Quality-factor and reflection-coefficient estimation using reflected surface waves

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SUMMARY

We propose a method for estimating the reflection coefficient of a subvertical boundary and the the quality factor of the medium between a receiver and the subvertical boundary. The method uses surface waves from transient deterministic sources and is inspired by the occurrence of non-physical arrivals in seismic-interferometry results due to intrinsic losses in the medium. The quality-factor estimation with our method can be used as an alternative to and confirmation of results from the spectral-ratio method. We demonstrate our method on data from ultrasonic laboratory measurements.

INTRODUCTION

The seismic waves experience intrinsic losses when propagating through the rocks in the Earth. The effect of the loss of energy is quantified by the parameter quality factor (Q). A spatially detailed knowledge of Q is important for accurate interpretation of processes in and the composition of the Earth at different scales (e.g., Solomon, 1972; Klimentos, 1995; Zhubayev and Ghose, 2012). One of the traditional methods for Q-estimating is the spectral-ratio method (e.g., Jannsen et al., 1985; Tonn, 1991), which can be applied to transmission and reflection measurements.

Recently, Draganov et al. (2010) proposed an alternative method for Q-estimation. This method makes use of retrieved non-physical arrivals from body-wave seismic interferometry by crosscorrelation with transient sources (e.g., Wapenaar and Fokkema, 2006). These arrivals appear in the retrieved result due to intrinsic losses in the medium. The non-physical arrivals arise from correlation of arrivals reflected inside a later. Ruigrok (2012) used the same type of arrivals and showed how they can be used to estimated both Q above and the reflection coefficient at the top of the layer that causes the internal reflection.

In the following, we adapt the method of Ruigrok (2012) to surface waves. Using ultrasonic laboratory measurements, we show how it can be applied to estimate the surface-wave Q-value of the subsurface and the reflection coefficient at a subvertical boundary. This method can be seen as an alternative to the spectral-ratio method when the latter does not give results with sufficient certainty. This might be the case when the recording geometry consists of sparse receivers in a medium with lateral changes in the seismic parameters, e.g., in volcanic settings or in the presence of a subvertical fault zones. In such cases, the spectral-ratio method should be applied at single stations to estimate the Q-value between the station and a reflector, thus using a direct and a reflected arrival, to avoid erroneous results when the different receivers would be in media characterized by different intrinsic losses. In such cases, the method we propose could be applied at the same station to obtain an alternative estimate of the Q-value, but also to estimate the reflection coefficient of the reflecting boundary, which supplies extra information about the media.

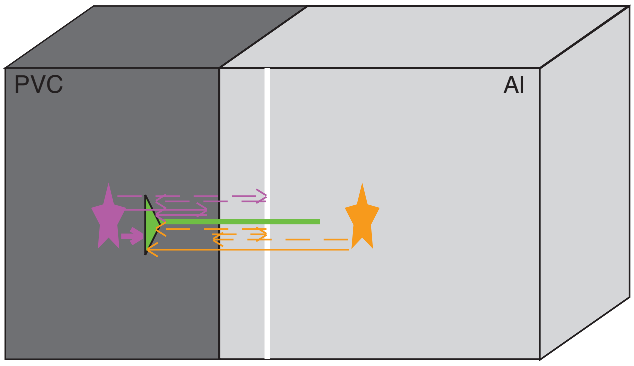

Figure 1: Laboratory setup to testing the proposed method. Using a scanning laser interferometer, ultrasonic measurements are made along a line (in green) on the surface of a sample consists of coupled together aluminum (Al) and polyvinyl chloride (PVC) blocks. The magenta and orange stars depict P-wave transducers used as seismic sources. The vertical white line depicts a groove in the Al block.

