High-Frequency Resonances in Borehole Geophones Bias Source Parameters of Induced Seismicity at Preston New Road, UK

Introduction

The high-frequency content of seismic events contains important information about their rupture process and source properties. However, instrument limitations at high frequencies can sometimes interfere with the signal, producing biased and misleading results. The smaller the event, the higher the frequency band of interest required. Thus, for microseismic events (magnitude < 2), accurate source analysis hinges on the instrument’s ability to record high-frequency signal without interference. During hydraulic fracturing operations, microseismic monitoring is commonly conducted by an array of geophones deployed in a nearby monitoring borehole. While close proximity of the geophones to injection provides the unparalleled low signal-to-noise ratio (SNR) required to detect microseismic events, geophones are also known for issues with resonances due to spurious frequencies, tube waves, and clamping (e.g., Faber and Maxwell, 1997; St-Onge and Eaton, 2011). Moment magnitude ($M_w$) and corner frequency ($f_c$), two important earthquake source parameters, depend on the shape of the frequency spectrum and are thus easily affected by geophone resonances. Accurate $M_w$ estimates relay the amount of energy released by earthquakes and are necessary for reliable $b$-values, a parameter used by hydraulic fracturing operators to evaluate real-time seismic hazard. Corner frequency is equally valuable as it is used to compute stress drop ($\Delta\sigma$). The stress drop contains information about the size of the rupture, which is used both by geomechanical modelers to evaluate the evolution of fracture growth and in seismic hazard analysis to evaluate the ground motions expected at the surface.

In this study, we analyse earthquake source parameters of induced microseismic data from the 2018 hydraulic fracturing operations at Preston New Road (PNR), UK. We examine how traditional earthquake source analysis procedures are affected by resonances in borehole geophones and discuss the implications this might have for hazard assessments.

Resonances Observed in the Preston New Road Dataset

The PNR microseismic dataset consists of an impressive 36,000+ events down to local magnitude -4, recorded on 24 three-component 15 Hz borehole geophones deployed in a nearby well. The geophone sensors sampled at 2000 Hz, producing useable frequency content up to 800-900 Hz after taking the Nyquist frequency and instrument anti-aliasing filters into consideration. While this frequency bandwidth should have been ideal for analysing microseismicity down to $M_w$ -2, the high-frequency content was contaminated by “bumps” from different types of resonance sources.

![Figure 1](image_url)  
*Figure 1 Example of resonances observed in the high-frequency seismic event spectrum. Three time windows are shown. Top left: pre-event noise. Top middle: window containing the main S-wave energy. Top right: Coda-wave window after the main earthquake energy has passed. Resonance peaks at 220 Hz and 365 Hz are seen both in the S- and coda-wave windows. Bottom: time series of the event with colour coded windows for the respective spectra highlighted.*
Figure 1 shows an example of the bumps. Interestingly, the quiescent, pre-event periods did not reveal any specific frequencies resonating except a 50 Hz electrical noise at times. However, during strong particle motion caused by a microseismic event, different resonance frequencies were excited. These resonance frequencies were constant throughout the acquisition period but appeared at different frequencies for different components and stations. The second component at station 4 is shown in Figure 1, where two main frequencies at 220 Hz and 365 Hz are excited and persist even after the main energy has passed through. The manufacturer of these particular sensors noted spurious frequencies above 365 Hz caused by resonance in the internal sensor components (Faber and Maxwell, 1997). This is likely the cause of the 365 Hz bump in Figure 1. Other common sources of geophone noise include tube waves travelling along the tube casing (e.g., Sun and McMechan, 1988), clamping issues in the locking arm resulting in bad coupling between the geophone and borehole casing (e.g., Gaiser et al., 1988, Yaskevich et al., 2019), and resonance in the borehole between clamped geophones (St-Onge and Eaton, 2011).

Source Analysis

An earthquake is generally described as a convolution of its source, path, and site terms. Thus, to retrieve the source parameters moment magnitude and corner frequency, the path and site terms have to first be accounted for. Traditionally, this is done by fitting the earthquake’s displacement Fourier spectrum to the Brune (1970) model. In the Brune model, a low-frequency plateau related to the moment magnitude transitions into a high-frequency fall-off slope, where the transition between the plateau and slope is known as the corner frequency, $f_c$. Mathematically, the displacement spectrum $\Omega(f)$ is described by:

$$\Omega(f) = \Omega_0 (1 + (f/f_c)^{2\gamma})^{-1/\gamma} \exp(-\pi ft/Q)$$  \hspace{1cm} (1)

where $f$ is frequency, $\Omega_0$ is the low-frequency plateau, $\gamma$ is a constant describing the shape of the spectrum, $t$ is the earthquake travel time, and $Q$ is the attenuation Quality factor. We refer to fitting the Brune model to an earthquake’s spectrum as single event fitting. One disadvantage of single event fitting is that it requires prior knowledge of $Q$. Due to the trade-off between $f_c$ and $Q$, any assumption made on the value of $Q$ will translate back into the estimated $f_c$.

