Seismic hazard analysis of an induced-seismicity sequence associated with a hydraulic-fracturing stimulation in a Duvernay shale play, western Canada

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Summary

Ground motions generated by seismic activity depend on various factors including event magnitude, hypocentral location and local site conditions. Accurate analysis of ground motion is critical to assess potential risk to nearby infrastructure. Hazard assessment methods developed for natural earthquakes can be applied to induced seismicity sequences. This study investigates ground motions generated by an induced seismicity sequence during a multi-stage hydraulic fracturing stimulation in a Duvernay shale play in central Alberta, western Canada. The sequence was monitored using a dense local array consisting of short-period and broadband seismometers, which we have combined with data from the regional seismological network of Alberta. These monitoring systems allow us to calibrate a Ground-Motion Prediction Equation (GMPE) for Peak-Ground Velocity (PGV) and Peak-Ground Acceleration (PGA) at both local and regional distances and to assess their potential impacts on local infrastructure by comparing measured ground motion with the Modified Mercalli Intensity (MMI) scale.

Introduction

The recent increase in the development of some parts of the Duvernay shale play, especially in the Fox Creek area in central Alberta has been closely associated with a sharp increase of seismic activity since late 2013 (Schultz et al., 2017). Induced seismicity has been linked with the hydraulic fracturing stimulations required to enhance the productivity of low-permeability reservoirs. Monitoring these activities requires the deployment of sensor arrays during and after stimulation, which are required to better understand the seismic hazard from anomalous seismicity - especially at close distances from the stimulated reservoirs. This manuscript presents a case study involving a multi-stage hydraulic-fracturing stimulation of the Duvernay Formation west of Fox Creek. The program was monitored using a near-surface array consisting of 1C and 3C 10-Hz geophones deployed in 27-metres deep boreholes, six broadband seismometers, and one Nanometrics Titan strong-motion accelerometer (Figure 1). During the well stimulation, 17 seismic events were detected by the regional seismological network of Alberta with reported local magnitudes between 2.0 and 3.77 (Stern, 2018).

The hypocentre locations of these 17 events was re-calculated based on the recorded seismograms from the local monitoring array, based on a velocity model derived from a dipole sonic log from a vertical well located near the stimulated reservoir. The site response for each of the local monitoring stations was characterized by direct measurement of the S-wave velocity of the upper 27 metres using waveforms recorded by geophones deployed in the local seismic monitoring boreholes. These measured values were compared with the commonly used Vs30 global database developed by the U.S. Geological Survey. The Peak-Ground Velocities (PGV) and Peak-Ground Accelerations (PGA) generated by these events were measured from the waveforms recorded from the six broadband seismometers and the strong-motion accelerometer, located at a hypocentral distance of less than 5 km away from the events. These local measurements complement ground-motion parameters measured with regional seismometers located up to 500 km away. This dataset was used to develop a site-specific Ground-Motion Prediction Equation (GMPE) for the Fox Creek area calibrated for local and regional distances.

