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Determining P- and S-wave velocities and Q-values from single ultrasound transmission measurements performed on cylindrical rock samples: it's possible, when…

Marc S. Boxberg[1,2], Mandy Duda[1], Katrin Löer[3,4], Wolfgang Friederich[1], Jörg Renner[1]

[1]Faculty of Geosciences, Institute of Geology, Mineralogy and Geophysics, Ruhr-Universität Bochum, Germany, [2]AICES and Faculty of Georesources and Materials Engineering, RWTH Aachen University, Germany
[3]Departement of Civil and Environmental Engineering, Bochum University of Applied Sciences , Germany, [4]Department of Geology and Geophysics, University of Aberdeen, UK

Determining elastic wave velocities and intrinsic attenuation of cylindrical rock samples by transmission of ultrasound signals appears to be a simple experimental task that is applied routinely in all sorts of geoscientific and engineering applications requiring basic sample characterization. Also, velocity tracking has become a valuable monitoring tool for changes in the state of a sample in the laboratory or a rock volume in situ.

P- and S-wave velocities are generally determined from first arrivals of signals excited by transducers specifically designed for the intended measurement. Determination of intrinsic attenuation has been performed with a range of methods, most of them relying either on a comparison between the sample under investigation with a standard material or by investigating the same material for various geometries.

Of the three properties addressed (P- and S-wave velocity and P-attenuation), P-wave velocity is probably the least challenging one. However, even for the first break controlling P-waves emerging onsets due to dispersion complicate the accurate determination of either their velocity or attenuation. The determination of S-wave velocities is even more hampered by interferences that result from converted P-wave arrivals interfering with the S-wave arrival. Attenuation estimates are generally subject to larger uncertainties than velocity measurements due to the high sensitivity of the amplitude to experimental conditions, such as sensor coupling or time of measurement.

Also, interferences of waves traveling on different paths may even affect the first arrival sequence and thus their amplitude variations may not reflect attenuation for a specific wave type alone. The achievable accuracy of determining S-wave velocity and intrinsic attenuation using standard procedures thus appears to be severely limited.

We suggest that all three parameters , P-wave velocity, S-wave velocity and intrinsic P- and S-wave attenuation, can be determined with high accuracy by full wave-form matching of a single ultrasound trace by a synthetic one. Laboratory samples with finite dimensions give rise to reflected and converted phases that bear information on P- and S-waves irrespective of the selected source signal. Enough information on both velocities is contained in the recognizable reflected and converted phases of the ultrasound trace. Attenuation is coded into these phases by their relative amplitudes because wave paths differ with the phases.

We derive recommendations for laboratory experiments from the results of our measurements on cylindrical samples of aluminum, polyoxymethylene and Carrara marble with different dimensions. We compare results from various standard analysis methods to those obtained from full waveform modelling and (non-automatic) inversion of single ultrasound traces. The substantial effort put into processing for our approach is particularly justified by the gained accuracy, when subtle variations in elastic properties, for example as response to changing P-T-conditions, are of interest, or when the amount of sample material is very limited.

Ultrasound transmission measurements

- Three materials were tested with 1 MHz, 12,7 mm P-wave transducers: aluminum (Alu), polyoxymethylene (Pom) and Carrara marble (Car).

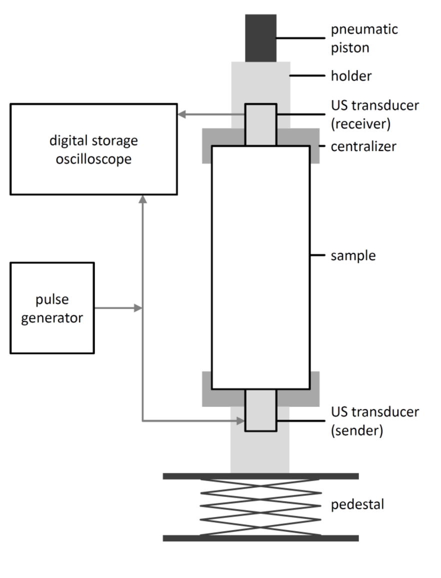


Figure 1: Experimental setup for ultrasound transmission. Reproducibility for travel times and amplitudes based on nine repeated measurements on one aluminum sample was quantified by calculating the amplitude and travel time variation of the strongest arrivals. **The amplitude and travel time deviation was lower than 0.84% and 0.07%, respectively**.

