Velocity Dispersion and Attenuation in Vibroseis Data

L. Flora Sun*
University of Toronto, Toronto, ON, Canada
lsun@physics.utoronto.ca

and

Bernd Milkereit
University of Toronto, Toronto, ON, Canada

Summary

Seismic waves in anelastic media experience attenuation and velocity dispersion. In conventional seismic data processing, velocity dispersion is often neglected partially because of insufficient observations on the exploration frequency band. In a medium of high attenuation, however, velocity dispersion is a concern. In order to detect velocity dispersion in the exploration seismic frequency band, a new signal processing method for uncorrelated Vibroseis data, cross-correlation with a moving window, has been developed. This method was applied to uncorrelated Vibroseis data from areas with different geological settings. The detected velocity dispersion, with the Kramers-Krönig relation, provides a new way to calculate the quality factor Q, which can be compared to those obtained from the spectral ratio method.

Introduction

Seismic waves in anelastic media experience attenuation and velocity dispersion from various energy absorbing mechanisms. The frequency dependence of attenuation and velocity depend on rock conditions, such as saturation, porosity, and pressure. Attenuation and velocity dispersion are linked by the Kramers-Krönig relation (Bourbié et al., 1987):

$$M_R(\omega) = M_0 + \frac{2\omega^2}{\pi}\int_0^\infty \frac{M_I(\alpha)}{\alpha}\frac{d\alpha}{\omega^2-\alpha}$$

$$M_I(\omega) = \frac{2}{\pi}\int_0^\infty \left(M_R(\alpha)-M_0\right)\frac{\omega d\alpha}{\alpha^2-\omega^2}$$

where M_R and M_I are the real and imaginary parts of the complex modulus M, respectively, and M_0=$M_R(0)$. The velocity and the quality factor Q are given by:

$$V(\omega) = \frac{\omega}{\omega_0}\sqrt{\frac{2\,|M(\omega)|^2}{\rho\left(|M(\omega)|+M_R(\omega)\right)}}, \quad \text{and} \quad Q(\omega) = \frac{M_R(\omega)}{M_I(\omega)}, \quad \text{respectively.}$$

For example, frequency-independent Q ("constant Q") is related to seismic velocity increasing linearly with log frequency ("linear dispersion"):

$$\frac{V(\omega)}{V(\omega_0)} = 1 + \frac{1}{\pi Q} \ln \frac{\omega}{\omega_0} \quad (1)$$

In general, a smaller Q is related to stronger velocity dispersion. In a medium with $Q < 30$, velocity dispersion is not negligible in the seismic frequency band (Molyneux and Schmitt, 1999). However, conventional seismic data processing often neglects velocity dispersion, because measurements of velocity dispersion in the seismic frequency band are difficult to obtain. Therefore, a robust method needs to be developed to detect velocity dispersion in exploration seismic data.

It is known that attenuation alters the power spectrum, while velocity dispersion changes the phase spectrum. Uncorrelated Vibroseis data are therefore appropriate for measuring attenuation and velocity dispersion in the exploration seismic frequency band. Broadband, long-baseline data are desirable to optimize measurements of small velocity dispersion. As for data acquisition geometry, VSP data are preferred because transmission seismograms are often easier to analyze than reflective (surface) seismograms.

The effect of velocity dispersion in uncorrelated Vibroseis data is similar to the Doppler Effect in marine Vibroseis surveys (Dragoset, 1988). Without velocity dispersion, the time-frequency (t-f) relation of the received sweep is parallel to that of the source sweep. When velocity dispersion exists, slope of the t-f relation of the received sweep deviates mildly from that of the source sweep. Once the velocity dispersion is determined, a data correction method similar to that for the Doppler Effect can be applied to the seismic data for better seismic imaging.

Furthermore, estimates of velocity dispersion offer an alternative way to determine Q values, through the Kramers-Krönig relation. These estimates can be compared to Q estimates from the spectral ratio method (Tonn, 1991).

Methodology

Different approaches to measuring velocity dispersion have been investigated. A time-domain method, crosscorrelation with a moving window (CCMW), has been found to be the most robust for field data (Sun and Milkereit, 2006). The key procedure of detecting velocity dispersion in uncorrelated Vibroseis data is to precisely determine the t-f relation of the received sweep. Conventional frequency-domain t-f decomposition (Castagna and Sun, 2006) does not produce a t-f relation of sufficient precision. The CCMW method conducts t-f decomposition by crosscorrelating the received sweep with a portion of the source sweep centered at a certain frequency. In this way, the arrival time of that frequency can be determined with great accuracy.

Usually, multiple events exist in a received Vibroseis sweep, and can be separated clearly in the t-f spectrum. Figure 1 shows the t-f spectra of uncorrelated Vibroseis sweeps from the Mallik 3L-38 gas hydrate research well in Mackenzie Delta, NWT, Canada (Dallimore et al., 2005). In the t-f spectrum of the received sweep, the bright diagonal stripe is the direct wave, and the later-arriving reflections appear above, and generally parallel to the direct wave. The events below the direct wave are source-generated harmonics. The stationary noise appears as vertical stripes, and random noise may also be in the background. Here we only measure velocity dispersion in the direct downgoing wave in VSP data.

