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Velocity dispersion in fractured rocks in a wide frequency range

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ABSTRACT

Experimental measurements of fracture-induced seismic waves velocity variations at frequencies ~1 kHz, ~40 kHz and ~1 MHz were performed directly in the field at the rocky outcrop and in the laboratory on specific rock samples collected from the outcrops. The peridotite–lherzolite outcrop appeared macroscopically uniform and contained three systems of visible parallel sub-vertical fractures. This rock has substantial bulk density and higher than average value of seismic wave velocity. The presence of fracture systems gives rise to its velocity anisotropy. The seismic waves passing through the rock fractures are subject to velocity dispersion and frequency dependent attenuation. Our data, obtained from field and laboratory measurements, were compared with theoretical model predictions. In this model we successfully used displacement discontinuity approach. For the velocity dispersion evaluation we used multi-frequency measurements. The a priori observation of orientations and densities of fracture sets allowed evaluation of their stiffness. Our approach revealed that the first arrivals of seismic waves can be used for evaluation of P-wave group velocities, the specific case, in which we expect anomalous velocity dispersion. Our observations contribute to the issue of up-scaling of well-log derived velocities in fractured rock to the scale of standard seismic exploration frequencies.

1. Introduction

Laboratory research of P-wave velocities in rock samples serves to evaluate rock properties under simple and clearly defined conditions. The use of such laboratory results for evaluating field measurements, however, requires the up-scaling of laboratory results. Seismic wave propagation through heterogeneous materials in laboratory and field conditions differs due to the difference in sample size/rock massif, frequencies and wave lengths. Both attenuation and time delay of seismic waves, resulting in strongly frequency-dependent velocities, are observed in rock massifs containing fractures. According to Schoenberg (1980) or Pyrak-Nolte et al. (1990) the fracture or set of parallel fractures in rock can be treated as non-welded interfaces, and the transmission of seismic waves can be expressed using the displacement discontinuity model. The analytical solution for group delay can be calculated and its frequency dependence established. This approach was successfully applied to assess fracture properties in ultrabasic rocks (Ivrea zone, north-western Italy, Vilhelm et al. (2010)) for seismic waves of frequencies 0.5–1.8 kHz and 700 kHz. In the present paper, these results are revised and completed with measurements at frequencies of 40–80 kHz. The four-order frequency range was achieved by a unique combination of seismic hammer and ultrasonic field measurements and high-frequency laboratory experiments. For the sake of brevity the field hammer measurements are further referred to as seismic (frequency around 1 kHz), field measurements with piezo-ceramic source as sonic measurements (frequency range approximately 40–80 kHz) and laboratory measurements performed with frequencies of the order in MHz are called ultrasonic. The sonic designation is not exact because the frequency exceeds 20 kHz; however this name is commonly used for sonic well logging method.

The given case study demonstrates that the velocity anisotropy due to the presence of a few fracture sets with different orientations in a rock massif can result even in a change of directions of the maximum and/or minimum velocities of elastic waves according to their frequencies. At the locality under study this is most pronounced for seismic and sonic measurements. The frequency of sonic measurement corresponds to the frequency of signals used in acoustic well logging. Such a difference in seismic and sonic signal frequency, therefore, can result, e.g., in erroneous assessment of the principal stress directions in the rock massif, or in an incorrect velocity model established from acoustic-log data for processing seismic reflection data.

2. Experiment

The measurement was made directly on the rock outcrop of peridotites and pyroxenites in the Ivrea zone (north-western Italy). These rocks are widely accepted to represent the boundary between the upper mantle and the deep crust (Lensch, 1968; Mehnert, 1975). These rocks are characterized by high bulk densities and high values of seismic wave velocities. The locality with outcrops of peridotite–lherzolite suitable for

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both field seismic measurements and sampling was found in the Sesia River Valley, between the villages of Balmuccia and Isola (Vilhelm et al., 2010).

At the surface of the outcrop, three systems of sub-vertical fractures were observed macroscopically. The first system is oriented from E to W. These fractures are opened and spaced at intervals of about 20 cm. Only fractures of this system could be observed continuously up to a distance of several meters. The second system of fractures, running N to S, consisted of tight fractures with a density of as much as 1 fracture per 10 cm. The third system of fractures was a system running from SW to NE. These fractures were tight, their fracture spacing being 50 cm. All observed systems of fractures were perceptible through the visible part of the rock outcrop. The rock body at the measurement site appeared macroscopically uniform, which should guarantee that measurements on different scales are influenced mostly by different measuring base lengths and not by the inhomogeneity of the rock massif.

The measurements were performed on three different scales: seismic measurements at a distance of about 10 m from a hammer source, sonic field measurements at a distance of about 0.5 m from a piezo-ceramic source, and laboratory time-of-flight ultrasonic measurements a source-receiver distance of 0.05 m by means of a piezo-ceramic high-frequency source.