- Suites of ten cylindrical samples (diameter of 40 mm) and lengths from 10 mm to 100 mm were tested.
- Our experimental procedure is the best-practice outcome for our setup comprising i.a.:

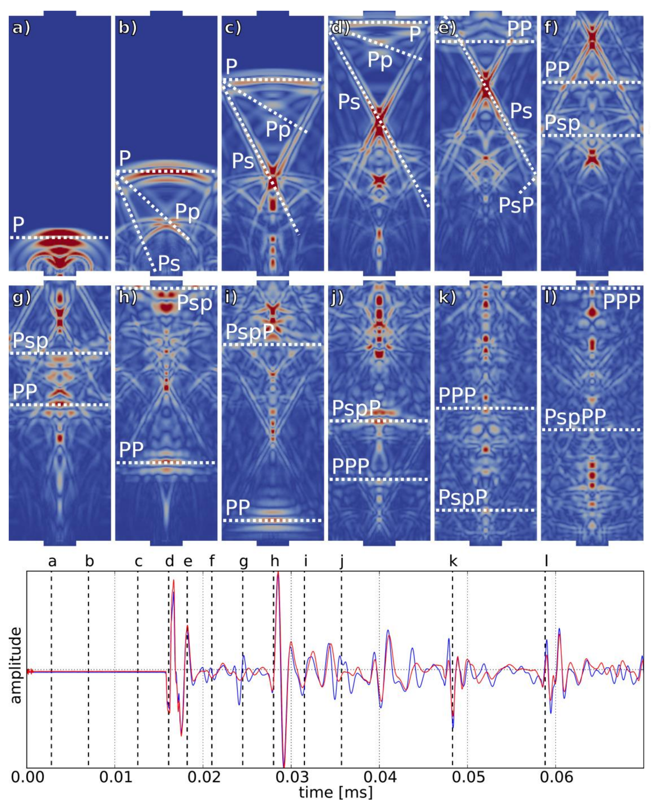
1. Use of ultrasound contact gel, **constant** coupling pressure > 1 atm and repeated time flow to provide high reproducibility;
2. Fulfillment of far field conditions to reduce amplitude uncertainties;
3. Clearing up of signal, i.e. no interferences from multiples or reflections affect the **analyzed signal**.

… following the workflow suggested below.

(i) Perform an **ultrasound transmission measurement** using a P-wave sensor
(ii) Determine the density of the sample
(iii) Estimate an **initial value for the P-wave velocity** using first onsets or cross-correlation techniques
(iv) Estimate an **initial value for the S-wave velocity**
(v) Run simulation to **obtain final velocities** via manual adjustments (or full waveform inversion, not applied here)
(vi) Estimate the **quality factor** using the proposed fitting of an exponential decay to the rms-ratio.

Full waveform modelling

- We use the open-source spectral finite-element software packages SPECFEM2D and SPECFEM3D initially developed by Komatitsch et al. (1997) to compute synthetic waveforms.



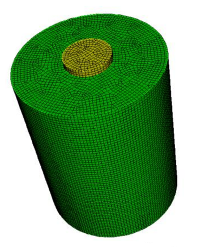


Figure 5: Left: Snapshots of the wavefield propagating through the cylinder with length 100 mm for a slice parallel to the y-z plane through the sample's center. The snapshots a) to l) correspond to times marked in the seismograms below with vertical dashed lines. Laboratory and synthetic data are colored in red and blue, respectively. Top: Mesh of a cylinder with a diameter of 40 mm and a length of 50 mm.

