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ISRM SUGGESTED METHOD

Upgraded ISRM Suggested Method for Determining Sound Velocity by Ultrasonic Pulse Transmission Technique

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1 Introduction

Ultrasonic testing is one of the most widely used non-destructive testing methods for rock material characterization (Lama and Vutukuri 1978). The method is based on the generation, transmission and reception of small-amplitude wave trains of adjustable pulse length and ultrasonic pulse frequencies.

Wave propagation can be considered as transfer or passage of strain energy through a medium (e.g., Eringen 1980; Jaeger et al. 2007). In routine material testing, microstructural characteristics (encompassing mineralogy, size and shape distribution of voids and grains and their relative arrangements) of the medium determine the rate of energy dissipation, uniquely modify the frequency spectrum and define the velocities of different propagation modes, e.g., compressional and shear. Therefore, the wave velocities and their amplitude-frequency spectra are related to the material's physical and mechanical properties that are also strongly related to the microstructural characteristics. This relationship constitutes the basis of ultrasonic tests, but also poses great challenges for improvement of its precision and offers opportunities for a wider range of applications.

2 Scope

The original suggested methods (Rummel and Van Heerden 1978; ISRM 2007) consist of three different approaches for the laboratory determination of sound velocity. These approaches utilize waves generated at different frequency ranges and require different specimen shapes, testing and analysis procedures. This upgraded suggested method covers the first two approaches, the so-called high (100 kHz–2 MHz) and low (2–30 kHz) frequency ultrasonic pulse techniques, while the resonant approach will be presented in a companion suggested method. This upgrade (a) unifies the two ultrasonic approaches by a generalized scheme applicable to any specimen shape/size at any frequency within the ultrasonic range (>20 kHz), (b) emphasizes the peculiarities and particulars of rocks as ultrasonic test materials, and (c) suggests possible modifications/adjustments in test procedures and specimen preparation to account for the special microstructural features encountered in common rock types.

In the pulse method of ultrasonic testing, generating sound wave trains and detecting their propagation through solids can be achieved by a single transducer (pulse-echo technique) or by a pair of transducers (pitch-catch technique). The pulse-echo technique is designed for locating flaws forming seismic impedance contrasts within the host material. The pitch-catch technique can be used in three different configurations of transducer pairs depending on the accessibility of test surfaces (Fig. 1). This suggested method concentrates on the issues pertaining to the direct-transmission configuration of the pitch-catch technique, and thus the influences of the near field length and beam spread on transducer selection and test procedures are not discussed. Note that the direct-transmission configuration is preferred to the others because the direction and length

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Please send any written comments on this ISRM Suggested Method to Prof. Resat Ulusay, President of the ISRM Commission on Testing Methods, Hacettepe University, Department of Geological Engineering, 06800 Beytepe, Ankara, Turkey.

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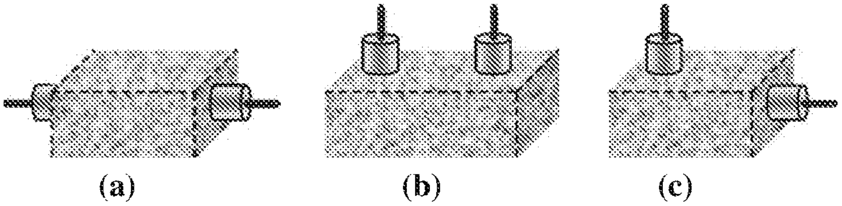


Fig. 1 Basic configurations of transducer pairs (transmitter–receiver) used in pitch-catch technique: **a** direct (through) transmission; **b** indirect (surface) transmission; and **c** semi-direct (edge) transmission

of path along which the wave-front travels is known with greater certainty and that the test results are not influenced by possible damage or deterioration of specimen surface and/or edges.

Ultrasonic P-wave velocity (V_P) and S-wave velocity (V_S) are customarily used in establishing predictive correlations (mainly with porosity, strength and static modulus) and in determining dynamic elastic constants. The ultrasonic test system as a non-destructive tool should also be used routinely for examination of uniformity/integrity and anisotropy of other test specimens to reduce or explain scatters in rock mechanics test results. This examination can be conducted by determining the velocity over a grid-pattern on large surfaces or by velocity profiling along one or more traverses on narrower surfaces. Rectangular blocks provide an opportunity for determining the principal axes of velocity anisotropy on rock specimens with banded, laminated, foliated, phyllitic, schistose and similar orientated fabric that may impart directional dependencies to strength and deformation resistance. Oriented cylindrical cores and sphere-shaped specimens, where available, may also be used for this purpose.