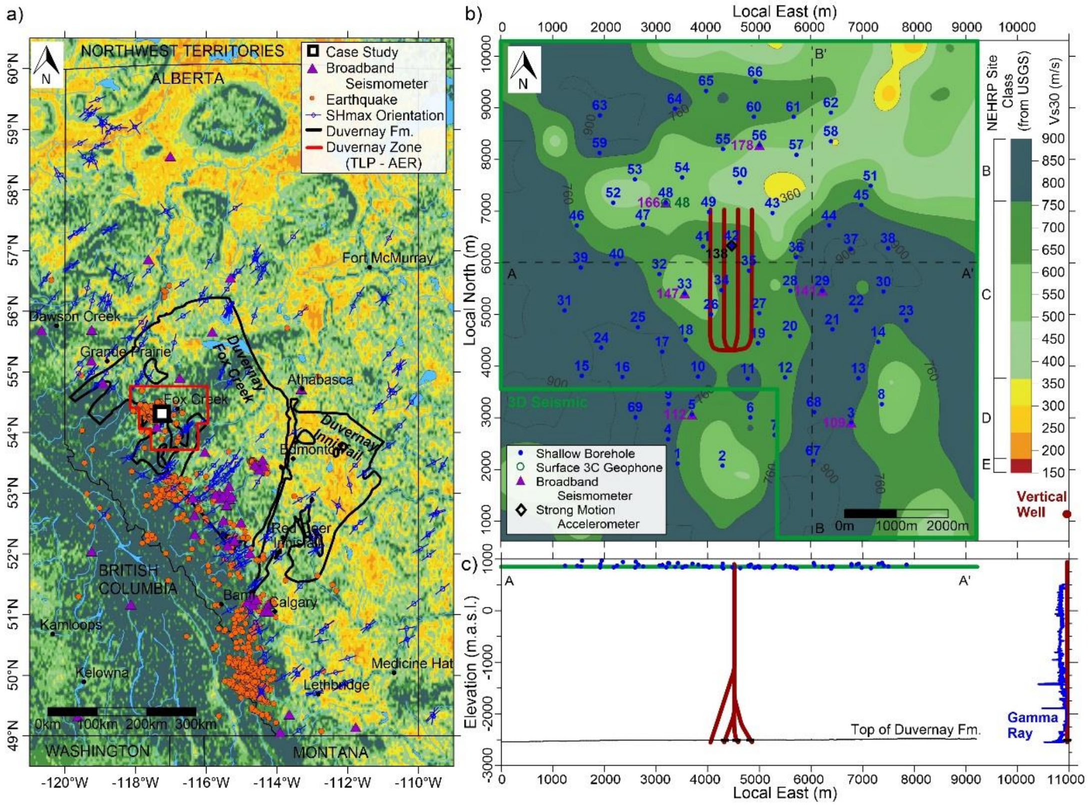

Figure 1. a) Regional seismological monitoring of natural and induced seismicity in Alberta, Canada, overlaid onto a map of NEHRP site class based on the proxy values of Vs30 from the U.S. Geological Survey (Allen & Wald, 2007). b) Enlargement of the study area with the NEHRP site class and Vs30 shown in a), and the four stimulated horizontal wells monitored with 69 borehole 3C stations, six surface broadband seismometers, one surface 3C geophone, and one strong-motion accelerometer. c) Cross section of the study area with the top of the Duvernay Formation and the gamma-ray log of the vertical well.

NEHRP site class	Description	*Vs* (m/s)	SPT blow count	*Su* (kPa)
A	Hard rock	> 1500	-	-
B	Rock	760-1500	-	-
C	Soft rock / very dense soil	360-760	> 50	> 100
D	Stiff soil	180-360	15-50	50 – 100
E	Soft soil	< 180	< 15	< 50
F	Soils requiring site-specific evaluations	-	-	-

Table 1. NEHRP (National Earthquake Hazards Reduction Program) site class definition from the average shear-wave velocity (Vs), blow count from Standard Penetrations Tests (SPT), and undrained soil strength (Su), of the shallowest 30 metres (Building Seismic Safety Council, 1997).

Site Soil Classification and Amplification Factors

The ground motions generated by any seismic event can be amplified by the near-surface conditions where the seismic station -or any sensitive infrastructure- is placed. These near-surface conditions can be standardized based on the average shear-wave velocity of the shallowest 30 metres (Vs30). Table 1 shows the Vs30 classification from the National Earthquake Hazards Reduction Program (NEHRP), where a site can be classified from soft soil to hard rock. This parameter can be first estimated from the proxy for the seismic site conditions released by the U.S. Geological Survey for the entire globe based on high-resolution topographic data (Allen & Wald, 2007). As shown in Figure 1a, the site conditions (Vs30) for Alberta, as reported by the USGS, varies between 220 and 900 m/s and for most of the studied area (Figure 1b) between 360 and 900 m/s, that corresponds to a site classes C (soft rock / very dense soil) and B (rock) from NEHRP classification (Table 1). This parameter can also be estimated from the recorded waveforms of the detected seismic events by the local near-surface monitoring array, as some of these stations have both a broadband seismometer at the surface level and a 3C 10-Hz geophone installed 27-metres deep (making it a close approximation to the 30-metre deep criteria).

Hypocentre Relocations and Ground-Motion Prediction Equations (GMPE's)

The hypocentre of the studied events was relocated from the recorded waveforms of the local monitoring network and from a local velocity model derived from the dipole sonic log of the nearby vertical well shown in Figure 1b and c. These relocated hypocentres were obtained to improve the accuracy of the hypocentral distance (R) required to derive a Ground-Motion Prediction Equation (GMPE) for these events. The Peak-Ground Velocity (PGV) was measured from the horizontal components of all the monitoring stations (both local and regional) for each event, yielding 689 measurements for the studied 17 events, covering a local magnitude range between 2.0 and 3.77 and a hypocentral distance range between 3.4 and 470 km. The local broadband seismometers clipped for the events of $M_L > 3.6$. These records were removed from the ground motion database before fitting the GMPE for PGV. The Peak-Ground-Acceleration (PGA) of the same events were measured from the Strong-Motion-Accelerometer, where none of the recorded waveforms clipped.

