IMPACT AND MEASUREMENTS USING A PAIR OF PIEZO-CERAMIC PICK-UPS

The near-surface layers of weathered rocks or earths absorb considerable amounts of seismic wave energy. In the case of measuring on a rock outcrop or in a working, where these layers are absent, one can use a low-energy seismic source, e.g., a light-weight hammer. The advantage of this source is that the seismic signal generated has frequencies in the upper hundreds of Hz to first tens of Hz. Moreover, the energy of the generated seismic wave is high enough to be recorded at a distance of several metres.

The field measurements were carried out in the magnesite mine Lubeník in Slovakia. Magnesite is won here by open room exploitation method. The rock is fractured by blasting. The measurement itself was carried out on a vertical wall of an abandoned room on the VIIth level at a depth of 200 m below the surface. The place chosen for the measurement is located in a part of the mine in which the exploitation has been stopped, and which is sufficiently distant from places of current mining and other mine activities (transportation, ventilation, pumping stations) with regard to the level of seismic noise at this time.

Circular measurements of anisotropy and simple profile measurements on the vertical walls of the room have been carried out. The seismic wave energy was excited by impact of a small hammer (weight 200 g) on a metal plate. The generated seismic waves were recorded by a pair of piezo-ceramic KD 35 pick-ups (MMF, Radebeul, Germany). The pick-ups record

Table 3 Prevailing frequencies of sounding signals using a light-weight impact source and piezo-sensors. The Lubeník Mine.

Source distance [m]	P-wave [kHz]	S-wave [kHz]	P-wave length [m]	S-wave length [m]
0.5	14	10	0.5	0.4
4	3	4	2.3	0.9

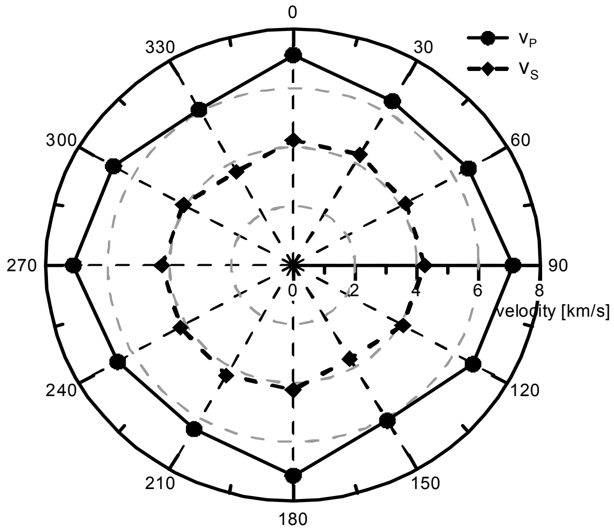

Fig. 4 Velocities of P- and S-waves on the vertical pillar wall. Magnesite Lubeník Mine.

signals up to frequencies of 20 kHz. The pair of pick-ups was mounted on a duralumin cylinder, diameter 7 cm and height 9.5 cm. The base of this pick-up carrier was fixed with plaster to the surface of the rock massif. The pick-up located along the axis of the cylinder, on its upper base, was earmarked for recording of P-waves. In recording S-waves, the second of the pair of pick-ups was located on the cylindrical surface of the carrier. In measuring the arrival of the S-wave, the pick-up carrier was oriented so that the S-wave sensor pointed towards the place where the seismic energy was generated. The measurement of the directional dependence of the S-wave velocity thus required the orientation of this pick-up on the cylinder to be changed with regard to the actual position of the source. This was done by preparing points, with a ground seating surface and a threaded orifice, at steps of 30° on the cylindrical surface of the pick-up carrier for positioning the sensor. Instead of revolving the pick-up carrier, the position of the S-wave sensor was thus changed by fixing it in another position on the carrier. This arrangement is advantageous in that it is not necessary to apply the plaster repeatedly to the pick-ups, which would be very time-consuming. At the same time, the recording conditions for the anisotropy measurements remain unchanged (at least on the part of the sensors).

