Induced Seismicity Monitoring: Broadband Seismometers and Geophone Comparison

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Summary

The risks associated with induced seismicity have risen in prominence with the occurrence of several large earthquakes characterized as induced, which have caused public concern in multiple jurisdictions. As a result, regulatory bodies have mandated risk mitigation strategies to govern the associated activities. These include monitoring programs, which involve the deployment of real-time seismic networks. There are several challenges and options to consider when planning and realizing a monitoring network, including the choice of ground motion sensing technology. This study evaluates the performance of two types of instruments in terms of their suitability for induced seismic monitoring: broadband seismometers and geophones.

Two geophone and broadband seismometer pairs were co-located in a real-world induced seismic monitoring (ISM) deployment. The co-located geophone and broadband seismometer were positioned within 3m of each other and, as such, were subject to the same ground motion. The subsequent impact on key ISM network performance criteria, event magnitude measurements and ground motion computations, are examined for each sensing technology.

It was found that event magnitudes generated using the geophone data generally underestimate the broadband event magnitude, for events at typical ISM hypocentral distances, 10 to 50 km. This effect is the result of magnitude saturation, due to the inability of the geophone to measure low-frequency motions associated with large events. Further, it was found that peak ground velocities calculated using the geophone data were also underestimated for study events.

Introduction

Change of in-situ stresses on existing faults caused by human activities (e.g., mining, dam impoundment, geothermal reservoir stimulation, wastewater injection, hydraulic fracturing and CO2 sequestration) may induce earthquakes on critically-stressed fault segments. A number of induced earthquakes with magnitudes M>3 were recorded in British Columbia, Alberta, Ohio and Oklahoma, since 2013. In response to growing induced seismicity rates, many jurisdictions have mandated near real-time seismic monitoring around injection operations. The data products from monitoring systems are used as drivers of operational traffic light systems designed to mitigate risks associated with induced seismicity. Most traffic light protocols developed to date use magnitude-based staged thresholds. For example, the Alberta Energy Regulator mandates traffic-light systems for all hydraulic fracturing or wastewater injection operations in Duvernay, Alberta with yellow and red traffic light thresholds set to M2.0 and M4.0 respectively. Ground motions, which are used to estimate the impact of earthquakes and specify seismic hazard have been proposed as an enhancement to the existing traffic light protocols. Incorporating ground motions into traffic light protocols can allow mitigation of induced seismicity risks more efficiently.

Given the large costs associated with operational shutdowns, it is important that the choice of sensing technology not impact the accuracy of the data products (source parameters or ground motions) used to drive traffic light protocols. Two of the commonly used sensor types in ISM applications are:

- Broadband seismometers
- Geophones

Broadband seismometers are high performing instruments rooted in earthquake seismology, whereas geophones are traditionally used in large quantities for active seismic surveys in exploration applications. In general, broadband seismometers have a larger passband than geophones, and can record ground motions to much lower frequencies. The low corner frequency for a geophone is typically in the 1 to 15Hz range, whereas a broadband seismometer, depending on the model, can record down to 240 seconds (4.2 mHz). A low corner period of 20 seconds (50 mHz) is typical for broadband seismometers used in ISM applications.

Induced seismic monitoring networks typically record events in the magnitude range M0.0 to M4.6 (largest recorded event characterized as induced) at a hypocentral distance range of 5 km (single pad local monitoring networks) to 30 km (multi-pad regional monitoring networks). The frequency content of such events is in the 0.1 to 100 Hz range.

Figure 1 provides a comparison of the self-noise and frequency response for geophones and broadband seismometers relative to Brune-modeled (Brune, 1970) event spectra for M-1.0/0.0/1.0 events recorded at 5 – 30 km distances. In order to accurately estimate event source parameters, the instruments have to record and image the low frequency plateau and the corner frequency of the event spectra (Ackerly, 2012). High sensitivity geophones have a reasonable noise floor, when connected to high gain digitizers, for the detection of smaller events but do not have the instrument response to image the low frequency content of larger magnitude events. They would consequently be expected to saturate and under-estimate source size and ground motions associated with larger events.

