ISM Traffic Light Thresholds: Western Alberta M_L Case Study

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Summary

ISM traffic light protocols are implemented to manage induced seismic risk associated with Oil and Gas extraction activity. Incorrect application of protocols can have significant consequences for operators, associated communities and other stakeholders. Accordingly, it is critical that the triggering criteria is based on inputs which are as accurate as possible. We examine a western Alberta case study for a common triggering criteria, local magnitude. We develop a region-specific local magnitude formula that improves measurement accuracy in comparison to other standard methods, and demonstrate the potential impact of the discrepancy using a real event.

Introduction

In recent years, the growing body of evidence associating various unconventional Oil and Gas extraction activities with increased seismicity rates has compelled regulatory bodies in many jurisdictions to take action. Several regulatory bodies have mandated monitoring systems and defined “traffic light” protocols which operators must follow, in an effort to manage induced seismic risk. These frameworks typically include deployment of a real-time seismic monitoring network in the region of interest to support 24/7 event detection and analysis. Upon detection and confirmation of an event, the traffic light protocol defines the mitigating action(s) to be taken by the operator, based on the characteristics of the event. Protocols are generally based upon the magnitude of the event and have an escalating scale of responses, from taking no action to an immediate operational shutdown. An indefinite shutdown is major disruption and very costly to an Oil and Gas operator. Thus, it is critically important that the criteria used to trigger traffic light protocols is carefully considered and well defined. It must ensure consistency in application between competing operators, and must be reliably and accurately measureable in a manner that is scientifically sound. This can be challenging, as there are several different magnitude scales used to measure the size of an earthquake, each with advantages and disadvantages, and varying degrees of applicability to different situations.

Local Magnitude Thresholds

Local magnitude (M_L) is commonly used to estimate the size of an earthquake, and is often used to drive traffic light protocols in induced seismicity monitoring applications. For instance, Alberta Energy Regulator Subsurface Order No. 2 explicitly defines the actions to be taken in response to induced events in terms of staged M_L thresholds. This example is examined in detail in the case study which follows.

M_L has the advantage of being easy to calculate. This is important within a 24/7 monitoring context, where the traffic light protocol must be initiated as soon as possible following an event to mitigate further potential risk.

A standard formulation of Richter’s local magnitude is written as (Richter, 1935, 1958; Hutton and Boore, 1987; Eaton, 1982; Miao and Langston, 2007):

$$M_L = \log(A) - \log A_0 + S \qquad (1)$$

where A is half of the peak-to-peak amplitude (mm) of a horizontal component on a standard Wood-Anderson (WA) seismometer, $-\log A_0$ is the distance-correction function that reflects the overall attenuation attributes in the region of interest, and S is the station correction defined relative to a reference site condition. In order to maintain Richter’s (1935) original definition of M_L, $-\log A_0$ is defined such that 1 mm of amplitude on a WA instrument located at a reference site at 100 km away from an event would register as a magnitude 3 event.

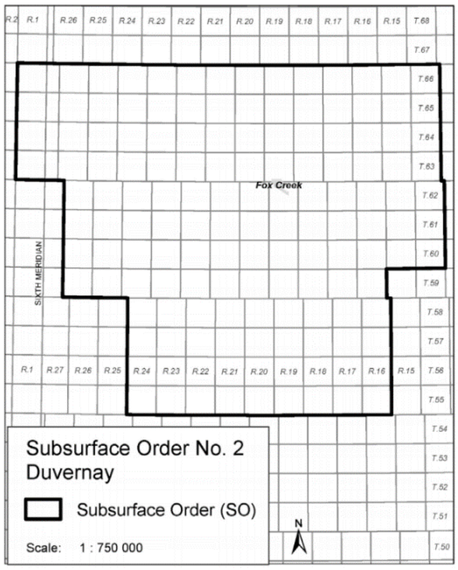
Standard M_L formulas derived from California data (e.g., Hutton and Boore, 1987; Eaton, 1992) are generally used in regions where empirical data are insufficient to develop a robust regional attenuation model. This can result in biased M_L estimates if the adopted model does not comply with the attenuation characteristics of the target region. Proper correction of observed amplitudes for regional attenuation and site effects is an important prerequisite for accurate magnitude estimations which drive high stakes traffic light protocols.