The signal from the sensors is amplified by broadband preamplifiers with optional amplification of 20/40 dB. A Cleverscope CS328 oscilloscope was used to record the sounding signals. This is a USB-connected PC-based oscilloscope. Its hardware includes two 14-bit analogue channels sampled simultaneously at up to 100 MSa/s. The records are stored in the master computer, their lengths being restricted by the 2M samples per channel memory. The recording is triggered by an external hardware trigger system. This was realized by connecting the electric circuit between the metal plate and the hammer at the time of impact. Resistance against repeated triggering is secured by setting the guard time of the triggering block.

The circular anisotropy measurement was carried out on a vertical, roughly planar pillar wall. The pick-up carrier was fixed to the surface of the pillar wall into the centre of a circle 1 m in radius. The places of generation of seismic energy were distributed along this circle at steps of 30°. The profile measurement was also carried out on the pillar wall in the corridor along the pillar, perpendicular to the plane of circular measurement. The length of the profile was 4 m. The measurements were carried out at fixed positions of the pick-ups and variable distance of the point of impact. The records were made at a sampling frequency of 128 kHz. Their duration was 30 ms and the pre-triggering time was 5 ms. The prevailing signal frequency is in this case shown in Table 3. This table indicates that the medium is characterized by a pronounced frequency-dependent attenuation.

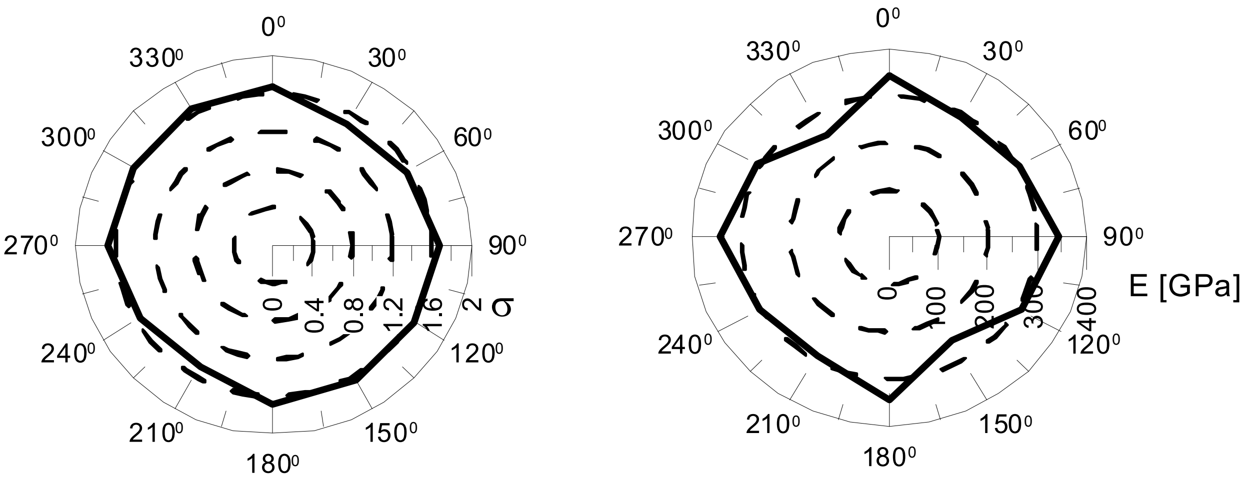

Fig. 5 Anisotropy of Poisson's ratio σ and Young's modulus *E*. Magnesite Lubeník Mine.