3 Apparatus

Ultrasonic test systems have substantially benefitted from the technological advances in the past three decades. There are now many commercially available advanced test system alternatives with digital waveform display, processing and storage capabilities. It is no longer possible or necessary to include such a vast amount of easily accessible information in testing standards for specific materials. However, a typical layout of essential ultrasonic testing system components is shown in Fig. 2 as a preliminary guideline. These components include a signal generator to trigger timer to mark the beginning of each excitation pulse interval, an arrival timer in the form of a threshold trigger and/or an oscilloscope for visual analysis of the waveform, amplifiers and filters for signal enhancement, and a data acquisition unit interfacing with the apparatus. Two separate transmitter–receiver transducer pairs are needed for the determination of P- and S-wave velocities. Each (piezoelectric) transducer pair may have a nominal frequency between 20 kHz and 2 MHz, but the 50–500 kHz range is recommended for practical purposes.

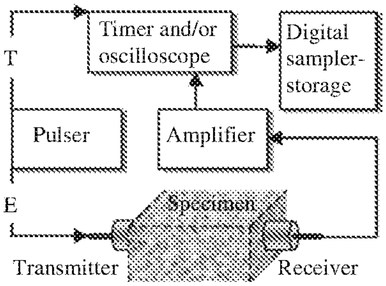


Fig. 2 A simplified layout of basic components of an ultrasonic apparatus. (*E* transmitter excitation signal, *T* timer trigger signal)

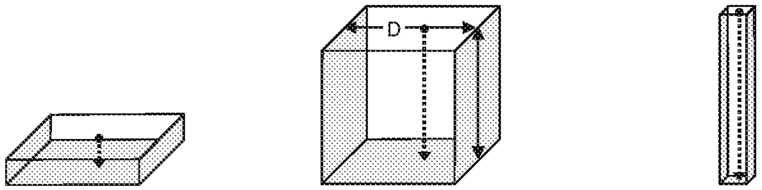
4 Sample Preparation

When testing rock materials, it should be remembered that in situ microstructures are inevitably altered in varying degrees during recovery, transport, storage and preparation, but this can be minimized using right tools and procedures and exercising care in all stages. The direct-transmission transducer configuration requires test specimens with smooth (using fine sandpaper), flat (specified by a maximum gap size between specimen surface and standard straightedge, which accommodates <0.025 mm thick feeler gage) and parallel (<1 mm/100 mm of wave travel path length) faces. Each specimen dimension (as specified later in Fig. 3) should be measured at several points with a precision of ±0.01 mm.

5 Test Procedure

Ultrasonic test procedure for pitch-catch configurations is quite straightforward especially if analysis of frequency spectrum is not to be conducted. Determination of V_P and V_S of a test specimen requires measurement of two basic variables: the length of wave travel path L (taken as the shortest distance between transmitter and receiver transducers) and the length of travel time of each wave type (t_P and t_S). The latter corresponds to identification of P- and

Fig. 3 Three distinct specimen shapes with corresponding limiting dimensions and velocity expressions



SLAB	BLOCK	BAR
$L/D \leq 0.1$	$L/D \approx 1$	$L/D \geq 10$
$\lambda \leq 0.1\,D$	$\lambda \leq 0.1\,D$	$\lambda \geq 5\,D$
$L \geq 10\,d_g$		
$V_P = \sqrt{\frac{E_d}{\rho}\frac{1}{(1+\nu_d)(1-\nu_d)}}$	$V_P = \sqrt{\frac{E_d}{\rho}\frac{(1-\nu_d)}{(1-2\nu_d)(1+\nu_d)}}$	$V_P = \sqrt{\frac{E_d}{\rho}}$
$V_S = \sqrt{\frac{G_d}{\rho}} = \sqrt{\frac{E_d}{\rho}\frac{1}{2(1+\nu_d)}}$		
$\nu_d = 1 - 2\frac{V_S^2}{V_P^2}$	$\nu_d = \frac{V_S^2 - 0.5\,V_P^2}{V_S^2 - V_P^2}$	$\nu_d = 0.5\frac{V_P^2}{V_S^2} - 1$

d_g: average grain size (equivalent spherical diameter)

S-wave arrivals on the oscilloscope traces. There are, however, a number of important issues that influence the test results as highlighted below:

(a) A thorough description of microstructural composition (especially any discrete features or boundaries that are likely to create significant acoustic mismatch).

(b) Specimens can be tested *dry* or *fully saturated* or *at* in situ *moisture content*. Procedures to achieve and maintain these conditions as provided in the relevant suggested methods should be followed (ISRM 2007).

