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High Quality Induced Seismic Monitoring: Strategies and Applications

Dario Baturan, Emrah Yenier, Andrew Law, Sepideh Karimi*
Nanometrics Inc., dariobaturan@nanometrics.ca

Summary

We examine the importance of designing induced seismic monitoring (ISM) networks to provide the richest data sets possible with benefits to operators beyond basic regulatory compliance. Using examples from operational Montney and Duvernay ISM networks, we highlight the impact of network performance modeling, data sharing and instrumentation on the quality of generated data products and event catalogs. We illustrate the application of enhanced data sets in evaluating the effectiveness of yellow traffic light-initated mitigation techniques and improving the accuracy of scientific research outputs.

Introduction

Induced seismicity is a well-known phenomenon. Rarely are induced seismic events large enough to be either felt locally or detected by regional seismic networks. However, between 2013 and 2015, a number of induced seismic events with magnitudes above M3.5 were recorded in British Columbia and Alberta. Following increased public awareness and media scrutiny, energy regulators in the two provinces have put in place protocols to mitigate risks associated with induced seismicity. The regulations mandate the deployment of real-time induced seismic monitoring (ISM) networks as drivers of operational traffic light systems.

In this paper, we seek to address some of the ways operators can maximize the utility of deployed ISM networks. We show the impact of network modeling, noise measurements, station placement, and sensor frequency response and noise floor on the network event detection thresholds. Well-designed ISM networks account for monitoring protocol robustness and result in richer event catalogs, which in turn enable seismicity rate and b-value computations as well as detections of out of zone fracture growth. These parameters can be used to help manage risk by allowing operators to evaluate mitigation strategies with lower-magnitude detections before encountering yellow and red traffic light alert events. In addition, we demonstrate the advantages of merging high quality geographically-distributed data sets for scientific research purposes. In particular, we show that the combination of private and public ISM data sets allows for regional calibration of local (Richter) magnitude scale for western Alberta (Yenier et al, 2016). Scientific research of this type plays a crucial role in reducing the uncertainty associated with data products (magnitudes or ground motions) used to drive traffic light protocols (TLPs).

Theory, Method and Examples

Most regulations outline monitoring requirements in terms of region of interest, magnitude-based yellow/red traffic light thresholds and, in some cases, event location uncertainty. With no pre-existing high-resolution earthquake catalogs for the regions to be monitored, we turn to modeling to determine the optimal number and placement of seismic stations required to meet the monitoring mandate and generate the richest event catalog possible (Wesley, 2015).

Nosie field characteristics play a crucial role in determining the lowest detectable magnitude threshold for each station and, by extension, overall ISM network magnitude of completeness Mc. Figure 1 b illustrates initial Mc modeling results for a 4-station single-well ISM network in Utica shale play in Ohio. Figure 1 c illustrates the performance of the same 4-station network with station locations adjusted to account for the measured noise field shown in Figure 1 a. In this particular example, strategic station placement to avoid high-noise areas improves the estimated Mc by 0.2 magnitude units without adding new stations (i.e. keeping the cost the same) or compromising on event location uncertainty. Appropriate station placement results in a more complete event catalog which, in turn, may allow the operators to better manage risk.