Velocities: P-wave velocities are easiest (but not easy) to quantify, S-wave velocities are imprecise

- We determined P-wave velocity with (1) manual picking of first breaks, (2) "group" travel times (cross-correlation of full signal), and (3) "phase" travel times (cross-correlation of first arrival). The latter two require measurements at different lengths (e.g. Tonn, 1989).

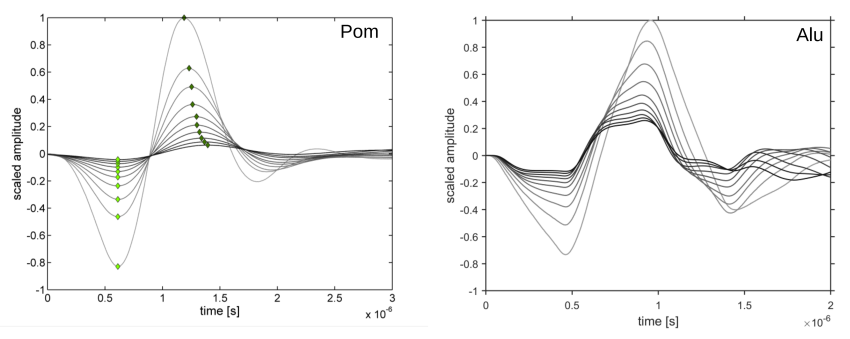


Figure 2: Example of first arrivals of Pom (left) and Alu (right) samples corrected for their phase travel times. Light and dark green diamonds (left) indicate first minima and first maxima, respectively. Amplitude scales to absolute maximum in the shown time interval.

Table 1: Results of the velocity analysis. Average velocities were determined from their individual ratios of sample lengths to travel times (minus system time). Interpolated velocities were determined from the slope of sample length vs travel time.

	Alu			Pom			Car		
Method	1	2	3	1	2	3	1	2	3
Average [m/s]	6380	6545	6557	2376	2342	2344	5585	5569	5604
St.dev [m/s]	8	27	23	13	3	2	158	190	173
Interpolated [m/s]	6379	6538	6553	2379	234	2344	5360	5296	5362
St.err [m/s]	2	14	13	4	1	1	70	63	65

The agreement between laboratory measurements and synthetic seismograms is remarkable.

Figure 8: Recorded (red) and synthetic (blue) seismograms for homogeneous and isotropic aluminum cylinders with a diameter of 40 mm: length of the cylinders on the vertical axis and time on the horizontal axis. The synthetic seismograms were calculated for a 3D-model assuming purely elastic behavior. Every seismogram is normalized to its maximum amplitude. The dashed grey lines indicate the prominent phases.