THE LABORATORY SETUP

To demonstrate the method we propose, we acquire data on a sample consisting of an aluminium (Al) block and a polyvinyl chloride (PVC) block coupled together by acoustic couplant, see Figure 1. To obtain internal reflections, at 30.5 mm from the PVC/Al interface we create a groove in the Al block that is parallel to the interface (the vertical white line in Figure 1). The groove is approximately 2 mm wide and 10 mm deep. As a source of surface waves we use a P-wave transducer set at 2 MHz and 400 V. The source is used on doth sides of the PVC/Al interface. On the PVC block, the source is placed 45 mm from the interface, while on the Al block it is placed 43 mm from the groove (magenta and orange stars in Figure 1 and called PVC source and Al source, respectively). We measure the displacement at 701 receiver points (a point is represented by the triangle in Figure 1) spaced at 0.05 inch (0.127 mm) in a direction perpendicular to the surface. We make the measurements using a scanning laser interferometer, based on a constant-wave 250 mW Nd:YAG laser at 532 nm with a flat response between 20 kHz and 20 MHz (see Blum et al., 2010). The receiver points are along a line (in green in Figure 1) starting at 31.6 mm from the PVC/Al interface (13.4 mm from the PCV source) and finishing 26.8 mm away from the groove (16.2 mm from the Al source). The time sampling of the measurements is 50 ns. The actually recorded surface-wave energy at the majority of the receiver points from the PVC source is lower than 600 kHz and from the Al source is lower than 1 MHz. This is despite the high centre frequency of the source transducer. Because we measure the vertical component of the displacement, the recorded surface waves are Rayleigh waves.

METHOD

To explain the method, we use the sketch of the laboratory setup in Figure 1. Suppose we have a 1D medium (as is the sample along the line) and want to retrieve the surface-wave part of the Green's function at a receiver point along the line (the triangle in Figure 1). The retrieval can be achieved for example by seismic interferometry with transient sources (Wapenaar and Fokkema, 2006). For this, we need to autocorrelate the recordings at the receiver point from two plane-wave sources that form one line with the receiver point and are situated on opposite sides of it (effectively enclose it). Such are the magenta and the orange sources. The retrieved result from seismic interferometry, representing a measurement from a collocated virtual source and receiver, should contain the reflected surface wave from the PVC/Al interface, the reflected surface wave from the groove and the internal multiples of the latter. The reflection from the PVC/Al boundary is retrieved from the correlation of the thick solid magenta (*tksm*) arrival with the thin solid magenta (*tnsm*) arrival. The reflection from the groove is retrieved from the correlation of the *tksm* with the dashed magenta (*dm*) arrival. In the correlation process, also the *tnsm* and the *dm* arrivals will correlate. This would result in the removal of the common travel path, which is effectively the path of the *tnsm* arrival, and will result in the retrieval of a non-physical (ghost) reflection from inside the layer between the PVC/Al interface and the groove as if measured with collocated virtual source and receiver placed directly at the PVC/Al interface. This ghost reflection will be eliminated in the final retrieved result by to the summation of the correlated measured arrivals from the orange source. The correlation of the solid orange (*so*) arrival with the dashed orange (*do*) arrival will also result in a retrieval of a ghost reflection between the PVC/Al interface and the groove, but with polarity opposite to the one of the magenta ghost. In the summation step of the interferometric retrieval, the magenta and orange ghosts will interact destructively and the ghost reflection will be suppressed. When in the autocorrelation are used also the multiple reflections between the PVC/Al interface and the groove, the ghost reflection will be completely eliminated from the final retrieved interferometric result. The elimination, though, would happen in the case of a losses medium (for which case seismic interferometry by crosscorrelation is derived). When the waves experience intrinsic losses, the ghost reflection will not be eliminated. This fact was used by Ruigrok (2012) and Draganov et al. (2013) to estimate the Q-value of the medium using body waves. Here, we adapt the method from Ruigrok (2012) to surface waves, as with this method also the reflection coefficient at the PVC/Al boundary can be estimated.

For the estimation of Q between the Earth's surface and a layer causing the internal reflection, Ruigrok (2012) proposed to use the amplitudes of six arrivals recorded at the surface due to a transient source in the subsurface. The arrivals are used to derive relations between ratios of their amplitudes and Q and the reflection coefficient. The derivation uses the fact that the differences in the amplitude damping of the chosen six arrivals are only due to extra propagation between the layer and the surface.

In our case, we use two sources at the surface. As the two sources are on different sides of the receiver point, the waves they generate propagate through different parts of the medium and can be damed in a different way. Furthermore, this damping would be depend on the respective distance of the sources to the receiver point. To eliminate such dependance, we propose to normalize the recordings at the receiver point by the amplitude of the direct surface-wave arrival. Normalization of the *tnsm* by the *tksm* (the direct-surface wave) arrival means dividing their amplitudes (A_{tnsm} and A_{tksm}, respectively):

$$\frac{A_{tnsm}}{A_{tksm}} = \frac{A_{tksm} e^{-2\frac{t_1 2\pi f_0}{Q_{PVC}}} r_{PVC/Al}}{A_{tksm}} = e^{-2\frac{t_1 2\pi f_0}{Q_{PVC}}} r_{PVC/Al}, \tag{1}$$

where t_1 is the one-way travel time of the Rayleigh wave from the receiver point to the PVC/Al interface, f_0 is the centre frequency of the signal, Q_{PVC} is the quality factor of the PVC, and $r_{PVC/Al}$ is the reflection coefficient at the PVC/Al interface. The equation does not contain geometrical-spreading terms, as we have assumed plane-wave source. The equation gives one relation between for Q_{PVC} and $r_{PVC/Al}$.

