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ACTIVE ULTRASOUND IN GEOLOGICAL RESEARCH IN KLADNO

Karel MALINSKÝ, Jaroslav PLOCEK

Faculty of Electrical Engineering, Czech Technical University
Technická 2, 166 27 Praha 6, Czech Republic

Abstract. The use of active ultrasound (cross–hole ultrasonic sounding) as part of complex geotechnic research in the Kladno – 2 Mayrau mine is described in this paper. Having passed through the rockmass, the ultrasonic waves bear information about the rockmass. Attenuation and the velocity of sound (passing time) are measured. Dispersion is assumed as negligible. The presence of water in the rockmass is substantional: water is used as an immersion. The degree of saturation of the rockmass by water must be checked. – The multiple scattering in the coarse–grained sandstone occurs but remains constant and does not affect the results of the measurement (unless microcracks etc. occur). The interferometric method of evaluating the changes of time (velocity) of ultrasound enables the achievement of a satisfactory precision in the results.

Keywords: ultrasound, velocity, attenuation, dispersion, scattering, velocimetry, interferometry

Ultrasound, its Wavelengths, Attenuation, Dispersion

Ultrasound is frequently used in science and technology. In geophysics, it is sometimes referred to as "seismic waves at ultrasonic frequencies", "kHz – seismic waves" and similar. The difference between ultrasound and seismic waves consists only in their wavelength – all other distinctions (attenuation, resolution ability) ensue from the different wavelength.

Ultrasound is the production of mechanic (acoustic) vibrations with frequencies above 16 kHz, often comprising of frequencies well above 100 MHz. Nevertheless, waves with frequencies above 100 kHz approx. barely extend in rocks because of their high attenuation. The term "attenuation" may be used for the case where the rock may be assumed to be homogeneous in respect to the wavelength (λ), i.e. when the size of inhomogeneities is smaller than the wavelength. For ultrasound with a frequency of 50 kHz in sandstone (typical velocity of sound is 2500 m/s), the wavelength is $\lambda = 5$ cm. In most cases, the sandstone may be assumed to be a continuum for these ultrasonic waves. So it is in the case of Kladno sandstone layers (at least in the place examined).

Relations between the absorption and dispersion of waves were established by Kramers and Kronig (1928) for the case of X–rays, indeed the way they solved the problem was quite general and independent from the wave mechanism (the only principle required in order to obtain the relations was that of causality) and the solution is valid for any waves [Futterman 1962, Lamb 1962]. While continuing doubt has been expressed in the literature of theoretical and experimental seismology about the existence of dispersion for body waves in the Earth and the real magnitude of dispersion, i.e. $\mathrm{d}c(\omega)/\mathrm{d}\omega$ (c is the velocity of sound, $\omega = 2\pi f$, f is the frequency of ultrasonic waves), is as rule quite negligible, the Kramers–Kronig relations for the dispersive attenuation α lead to the locally (in the frequency region) verifiable equation [O'Donnell 1981]

$$\alpha(\omega) = \frac{\mathrm{d}c(\omega)}{\mathrm{d}\omega} \cdot \frac{\pi\omega^2}{2c^2} \,.$$

The upper limit for the dispersion $\mathrm{d}c(\omega)/\mathrm{d}\omega$ as calculated from the results of our measurements in Kladno is $\mathrm{d}c(\omega)/\mathrm{d}\omega = 0.00076\,\mathrm{m}$. Such a value is quite incompatible with the theory of wave motion in fluid–saturated porous media [King 1966]. In our case of rather coarse–grained sandstone, the substantional rate of pores exceeds 0.001 cm in dia. It is the low frequency range around 50 kHz for which flow of the liquid through the pores is of Poiseuille type. Two coupled dilatational modes are possible (corresponding to the acoustic and optical dispersion branches of diatomic lattice vibrations in solid state physics) with liquid and solid moving in–phase and out–of–phase, resp., with the waves of the second mode attenuating rapidly and having no importance. The difference between the two limiting velocities (for low and high ultrasonic frequencies), in our case of poorly lithified sandstone, is less than 1 %. Thus, the dispersion and related effects (the dispersive attenuation α) is negligible. – The role of the dispersive attenuation in the entire attenuation might be evaluated after ascertaining the velocity of sound for another frequency near to 50 kHz and comparing with the formula mentioned.

The Role of Water

The content of pore water plays an important role in geology, mainly in applied geotechnical sciences, in mining and in seismology. Water (and other liquids as well, but water is abundant nearly everywhere) migrates along gravitational fields and pressure gradients. Especially, the appearance of a vast amount of microcracks in the first stage of an earthquake may be followed by the changes of pore water content.