M_L Threshold Case Study: Western Alberta

Background

On February 19th 2015, in response to increased seismicity in the Duvernay Zone northwest of Edmonton, the Alberta Energy Regulator (AER) issued Subsurface Order No. 2 (SSO #2). Among other requirements, SSO #2 states the following:

- Operators must have a seismic monitoring system in the place which is "sufficient to detect a 2.0 local magnitude (M_L) seismic event within 5 kilometers (km) of any affected well".
- "During hydraulic fracturing operations on any affected well, the licensee must immediately report to the AER … any seismic event recorded by or on behalf of the licensee or by any other source available to the licensee of 2.0 ML or greater within 5 km of the affected well."
- "During hydraulic fracturing operations on any affected well, the licensee must immediately report to the AER … any seismic event recorded by or on behalf of the licensee or by any other source available to the licensee of 4.0 ML or greater within 5 km of the affected well; it must also immediately cease hydraulic fracturing operations at the affected well, and return the affected well to a safe state."



In this study, we develop a regionally-calibrated M_L formula for western Alberta, and examine its relative impact on magnitude estimates, and subsequent triggering of the SSO #2 protocol, in comparison to other common M_L formulas.

The regionally-calibrated formula is developed using a rich ground-motion dataset compiled from regional and local seismic networks in Alberta. We examine the earthquakes and mining/quarry blasts in terms of their amplitude decay with distance. Both event types show similar attenuation attributes with a strong Moho bounce effect. We show that standard M_L models fail to capture the rates and shape of amplitude attenuation in western Alberta, resulting in overestimated magnitudes compared to the derived M_L formula. Our results highlight the importance of accurate region-specific modeling of attenuation attributes for induced seismicity traffic light applications.

Amplitude Dataset

High-quality recordings of manually-reviewed seismic and blast events from September 2013 to August 2015 are compiled from regional and local networks in western Alberta. Peak amplitudes of simulated Wood-Anderson (WA) instruments with static magnification of 2080 (IASPEI, 2013) are measured for analysis of regional attenuation. We consider events and stations with at least 5 amplitude readings up to a distance of 600 km. A total of 44285 horizontal-component records from 2366 earthquakes, and 20484 horizontal-component records from 1134 mine/quarry blasts are used in this study. Figure 1 shows the magnitude and distance distribution of the amplitude dataset, and the surface projection of raypaths across the region. The compiled dataset mostly consists of earthquake records at close distances, and is dominated by blast records at far distances. Within the region of interest, the raypaths are dense and travel in every direction such that there should be no directional biases introduced.

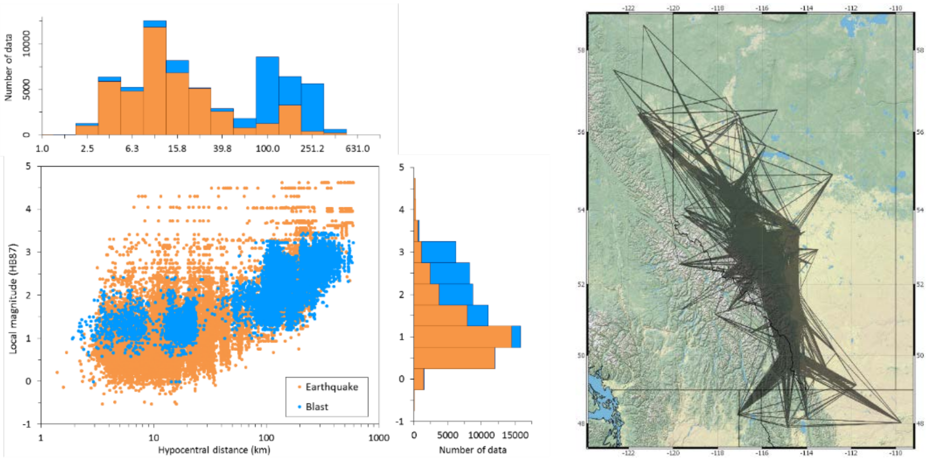


Figure 1. Left – Magnitude and distance distribution of Wood-Anderson amplitudes for earthquake and blast recordings used in this study. Event magnitudes are estimated based on Hutton and Boore (1987) for preliminary assessment of the amplitude dataset. Right – Regional coverage of the surface projection of raypaths for study events.

