Estimation of Q: a comparison of different computational methods

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Summary

In this article, four methods of Q estimation are investigated: the spectral-ratio method, a match-technique method, a spectrum modeling method and a time-domain match-filter method. Their accuracy and the reliability of Q estimation are evaluated using synthetic data and real VSP data. Testing results demonstrate that the time-domain match-filter method is more robust to noise and more suitable for application to reflection data than other three methods.

Introduction

The knowledge of Q is very desirable. There are various methods for Q estimation. However, the estimation results are usually sensitive to noise. Cheng and Margrave (2012) proposed a time-domain match-filter method for Q estimation, which was shown to be robust to noise and suitable for application to surface reflection data. Theoretically, the match-filter method is a sophisticated wavelet-modeling method, which is a time-domain alternative to spectrum-modeling method (Janssen et al., 1985; Tonn, 1991; Blias, 2011). The spectrum-modeling method is a modified approach to the spectral-ratio method without taking division of spectra. In addition, the match-filter method and the match-technique method (Raikes and White, 1984; Tonn, 1991) employ the idea of matching at different stages of their Q-estimation procedures. Therefore, the above four methods all have theoretical connections but are distinctly different. It is worthwhile to make a comparison between these methods in terms of their underlying theory, accuracy and reliability of estimation results. The purpose of our work is to investigate the four different methods for Q estimation, the classic spectral ratio method, spectrum-modeling method, match-technique method and match-filter method.

Theory of Q estimation methods

Suppose that $\mathrm{a}_1(t)$ and $\mathrm{a}_2(t)$ are the two local wavelets near time t_1 and t_2 in a seismic record respectively. $|\mathrm{A}_1(f)|$ and $|\mathrm{A}_2(f)|$ are the corresponding amplitude spectra of the local wavelets. For the spectral-ratio method, the logarithmic spectral ratios of the amplitude spectra are computed. Then Q can be estimated by fitting a straight line to the calculated spectral ratios over a chosen frequency band. The spectrum modeling method compares the amplitude spectra of the local wavelets directly. Optimal Q is obtained through such a way that $|\mathrm{A}_1(f)|$ is modified by varying Q until an optimum approximation to $|\mathrm{A}_2(f)|$ is obtained.

Raikes and White (1984) proposed a match technique for Q estimation. By matching the two local wavelets, the forward filter $\mathrm{h}_{12}(\mathrm{t})$ is estimated by predicting $\mathrm{a}_2(\mathrm{t})$ from $\mathrm{a}_1(\mathrm{t})$. Similarly, a backward filter $\mathrm{h}_{21}(\mathrm{t})$ can be obtained by predicting $\mathrm{a}_1(\mathrm{t})$ from $\mathrm{a}_2(\mathrm{t})$. Then, the transfer functions $\mathrm{H}_{12}(\mathrm{f})$ and $\mathrm{H}_{21}(\mathrm{f})$ can be computed from $\mathrm{h}_{12}(\mathrm{t})$ and $\mathrm{h}_{21}(\mathrm{t})$ by taking Fourier transform. Following that, the power spectral ratios over a specific frequency band are estimated from the geometric mean value of $|\mathrm{H}_{12}(\mathrm{f})|^2$ and $|\mathrm{H}_{21}(\mathrm{f})|^{-2}$. Finally, Q is estimated from the logarithmic power spectral ratios. Generally, the match-technique method described here can be regarded as a spectral-ratio method with spectrum estimation using matching techniques.