The following is the implemented GMPE for this dataset (Equation 4 from from Atkinson, 2015):

$$\log_{10}(Y) = C_0 + C_1 M + C_2 M^2 + C_3 \log_{10} R + C_4 R, \quad (1)$$

where Y is the ground motion parameter (PGV or PGA), M is the magnitude (in this case the Local Magnitude M_L reported for each event), R is the hypocentral distances, and C_0 to C_4 are the correlation coefficients. Figure 2 shows the obtained GMPE's for PGV and PGA for the studied events, where a sharp variation is observed at a hypocentral distance of 160-170 km due to the Moho bounce effect in central Alberta. This bounce effect is consistent with the one observed in the Western Canada Sedimentary Basin for hypocentral distances between 100 and 200 km (Yenier, 2017). The correlation coefficients for the obtained GMPE's are listed in Table 2.

	PGV (cm/s)		PGA (cm/s^2)	
Hypocentral Distance (*R*)	**< 160 km**	**> 160 km**	**< 160 km**	**> 160 km**
C_0	-3.9246	8.5823	-1.1477	9.7506
C_1	0.6615	0.0913	0.0838	0.7223
C_2	0.0420	0.0931	0.1517	0.0104
C_3	-0.3376	-6.2671	-0.6389	-6.8414
C_4	-0.009	0.0079	-0.0097	0.0097
R^2	0.8367		0.5721	

Table 2. Obtained coefficients (from Equation 1) and coefficients of determination (R^2) of the GMPE for PGV and PGA shown in Figure 2.

MMI	Perceived Shaking	Potential Damage	PGV (cm/s)	PGA (cm/s^2)	PGA (%g)
II	Weak	None	0.02	0	0.000
III	Weak	None	0.09	1	0.001
IV	Light	None	0.31	8	0.008
V	Moderate	Very Light	5.2	43	0.043
VI	Strong	Light	9.5	116	0.119
VII	Very Strong	Moderate	14	165	0.169
VIII	Severe	Mod./Heavy	35	360	0.367

Table 3. Potential damage related to PGV and PGA for each Modified Mercalli Intensity (MMI) level (Atkinson & Kaka, 2007).

Seismic Hazard Analysis and Applicable Regulations

The Alberta Energy Regulator (AER) implemented in 2015 a local magnitude-based Induced-Seismicity Traffic-Light Protocol (IS-TLP) for the Duvernay Zone near Fox Creek (Figure 1) in response to the increased risk on injection-induced seismicity (Shipman et al., 2018). This TLP stipulates that operators must report to the regulator when a seismic event of M_L between 2.0 and 4.0 is detected (amber light), and operations must be immediately ceased when a seismic event of M_L above 4.0 is detected within 5 km of a hydraulic fracturing well (red light). This criteria, based entirely on a magnitude scale, may be prone to controversy due to inherent uncertainty in magnitude calculations (Kao et al., 2018). In addition, the land disturbance and possible damages caused by any seismic event depend on the ground motions that it generate, which vary depending on hypocentral distance, local site conditions and magnitude. A GMPE, as the ones obtained in this study for the Fox Creek area, conveniently correlates these parameters, allowing a more detailed seismic hazard analysis. Table 3 shows a proposed correlation between ground-mortion parameters (PGV and PGA) with the Modified Mercalli Intensity scale (MMI) that characterize the potential damage that a determined ground motion level can generate. These parameters are also shown in Figure 2 with the obtained GMPE's, where no measured ground motion exceded level V from the MMI scale, meaning that some of these events could have been perceived at close distances but none of them had the potential to cause any property damage. A PGA threshold of 2% of the gravity acceleration implemented by the British Columbia Oil and Gas Commission (BCOGC) for their TLP in two areas in Northeast BC (not applicable in Alberta), is also shown for comparison in Figure 2. In this case, only one event exceeded this threshold.