The second relation is obtained using the amplitudes of the arrivals that retrieve the ghost reflection between the PVC/Al interface and the groove. Correlation of the normalized *tnsm* with the *dm* arrival means multiplication of their normalized amplitudes (A^{norm}_{tnsm} and A^{norm}_{dn}, respectively):

$$A^{norm}_{tnsm} * A^{norm}_{dn} = e^{-4\frac{t_1 2\pi f_0}{Q_{PVC}}} r_{PVC/Al} e^{-2\frac{t_2 2\pi f_0}{Q_{Al}}} T_{PVC/Al} r_{groove} T_{Al/PVC}, \tag{2}$$

where t_2 is the one-way travel time of the Rayleigh wave between the PVC/Al interface and the groove, r_{groove} is the reflection coefficient at the groove, and $T_{PVC/Al}$ and $T_{Al/PVC}$ are the transmission coefficients for the Rayleigh waves passing from the PVC to the Al and from the Al to the PVC, respectively. Correlation of the normalized *so* with the *do* arrival from orange source again means multiplication of their normalized amplitudes (A^{norm}_{so} and A^{norm}_{do}, respectively):

$$A^{norm}_{sb} * A^{norm}_{db} = r_{Al/PVC} e^{-2\frac{t_2 2\pi f_0}{Q_{Al}}} r_{groove}. \tag{3}$$

Dividing equation 2 by equation 3 and using $r_{Al/PVC} = -r_{PVC/Al}$ and $T_{PVC/Al} T_{Al/PVC} = 1 - r^2_{PVC/Al}$, we obtain

$$\frac{A^{norm}_{tnsm} * A^{norm}_{dm}}{A^{norm}_{so} * A^{norm}_{do}} = -e^{-4\frac{t_1 2\pi f_0}{Q_{PVC}}} (1 - r^2_{PVC/Al}). \tag{4}$$

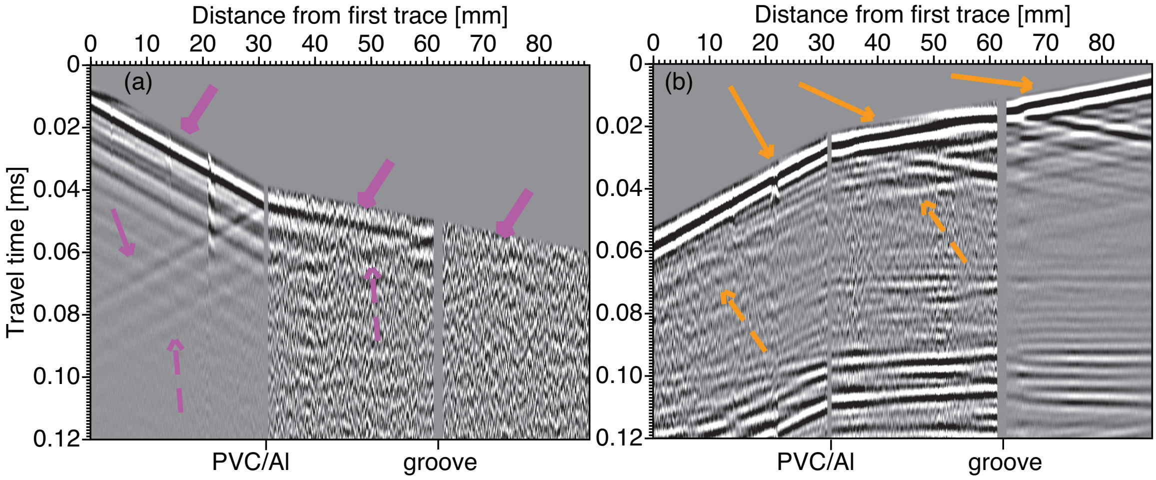

Figure 2: Recorded responses along the receiver line from the (a) PVC source and (b) Al source. Each trace in both images has been normalized to its maximum, frequency-filtered, and top-muted. Additionally, for visualization purposes, the images have been clipped.