(c) As each specimen may be tested in more than a single direction, include a sketch or a photograph showing orientation of each travel path with reference to the specimen's planar fabric (bedding planes, laminations, schistocity, etc.) or to long axes of elongated or lenticular features (clasts, fragments, inclusions, fossils, etc.).

(d) A thin layer of coupling medium should be used to ensure efficient and uniform energy transfer from/to the transducers. There are a large variety of options (including phenyl salicylate, high-vacuum grease, glycerin, putty, Vaseline, oil) but a high viscosity medium (e.g., epoxy resin) is needed if S-wave velocity is to be measured.

(e) The transducers should be positioned and aligned to produce an acoustic axis (center beam) that is normal to both faces.

(f) In direct-transmission test configuration, a custom-made benchtop load frame with an in-built low-capacity load transducer can be used for coaxial positioning of the transducers and for maintaining a small coupling stress (~ 10 kPa) for a given transducer diameter.

(g) Note that the minimum coupling stress at which wave travel times stabilize may vary substantially with rock type and the degree of microstructural damage. Also beware of the possibility of internal shearing or exfoliation of specimens with strong anisotropy when loaded oblique or normal, respectively, to anisotropy planes. In anisotropic and weak rocks, when applying seating/coupling load, observe any changes in the velocities at 5–10 N load increments and report such variations. For small diameter transducers, observe any settlement into the specimens and report any changes in travel path length (0.1 mm/100 mm) upon the application of the seating load.

(h) The measured wave travel time through a specimen may need to be corrected for a small amount of system response delay time. The system delay correction needs to be readjusted each time a new transducer pair is used. This delay can be determined (Rummel and Van Heerden 1978; ISRM 2007): (a) by placing the transmitting and receiving transducers in direct contact with each other and measuring the travel time at zero length; and (b) by measuring the travel time on a number of standard specimens of different lengths and extending the best-fit line to the time-distance data pairs to zero length (recommended for S-wave transducers).

(i) A reference bar with a known velocity or a reference spacer with a known transit time should be used to regularly monitor any drift in the measured values.

(j) When the transducers are coupled manually by hand, the travel times should be measured for at least three times applying different pressures, and if possible, the received waveform should be recorded for about 10 pulse intervals.

6 Calculations

The velocities of P- and S-waves are determined from $V_P = L/t_P$ and $V_S = L/t_S$, where L is the travel path length and t_P and t_S are travel times for P- and S-waves, respectively. The approximate analytical solutions that link the velocity of sound wave propagation through isotropic and homogeneous solids to the elastic constants (White 1983; Jaeger et al. 2007) are based on two fundamental assumptions. It is important to understand these to select the most appropriate model for utilization of wave velocity (V_P and V_S) and to interpret/calibrate the differences in test results from different specimens and/or transducers. These assumptions are explained below and illustrated in Fig. 3:

1. The first assumption establishes the effects of boundary interference via specimen's minimum dimension (D) (twice the shortest distance from the transducer center to the specimen boundary) relative to specimen's length (L) (shape factor) and to the wavelength (λ) at a given transducer frequency (f). For the direct-transmission configuration, three distinct shapes (and corresponding wave propagation patterns) can be identified for rectangular (slab, block and bar) and cylindrical (disk, block and rod) specimens.
2. The second assumption defines the scale at which a material can be tested to ensure representative and reproducible results. For granular materials, in which variations in grain compositions, grain boundary types and pores form the dominant features of microstructure, this scale can be expressed in terms of the number of grains along the wave propagation path, which is equal to the specimen's length (L) in the direct-transmission configuration.

Figure 3 also provides the analytical solutions that should be selected carefully for each specimen and test condition expecting that these assumptions will not be met in most practical cases.

For purposes of predicting the dynamic elastic constants, standard rock mechanics test specimens (D 50–60 mm and L/D 2–2.5) can be classified as a block-bar specimen, where the measured velocity will be closer to that of a bar at high frequency and vice versa. There are, however, a few tests (e.g., indirect tension, block punch) that require slab- or disk-like specimens with L/D ratios of less than 1.

If the block specimen (approximating infinite medium conditions) is taken as a reference, the velocity of P-waves can be shown to decrease in both slab and bar specimens as a function of the Poisson's ratio (v), revealing a relative order of magnitudes of $V_{\text{P-Block}} > V_{\text{P-Slab}} > V_{\text{P-Bar}}$. For example, for a rock material with $v = 0.30$, slab- and bar-like specimens may produce up to 10 and 14 % lower velocities than a block specimen of the same material, respectively.

