

Q Determination, Corner Frequency and Spectral Characteristics of Microseismicity Induced by Hydraulic Fracturing

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Summary

Simple models of fault displacement yield acceleration and displacement spectra from which seismic moment and corner frequency can be determined. The classic Brune model is used here to predict the shape of the source spectrum and to provide scaling relationships between spectral and source parameters. In order to obtain reliable estimates of the source spectrum, the effects of attenuation need to be estimated and corrected. In this preliminary study, $Q_P = 25 \pm 7$ and $Q_S = 22.5 \pm 10$ are obtained by applying the spectral-ratio method to a selected set of 10 microseismic events with high signal-to-noise ratio. The Brune model is then fit to several observed S waveforms, yielding source parameters that depend strongly on the geophone sensitivity, instrument gain and Q . More work is needed to reduce uncertainty in these estimates, but these initial results show promise for spectral characterization of microseismic events. The attenuation considerations in this work provide potentially useful constraints for predicting magnitude detection distance relations and suggest that, even neglecting near surface attenuation, only low-frequency (~ 50 Hz) P waves could be observed at propagation distances of ~ 3 km required for surface monitoring.

Introduction

The spatial dimensions of a microseismic event are subtly encoded in the spectral characteristics of the radiated seismic waves. Intuitively, we expect events with a relatively large magnitude to emit elastic waves that are enriched in low-frequency components - and vice versa. Simple models, such as the classic Brune model (Brune 1970, 1971) for slip on a circular crack, predict the shape of the source spectrum and provide scaling relationships between spectral parameters (corner frequency, low-frequency plateau) and source parameters (slip area and seismic moment). If these models are truly representative of physical rupture processes, constraints on rupture dimensions derived from spectral analysis of radiated seismic waves could provide valuable insights for geomechanical characterization of induced microseismicity. Indeed, for source characterization using typical narrow-aperture recording geometries, spectral analysis is potentially more robust than other approaches such as moment-tensor inversion. The spectral characteristics of recorded seismic waves, however, are strongly influenced by path effects from the hypocenter to the geophone. In order to obtain reliable estimates of the source spectrum, the attenuation properties of the medium (most simply represented using the quality factor, Q) are therefore needed.

This paper explores the feasibility of extracting reliable spectral parameters from microseismic data acquired for hydraulic fracture monitoring (HFM). Waveform examples of microseismic events from raw field data are analyzed to estimate attenuation parameters (Q_P and Q_S) using the spectral-ratio method. Brune source parameters are then estimated for the data by fitting model spectra to computed displacement

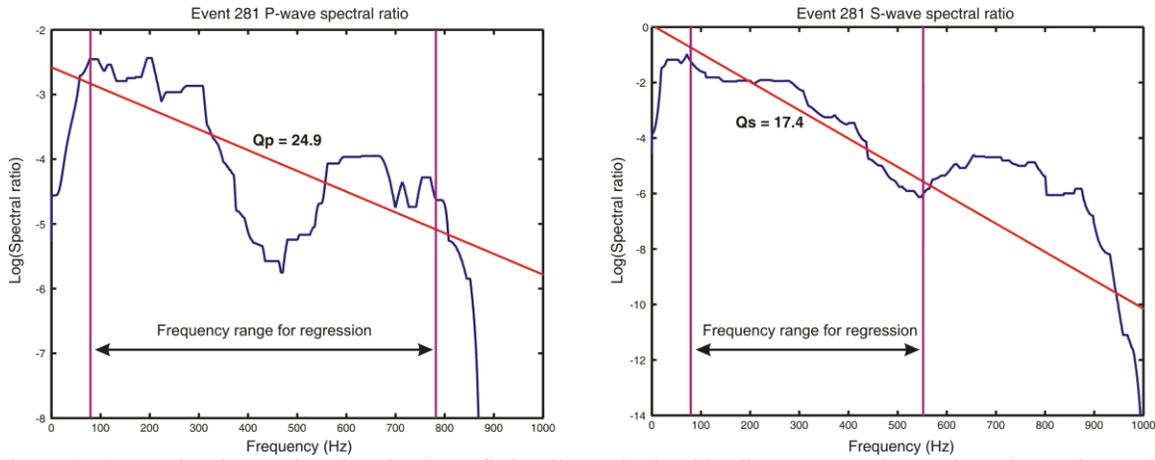


Figure 1: Spectral ratio graphs, showing best-fitting lines obtained by linear regression and used to estimate Q .

and acceleration spectra. Finally, the expected consequences for magnitude-detection threshold are considered.

Theory

Attenuation (Q) can be estimated from microseismic data using an approach similar to VSP (e.g., Xu and Stewart, 2006). Microseismic events were selected for analysis based on signal-to-noise ratio (SNR). Qualitatively, the effects of Q are apparent in the raw data – i.e., the pulse changes and broadens with increasing distance from the source. For a given wave type (P or S) recorded on two downhole receivers, the ratio of spectral amplitudes is given by:

$$\frac{|A_1(\omega)|}{|A_2(\omega)|} = e^{-\frac{|\omega|}{2Q}(t_2-t_1)}, \quad (1)$$

where t_1 and t_2 are the arrival times and $Q = Q_P$ or Q_S is assumed to be independent of frequency. As illustrated in Figure 1, after taking the ratio of the amplitude spectra, the slope of the best fitting straight line on a log-log plot versus frequency can be used to measure Q (Xu and Stewart, 2006).