In processing the records made, the signals recorded along the profile were processed first. The arrival times of P- and S-waves were determined. Linear travel-time curves of the direct P- and S-wave were obtained. Their slope was used to determine the velocities of seismic waves: v_P = 7000 m/s and v_S = 3700 m/s. By extrapolating the travel-time curves towards the source (zero offset) it was possible to check out the delay times caused by the finite dimensions of the pick-up carriers, first determined by calibration in the laboratory. These delays were used to correct the times in computing the velocities in dependence on direction, determined by circular measurements. The directional dependence of the P- and S-wave velocities is shown in Figure 4. This directional dependence is construed as point symmetric; the average was computed for the times observed at the opposite points of the measuring circle. This average was used for the computation of the velocities of seismic P- and S-waves. This procedure should suppress the effect of medium inhomogeneities, if any. The determined P- and S-wave velocities were used to determine the directional dependence of Poisson's ratio σ and Young's modulus *E*. Bulk density ρ = 2.90 g cm^{-3} was used in computing Young's modulus. The directional dependence of the elastic constants is displayed in Figure 5.

In this particular case, no more pronounced velocity anisotropy was observed. The ratio v_P / v_S is relatively stable and falls within the interval 1.56 to 1.69 with the exception of the direction 30° (or 210°) where it drops to 1.49. That is why the value of the Poisson ratio is practically constant and its minimum occurs for 30° (or 210°). The values of the Poisson's ratio and the high values of the P-wave velocities indicate that the medium is nearly non-fractured, and any fissures could be closed thanks to the stress in the pillar. The decrease of high frequencies observed in measuring at a distance of 4 m on the lateral side of the pillar is associated with the macroscopically observed deformation, across which the measurement at a distance of 4 m was made.

MEASUREMENT WITH THE AID OF SEISMIC WAVES GENERATED BY HIGH-FREQUENCY PIEZO-ELECTRIC TRANSDUCERS

In high-frequency measurement, a piezo-ceramic sensor is used as the source of seismic waves instead of an impact. The energy of the seismic waves, generated in this manner, is usually significantly lower than that generated by an impact source. Moreover, if sounding signals of frequencies higher than 100 kHz are used, the waves in a rock medium are attenuated quite considerably as compared to the waves generated by an impact source with relatively low frequencies. The measurements may thus usually be carried out on a base 1 m in length on rock outcrops, or in underground workings, where the weathered layer is absent.

The measurement geometry, in which the source and pick-up are located on the roughly planar surface of the outcrop, enables simultaneous recording of P- and S-waves to be made by a suitable choice of the receiving element. A piezo-ceramic sensor, excited by a high-voltage electric pulse, can be used as the source of seismic energy. The duration of the leading edge of the 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) allows the sounding wave frequency to be affected.

The field measurements were made in the locality of Bedřichov. A horizontal gallery has been excavated in the granodiorites, which serves to pipe water to the water processing plant. The gallery has

Table 4 P- and S-wave velocities and their prevailing frequencies. Derived material constants (Poisson's ratio σ and Young's modulus E).

			dist. >50 cm		dist. = 25 cm				
	v_p [m/s]	v_s [m/s]	f_P [kHz]	f_S [kHz]	f_P [kHz]	f_S [kHz]	v_p/v_s	σ	E [GPa]
machine boring	5840	3080	50-80	40-70	-	-	1.90	0.31	67
manual boring	4570	2260	10-20	10-20	100-130	90-100	2.02	0.34	37

been partly excavated using a mechanical boring machine and partly manually, by firing explosives in shot holes runs in the head of the gallery. The rock in both parts of the gallery has thus been fractured to a different degree. The measurements were made close to the point of transition from one method of advancing to another to be able to compare the results of the measurements in both types of tunnelling.

Piezo-ceramic pick-ups, fixed to the cleaned surface of the gallery wall with plaster directly, were used for the measurement. Experimentally it was found that the mutual orientation of the P-wave source and receiver was very important in recording S-waves. Strong S-waves were recorded if the radiation characteristic of the P-wave source was perpendicular to the measuring base (in particular cases this was the direction perpendicular to the measured rock surface) and the maximum sensitivity axis of the S-wave piezo-electric transducer was pointing towards the source (i.e. in the plane of the surface). The most suitable wave source proved to be the 1 MHz/0.5" sensor for exciting P-waves (V153-RM, Panametrix). The piezo-ceramic sensor for recording S-waves was constructed to enable the recording of horizontally polarized waves. A 0.1 MHz/1.0" S-wave sensor (V1548, Olympus – NDT) was used.