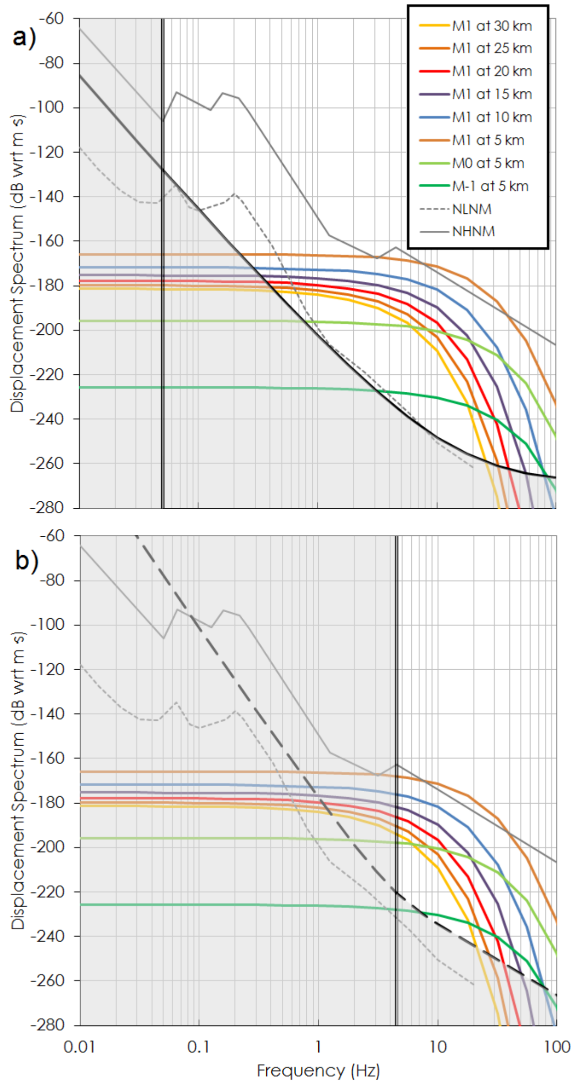

Figure 1. Lower corner frequency and noise floor of 20s seismometer (a) and high-sensitivity 4.5 Hz geophone (b) with New Low Noise Model (NLNM) and New High Noise Model (NHNM) gray lines shown for site noise reference.

Case Study: Side-by-Side Ground Motion Recordings

This study was undertaken to evaluate the relative performance of broadband seismometers and geophones in a real-world regional ISM application. As part of a long term ISM monitoring project in western Canada, two sites were selected to host both a broadband seismometer and a geophone.

- Site A:
  - Trillium Compact Posthole Broadband Seismometer
  - GSC-11D 4.5Hz Geophone

- Site B:
  - Trillium Compact Posthole Broadband Seismometer
  - GS-One 10Hz Geophone

All sites utilized Centaur digitizers, with high gain variants for the geophones. Over the course of the study period, seismicity associated with fault activation was recorded at local and regional distances. 39 of the detected events, with magnitudes between M1.5 and M2.4, were selected for further analysis. The broadband seismometer and geophone datasets were compared in the following areas:

- Moment magnitude
- Ground motion computations

Analysis

Moment Magnitude:

The traffic light protocols mandate implementation of risk mitigation operational protocols in response to induced events above certain magnitude, in order to lower the likelihood of triggering large events. Obtaining reliable magnitude estimates is critically important in terms of effectiveness of traffic light protocols. Of various magnitude scales, moment magnitude (Mw) is the best single measure of overall size of an earthquake because it is directly related to the seismic moment, and is not subject to saturation.

The usable bandwidth of sensors used in ISM applications can influence the reliability of estimated event magnitudes. To illustrate this problem, Mw estimates obtained from waveforms recorded by co-located broadband seismometers and geophones were compared for a M2.0 event detected at 22 km distance. The apparent source spectrum of the event was estimated by correcting waveforms for attenuation and site effects. S waves from the two orthogonal horizontal components were used in this exercise. The geometrical spreading in the region was assumed as 1/R. A frequency-dependent quality factor (Q) proposed for western North America (Raoof et al., 1999) was used for playing back the anelastic attenuation effects. Local site effects were modeled by site factors of Boore and Joyner (1997), assuming that the sensors are located on a generic rock site.