Cheng and Margrave (2012) proposed a match-filter method, which is conducted in three stages. First the smoothed amplitude spectra of the local wavelets are computed. Thom son (1982) proposed a multitaper method for smooth, high resolution spectral estimation, which has been shown to provide low-variance estimation with less spectral leakage when applied to seismic data (Park et al., 1987; Neep et al., 1996). Then, the minimum-phase equivalent wavelets (embedded wavelets) $\mathrm{w}_1(\mathrm{t})$ and $\mathrm{w}_2(\mathrm{t})$ can be computed from smoothed amplitude spectra. Finally, Q can be estimated by finding the best forward Q filter that best matches the shallow wavelet to the deeper wavelet, which can be formulated as

$$\mathrm{Q}_{\mathrm{est}} = min_Q \|\mathrm{w}_1(\mathrm{t}) * \mathrm{I}(\mathrm{Q},\mathrm{t}) - \mu \mathrm{w}_2(\mathrm{t})\|^2,$$

where $*$ denotes convolution, the minimization is taken over the range of possible Q values; $\mathrm{I}(\mathrm{Q},\mathrm{t})$ is the impulse response corresponding to the attenuation function with a quality factor value Q and travel time $(t_2 - t_1)$ and can be formulated as

$$\mathrm{I}(\mathrm{Q},\mathrm{t}) = F^{-1}(\exp\left(\frac{-\pi f(t_2-t_1)}{Q} - \mathrm{iH}(\frac{\pi f(t_2-t_1)}{Q})\right)),$$

where H denotes the Hilbert transform, F is the Fourier transform, and μ is a constant scaling factor and can be calculated as

$$\mu = \frac{\int_{-\infty}^{\infty}(\mathrm{w}_1(\mathrm{t})*\mathrm{I}(\mathrm{Q},\mathrm{t}))\,\mathrm{w}_2(\mathrm{t})\mathrm{dt}}{\int_{-\infty}^{\infty}\mathrm{w}_2{}^2(\mathrm{t})\mathrm{dt}}.$$

The spectral-ratio method, spectrum-modeling method and match-technique method are frequency-domain methods. All of them need to define a frequency range where signal dominates for better estimation. For the implementation of these three methods in this paper, the frequency band is given manually as an input parameter. Compared to spectral-ratio method and match-technique method, the match-filter method avoids spectral division. Compared to the spectrum-modeling method, the match-filter method matches the spectra in the time domain. In this paper, the performance of these four methods will be evaluated by synthetic data and real VSP data.

Examples

First, synthetic VSP data are used to evaluate the four methods, which can be regarded as reflection data with isolated reflectors. A synthetic attenuated seismic trace was created by a nons tationary convolution model proposed by Margrave (1998), using two isolated reflectors, a constant Q value of 80 and signal to noise ratio (SNR) of 4, as shown in figure 1. So, the two events can be used for Q estimation. To make a more general comparison of performance for the four estimation methods in presence of noise, 200 seismic traces are created by adding 200 different random noise series of the same level (SNR=4), which are similar to the trace shown in figure 1. Then Q estimation is conducted using these noisy data. The histograms of the estimated Q values are shown in figure 2 - 5. We can see that results of match-filter method have the best results with the closest mean value of 80.79 and the smallest standard deviation of 7.07. The results of other three methods are comparable to one another.

Then, synthetic reflection data is used to evaluate the four methods. Figure 6 shows a synthetic seismic trace is created using a random reflectivity series, a constant Q of 80. Then, 200 attenuated seismic traces are created using 200 different random reflectivity series with SNR=4 , from which 200 pairs of local reflected waves (100ms-500ms, 900ms-1300ms) are obtained to conduct the Q estimation experiment using the four Q estimations. The results are shown in figure 7 - 10. We can see that the match-filter method gives a good result with the closest mean value of 83.14 and the smallest standard deviation of 17.41, while other three methods give unreliable results with significantly deviated mean values and large standard deviation values.

Finally, real VSP data is used to test the Q estimation methods. Figure 11 shows field zero-offset P-wave VSP d ata after up-going wave suppression. With a fixed trace interval of 100, 230 pairs of windowed VSP traces shown in figure 54 are chosen for Q estimation, of which the first pair are the VSP trace 101 and trace 201 and the last pair are VSP trace 330 and trace 430. The results are shown in figure 12. We can see that the estimation results are similar and have the same trend of variations in most cases, while match-filter method and s pectrum-modeling method gives more stable results in some cases. Then, 80 pairs of windowed VSP traces with fixed trace interval of 250 are used to investigated the four methods, of which the first pair are the VSP trace 101 and trace 351 and the last pair are VSP trace 180 and trace 430. The results for Q estimation are shown in figure 13. With a larger trace interval (travel-time difference), the attenuation between the two trace becomes more measurable. We can see that the results of spectral-ratio method and match-technique method are more stable, and the four methods give more consistent estimation.