A simple model for displacement on a fault during an earthquake is given by

$$d(t) = D \left[1 - (1 + t/\tau) e^{-t/\tau} \right], \quad (2)$$

where D is the net displacement and τ is called the rise-time parameter. The far-field acceleration spectrum of elastic waves radiated from such a source is (Beresnev, 2001)

$$a(\omega) = \frac{M_0 \omega^2}{1 + \left(\frac{\omega}{\omega_c} \right)^2}, \quad (3)$$

where \sim denotes the Fourier transform, $\omega = 2\pi f$ and $\omega_c \equiv 1/\tau$ is called the corner frequency. The corresponding displacement spectrum is given by

$$\bar{d}(\omega) = \frac{M_0}{1 + \left(\frac{\omega}{\omega_c}\right)^2} \quad (4)$$

Equations (3) and (4) imply that

$$\lim_{\omega \rightarrow \infty} a = M_0 \omega_c \quad (5)$$

and

$$\lim_{\omega \rightarrow 0} \bar{d} = M_0 \quad (6)$$

Finally, the source radius is given by

$$R \approx 2.34 \frac{V_s}{\omega_c} \quad (7)$$

where V_s is the shear-wave velocity of the medium. This relation assumes that after nucleation the rupture front propagates across the crack at velocity V_s . The source radius provides a crude estimate of the characteristic rupture size, although caution is required in the interpretation of this parameter (Beresnev, 2001).

Examples

Brune source parameters were determined for a selected set of microseismic events using a model-fitting approach. The procedure to estimate the parameters was:

1. Compute the spectrum from the raw unfiltered data by applying a Gaussian window and taking the Fourier transform. The spectrum is then scaled by a factor that accounts for the sensitivity of the recording system.
2. Correct the spectrum for the effects of Q based on equation 1.
3. Since geophones measure particle velocity, the spectrum obtained in step 1 is the velocity spectrum. The velocity spectrum is transformed to a displacement spectrum by dividing by the parameter $i\omega$. Similarly, the velocity spectrum is transformed to acceleration by multiplying by the factor $i\omega$.
4. Estimate the low-frequency asymptotic limit of the displacement spectrum (eq. 6) by calculating the average value within a user-selected range of frequencies.
5. Estimate the high-frequency asymptotic limit of the acceleration spectrum (eq. 5) by calculating the average value within a user-selected range of frequencies.
6. Calculate the Brune parameters (M_0 and corner frequency) and overlay the computed Brune spectra for displacement and acceleration onto the observed spectra. Adjust the Brune parameters if needed until an acceptable fit is obtained.

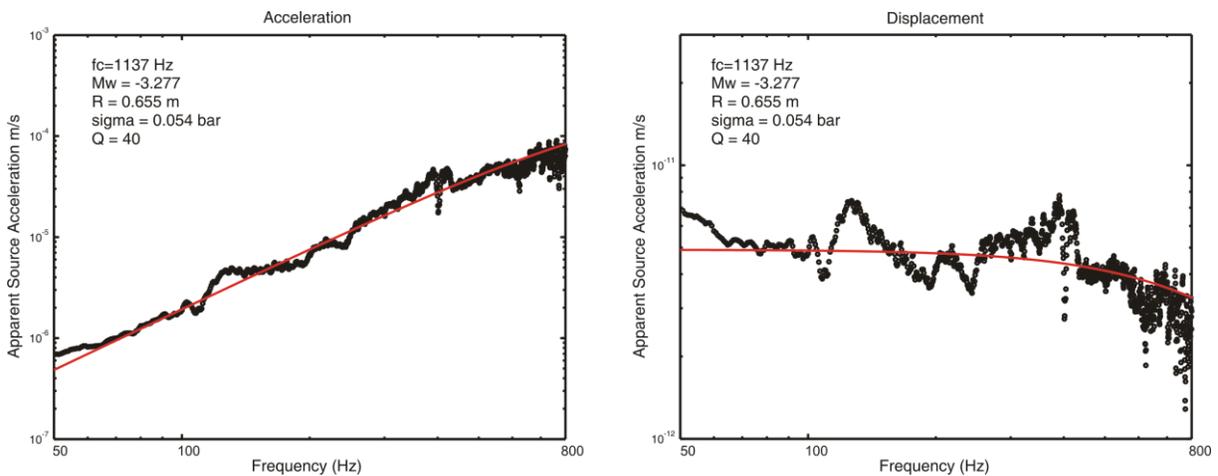


Figure 2: Acceleration (left) and displacement (right) spectra for a high SNR S wave from a microseismic event, showing interpreted Brune parameters (corner frequency, moment magnitude, source radius and stress drop).

Figure 2 shows an example of a spectrum for a S wave generated by a microseismic event. It was determined (by trial and error) that the Q estimates obtained using the spectral-ratio approach are incompatible with the Brune fitting procedure – a slight increase in Q to 40 is required to achieve a satisfactory fit to the spectrum. The inferred Brune source radius for this event is 0.655 m, which provides a crude estimate of the fracture length associated with this event.

Conclusions

The Brune source model provides a potential means to calculate source parameters for microseismic events, including spatial scale (Brune source radius). In order to obtain reliable results, however, careful corrections need to be applied for attenuation along the path from the source to receiver. In this preliminary study, Q values of 25 ± 7 (P waves) and 22.5 ± 10 were obtained by applying the spectral-ratio method to a selected set of 10 high SNR microseismic events. The Brune model was then fit to several observed S waveforms, yielding source parameters that depend strongly on the assumed scaling and Q . More work is needed to reduce uncertainty in these estimates, but the initial results show promise that this might be a useful approach to characterize the spectral properties of events. The attenuation considerations in this work also provide potentially useful constraints for predicting magnitude-detection distance.

Acknowledgements

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