Data [Yu 1993] from coals show strong variations of compressional wave velocity by water saturation. On average, compressional wave velocity increases by 23 % with water saturation. On the other hand, the velocity of shear waves remains nearly unaffected by the water content. The difference may be easily explained from the fact that the shear waves do not propagate through liquids.

Sound velocities in sands in various state of consolidation and in sandstones have been thoroughly studied [Hughes, Kelly 1952], [Gist 1993], [Blangy 1993], [Mavko 1994]. In general, a linear dependence of the compressional velocity on the saturation of pores is consistent with all published data for quartzose sandstones.

Nevertheless, in partially saturated rock (which may occur near the excavation even in otherwise entirely saturated sandstone), the saturation differs for pores of various dimension, and a kind of hysteresis may occur.

In suitably stiff materials such as some claystones, water immersion is not necessary and a dry coupling is sufficient [Yonglian Sun 1993], but for our reasons water is essential as an impedance match between the ultrasonic transducers and the rockmass.

THE PROBLEM OF MULTIPLE SCATTERING

No matter what has been mentioned about the homogeneity of the rock as a plausible approximation concerning attenuation, the Kladno sandstone is highly inhomogeneous and the acoustic signal on the surface of the receiving transducer is no doubt a result of the interaction of ultrasonic wavelets scattered from many grains, so multiple scattering is dominant. The result is a "grain noise": the pattern depending on both the frequency content of the transmitted signal and the position of the transducer in the rockmass. This grain noise complicates all pulse–echo acoustic methods. The problem of grain noise led us to the development of a continuous–wave (CW) technique. Using a crystal controlled sine wave (not to mention the slow auxiliary modulation and intermittent calibration pauses) and fixing the position of both transducers in their boreholes solves the problem. The frequency and geometry remains stable, the only problem being the Rayleigh type of scattering: with the wavenumber $k = 2\pi/\lambda = 100\,\mathrm{m}^{-1}$ approx., $ka \leq 0.5$ for most sandstone grains, where the scattering depends on $(ka)^4$. (a is the characteristic dimension of the grain.) Nevertheless, the size distribution effect allows us to neglect the influence of varying wavelengths [Thorne 1992] for changes in the velocity of sound less than 5 %.

VELOCITY OF P WAVES SPREADING, THE EFFECT OF STRAIN/STRESS

The velocity of sound (P waves in our case) as a function of rock stress has been measured by many authors [King 1966, Yu 1991, Yu 1993]. The velocity of sound in sandstones increases with hydrostatic pressure: the velocity increases by 10 % with the increase of pressure from zero to 7 MPa. For higher pressures, the increase in velocity diminishes and velocity remains stable for pressures above 30 MPa.

High stress concentration, and mainly shear stress, follows with the growth of microcracks. These microcracks lead in contrast to a decrease in velocity and to an increase in attenuation. Stacey (1976) determined that compressional waves are less sensitive to such irregularities. Lockner (1977) proposed that ultrasonic wave attenuation is more sensitive than velocity to the presence of such microfractures [Shea 1988].

THE METHOD OF MEASURING

For ultrasonic measuring in Kladno – 2 Mayrau mine, the continuous–wave method with two piezoceramic ring–shaped transducers was used.

Both transducers show the same directivity charts. The directivity chart in the perpendicular plane is circular within 3 dB. In the axial plane, the directivity chart approaches the theoretical curve for $ka = 4.4$ (a is the height of the cylinder, $a = 21$ mm and $k = 2\pi/\lambda$ is the wavenumber, $k = 209\,\mathrm{m}^{-1}$ in water – Fig.1). The directivity chart in the rock ($k = 120\,\mathrm{m}^{-1}$) is certainly broader.

