Connecting Induced Seismicity from Hydraulic Fracturing with Seismic Hazard

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Summary

There has been growing concern over seismic hazard associated with stimulation and injection programs in the oil and gas industry over the last several years, sparked by a number of incidents of seismic events felt on surface near petroleum field operations. In response, several jurisdictions have enacted regulations requiring modification or temporary shut-down of operations in wells close to earthquakes which exceed certain magnitude thresholds. These recently proposed magnitude-based “traffic light” systems break from existing standards and regulations related to seismic hazard, which are based on measured ground shaking (velocity and acceleration). Observed shaking, and the associated risk of damage or injury, is determined by several factors including both earthquake source characteristics and site- and raypath-specific conditions. Injection-induced seismicity tends to produce significantly less shaking than tectonic events of the same magnitude due to differences in stress release behaviour. Shaking can be directly measured by seismic instruments and directly related to building codes and structural design specifications. To achieve a more consistent and reliable regulatory standard, we propose the use of ground motion, rather than magnitude, for evaluation of the seismic hazard associated with injection-induced seismicity.

Introduction

Several recent incidents of felt seismicity associated with hydrocarbon extraction operations such as hydraulic fracturing and wastewater disposal have received significant attention from regulators and mainstream media. Seismic monitoring networks have also recorded significant numbers of earthquakes which have moment magnitude greater than 0.0, but are not felt by on the surface (see figure 1). Several jurisdictions have regulated so-called “traffic light” systems in response to induced/triggered seismicity, the majority of which are based on earthquake magnitude thresholds. Thresholds and operational responses vary widely between jurisdictions, resulting in a degree of inconsistency, but the greater problem is that magnitude is not directly connected to seismic hazard and is therefore not necessarily the most pertinent parameter to monitor.

Magnitude is the most commonly reported characteristic of an earthquake. However, earthquakes are complex processes that cannot be fully described by a single number; reducing the characterization of seismic events to their magnitudes ignores much of the factors that control the effects of the earthquake far from the source. For example, seismic hazard, the potential for an earthquake to cause damage, is measured in probabilities of exceeding certain ground motion thresholds, and depends on several earthquake parameters including magnitude, depth, stress release, and radiation pattern. Ground shaking is also dependent on site conditions, as different soil and rock types will respond differently to incoming seismic waves. The convenience of seismic hazard based on ground motion is that it can immediately be related to existing building codes and structural design specifications. Ground motion is also directly measured by seismic sensors, eliminating a source of uncertainty associated with disagreement between magnitude estimates from different monitoring groups (e.g. regional (USGS/NRCan) and local (industryowned) networks). By considering regulatory approaches based on ground motion, it may be possible to remove the vagueness and ambiguity associated with recently proposed traffic light systems.

Despite its relatively recent association with the oil and gas industry, induced seismicity is not a new issue. Earthquake activity has been associated with mining and geothermal operations for decades. The induced/triggered seismicity that has been recorded to date near petroleum operations is low enough in magnitude (M<6.0) that the greatest hazard associated with these events is ground shaking (GWPC/IOGCC, 2015). There are several existing regulatory standards that address analogous ground motion from other sources, for example, shaking due to blasting (mining- or construction-related) and vibrations from industrial activities. These regulations could be applied or adapted to be used in induced seismicity monitoring.

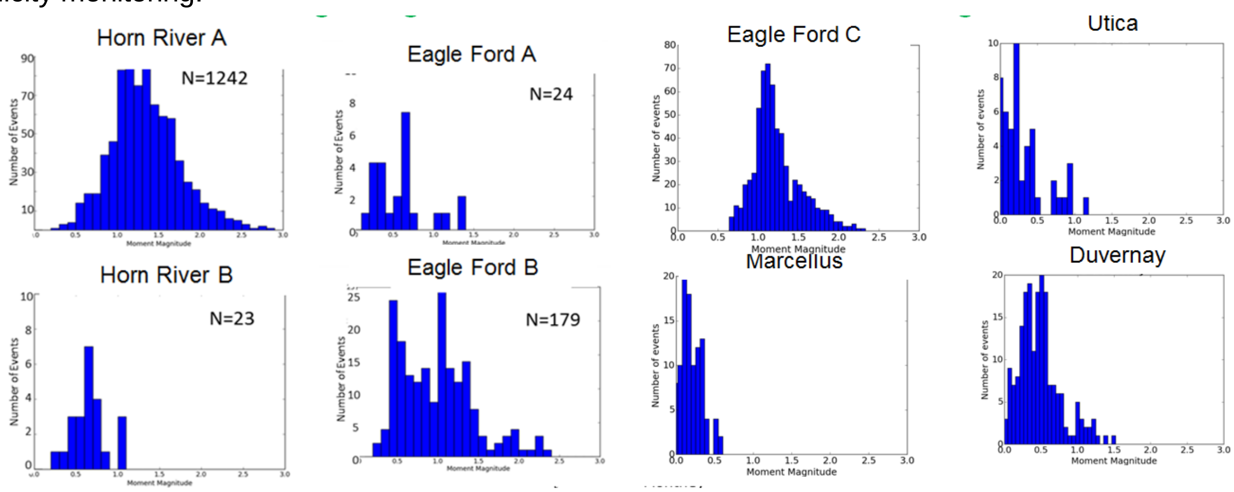


Figure 1 *Magnitude histograms of the >M0 events detected from surface monitoring of a number of different shale plays in North America.*