Using equations 1 and 4 we can solve for the quality factor Q_{PVC} and zero-offset plane-wave reflection coefficient $r_{PVC/Al}$, because the left-hand sides of the two equations can be obtained from the measured data directly or from the autocorrelations for retrieving the ghost reflections.

RESULTS FROM THE LABORATORY EXPERIMENT

Figures 2 show the measured responses along the complete line of receiver points from the PVC (Figure 2a) and the Al (Figure 2b) sources after applying the mentioned-above normalization. We apply the amplitude normalization by dividing each trace by the amplitude of the direct Rayleigh wave at that receiver point, i.e., by the arrival indicated by the *tksm* and the *so* pointers in Figure 2(a,b). The amplitude normalization eliminates amplitude differences of the arrivals we we need for equations 1 and 4 that are not caused by intrinsic losses between the receiver points and the PVC/Al interface. But that does not account for differences in the frequency spectra of the arrivals from the two sources due to propagation through different parts of the medium and thus different loss of the higher frequencies. We equalize the spectra of the arrivals from the two sources by applying the same band-pass filter to them between 110 kHz and 300 kHz. This filter is chosen such that the Rayleigh waves reflected between the PVC/Al interface and the groove from both sources (indicated by the *tnsm*, *dm*, and *do* pointers in Figure 2a,b) will still remain in the filtered result. On the other hand, the filter also aims at suppressing reflected surface waves from the left and right vertical limits of the sample. Such arrivals interfere with the reflected Rayleigh waves from the PVC/Al interface and the groove and might result in erroneous estimation of the Q (using the method we propose, but also the spectral-ratio method) and the reflection coefficient.

As we use a controlled laboratory dataset, we can calculated the expected arrival times of the reflected surface-wave arrivals whose amplitudes we want to use in equations 1 and 4 (and that contribute to the retrieval of ghost reflections). In a field experiment,identification in such a way might not even be possible. But the identification of ghost reflections can be achieved after the autocorrelation of the recordings from each of the sources. Draganov et al. (2013) showed with numerical results that the ghost reflection exhibits a change of polarity when the receiver, at which it is retrieved, crosses the boundary of the layer that causes the ghost to appear. In our case, this is the PVC/Al interface. Once the ghost reflection is recognized in such a way, the amplitudes of the ghost reflections due to each source, and which represent the numerator and denominator in equation 4, can be taken directly from the autocorrelation result and used in equation 4.

In our data, there is still interference from waves that have reflected from the vertical boundaries of the sample. After autocorrelation, such correlated events might fall at the time of the retrieved ghost reflections and interfere with their amplitudes. Because of this, we choose to pick the amplitudes from the measured data. To further suppress arrivals different from the ones indicated by the thin solid and dashed pointers in Figure 2(a,b), we apply frequency-wavenumber fan filter to filter our reflected waves from the left vertical boundary of the sample (to the left of the magenta source in Figure 1). This is followed by muting of all arrivals, but the *tnsm*, *dm*, *so*, and *do* ones. In Figure 3(a,b) we show the result of these two processing steps for the receiver points to the left of the PVC/Al interface, as these measurements are used to estimate Q_{PVC} and $r_{PVC/Al}$.

We pick the amplitudes needed for the calculation of the left-hand sides of equations 1 and 4 from the result in Figure 3(a,b). The derivations suppose plane-wave sources, which is not the case for the physical transducer source. Because of that, we apply a surface-wave geometrical-spreading correction to the picked values. We calculate results for recordings at receiver points distanced from the left-most receiver point by 7.37 mm, 9.91 mm, 12.45 mm, 14.99 mm, and 18.80 mm (corresponding