The signals from the sensors were amplified by broadband pre-amplifiers with adjustable amplification of 20/40 dB. A four-channel DSO1024A oscilloscope (Agilent), which is designed for recording signals with frequencies of up to 200 MHz, was used for recording. Its maximum sampling frequency is 2 GSa/s and it enables records of up to 20 thousand samples per channel to be stored. It uses an 8-bit A/D converter, and to improve the signal-to-noise ratio and dynamic range up to 256 records can be averaged. As regards work in the field, its advantage is the possibility of storing the records made on a USB flash disk. An ultrasonic 5072PR pulser (Olympus) was used to excite the high-frequency elastic waves. It enables electric pulses of up to 360 V with a 5-ns leading edge to be generated. The repetition frequency of pulse transmission may be set to 0.1 kHz which makes it possible to reach the required number of signal averaging in short time and simultaneously a repetition period is shorter than the length of the record (maximum 2 ms).

The ultrasonic sounding was carried out along a horizontal profile on the adit wall at a height of about 1.5 m above the footwall. Arrival times of P- and S-waves were used to determine the velocities. These times were applied in constructing the corresponding travel-time curves of direct waves. The P- and S-wave travel-time curves in the sections of mechanical and manual advance are practically linear with a minimum scatter. The slope of the travel-time curves was used to compute the velocities. Their values are given in Table 4.

As regards the measurements in places of mechanical tunnelling, it was possible to identify the arrivals of P- and S-waves reliably to a distance of 1.5 to 2 m from the ultrasonic source. This is evidence of a very low degree of fracturing of the rock massif. The velocity values recorded at a distance of 0.5 m did not differ from the velocities determined on the 2 m base, which proves that fracturing due to tunnelling, if any, was restricted to a layer a few centimetres thick at the most. Analogous measurements made in the same rock medium, but where explosives were used to advance, showed that marked attenuation occurs. The method of measurement used could only be applied to distances of no more than 0.5 m. If the distance between the source and receiver was larger, it was impossible to determine the arrivals of seismic waves reliably due to high attenuation. The observed velocities of P- and S-waves are markedly lower as compared to the case of the non-fractured massif (see Table 4). The difference between the places of manual and mechanical advance could also be observed on the frequency of the recorded signal. In sounding to a distance of 50 cm the prevailing frequency was observed to decrease in the place of manual advance as opposed to the place of mechanical advance: 4 to 5 times with P-waves and 3 to 4 times with S-waves.

Measurements at a distance of 25 cm in the place of mechanical advance indicate that the P-wave's wavelength was 4 to 5 cm (the S-wave only 2.5 cm). This wave was very strongly damped, which could be connected with the dimensions of inhomogeneities and cracks coming close to the wavelength.

In the case of high-frequency sounding the favourable property of the recorded seismic waves was the distinct separation of P- and S-waves.

Using the value of granodiorite bulk density ρ = 2.62 g cm^{-3} (Klomínský et al., 2005) it was possible to compute the corresponding moduli – see Table 4.

Apart from high-frequency sounding, also impact measurements with a 48-channel Terraloc IV engineering seismograph were made in the adit. The prevailing frequency of P-waves was 2 kHz and S-waves 1 kHz along a measuring base of up to 70 m (Jirků, in print). By comparing the observed velocities in the section of the adit where the impact measurements were made with the velocities determined by high-frequency sounding in the section of mechanical tunnelling, it was found that the velocity values agreed exceptionally well. This may be considered proof that the rock massif is not deformed in the place of mechanical advance. In places of manual advance, these measurements, due to the distance between the seismic source and geophones being larger than about 10 m, did not display the effect of fracturing due to advance. The frequency interval used to determine the velocity of seismic waves in the given case by impact measurements and high-frequency sounding encompasses nearly two orders of magnitude. It was found that, in the given case, velocity dispersion, which is otherwise frequently observed in the presence of a system of parallel cracks (Vilhelm et al., 2008; Vilhelm et al., 2010), did not occur. This dispersion depends on the stiffness of the cracks. One may, therefore, assume that, in the given case, the rocks are either not fractured, or the fractures are markedly closed and display high values of stiffness.