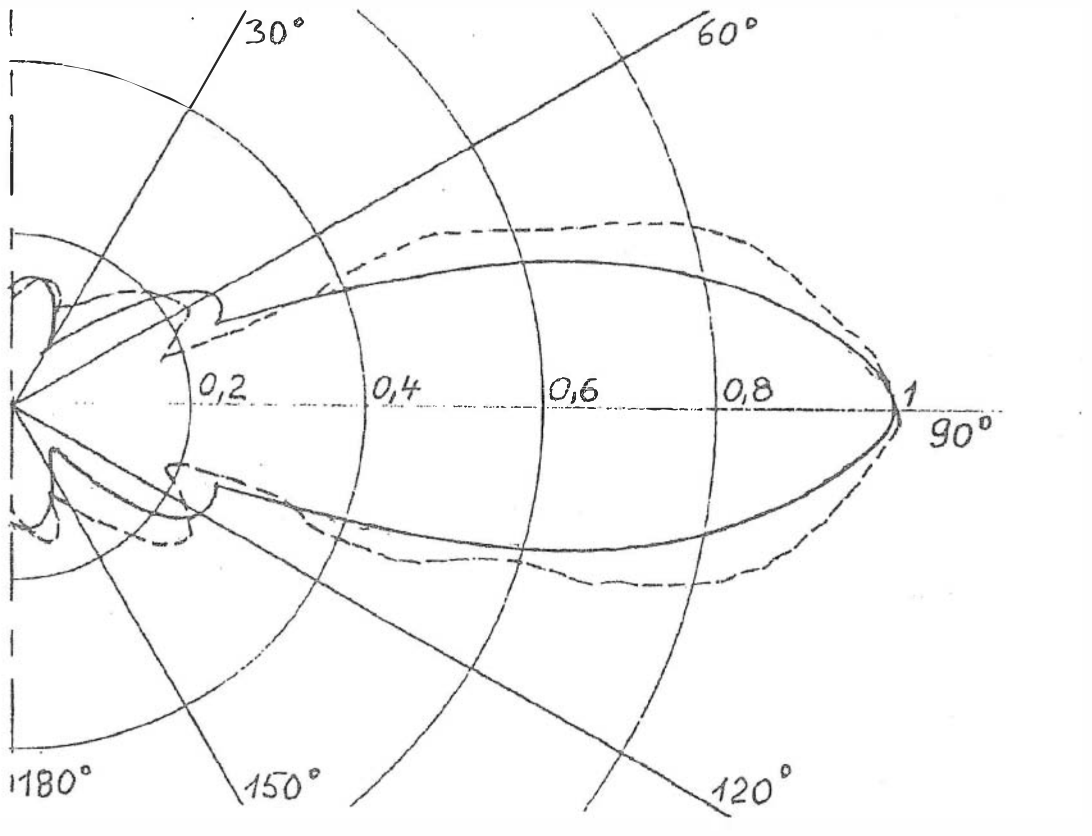

FIG.1 : Normalized directivity charts of the pressure amplitude of a piezoceramic ring with plugs:
———— calculated for $ka = 4.4$
– – – – – – measured in a water tank.

For best results, the axes of both transducers have to be parallel within 5° – with this condition maintained during the measuring. Both transducers are located in two parallel boreholes 2.5 m deep. They are inclined at an angle of 35° under the horizontal. After the mud has been removed, the boreholes are still full of water. The distance between transducers is 0.97 m.

The device works at frequency $f = 48.55$ kHz. The sinewave signal is not modulated (the device allows the amplitude modulation for measuring delays exceeding $T = 1/f$, but this feature is not necessary for small distances between transducers). The ultrasound is received by the second transducer and converted to an electric signal. The amplitude of the signal received and the phase difference between the emitted and received signal are measured and recorded.

The "A" (amplitude) channel of the receiving system measures the level A_2, of the signal that has passed through the rock. A_1 is the level of the signal reached in direct connection between both transducers (a calibration level, measured in laboratory in a special water basin). The attenuation rate, α, is

$$\alpha = \frac{1}{d} \cdot \ln(A_1/A_2) \qquad (m^{-1})$$

where d is the distance between transducers ($d = 0.97\,m$ for the measuring).

For the time being, the PC programme does not allow the direct evaluation of α. Nevertheless, the aim of the measuring consist more in recording changes of attenuation and their correlation with other measurements. For A_1 = const, the mere time rate of A_2 is sufficient for this.

Changes in the velocity of sound in the rock are evaluated from measured data in the "φ" channel where phase differences between transmitted and received sinewave signals are recorded

$$\triangle c = -\triangle\varphi \cdot \frac{c^2}{\omega d}$$

where $d = 0.97\,m$, $\omega = 2\pi f$, $f = 48.55\,kHz$. The velocity c may be evaluated from cores in a laboratory.

THE ACCURACY OF THE METHOD

For measuring the velocity of sound, the pulse–echo method is standard. The pulse–echo method is often used for measuring in geophysical laboratory research and most data published have used this method. Nevertheless, for establishing the influence of stress in the rockmass on the velocity of sound, and distinguishing the above–mentioned effects of increasing stress and microfracturing, temporal changes in velocity are substantional. And so the accuracy of pulse–echo methods (1 % or more) is no longer sufficient.