Once V_P and V_S are determined for a specimen, the dynamic (ultrasonic-based) Poisson's ratio (v_d) can be calculated as shown in the last row of Fig. 3. The Poisson's ratio value can then be used to predict the dynamic Young's (E_d) and shear (G_d) moduli based on the measured or predicted value of the specimen's density. Note that the values of these dynamic elastic constants are expected to differ from the static ones derived from actual loading experiments.

7 Reporting of Results

The report should include the following information:

(a) Lithological description of the test specimens (preferably in the order of strength, color, texture/fabric, weathering/alteration, rock name with grain size as prefix).

(b) Geographic location of source area and coordinates of sampling points.

(c) Geological setting (formation name, proximity or association with geological features, e.g., faults, shear zones, dykes, lenses, narrow valleys, high cliffs).

(d) Sample recovery and in situ conditions (drilling/coring techniques; method of quarry production; weathering and fracturing degrees in the sampling intervals/exposures).

(e) Specimens (length and conditions of storage; preparation procedures including method of drying or saturation; smoothness and parallelity of opposite faces; microstructural descriptions of grain and void structures).

(f) Physical properties (density, porosity and water content) and static elastic constants (e.g., E_s and v_s).

(g) Test system (manufacturer and model number or complete technical specifications of the system and the transducers; calibration date and method).

(h) Test procedure (date and method of transducer calibration; transducer configurations and alignment; transducer-specimen coupling medium; means (manual or mechanical) and level of seating/coupling force).

(i) Specimen shape and dimensions; position and length of each travel path on specimen surfaces; minimum lateral dimension for each position.

(j) Relative orientation of travel path (acoustic axis) to nearby geological features and to intact rock anisotropy (e.g., lamination, foliation, schistosity, lineation).

(k) P- and S-wave velocities recorded at each transducer position and along each travel path orientation; mean and standard deviation of velocity variations within and among specimens.

(l) Predicted values of dynamic elastic constants and the selected velocity model (Fig. 3).

8 Notes and Recommendations

8.1 Terminology

The term "sound" is often used to refer to mechanical (body and surface) waves that can travel through any medium and at any frequency. "Sound" as used in the title of this suggested method specifically denotes body waves propagating through rock materials at ultrasonic frequencies.

P- and S-waves are both body waves, which can be generated at the boundary or the interior of a medium and propagate through that medium (i.e., unlike surface waves that are confined to a boundary zone). P- and S-waves are often defined by different pairs of terms highlighting different aspects of their propagation: (1) irrotational–equivoluminal (nature of elemental deformation); (2) longitudinal–transverse (particle displacement direction); (3) compressional and/or dilatational–shear (particle displacement mechanics); and (4) Primary–Secondary (arrival order).

8.2 Limitations for Sample Dimensions

As discussed in "Calculations" section, this test can be performed practically on any specimen without limitations on shape or dimensions. The only limitation that may be imposed relates to the possibility of excessive weakening of signal strength due to attenuation of wave energy if the travel length is too long. Because rock materials exhibit a wide range of attenuation coefficients for different lithologies, weathering states and along different directions, the maximum travel length (penetration depth) at which a clearly distinguishable waveform and/or a stable signal can be recorded is variable. For a given specimen, the coefficient of attenuation due to scattering is strongly dependent on the transducer frequency, which favors a shorter specimen length when using high frequency transducers.

8.3 Representation of Field Conditions in Laboratory Testing

It should be borne in mind that predicting in situ properties based on laboratory test results is complicated due to inadequate representation of field conditions. In situ stress and its anisotropy, pore fluid type and pressure, and saturation degree alter the microstructure of rock materials and hence its wave propagation characteristics in many different ways. Discussion of specialized tests and experimental setup to simulate such field conditions are beyond the scope of this suggested method.

8.4 Calculation of Elastic Constants in Transversely Anisotropic Rocks

Most common form of anisotropy in rock materials is the transverse or polar type imparted by unidirectional compaction during burial of sedimentary rocks, development foliation in metamorphic rocks, etc. Determination of elastic constants and quantification of anisotropy is possible from measurement of P- and S-wave velocities normal, parallel and at an angle of exactly 45° to the plane of anisotropy (Thomsen 1986). Considering that testing at the inclined angle may not often be possible in practice, the users are encouraged to determine the velocities in the normal and parallel directions, which will help determine four of the five elastic moduli of transversely isotropic rock materials, as well as quantify the degree of their P- and S-wave velocity anisotropies.

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