If the velocity increases roughly linearly with log frequency, a constant Q value can be calculated using Equation 1. In the following text, we will use Q_{kk} for the Q estimate from the Kramers-Krönig relation (Equation 1), and Q_{sr} for the Q estimate from the spectral ratio method.

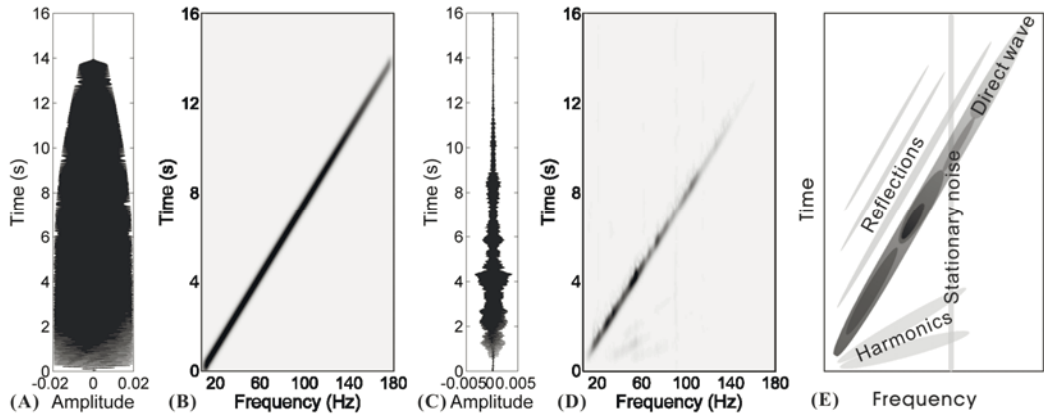

Figure 1. The principle of detecting velocity dispersion in uncorrelated Vibroseis data. A, the waveform and B, the t-f spectrum of the source sweep; C, the waveform and D, the t-f spectrum of the received sweep. E, a sketch of the events in D. The gray scale in B and D is amplitude. The data in A to D are from the Mallik 3L-38 well.

Example 1: Raw Vibroseis VSP Data from Mallik 3L-38 Well

The Mallik 3L-38 well is in the Mackenzie Delta, a highly attenuating and scattering area due to permafrost, water-saturated sediments, and gas hydrates. The CCMW method was applied to the raw Vibroseis VSP data obtained in this well. The source sweep was 14 s long, 8–180 or 8–120 Hz, with a sampling rate of 2 ms. The high data quality enabled automatic arrival picking at each frequency. Frequency dependence of the velocity is systematic. In general, velocity increases with frequency. This is the so-called "linear dispersion", and is related to the background constant-Q attenuation. In addition to this trend, there are superimposed perturbations changing gradually with depth and offset. These perturbations are probably a result of strong scattering in the permafrost, but need further investigation. Figure 2 shows the linear dispersion of the direct downgoing waves in the zero-offset traces at depths 560–1145 m, and the main lithologies at the survey site. Figure 3 compares Q_{kk} and Q_{sr} of the direct waves in these traces. The velocity and Q estimates in Figures 2 and 3 are average values from the surface source location to the receivers in the borehole.

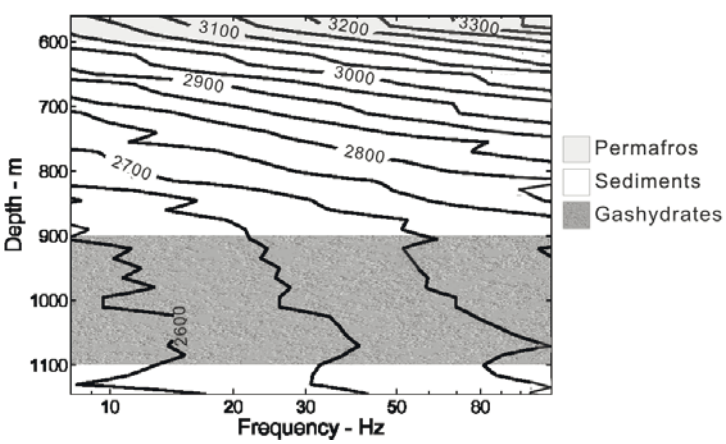

Figure 2. Contour map of velocity dispersion in the Vibroseis data from the Mallik 3L-38 well, superimposed are the main lithologies. The numbers on the contours are average velocity (in m/s) from the surface to the borehole receivers.