The seismic measurements were carried out with a 24-channel Geode engineering seismograph by Geometrics (USA); its frequency range is 1.75 Hz to 20 kHz. The sampling frequency chosen was 50 kHz. Standard, 24 Hz, vertical electro-dynamic geophones were employed. To ensure good geophone coupling, the geophones were stuck to the surface of the outcrop with plaster. The seismic energy was generated by striking a small metal plate with a 1-kg hammer. The frequency of the recorded P-waves lies between 0.5 and 1.8 kHz. The time of impact was determined by the electric contact between the hammer and the metal plate. The quality of the seismograms enabled to use the first breaks to determine P-wave arrivals.

The P-wave velocity was calculated from the travel times determined at a distance of approx. 7 m from the seismic source. Six different directions of measuring profiles were used to determine directional velocity dependence in angular steps of 30 degrees. The velocities were determined from the slope of the travel-time curves. A more detailed description of this measurement can be found in Vilhelm et al. (2010).

A piezo-ceramic sensor was used as the source for sonic field measurements. The energy of the waves, generated in this manner, is usually significantly lower than that generated by an impact source. Moreover, if the 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 must thus usually be carried out on a base not longer than 1 m.

The duration 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) allow the sounding wave frequency to be affected. A suitable wave source proved to be the 1 MHz/0.5″ S-sensor V153-RM, by Panametrix for exciting P-waves spreading in the direction along the rock surface. 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 rise time to be generated. The repetition frequency of pulse transmission was set to 0.1 kHz which makes it possible to reach the required number of signal averaging in a short time and simultaneously keeping the repetition period shorter than the length of the record (the record length was shorter than 2 ms).

Piezo-ceramic 100 kHz S-sensors Olympus V1548, fixed to the cleaned rock outcrop surface with plaster, were used for registration of P-waves spreading along rock surface. This type of transducer coupling to the rock surface can solve at least partly the problem of repeatability of seismic signal excitation and measurement (Živor et al., 2011). The repeatability of measurements is considered a serious problem. For example Marelli et al. (2010) found that, for better repeatability, the use of hydrophones in a borehole with water can be recommended.

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. To improve the signal-to-noise ratio and dynamic range up to 256 records can be averaged. The readability of the first onset data can be increased by using high gain. This setting usually results in overloading the record for the waves in later arrivals. This issue can be resolved by successive recording of two records with high and low gains. The recorded data could be stored in the field on a USB flash disk.

For this sonic measurement a sampling frequency of 25 MHz was used. The frequency of the recorded P-waves was in the interval of 40–80 kHz. The P-wave velocity was calculated from the travel times determined at two distances of approx. 0.25 and 0.5 m from the seismic source. Four different directions of measuring profiles were used to determine the directional velocity dependence at angular steps of 45 degrees. The velocities were determined from the slope of the travel-time curves.

Laboratory time-of-flight ultrasonic measurements were made using the pulse-transmission technique on spherical rock specimens, 5 cm in diameter (Pros, 1977; Pros and Podroušková, 1974). The employed method makes it possible to measure in many directions, whereby the multi-directional dependence of the velocity of P-waves can be established. A pair of piezo-ceramic transducers rotates on the surface of the spherical sample along a meridian and parallel coordinate grid in steps of 15° in both directions. In all, 132 velocity measurements were made in different directions. The frequency of the sounding pulse was about 3.6 MHz. The sampling frequency of the recorded signals was 100 MHz. The directional velocity dependence obtained can be expressed in terms of the distribution of the velocity over a spherical surface. The velocity measurements can, moreover, be performed under confining pressure conditions, the maximum hydrostatic pressure being 400 MPa.

Laboratory measurements were carried out on specimens, collected as oriented samples from the studied peridotite outcrop. The spherical specimen was dried and coated by epoxy to prevent the penetration of loading fluids into pores and cracks. The accuracy of the spherical sample shape was ± 0.01 mm. The inaccuracy of the velocity determination was approximately 50 m/s. This inaccuracy was caused mainly by the uncertainty in onset time determination.

The weak dependence of velocity on hydrostatic pressure is evidence that the specimen contains a minimum of open cracks or systems of open cracks, which also agrees with the high value of the measured bulk density of the rock (3500 kg/m^3). The increase in the P-wave velocities is only 3% under a confining pressure of 400 MPa. The velocity anisotropy (maximum and minimum velocity values and their orientation) remained almost stable during loading. It was found that the direction of the highest velocity is roughly perpendicular to the outcrop surface. In the plane perpendicular to this direction (i.e. in the plane of the outcrop surface) however, nearly the lowest velocities were observed.

The velocities determined under laboratory conditions at atmospheric pressure (0.1 MPa) were used for comparison with field measurements. Only the data corresponding to the outcrop surface plane in the field were used. The difference between the lowest and the highest velocity in this plane was 110 m/s. This corresponds to 1.5% of the average velocity of 7730 m/s determined for the considered plane. A more detailed description of this measurement can be found in Vilhelm et al. (2010).

3. Results of measurements and data processing

In the case of seismic and sonic field measurements the velocities of elastic P-waves were determined as the slope of the travel-time