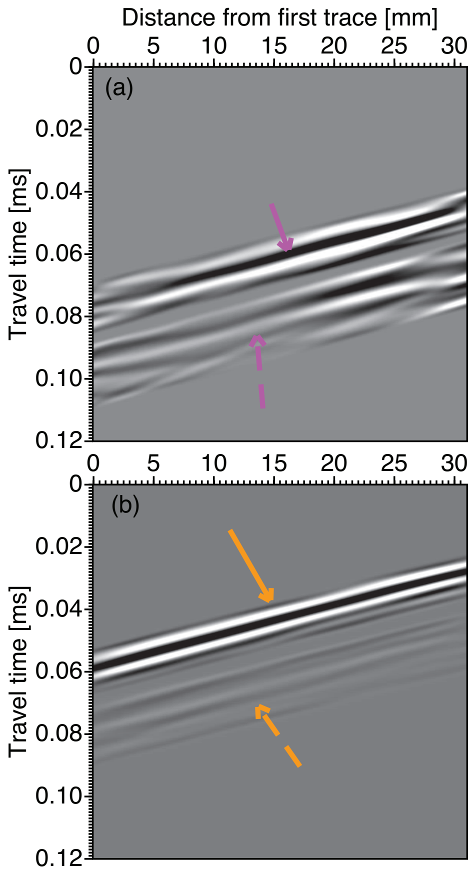

Figure 3: As in Figure 2 but after application of a frequency-wavenumber fan filter and muting showing only the traces to the left of the PVC/Al interface.

to traces 59, 79, 99, 119, and 149). The estimated Q_{PVC} and $r_{PVC/Al}$ are given in the second and third columns in Table 1. In the two bottom rows, we also show the calculated average value and the standard deviation σ. It can be seen that the estimated values for the different traces are close to each other and have little scatter around the average value.

For comparison, we estimate Q_{PVC} at the same receiver points using the spectral-ratio method (e.g., Jannsen et al., 1985; Tonn, 1991). For the estimation, we use the ratio between the reflection from the PVC/Al interface and the direct Rayleigh arrival. Also with this method, we estimate Q_{PVC} after application of the band-pass filtering between 110 kHz and 300 kHz and the frequency-wavenumber filtering that aim to suppress interfering events. It can be seen from the fourth column in Table 1 that the average Q_{PVC} is 13.24, which is about 7 % higher than the average value obtained with the method we propose. In can be seen that the one-σ intervals around the averages from the two methods overlap. The spectral-ratio results show higher scatter around their average value compared to the results from the method we propose.

Trace number	Q_{PVC}	$r_{PVC/Al}$	Q_{PVC} from SR
59	12.47	0.55	14.75
79	13.18	0.52	13.05
99	12.09	0.53	12.78
119	12.06	0.50	13.17
149	11.92	0.48	12.45
average	12.35	0.51	13.24
σ	0.46	0.02	0.79

Table 1: Estimated Q_{PVC} and $r_{PVC/Al}$. The results in the second and the third columns are obtained using the method we propose, while the results in the fourth column are estimated using the spectral-ratio (SR) method. The last two rows show the averages and the standard deviations (σ) of the traces.

Knowing the surface-wave velocities and densities on both sides of the PVC/Al interface, would allow the calculation of the theoretically expected $r_{PVC/Al}$ at the interface. We calculate the Rayleigh-wave velocities from the measured direct arrivals: for the PVC we obtain 990 m/s and for the Al we obtain 2900 m/s. The densities of the PVC and the Al we take from the literature as 1360 kg/m^3 and 2700 kg/m^3, respectively. Using these values, we calculate a theoretical $r_{PVC/Al} = 0.71$. The average value of $r_{PVC/Al} = 0.51$ in Table 1 is lower than the theoretical value, which is an indication that the PVC/Al interface is imperfectly welded. It still needs to be investigated what is the influence of imperfectly welded interfaces on the estimation procedure using equations 1 and 4.

CONCLUSIONS

We propose a method that uses surface waves reflected from subvertical interfaces to estimated the quality factor of the medium between a receiver and one of the interface and the reflection coefficient at the same interface. The method uses surface waves from two transient sources. Using ultrasonic laboratory data, we show how the method can be applied in practice. The data is recorded on a sample consisting of a polyvinyl chloride (PVC) block and an aluminum (Al) block coupled together. The Al block contained a groove, which is parallel to the PVC/Al interface. We use two ratios between direct Rayleigh waves, Rayileigh reflections from the PVC/Al interface and the groove, and an internal Rayleigh reflection between the PVC/Al interface and the groove to estimate the quality factor of the PVC $Q_{PVC} = 12.35$ and the reflection coefficient at the interface $r_{PVC/Al} = 0.51$. The reflection coefficient is smaller than the theoretically calculated value of 0.71, indicating an imperfectly welded interface. For comparison, we estimate $Q_{PVC} = 13.24$ using the spectral-ratio method. The fact that the two estimated Q_{PVC} are very close to each other confirms that our new approach is a viable alternative of the spectral-ratio method.

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