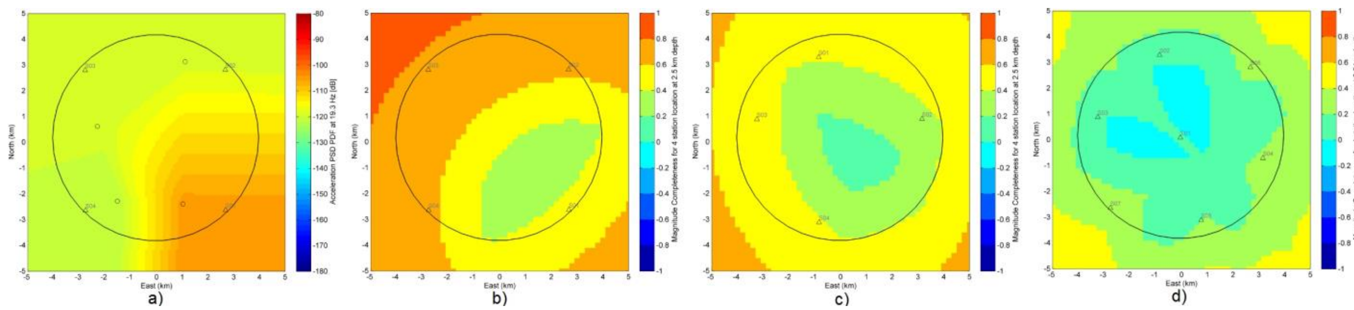

Figure 1: Noise field acceleration PSD (a) used as an input in basic 4-station network performance modeling in terms of Mc for initial (b) and optimal (c) station placement. In addition, we illustrate the effect on region of interest Mc of adding 3 more stations (d).

Network performance modeling also allows us to evaluate the robustness of ISM protocols. Figure 2 shows an example from a TransAlta-mandated 8-station network installed in the vicinity of the Brazeau dam in Alberta. Areas in the monitoring zone where the average Mc is above the specified yellow traffic light threshold are shaded in orange. Simulation of single or multiple station outages reveals that the average Mc in the monitoring zone rises above the yellow traffic light threshold if more than a single station goes down. A robust monitoring protocol should therefore include an alert to indicate that the network is not meeting its operating mandate if two or more stations experience simultaneous outages.

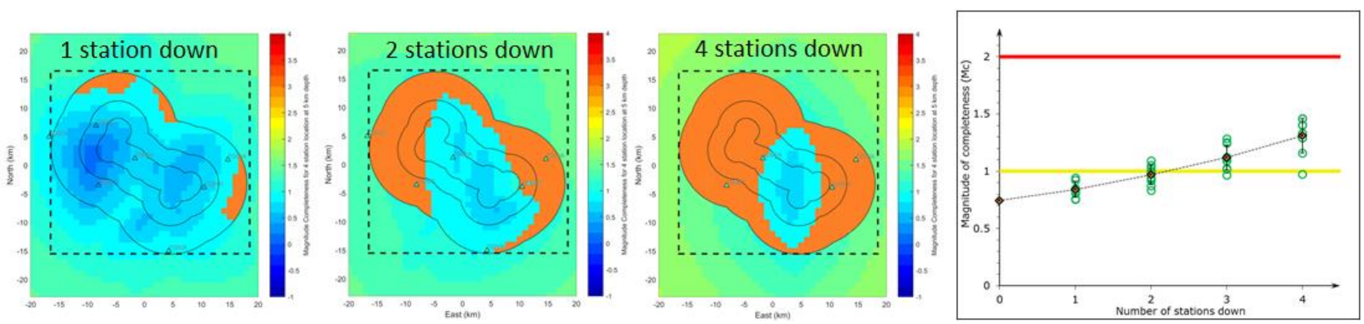

Figure 2: Impact of station outages on the Mc of the Brazeau dam, Alberta ISM network where yellow traffic light threshold is set at M1.0

Induced seismic monitoring networks typically record events in the magnitude range M0.0 to M4.6 (largest recorded event characterized as induced) at 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 3 provides a comparison of the self noise and frequency response for three common instrument types used in seismic monitoring 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). The accelerometer dynamic range is well-suited to detection of large events at small distances, but instrument self-noise interferes with detection of lower magntiude events especially at larger distances. High sensitivity geophones have a reasonable noise floor 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.