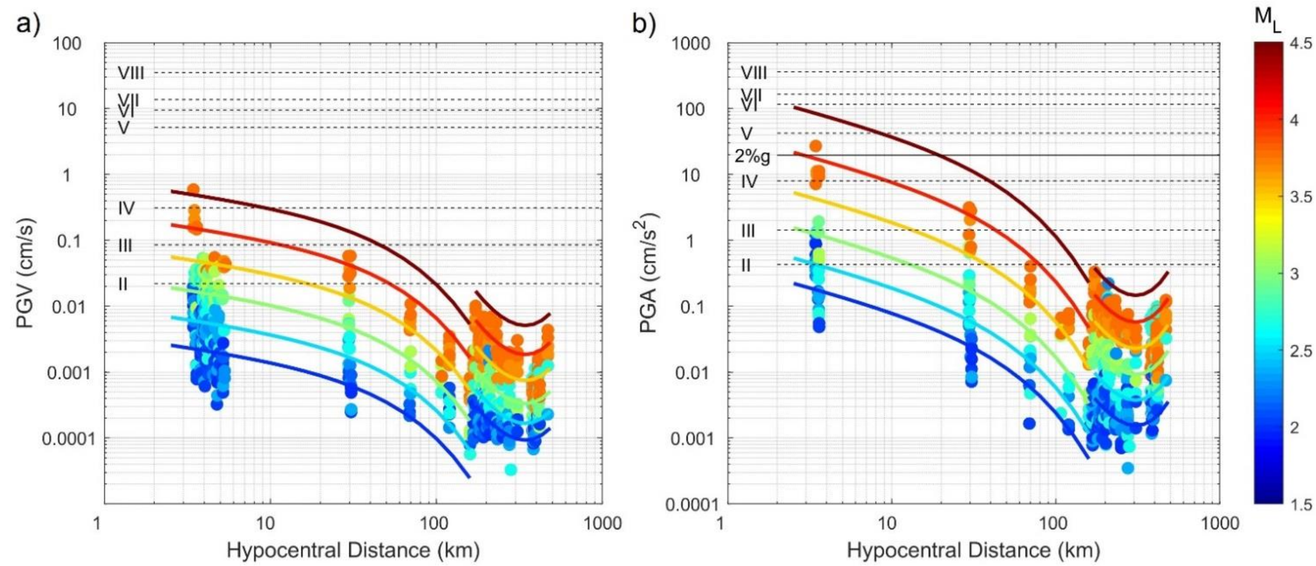

Figure 2. Obtained GMPE's (from Equation 1 and Table 2) for Peak-Ground-Velocity (PGV) and Peak-Ground-Acceleration for the Fox Creek area, with the Modified Mercalli Intensity (MMI) scale from Table 3. Note a sharp variation in the GMPE's (contour lines) at a hypocentral distance of 160 km caused by the Moho bounce effect.

Conclusions

We have developed a site-specific Ground-Motion Prediction Equations (GMPE) for the Fox Creek area, which uses the reported local magnitude of seismic events to estimate ground motions at different distances. This GMPE allows a convenient correlation among different regulations applicable to induced seismicity based on different parameters. The calibration of the GMPE's at close distances was possible thanks to the installation of a dense local monitoring array, which allowed more accurate hypocentre locations and therefore more accurate hypocentral distances. The duality of the local monitoring array (i.e. the installation of both short-period and broadband sensors) also allowed a reliable measurement of low-frequency ground motions as those expected for the "amber" light events (events of $2.0 > M_L > 4.0$) detected during the studied hydraulic-fracturing stimulation. The additional installation of a strong-motion accelerometer mitigated a clipping problem observed for some waveforms recorded with the short period and broadband seismometers. Finally, the seismic hazard of the studied events was assessed directly from the measured ground motions (and the GMPE's obtained from them) by comparing them with the Modified Mercalli Intensity scale (MMI) from different ground-motion levels. In this case, no event surpassed level V from the MMI scale, meaning that none had any potential to cause infrastructure damage.

Acknowledgements

We thank to all the sponsors of the Microseismc Industry Consortium at the University of Calgary, and the Natural Science and Engineering Research Council of Canada (NSERC) for providing financial support (grant IRCPJ/485692-2014). We also thank the operator companies of the studied shale-gas reservoir for supporting the near-surface local seismic monitoring program acquired under license using MicroSeismic Inc.'s BuriedArray® design.

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