Conclusions

The relative performances of spectral-ratio method, spectrum-modeling method, match-technique method and match-filter method are evaluated in this paper. Testing on synthetic seismic traces shows that the match-filter method, compared to the classic spectral-ratio method, is robust to noise and more suitable to be applied to reflection data. Testing on real VSP data shows that match-filter method and spectrum-modeling method are more stable compared to spectral-ratio method and match-technique method, since no spectral division is involved in their algorithms, and all the four methods can obtain similar results at most cases when VSP data with high SNR is used for Q estimation.

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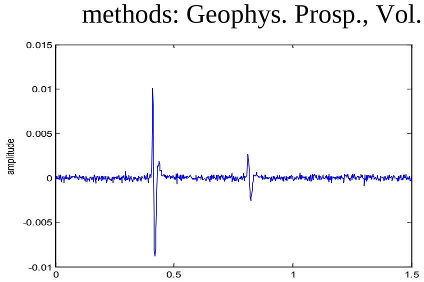

Figure 1. Synthetic attenuated seismic trace created with two isolated events (Q=80, SNR=4)

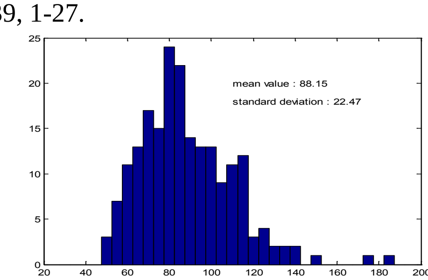

Figure 2. Histogram of estimated Q values by the spectral ratio method using 200 synthetic seismic traces with isolated events (SNR=4).

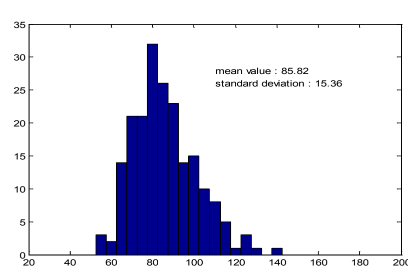

Figure 3. Histogram of estimated Q values by spectrum-modeling method using 200 synthetic seismic traces with isolated events (SNR=4).

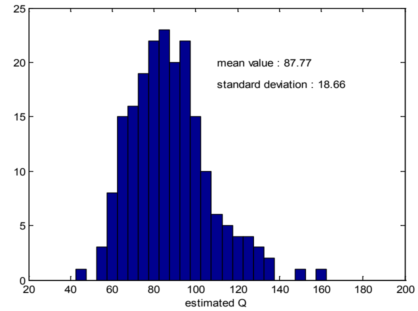

Figure 4. Histogram of estimated Q values by match-technique method using 200 synthetic seismic traces with isolated events (SNR=4).

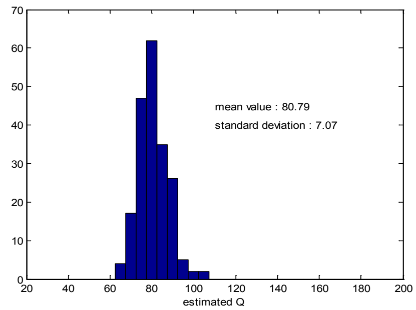

Figure 5. Histogram of estimated Q values by match-filter method using 200 synthetic seismic traces with isolated events (SNR=4).

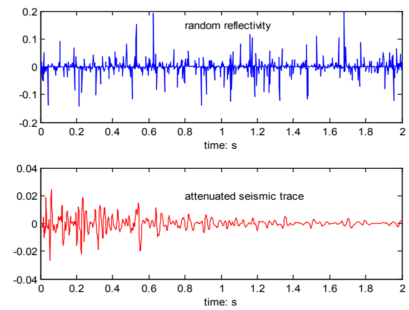

Figure 6. Synthetic attenuated seismic trace created using random reflectivity (Q=80).