Regulation of Induced Seismicity

Several jurisdictions in North America and abroad have adopted regulations within the last 5-10 years regarding induced seismicity from petroleum field operations. The vast majority of these are based on earthquake magnitude thresholds. Figure 2 illustrates the thresholds defined for a few jurisdictions. Any seismic event with a magnitude in the red range warrants immediate suspension of field operations for any well within a specified radius of the event's location, with field activities resuming only after consultation with the relevant regulatory agency and implementation of an approved mitigation and monitoring strategy. Some areas also have an intermediate, or "yellow light", threshold such that seismic activity in this range will require nearby wells to modify their operations to reduce the risk of further seismicity. Illinois also includes a provision for suspension of operations if multiple "yellow light" seismic events occur in the vicinity of the same well.

In the mining and construction industries, ground motion due to blasting and equipment has been regulated for decades. Thresholds for these regulations are defined as frequency-dependent limits on ground velocity or acceleration. Figure 3 shows examples of ground motion thresholds from the United States Bureau of Mines and the British Standards. These thresholds are defined such that industrial activity will not cause nuisance to nearby people or damage to structures. The Universal Building Code and other local building codes provide required design specifications for shaking which all structures should be able to withstand without failure. These existing regulations may be easily tied to seismic hazard, as both are based on actual ground motion.

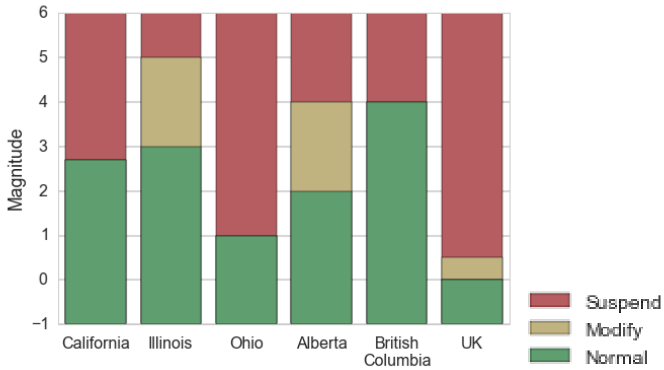


Figure 2 *Magnitude thresholds for induced seismicity regulations in selected jurisdictions.*

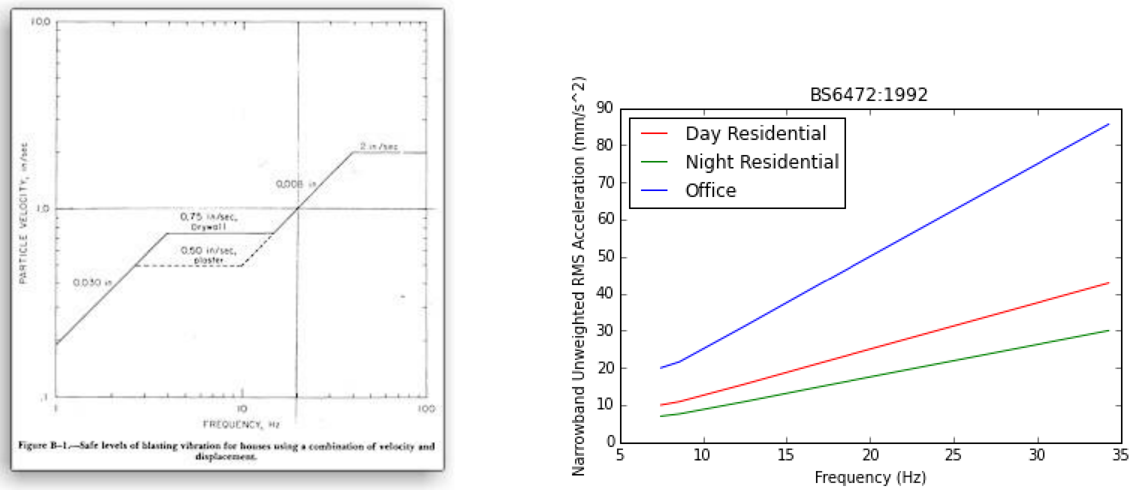
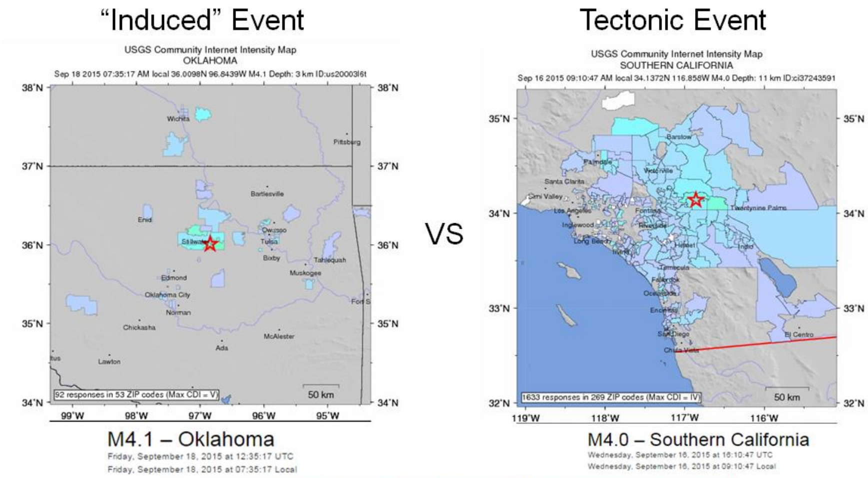