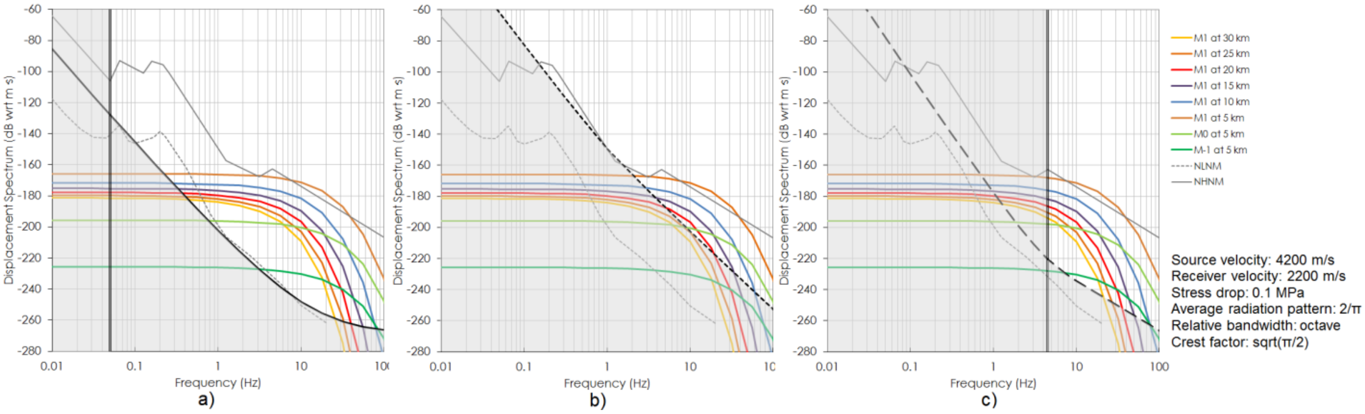

Figure 3: Lower corner frequency and noise floor of 20s seismometer (a), MEMS accelerometer (b) and high-sensitivity 4.5 Hz geophone (c) with New Low Noise Model (NLNM) and New High Noise Model (NHNM) gray lines shown for site noise reference.

The low noise floor of the broadband seismometer, in combination with favorable surface noise conditions, allows for detection of events below M0.0 at short distances and magnitudes higher than M0.0 at regional distances. Figure 4 a shows a data set generated by a 6-station Montney ISM network utilizing broadband seismometers. The 5-week deployment generated ~1200 events ranging in magnitude from -0.8 to 1.2 with Mc of -0.1 (Law et al, 2016). Figure 4 b depicts a regional Duvernay ISM network that recorded ~200 events in the vicinity of a hydraulic fracture operation over a 20-day period ranging in magnitude from 0.4 to 3.1.

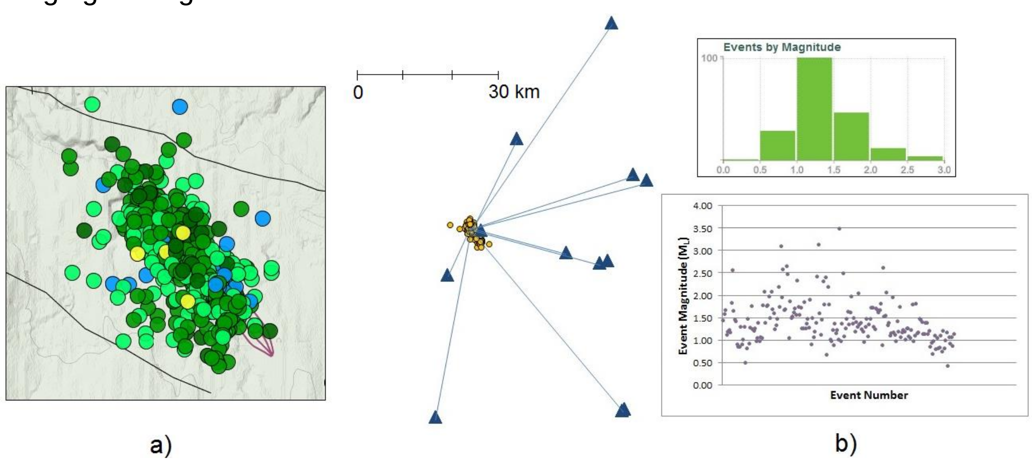

Figure 4: Examples of Montney (a) and Duvernay (b) ISM network data sets generated with low noise floor BB seismometers that can assist operators with managing risk associated with larger event occurrence

Richer catalogs containing events orders of magnitude below traffic light thresholds may allow operators to track the effectiveness of mitigation techniques (delaying or skipping stages, reduction of pumping volumes and rates) implemented in case of yellow traffic light alerts. As illustrated in Figure 4, data analyzed from the seismic stations in the vicinity of large induced seismic events in British Columbia and Alberta has shown that they were preceeded and followed by a large number of lower magnitude events. Consequently, seismicity rate and potentaily b-value variations can be used to verify the impact of the initiated operational changes. Both parameters require accurate detection of events with magnitudes well below traffic light thresholds. This can be achieved in part with the use of low noise floor instrumentation, careful site selection and an increase in the number of deployed stations.