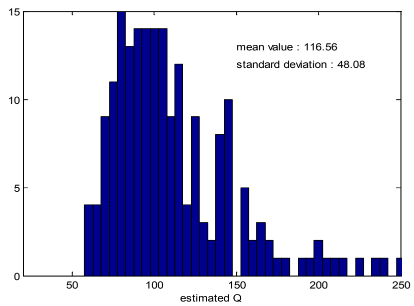

Figure 7. Histogram of estimated Q values by the spectral ratio method using 200 synthetic seismic traces (SNR=4).

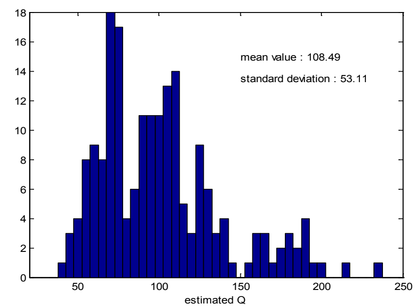

Figure 8. Histogram of estimated Q values by spectrum-modeling method using 200 synthetic seismic traces (SNR=4).

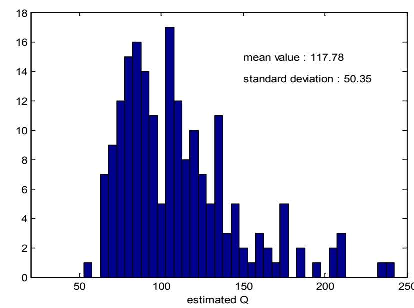

Figure 9. Histogram of estimated Q values by match-technique method using 200 synthetic seismic traces (SNR=4).

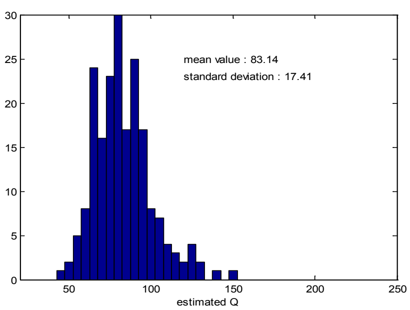

Figure 10. Histogram of estimated Q values by match-filter method using 200 synthetic seismic traces (SNR=4).

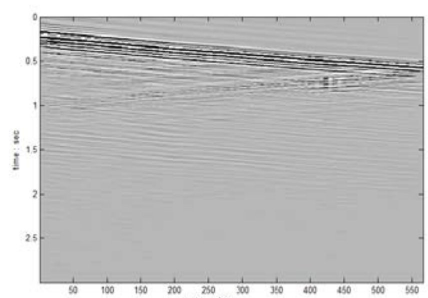

Figure 11. real VSP data with up-going wave suppression.

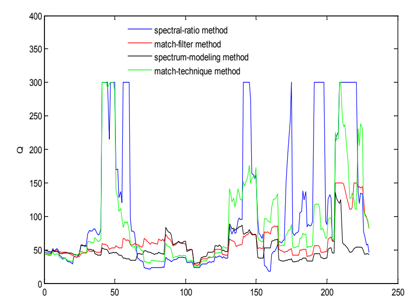

Figure 12. Q estimation using 230 pairs of VSP traces shown in figure 11 with fixed trace interval of 100.

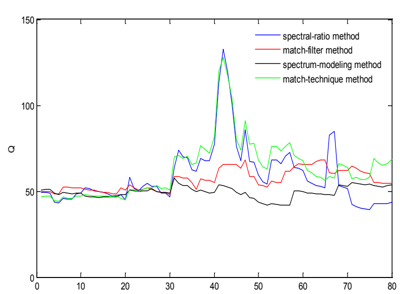

Figure 13. Q estimation using 230 pairs of VSP traces shown in figure 11 with fixed trace interval of 250.