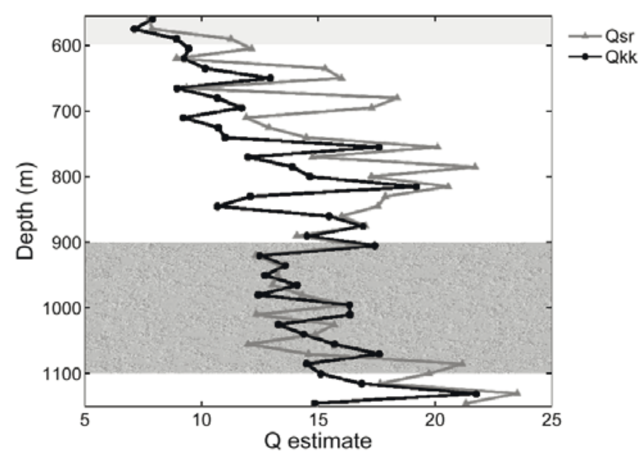

Figure 3. Average Qsr (grey line with triangles) and Qkk (black line with dots) calculated from the velocity dispersion shown in Fig. 2. Lithologies as in Fig. 2.

Example 2: Raw Vibroseis Data from McArthur River Mine Borehole MAC-218

The McArthur River mine borehole MAC-218 is in the Athabasca Basin, Saskatchewan, Canada (White et al., 2003). This area is mostly fractured metamorphosed sediments. The CCMW method was applied to the Vibroseis data from this borehole. The source sweep was 12 or 8 s long, 20–300 or 20–200 Hz, with a sampling rate of 0.5 ms. Arrivals were manually picked at control frequencies, followed by interpolation. Figure 4 shows the first 0.2 s of the vertical component of the correlated VSP, at an offset of 27 m, with a notch filter at 60 Hz and a lowpass filtered at 350 Hz. Figure 5 shows the spectral ratio of the first break in the trace at 347.5 m (as marked in Figure 4), to the source signal. The Q_{sr} was 18 on the 50–280 Hz band. Figure 6 shows the velocity dispersion of the direct downgoing wave in the raw data of the same trace. Arrival picking was conducted up to 160 Hz, due to the low signal-to-noise ratio at higher frequencies. The Q_{kk} was 9 on 50–160 Hz band.

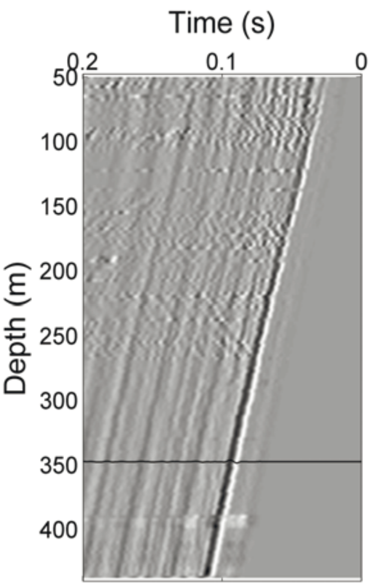

Figure 4. (left) The first 0.2 s of the vertical component of the correlated Vibroseis VSP (filtered and muted) from McArthur River mine borehole MAC-218, 27 m offset.

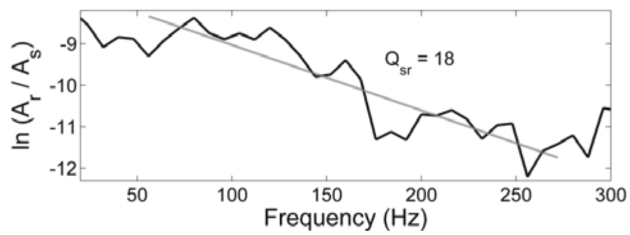

Figure 5. (above) Spectral ratio of the first break of the Vibroseis trace marked by a curve in Fig. 4. The straight line shows the linear fit in the 50–280 Hz band.

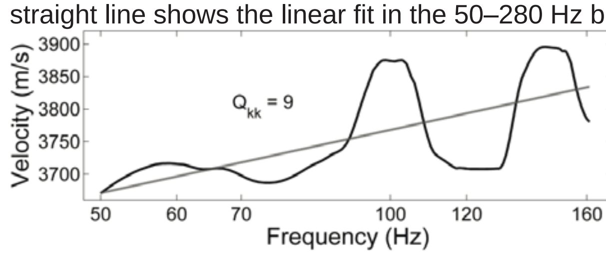

Figure 6. (right) Velocity dispersion of the first break in the raw data of the trace marked in Fig. 4. The straight line shows the linear fit in 50–160 Hz band.

Conclusion and outlook

Using uncorrelated Vibroseis data, velocity dispersion can be accurately measured with the CCMW method. This provides a new method to estimate Q, using the Kramers-Krönig relation.

Attenuation and velocity dispersion are significant for seismic data processing and interpretation. As the next stage of our research, the observed attenuation and velocity dispersion will be interpreted by fitting them into various petrophysical models. For Vibroseis deconvolution, a robust method to correct the waveform distortion due to attenuation and velocity dispersion will be developed.

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