A popular alternative procedure to retrieve source parameters is the spectral ratio method (e.g., Abercrombie, 2015). To avoid assumptions about the earthquake’s propagation effects, the spectral ratio method uses a smaller, collocated event as an empirical Green’s function (EGF), assuming that it shares the same path and site terms as the earthquake of interest. In practice, the procedure takes the ratio between the large and small earthquakes’ Brune models, effectively cancelling out the $Q$ term and any other path and site effects. This is useful in the case of borehole data, where resonance frequencies are introduced at the site by geophones and difficult to describe mathematically. Figure 2 illustrates the

![Figure 2](image-url)  \hspace{1cm} Figure 2 Two common methods to retrieve corner frequency ($f_c$). Left: illustration of an earthquake (large, blue star) and an EGF (small, red star) on a fault and its raypath to a station (triangle). Middle: single event fitting applied to the earthquake’s displacement spectrum (solid, blue line), with the resultant best-fit model (dashed line) and $f_c$ (inverted, blue triangle) highlighted. Right: example of spectral ratio fitting, where the earthquake’s spectrum is divided by the EGF’s spectrum (solid, red line), resulting in the spectral ratio (solid, purple line). Best-fit model and its $f_c$ (inverted, purple triangle) and the $f_c$ from single event fitting are highlighted.
single event and spectral ratio fitting methods. The single event procedure is highly sensitive to any bumps in the spectrum, such as those caused by resonating geophones. On the other hand, in the spectral ratio method, the bumps can cancel out because they are also present in the EGF spectrum. The spectral ratio method tends to produce slightly higher corner frequencies than the single event method, commonly interpreted as better removal of propagation effects (e.g., Ide et al., 2003).

While corner frequencies from the spectral ratio method are usually viewed as more accurate, there are disadvantages. For example, the method requires available EGF earthquakes. Strict criteria are generally applied to find EGFs, such as high cross-correlation coefficients, a minimum magnitude difference, and an acceptable SNR. Together, these criteria limit the number of earthquakes that can act as target earthquakes. Thus, while single event fitting can be applied to any earthquake with sufficient SNR, the spectral ratio method can only be applied to the larger earthquakes in a catalogue. Single event fitting also has the advantage of being quicker and is thus often used by hydraulic fracturing operators. We apply both single event and spectral ratio fitting to the PNR dataset to evaluate how they perform with data contaminated by high-frequency resonances.

Results and Discussion

We analyse 17,000 events above $M_w$ -2 from the PNR microseismic catalogue using the single event method, and the 296 events above $M_w$ -0.5 using the spectral ratio method. Figure 3 displays single event fitting applied to two different earthquake records. In both cases, there are high-frequency resonance bumps that cause an over- or underestimation in moment magnitude. Accurate magnitudes are crucial for $b$-value calculations, which reflect the rate of earthquakes and are used to forecast microseismicity. Even magnitude differences as small as 0.2 moment magnitude units can affect the $b$-value and, in the worst case, lead to operators making inappropriate decisions with regards to the injection rates and pressures. Likewise, we find that corner frequency is sensitive to the location of the resonance bumps and can also be over- or underestimated. Corner frequency is cubed to calculate stress drop, thus small errors will have larger consequences for the stress drop estimates.

Out of the 296 events larger than $M_w$ -0.5 in the catalogue, we find sufficient EGFs for 262 events to apply the spectral ratio method. In contrast to single event fitting, the spectral ratio does not produce any magnitudes. These are usually obtained either through the single event fitting or focal mechanism analysis. We find that the spectral ratio method manages to remove the resonance frequencies and most likely does not over/underestimate the corner frequency to the same degree as single event fitting. Figure 4 compares the final corner frequency results from the single event and spectral ratio methods. As can be seen, there is a large spread and in general the single event value was within a factor of 2 of the spectral ratio results. On average the spectral ratio corner frequencies were ~10% larger. Considering that single event corner frequencies were likely both under- and overestimated, it is difficult to draw conclusions with respect to their relationship to one another.
Conclusions

Borehole geophones are known to have high-frequency resonance issues. To investigate if these resonance frequencies bias earthquake source parameters, we examine the high-frequency content of the induced seismicity borehole catalogue from Preston New Road, UK. We find that the resonance frequencies cause over- and underestimation of both moment magnitude and corner frequency using the single event Brune fitting method. Mis-specified magnitudes can bias $b$-values, which in turn can lead to inaccurate seismic rate estimations and hazard assessments. Similarly, mis-specified corner frequencies can bias stress drop and rupture size estimates. The resonance frequencies appear to cancel out using the spectral ratio method, but the large spread in corner frequencies suggests some are still affected by resonances. This study highlights the importance of taking resonance frequencies in borehole geophones into account for both operators and researchers analysing microseismic events.

References