Model and Regression Analysis

We compare the decay of WA amplitudes with distance for earthquakes and blast events in order to gain preliminary insights on the regional attenuation attributes. For this purpose, we calculate the geometric mean of amplitudes for each event at two different reference distance bins (10 km - 25 km and 100 km - 150 km) where empirical data are abundant. We normalize the observed amplitudes event-by-event with the mean amplitude calculated for the corresponding event and reference distance bin. This exercise effectively removes the source effects from observed WA amplitudes and reveals the attenuation characteristics in the region. However, it is worth noting that the normalized amplitudes still include site effects relative to the average site condition in each reference distance bin. Both earthquakes and blast events display similar attenuation attributes, as shown in Figure 2. There is a region where attenuation of WA amplitude slows markedly, which is believed to be due to "Moho-bounce" effect, a consequence of reflected and refracted phases joining the direct waves.

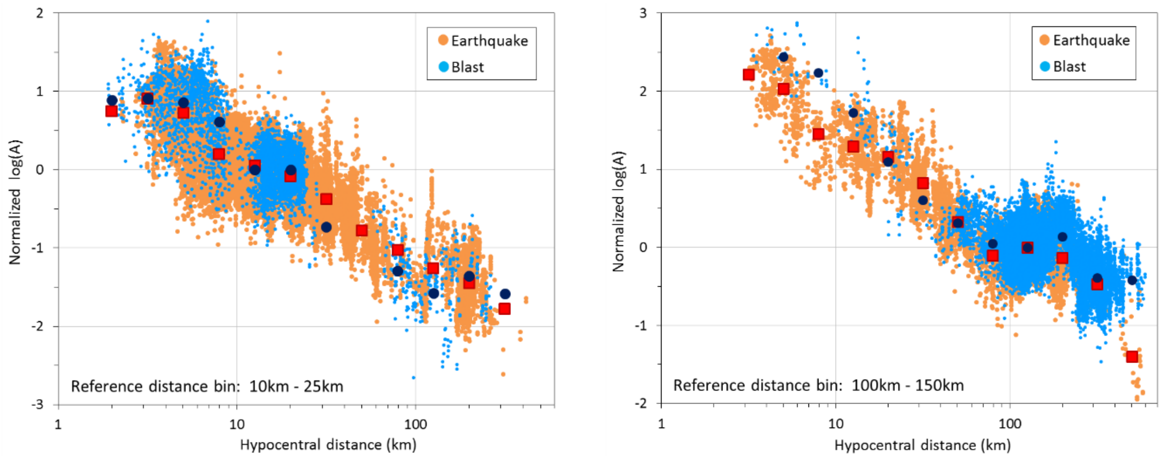


Figure 2. Attenuation of normalized WA amplitudes with distance for two reference distance bins: left – 10 km to 25 km, and right – 100 km to 150 km. Large symbols show the mean of normalized amplitudes calculated at log-spaced distance ranges.

Based on observations in Figure 2, we combine the amplitude datasets from seismic and blast events (despite a slight tendency for blasts to decay somewhat more steeply at close distance), and model the regional attenuation using a single trilinear function. We define the regional distance correction for western Alberta as:

$$-logA_0 = GS' + \gamma(R - 100) + 3 \quad (2)$$

where γ is the coefficient of anelastic attenuation, and *R* is the hypocentral distance (km). The *GS'* term represents the geometrical spreading normalized at *R* = 100 km to maintain the original definition of Richter (1935):

$$GS' = GS(R) - GS(R = 100\text{km}) \quad (3)$$

The decay of WA amplitudes due to geometrical spreading in western Alberta is defined as a trilinear function of hypocentral distance:

$$\text{GS}(R) = \begin{cases} b_1\log(R) & R \le R_1 \\ b_1\log(R_1) + b_2\log(R/R_1) & R_1 < R \le R_2 \\ b_1\log(R_1) + b_2\log(R_2/R_1) + b_3\log(R/R_2) & R > R_2 \end{cases} \quad (4)$$

where b_1, b_2 and b_3 are rates of geometrical spreading at three distance ranges defined by transition distances R_1 and R_2.