DISCUSSION

The velocity of seismic waves, determined by methods of surface measurements (i.e. refraction and reflection prospecting) in real inhomogeneous geological media have the nature of so-called interpretation velocities. These velocities thus represent, e.g., the mean velocity down to a particular depth, or layer velocity, etc. One value of the average velocity thus characterizes a certain volume of the medium. These average velocities give one an idea of the kinematics of propagation of seismic waves through a layer or medium up to a particular interface. However, average velocities do not have the nature of velocities of propagation of seismic waves in a particular material and are thus not generally suitable for computing material constants such as Young's modulus. Velocities, which can be used to compute moduli, are close to the velocities, determined under laboratory conditions on a sample or in a borehole by acoustic logging. However, even these methods encounter specific problems. For laboratory measurements, it is neceséry to use a collected sample, which represents the rock without natural fractures, which does not have natural humidity and has possibly been affected by the technology of preparing the test specimen itself. Well-logging provides velocities under natural conditions, but it is necessary to take into account the presence of the borehole, the effect of drilling fluids and sometimes also the uncertainty in automatically processing the S-wave velocities. It is, therefore, reasonable to deal with the technique of determining P- and S-wave velocities on rock outcrops in the field (on the surface, or in a working) as a method which tries to determine real velocities by coming as close as possible to the rock material of interest and choosing suitable measuring techniques, and thus is suitable for computing moduli.

The experimental measurements made allowed seismic sources to be compared. This was substantiated primarily by the strong effect of the frequency-dependent absorption in fractured rocks. This absorption is the cause of the marked dependence of frequency of the measured signal on the degree of fracturing of the rock massif, and a high-frequency source cannot, therefore, be used to measure along a longer trajectory of the seismic wave. It has been proved that relatively high frequencies of the signal (units of kHz) can be achieved by using a hammer weighing about 200 g. This source can be recommended if the measurements are being conducted over a distance of a few metres. To excite high-frequency (tens of kHz) S-waves, piezo-ceramic transducers, designed as receivers of P-waves, can be used to an advantage. The maximum of their directional radiation pattern is in the direction of the normal to the surface of the medium being sounded and they are thus an intensive source of S-waves polarized close to the source, perpendicular to the surface.

The use of a multi-component record represents a significantly more laborious exploitation of field measurements and, if the number of measuring channels is restricted, it reduces the number of measuring locations significantly. In some cases, however, the application of polarization analysis is the only way of reliably determining the arrival times of S-waves. Nevertheless, it was generally found that the wave field located at a distance from the source, comparable with the wavelength of seismic waves, has markedly variable properties. Not even polarization analysis will, therefore, provide a unique determination of the arrival of S-waves on all records. It is then important to draw on the correlation between neighbouring records and travel-time curves or to make use of the equality of reciprocal times. The application of the ReflexW program (Sandmeier Scientific Software) to the polarization analysis was unsuccessful in this case. The ReflexW program is quite flexible as regards representing the particle motion graph in 3D, as well as in arbitrary 2D sections, and provides for interactive reading and editing of times already recorded. In our case, however, the separate travel-time curves were most frequently formed only by four 3C records. In identifying the S-wave arrival times, mutual comparison of the separate travel-time curves was found to be of principal importance and, therefore, it was necessary to have the possibility of changing from displaying the data on one travel-time curve to displaying the data on another travel-time curve. This proved to be so tedious in the ReflexW program that it was found more convenient to prepare our own tool for reading the 3C records. With the aid of the means of the MATLAB programming environment, a program was prepared which enabled S-wave arrivals to be sought interactively in the graphic interface and compared with the times on other travel-time curves of the given profile, inclusive of the possibility of comparison with P-wave arrivals, etc. Moreover the script was prepared to be compatible with the formats of seismic records (SEG-2 format) and with formats of files with time readings in the ReflexW program. This made any interchange and combination of the application of the two programs possible.