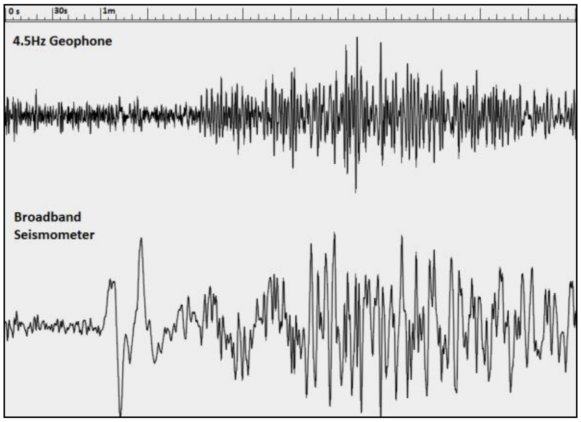

Figure 2. Example event ground motion recorded by co-located geophone and broadband seismometer at Site A

Moment magnitude of the event was determined by matching the apparent source spectrum with the theoretical Brune (1970) model at frequencies lower than the corner frequency. This was done for each sensor independently. Figure 3 shows Mw values determined from spectral fitting for broadband sensors and geophones co-located at sites A and B. As illustrated in the figure, both 4.5 Hz and 10 Hz geophones underestimate the Mw magnitude by ~0.3-0.4 magnitude units because the geophone instrument response filters out the low-frequency plateau, resulting in lower spectral amplitudes. Contrary to expectations, 10 Hz geophone located at site B attains slightly larger Mw magnitude than that of 4.5 Hz geophone. This might be due to larger site amplification and/or radiation pattern effects observed at site B relative to site A. The broadband sensor located at site B also attains larger Mw than that at site A, confirming the site amplification and/or radiation pattern discrepancy between the two sites.