In the continuous–wave method, the information available from the receiving transducer is the amplitude and phase of the received ultrasonic wave. The amplitude is directly measured and used for evaluating the attenuation. The phase is compared with the actual phase transmitted – thus the interferometric method. The accuracy of the interferometric measurement is proportional to the length of the base of the measurement (the distance between the transmitting and receiving transducer). The length of the base has been chosen in accordance with conditions at the site measured. Unfortunately, the attenuation of ultrasound in Kladno sandstone is so high that only very short distances ($d = 0.97\,m$) between transducers lead to a sufficient level of the signal being received. Thus, the baselength is $\triangle = 18.4\,\lambda$ (measured in wavelengths of the ultrasonic wave) and the theoretical deviation in the measuring time (velocity) changes is $(2 \times 2048 \times 18.4)^{-1} = 1.3 \,.\, 10^{-3}\,\%$. The feasible deviation is slightly greater because of the limited accuracy of the analogue phasemeter.

THE MEASURING

The described device for phase and attenuation measurements has been in progress in the Mayrau mine, Kladno, since March 31, 1994. At the same place, hydrogeological and convergometrical measurements are made. The device operated faultlessly until July 14, 1994. The initial value was $A_1/A_2 = 2.567 \,.\, 10^{-3}$ and $\alpha = 6.149\,\mathrm{m}^{-1}$. The changes in A were $+18 \div -66\,\%$ during the measuring (correspondingly $\triangle\alpha = -3\,\% \div +19.4\,\%$) The velocity of elastic waves was established on a borehole core with $c = 2536\,\mathrm{m/s}$. The entire phase shift $\triangle\varphi$ is 14.57°, corresponding thus with the velocity change $\triangle c = -5.8\,\mathrm{m/s}$.

Time plots of the amplitude and phase measurement have been made and compared with the results of other geophysical measurement from the same location. Nevertheless, no sufficient correlation between various methods has been found. The explanation may consist in the fact that the bases of these measurements differ slightly but distinctly.

CONCLUSIONS: VELOCIMETRY AS A MEANS IN PROGNOSTICS

Measuring the velocity of sound as a function of stress applied may be used for tensometric measurements inside the rock. However, the role of many complicating factors (inhomogeneity, water content etc.) does not allow a simple comparison between tensometric and velocimetric data. Other complicating factors have been described by Hudson and Cooling (1988): Any excavation disturbs the pre–existing stress field, the magnitudes of the principal stresses will change and the principal stress normal to the excavation boundary becomes zero, and the excavation acts as a "sink" for water in the rockmass. Further, the rock behaviour may be time dependent. The in situ stress will have stabilized over a geological time, but may be in a continuous state of change during the stress measurement. There may, however, still be a difference between local data and far–field tectonic component.

The actual velocity of sound (time of passing the acoustic signal between the transmitting and receiving transducers) depends on the actual state of the rockmass: the strain (the actual distance between transducers), the stress, the increase of microcracks, and the amount of water in them. Some of these features can be measured independently, and the complexity of measurements in the Kladno Mayrau mine gives the best opportunity for comparing measured data: especially the data measured before, during and after rockbursts. In this way, the difference between tensometric and velocimetric measurements (combined with measuring ultrasonic attenuation) allows us to find out the rise of microcracks and the danger of stress failure (unfortunately, the block failure may occur independently of the actual stress field in the place examined). As a matter of fact, conditions in the Kladno Mayrau mine (coarse–grained sandstone poorly lithified) are not the best for the use of these complex measurements. The repetition of these measurements in a more suitable rock would led to more satisfactory results.

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AKTIVNÍ ULTRAZVUK PŘI GEOLOGICKÉM ZKOUMÁNÍ NA KLADNĚ

V článku se popisuje užití aktivního ultrazvuku při komplexním geotechnickém průzkumu na dole Mayrau. Ultrazvukové vlny procházejí prostředím (horninou), zvukový signál přijatý přijímacím měničem tak v sobě nese informace o prostředí, kterým procházel. Měří se útlum a doba resp. rychlost šíření zvuku. Vliv disperze se hodnotí jako zanedbatelný. Podstatnou roli má přítomnost vody v hornině ve sledovaném místě: voda je zde nezbytným prostředkem k umožnění přenosu ultrazvuku do horniny, vzhledem k silné závislosti rychlosti a útlumu ultrazvuku na nasycení horniny vodou je však třeba sycení místa vodou kontrolovat.

Při průchodu ultrazvuku horninou dochází – zejména v tomto případě hrubozrnných nadložních pískovců silně narušených těžbou a dalšími aktivitami v místě – k mnohonásobnému rozptylu. Při pečlivé fixaci měničů a užití spojité harmonické ultrazvukové vlny však rozptylové efekty zůstávají konstantní v průběhu měření (kromě případu tvorby menších či větších trhlin nebo jiných dramatických změn v místě) a výsledek měření nezkreslují. Vyhodnocování změn doby průchodu (rychlosti šíření) ultrazvuku interferometricky umožňuje dopracovat se i v daném případě krátké báze dostatečně přesných výsledků.