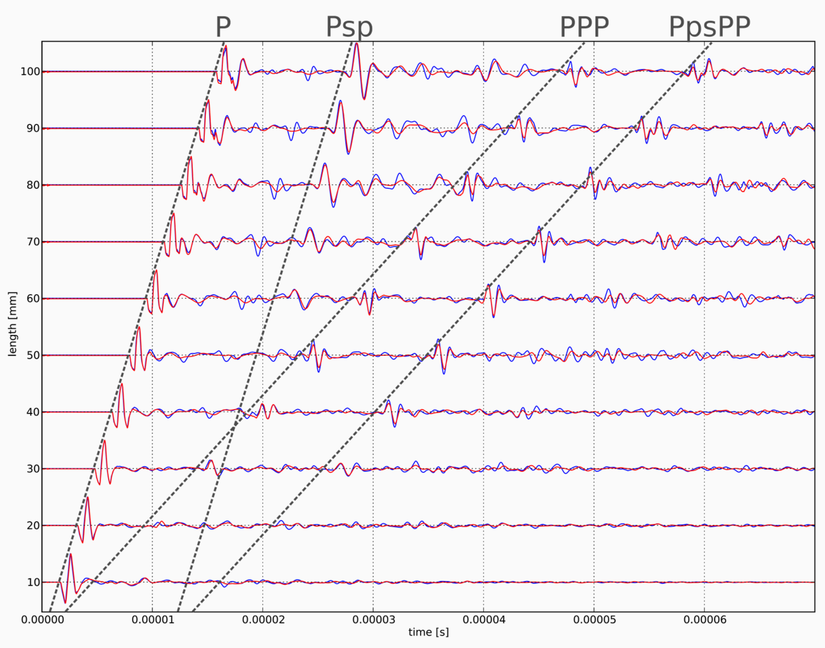
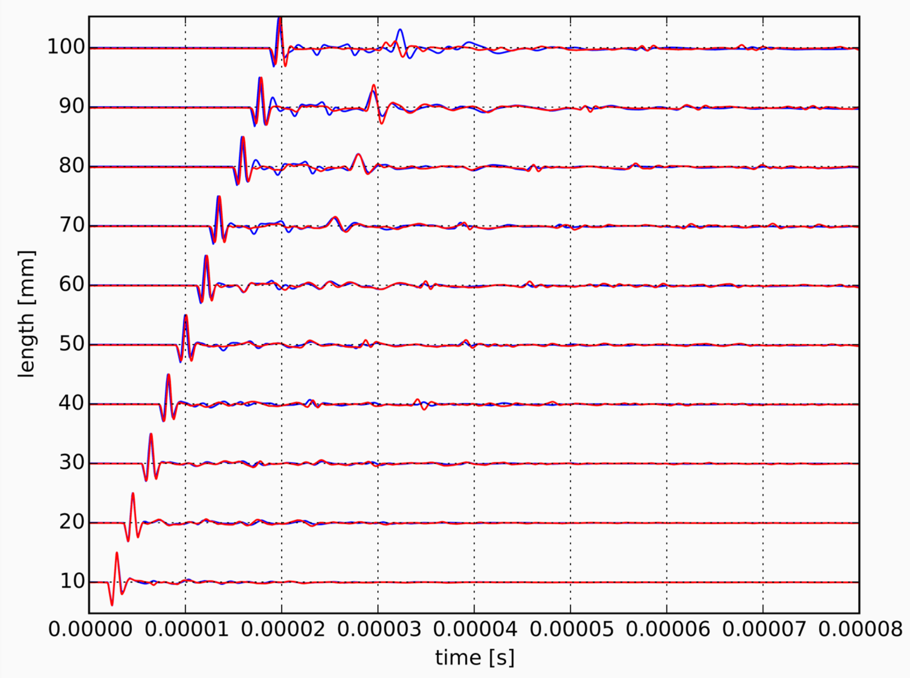


Figure 9: True seismograms (red) measured for ten rock samples of Carrara marble of different length, compared to synthetic seismograms (blue) computed with SPECFEM 3D using a quality factor of $Q_{\mu} = 22$ ($Q_P = 50$; ignoring samples longer than 70 mm).



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Komatitsch, D. (1997): Méthodes spectrales et éléments spectraux pour l'équation de l'élastodynamique 2D et 3D en milieu hétérogène, Dissertation, Institut de Physique du Globe de Paris, Paris.

Toksöz, M. N., Johnston, D. H., & Timur, A. (1979): Attenuation of seismic waves in dry and saturated rocks: I. Laboratory measurements, Geophysics, 44(4), 681–690.

Tonn, R. (1989): Comparison of seven methods for the computaion of q. Phys. Earth Planet. Int. 55, 259-268.

Velocities: Precise determination of S-wave velocity

- We explored the determination of S-wave velocity from identified Psp- and P-phases in the recorded seismograms. The time lag between the Psp- and the direct P-phase is caused by two contributions:

1. The difference in wave path and wave-front curvature between the twice reflected and back-converted P-wave and the direct P-wave, and
2. The lag of the wave path traveled with the slow S-wave speed.

	Alu		Car	
	V_P	V_S	V_P	V_S
Average [m/s]	6360	3170	5427	3113

Table 3: P- and S-wave velocities for aluminum samples and samples of Carrara marble.