To improve the reliability of the polarization analysis, other more progressive methods of processing seismograms were used, which were implemented in the above MATLAB script for the purposes of the polarization analysis of 3C seismograms. Applying the complex analysis of the seismic trace to the data of the transformed *z*-component enabled us to prove that the identified time corresponded to the arrival of the S-wave. For example, we tested whether the identified S-wave arrival was accompanied by an increase of the instantaneous amplitude (see, e.g., René et al., 1986). According to Vidale (1986) the time variation of the direction of the maximum polarization was sought from the data of 3C seismograms; the change in the degree of polarization in space and in the plane was tested. This analysis should contribute to distinguishing between the arrivals of various types of waves. The polarization analysis according to Jackson et al. (1991) was also tested simultaneously by singular value decomposition of the data matrix. This method is able to separate various interfering waves with regard to their polarization. In both cases, these more complicated analyses of 3C seismograms only proved the result of the simple analysis of the *z*-component, but provided no new information, which would simplify the identification of S-wave arrivals, in problematic cases.

From the point of view of method, it was verified that, if the device with the 8-bit A/D converter is used to record, it is convenient to repeat the measurements at different levels of amplification for reliable identification of P- and S-waves. The ratio of P- and S-wave amplitudes in relation to the usual level of noise is such that the P-waves are difficult to identify if the amplification for recording S-waves is set to optimum. For the reliable identification of the P-wave arrival times, it is usually convenient to repeat the record at a high sensitivity. In this case, however, the maximum amplitudes of S-waves usually exceed the record dynamic range. This problem is avoided if a 14-bit converter is used.

If piezo-ceramic transducers are used as sources of seismic energy, multiply repeated measurement can be used to an advantage. The addition is analogue to stacking of hammer impacts, but with a much more reliable conformity of the repeated exciting pulses. This so-called vertical stacking improves the signal-to-noise ratio and the dynamic range of the record (Klemperer, 1987). Since the first hundreds of signals can be stacked in a very short time, this operation appears to be considerably effective.

CONCLUSION

The purpose of the measurements described was to identify the longitudinal and transverse phases of man-made seismic waves under various geological conditions and in different geometric configurations. Parametric field measurements of elastic moduli of the rock medium were compared. The length of the measuring base varied in the interval of 0.25 to 10 m, and the frequencies of the exciting signals covered an interval of three orders of magnitude (100 Hz to 100 kHz). The relation between the wavelength and the length of the measuring base proved to be decisive for identifying the arrival of S-waves.

To optimize the identification of S-wave arrivals, various systems of monitoring and exciting seismic waves were tested. The use of 3C geophones and application of polarization analysis when measuring in the near zone may improve the reliability of detecting S-waves. In this zone, the wave field is complicated and varies rapidly in space. Better results can be achieved by using seismic sources with a higher signal frequency in combination with the corresponding seismic receiver characteristic.

In a medium with a near-surface weathered layer, or with a deformation, the impact of a hammer can be used as a seismic source. A more light-weight hammer produces a signal with a higher frequency than a heavy hammer, but the measurement range is smaller. With a view to possibility of determination of the S-wave arrival, it is convenient to apply the lightest possible hammer, with which the signal-to-noise ratio with respect to the arrival of the P-wave is still sufficient. In measuring in non fractured rocks (e.g., in rock outcrops) high-frequency sounding can be applied (signal frequency higher than 10 kHz) in which the source of seismic energy is a piezo-ceramic transducer. It is convenient to orient the maximum radiation pattern of the piezo-ceramic transducer perpendicular to the surface for reliable recording of P- and S-waves, and record the signals with piezo-ceramic sensors of S-waves.

These measuring systems enable the velocity anisotropy to be determined in the plane of measurement. The velocity values can then be used to compute the elastic constants of a rock medium.

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