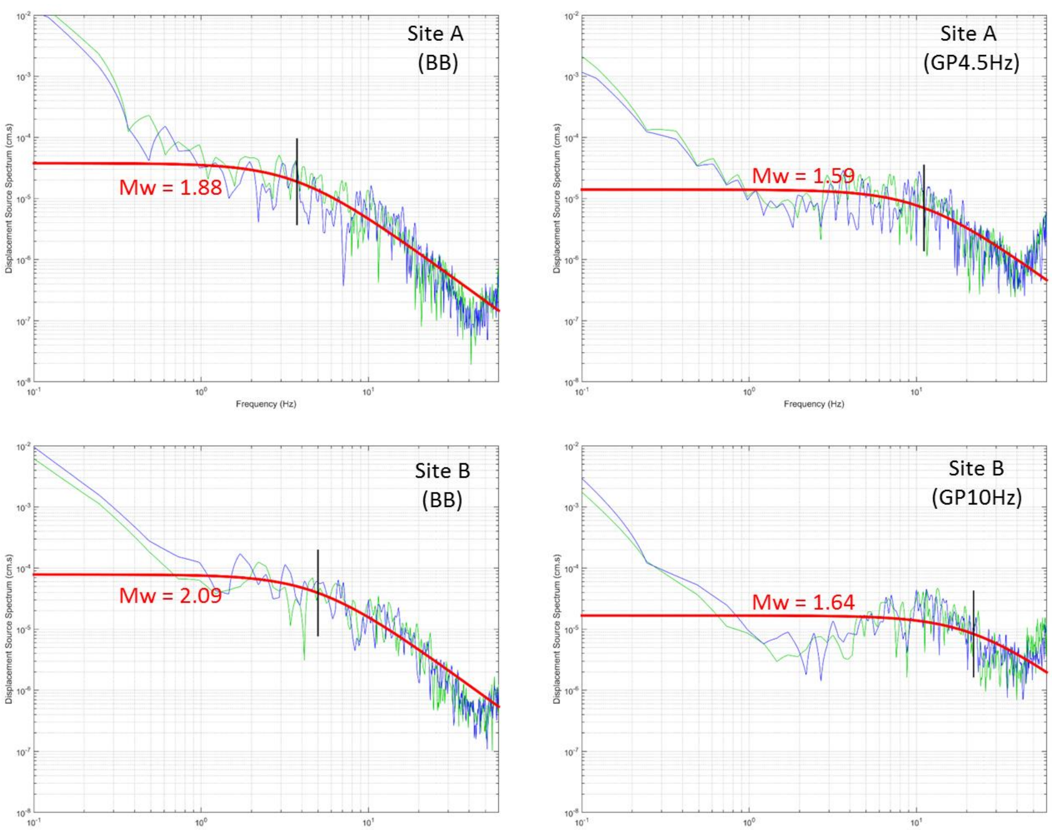

Figure 3. Brune model (red line) fitted to the apparent source spectra estimated from waveforms of broadband seismometers (BB) and geophones (GP4.5Hz and GP10Hz) co-located at sites A and B.

Peak Ground Motions

The amplitude of ground motion recordings obtained from 4.5 Hz and 10 Hz geophones were examined relative to those recorded by co-located broadband sensors in terms of peak ground motions. In this respect, the peak ground accelerations (PGA) and velocities (PGV) of selected events were compared for the two sensor types. Figure 4 shows the histograms for the amplitude ratio of peak motions recorded by geophones to that of broadband sensors. The 4.5 Hz geophone and broadband sensor at Site A attain similar PGA values. However, the 10 Hz geophone at Site B generally attains 30% lower PGA values than those recorded by the co-located broadband seismometer The discrepancy between geophones and broadband sensors is more pronounced for PGV. Geophones attain smaller PGV values than those recorded by the broadband sensors, mostly by 20% to 60%. The increased discrepancy in PGV values is primarily due to the fact that PGV is controlled by lower frequency motions in comparison to PGA, which are filtered by the instrument response of the geophones.

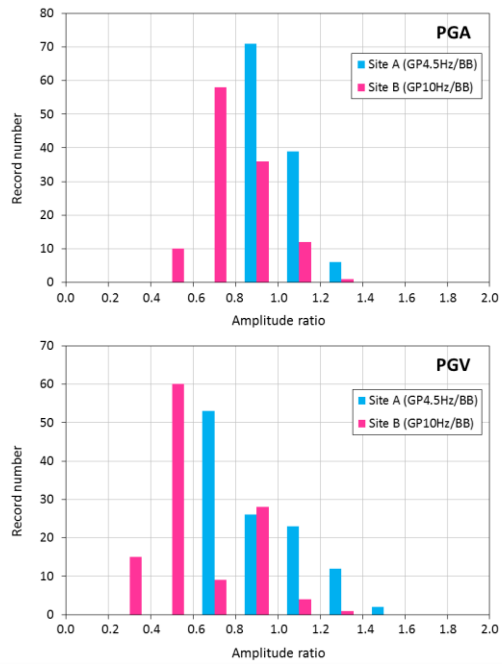

Figure 4. Histogram for the ratio of peak ground motions recorded by a geophone to that recorded by a co-located broadband sensor.

Conclusions

The ISM network performances of 4.5Hz and 10Hz geophones were examined in comparison to co-located broadband seismometers in terms of event magnitude estimates and recorded peak ground motion amplitudes, as part of a real-world induced seismicity monitoring deployment.

Event magnitudes determined from geophone data were found to underestimate the broadband event magnitude. This effect is the result of the geophone instrument response filtering out the low-frequency amplitudes, causing magnitude saturation for large events. It was also found that PGV values obtained by geophones were underestimated in comparison to those recorded by broadband sensors.

The findings of this study highlight the importance of utilizing broadband seismometers in ISM applications where accurate event magnitude and ground motion amplitudes are critical.