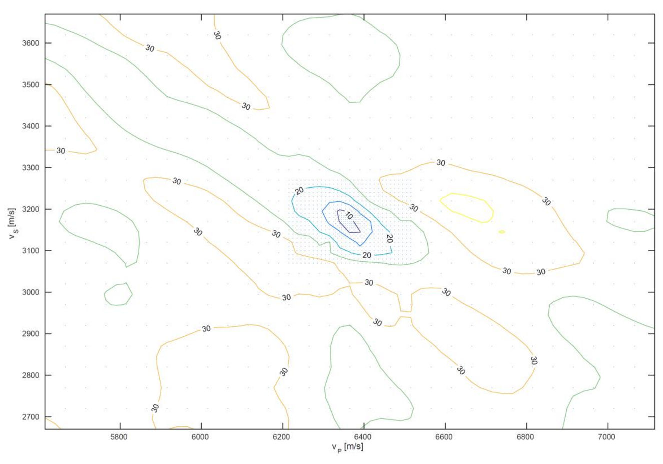

Figure 6: Contour plot of the misfit between computed and measured waveforms as a function of P-wave velocity V_P and S-wave velocity V_S for Alu. The small, blue dots represent the points where the misfit was actually calculated. The misfit surface was interpolated on a grid with equal spacing of 25 m/s. The contour interval is 5.

Amplitudes: standard methods to determine Q yielded no reasonable or robust results

- We applied amplitude decay and spectral ratio techniques to quantify intrinsic attenuation.
- All methods yielded inconsistent, unreasonable and/or weak results.
- Are our laboratory measurements not good enough?

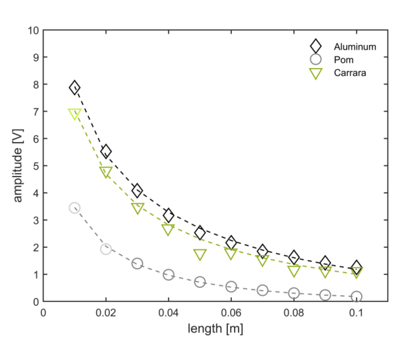

Figure 3: Amplitude decay with increasing sample length. Symbols show first minima, dashed lines are calculated from eq. (1) based on the parameters provided in Table 2.

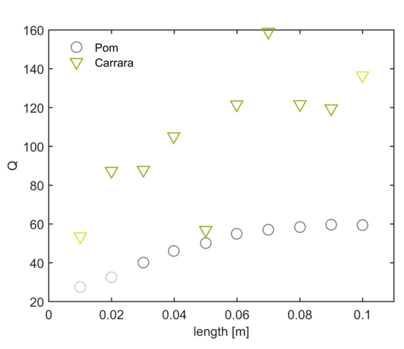

Figure 4: Results for Q from spectral ratio technique (with aluminum as reference) and different length for frequency range between 0.5 MHz and 0.8 MHz based on eq. (1) (Toksöz et al., 1979).

Amplitude decay	Alu	Pom	Car
q	1.4	0.49	1.08
A_{sys} [V]	**0.4**	**0.47**	0.43
f [MHz]	0.75	0.93	1.00
Q	33	60	55
V [m/s]	**6553**	**2344**	**5362**

$$A(x, f) = A_{sys} x^{-q} \exp\left[-\frac{\pi f}{QV} x\right] \quad (1)$$

Table 2: **Examples for** results of amplitude decay method (manual fitting procedure). Results for Q were non-unique, partly not reasonable and / or weakly determined. Bold values were determined independently.

Amplitudes: provide robust and reasonable estimates for the quality factor of P-waves

- We computed synthetic seismograms for cylinders of different lengths for an elastic medium with predetermined P- and S-wave velocities and compared their root-mean-square (rms) amplitudes for the whole waveform to that of the recorded seismograms.

- The application of this procedure to our laboratory measurements on aluminum samples yields an insignificant decay of rms-amplitude ratio with cylinder length confirming that the quality factor for this material is high. For Carrara marble samples we obtain a quality factor of $Q_P = 50$ when treating samples longer than 70 mm as outliers.

Figure 7: Ratio of root mean square (RMS) of laboratory measurements and elastically calculated seismograms for Alu (left) and Car (right) as a function of sample length.