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IMPACT OF INDUCED SEISMICITY ON THE EVALUATION OF SEISMIC HAZARD

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ABSTRACT: A case study of seismicity induced by hydraulic fracturing operations near Fox Creek, Alberta, is used to evaluate the extent to which the potential for induced seismicity at a site alters the pre-existing hazard from natural seismicity. We first overview the apparent correlation between seismicity and oil and gas activity, then explore the impact of an induced seismicity source on seismic hazard. We find that in low-to-moderate seismicity environments, the hazard from an induced-seismicity source, if one is activated in close proximity to a site, can greatly exceed the hazard from natural background seismicity over a wide frequency band, especially at the low probability levels of concern to critical structures. The most important parameters in determining the induced-seismicity hazard are the activation probability, the b-value of the initiated sequence, and the minimum and maximum magnitudes over which to integrate the hazard. The ground-motion prediction equations and their epistemic uncertainty are also important. Uncertainty in the value of the key input parameters to a hazard analysis implies large uncertainty (more than an order of magnitude) in the likelihood that induced seismicity will result in potentially-damaging ground motions.

1. Introduction

Induced seismicity is the occurrence of earthquakes that are triggered by industrial processes including energy technologies, mining, and reservoir impoundment. Induced seismicity has recently become a pressing global problem. Improvements in hydraulic fracturing and horizontal drilling have unlocked tight reservoirs around the world, ushering in a new oil and gas boom. The rise in the unconventional production of oil and gas has been coupled with a dramatic increase in the rate of seismicity in many parts of central North America in the last five to ten years (Ellsworth, 2013). In the central United States, the rate of moment magnitude (**M**) 3 and larger earthquakes has increased from a long-term average of 21 such earthquakes per year between 1970 and 2000, to 31 per year during 2000-2008, to 151 per year since 2008. Most oil and gas operations do not trigger seismicity above the felt threshold, but a small percentage of operations trigger events large enough to be felt (NRC, 2012), and an even smaller percentage trigger potentially-damaging events. For example, events as large as **M**5.7 are believed to have been triggered by deep disposal of fluids (Keranen et al., 2013; Sumy et al., 2014). The basic mechanism of induced seismicity is widely agreed-upon: it is caused by a change in pore fluid pressure and/or a change in the state of stress, which may cause re-activation of existing faults or fractures. However, currently we cannot predict the likelihood or magnitude of such events from specific planned operations because we do not have enough data on the complex natural rock systems, nor do we have validated predictive models.

Since about 2008, tight oil and gas reservoirs in western Canada have increasingly been developed by drilling wells horizontally through the reservoir rock, at depths of a few km, and using multi-stage hydraulic fracturing techniques to create new fractures in the reservoir, allowing hydrocarbons to migrate up the well bore. The horizontal segment of the well typically extends over a distance of ~1.8 to 3 km. A hydraulic fracture is a controlled, high-pressure injection of fluid and proppant to fracture the target formation.

Hydraulic fracturing in western Canada has in some instances been associated with significant induced seismicity. A series of earthquakes, the largest being **M**3.8, were triggered by hydraulic fracturing in the Horn River Basin of northeastern B.C. (B.C. Oil and Gas, 2012). In the last few years, several sequences of seismicity at the **M**>3 level have been induced by hydraulic fracturing in western Alberta and northeastern B.C. (Atkinson et al., 2015), with the largest events to date being just over **M**4. The maximum magnitude of the events that could be triggered is not yet known. One hypothesis holds that the maximum magnitude is limited only by the size of the fault that is re-activated (e.g. Petersen et al., 2015), while another postulates that the maximum magnitude will be limited by the cumulative volume of fluid injected into the area (e.g. McGarr, 2014).

In this paper, we explore the impact of induced seismicity on hazard at a site near Fox Creek, Alberta, using information from the new TransAlta/Nanometrics seismographic network, installed in 2014 in connection with the Canadian Induced Seismicity Collaboration at Western University (www.inducedseismicity.ca). Fox Creek makes a good case study because it is in an area of previously-low seismicity which suddenly became active in Dec. 2013, and has since hosted dozens of events of **M**>2.5, with observed events as large as **M**=3.9 The presumed cause of the seismicity is hydraulic fracturing, due to strong spatial and temporal correlation (Shultz et al., 2015). It is noteworthy that there are no disposal wells nearby, and therefore large-volume injection wells are not a potential cause for the induced seismicity. We first overview the apparent correlation between seismicity and oil and gas activity, then explore the impact of an induced seismicity source on seismic hazard. The focus here is on induced seismicity due to hydraulic fracturing in horizontal wells; we do not consider other potential induced-seismicity sources.