Results

We regress observed WA amplitudes based on Equations 1-4, in order to determine the model coefficients: b_1, b_2, b_3, R_1, R_2 , γ and an S term for each station. We grid search transition distances within 50 km ≤ R_1 ≤ 150 km and 100 km ≤ R_2 ≤ 300 km ranges with 10 km increments, and calculate all other model coefficients for each R_1-R_2 combination via regressions. The best-fitting parameter set is selected by minimizing the mean of absolute residuals. Table 1 lists the model coefficients of distance correction derived for western Alberta.

Table 1. Coefficients of distance correction (-logA_0) for western Alberta

R_1	R_2	b_1	b_2	b_3	γ
100	220	1.42	-0.78	1.70	0.0011

The regionally-calibrated distance correction model shows a good agreement with the empirical data, as shown in Figure 3. However, Hutton and Boore (1987) and Eaton (1992) models, which are commonly used for magnitude estimation in absence of a regional M_L formula, fail to capture the attenuation attributes in western Alberta. Both models over-correct for distance attenuation for R < 30 km and R > 100 km, and do not account for observed Moho-bounce effect. Note that M_L estimates from local and regional stations are affected by the biased distance corrections if region-specific attenuation attributes are not considered in magnitude calculations. We found that Hutton and Boore (1987) and Eaton (1992) models overestimate M_L for earthquakes in western Alberta, on average, by 0.35 and 0.47 magnitude units, respectively.

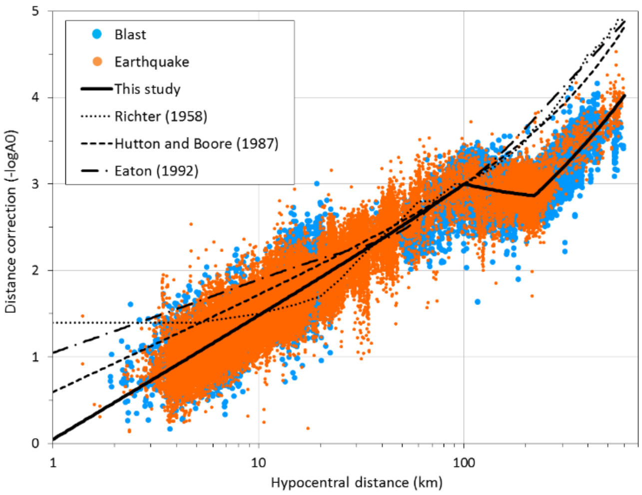


Figure 3. Comparison of the distance correction model (-logA_0) developed for western Alberta (solid line) and standard models that are commonly used for magnitude estimation in absence of a regionally-derived ML formula. Scatter dots indicate distance correction obtained from observed amplitudes after correcting for event magnitude and site effects.

Application

AER SSO #2 was issued following a large felt event in the Duvernay zone, at 2015-01-23 06:49:19UTC, reported to have local magnitude 4.4 using the standard Hutton and Boore formula. Applying the calibrated western Alberta local magnitude formula to this event decreases the magnitude from 4.4 to 3.9. Under the SSO#2 protocol, this represents the difference between an immediate red light shutdown and continued yellow-light operation. It is also important to note that the calibrated formula yields a measurement which is much closer to that other, more sophisticated, magnitude scales, further validating the result.

Table 2. Coefficients of distance correction (-logA_0) for western Alberta

Earthquake Time (UTC)	NRCan M_L	PGC RMT M_W	USGS NEIC M_b	NMX DSF M_W	Calibrated M_L
23/01/2015 06:49:19	4.4	3.7	3.9	3.8	3.9

*** Calibrated magnitude scale minimizes the discrepancy between M_L and other magnitudes (Mw, Mb).*

Conclusions

Accurate and consistent measurement of traffic light protocol criteria is critical to ensure fair and valid application. For local magnitude based protocols, not appropriately accounting for regional attenuation can be a source of significant error. We developed an empirically constrained M_L formula for earthquakes in western Alberta. The new M_L relationship employs a trilinear distance correction to capture observed attenuation effects in the region. It results in unbiased magnitude estimates with distance in western Alberta, and attains systematically lower M_L values than those computed based on default California-based local magnitude models. Our findings feature the key role of region-specific attenuation modeling in magnitude calculations for induced seismicity traffic light applications.

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