High-quality rich data sets (i.e. accuracy of the derived data products is not impacted by sensing instrumentation characteristics) produced by ISM networks can further be employed for investigation of source characteristics of induced events, region-specific ground motion attenuation, site characterization, and the overall impact of the induced seismicity on the seismic risk on local and regional scales. Findings of such studies can be used to improve traffic light protocols (TLPs). Existing magnitude-based TLPs do not account for the fact that earthquakes generate different levels of shaking at different locations depending on the distance to the source, regional attenuation and local site condition. Consequently, traffic light systems can be improved to include estimates of ground motion amplitudes as a measure of seismic risk associated with induced seismicity.

Reliable magnitude and ground motion estimates are critically important in this aspect and require robust modeling of regional source, attenuation and site effects. The accuracy of empirically-derived attenuation models used in magnitude and ground motion prediction equations (GMPEs) depends on the input data set distribution of source-to-site distances and azimuths.

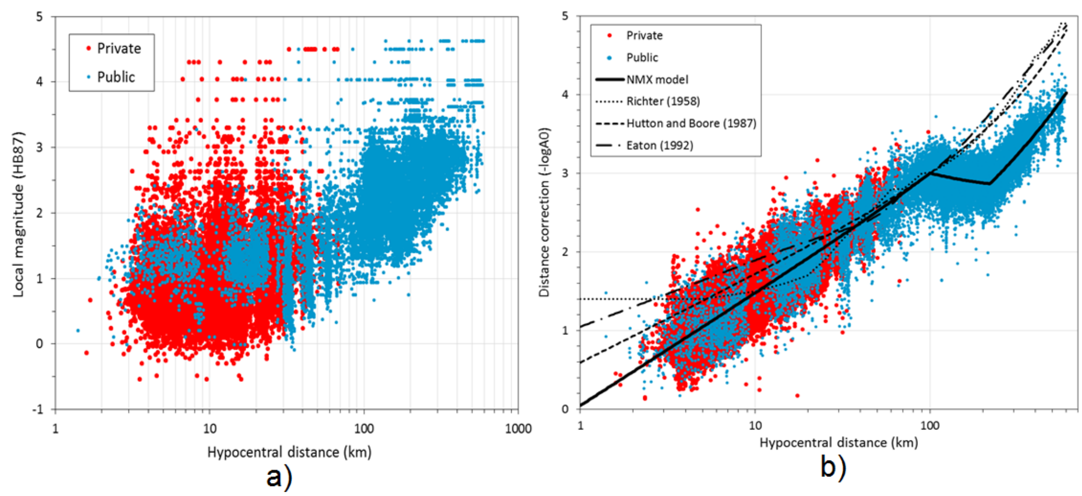

Figure 5: Magnitude-distance distribution (a) and Richter magnitude distance correction term (b) data set used by Yenier et al. (2016) to develop a calibrated M_L formula for western Alberta. Data is colored to denote whether it comes from private or public ISM networks.

As private and public data sets typically complement each other in terms of the coverage, data sharing is critically important for developing robust empirical models. Figure 5 illustrates an example of the public and private data sets being combined to develop a calibrated M_L equation for western Alberta (Yenier et al, 2016). Private networks have much better coverage at distances of less than 50 km, whereas public data are primarily obtained at distances of greater than 50 km. Both public and private data are required to develop an empirically well-constrained local (Richter) magnitude model applicable for wide distance ranges. It would not be possible to develop a robust empirical model at close distances, if data from private networks were excluded. This may result in biased magnitude estimates at close distances and a discrepancy between magnitudes reported by private and public networks. Data quality and availability are crucial to research efforts which benefit public, operators and regulatory bodies.

Conclusions

We have demonstrated the importance and utility of correct design and instrumentation of induced seismic monitoring networks to generate the highest quaility data sets and ensure robust operation. The enhanced event catalogs can be used to manage operations, reduce the risk of shutdowns and promote research aimed at reducing uncertainty associated with data products that drive the traffic light protocols. The accuracy and applicability of scientific research outputs is significantly enhanced if data from private ISM networks is used in combination with regional public data sets.

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