Figure 3 *(Left) Particle velocity exceedance threshold as a function of frequency from the United States Bureau of Mines (Siskind et al, 1989). (Right) British Standard 6472:1992 for RMS acceleration thresholds at representative frequencies.*

Measuring Shaking from Induced Seismicity

In a recent study, Hough (2014) examined the United States Geological Survey's "Did You Feel It?" reports for 11 instances of suspected injection-induced seismicity. By comparing those reports to the typical response from tectonic events of equal magnitude, Hough noted that the distribution of felt reports for the induced events was always smaller and concluded that the stress drops for induced seismicity are a factor of 2-10 less than tectonic events, as greater stress release produces more shaking. An example of these results is shown in Figure 4. The tectonic event is felt much farther away from the epicentre and at much stronger intensities that the potential induced event, even though they are estimated to be the same magnitude. For this reason, we propose the use of ground motion (velocity or acceleration) to evaluate seismic hazard for induced seismicity, rather than event magnitudes.

In order to understand the ground motion characteristics across a study area, we use point measures of acceleration and velocity in an empirical ground motion prediction equation (EGMPE) to interpolate over the Earth's surface in the region of interest. To determine the parameters of the EGMPE, a catalogue of seismicity is necessary. An EGMPE methodology has the potential to provide a more direct understanding of the effects of seismicity on hazard and risk than many current or proposed traffic light regulatory systems based on earthquake magnitude thresholds. The same magnitude of event can result in significantly different levels of ground shaking due to observed stress drops, event depth, radiation patterns, variations in geometrical spreading and attenuation, local surface conditions, and many other factors.



INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+
SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy

***Figure 4** Amount of 'felt' seismicity associated with a fluid-injection related induced event and a tectonic event as reported by the USGS's 'Did You Feel It?' campaign. The tectonic event was felt with greater intensity over a much larger area than the induced event. (Hough, 2014)*

Conclusions

Injection-induced seismicity and the associated seismic hazard is a complicated issue that should be addressed with a thorough understanding of the physics involved. Earthquake magnitude is a useful tool, but alone it is not enough to characterize the hazard of induced seismicity. Quantifying seismic hazard by the degree of ground shaking provides a more direct way of assessing this hazard, as well as an existing regulatory framework to build on for monitoring and mitigation purposes. Such an approach bring the oil and gas industry regulations in line with other industries where the response to ground motion is based on measured shaking, rather than

References

Alberta Energy Regulator. *Subsurface Order No. 2*. February 19, 2015.

Baig, A., Urbancic, T., and Bosman, K. *Maximum Magnitudes for Frac-Related Seismicity: Observations from Different Formations Across North America*. SEG 1st International Microseismic Technology Workshop, August 17-21, 2014.

British Columbia Oil & Gas Commission. *Investigation of Observed Seismicity in the Montney Trend*. December 2014.

Department of Energy & Climate Change, United Kingdom. *Traffic light monitoring system infographic*. December 2013.

Ground Water Protection Council and Interstate Oil and Gas Compact Commission. *Potential Injection-Induced Seismicity Associated with Oil & Gas Development: A Primer on Technical and Regulatory Considerations Informing Risk Management and Mitigation*. 2015.

Hough, Susan E. *Shaking from injection-induced earthquakes in the Central and Eastern United States.* 2014. *Bull. Seism. Soc. Am.*, **104**, pp. 2619–2626 doi: 10.1785/0120140099

Illinois Department of Natural Resources. *Notice of Proposed Amendment: 62-240 Illinois Oil and Gas Act*. 2013.

Nicholson, Barclay R. *Induced Seismicity Legal Issues Break New Ground*. Law360, May 15, 2015. *http://www.law360.com/articles/654837/induced-seismicity-legal-issues-break-new-ground*

Siskind, D.E., Stagg, M.S., Kopp, J.W. and Dowding, C.H. *Structure Response and Damage Produced by Ground Vibration From Surface Mine Blasting*. United States Bureau of Mines - Report of Investigations 8507. 1989.