2. Spatial and Temporal Correlation between Earthquakes and Wells

In Figure 1 we provide an overview of seismicity and the locations of hydraulically-fractured horizontal wells (HF wells) in western Alberta. Locations and magnitudes of earthquakes were obtained using catalogue information from the TransAlta/Nanometrics seismographic network in Alberta (available at www.inducedseismicity.ca), while the information on HF wells comes from the public records of the Alberta Energy Regulator (AER). Figure 2 shows the number of events and the number of HF wells since 2000 in Alberta. It is apparent that the number of HF wells increased greatly in western Alberta as of 2010, and as of 2013 there has been a marked increase of detected seismic events at the **M**>2 level. However, the number of seismographic stations has also increased since 2010, which is undoubtedly at least partly responsible for the increased number of **M**>2 events. It should be noted that the detection threshold is not as low as **M**2 in all parts of western Alberta, even today, so that the detected number of **M**>2 events should be considered as a lower bound on the number of **M**>2 events that actually occurred. It is interesting in Figure 2 that a small number of HF wells appears to be associated with a relatively large number of earthquakes.

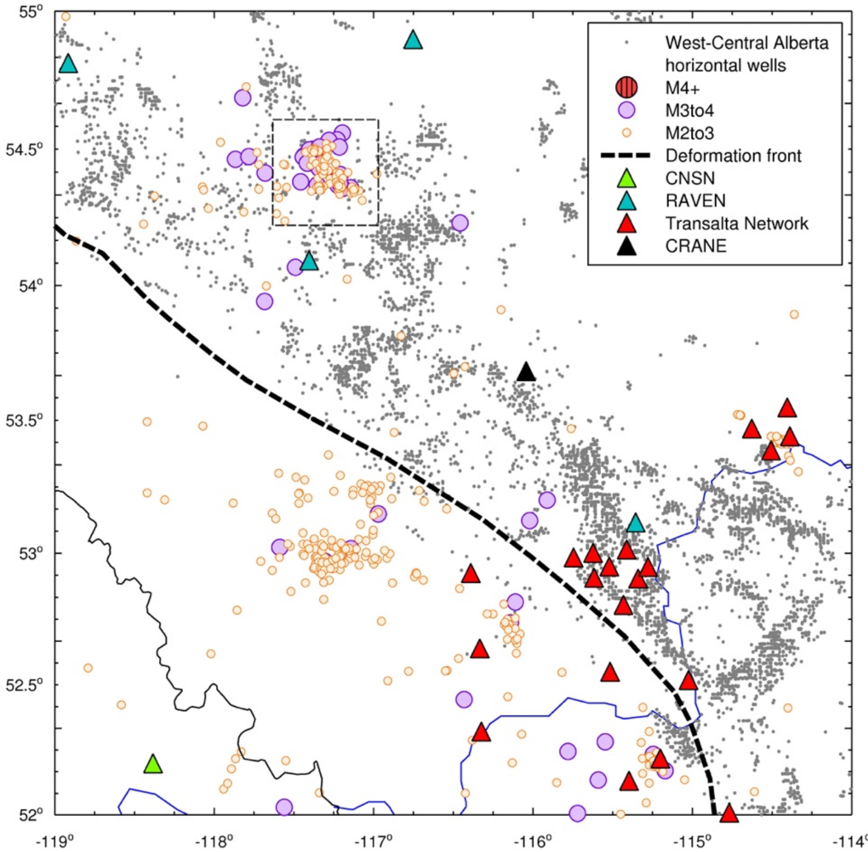

Fig. 1 – Seismicity in Alberta of M>2 since 2007. Events are colour-coded based on their moment magnitude. Seismic stations from different networks shown by triangles. Grey dots are the location of hydraulically-fractured wells. Approximate trace of the Rocky Mountain deformation front is shown with black dashed line. Fox Creek area denoted by black dashed box.

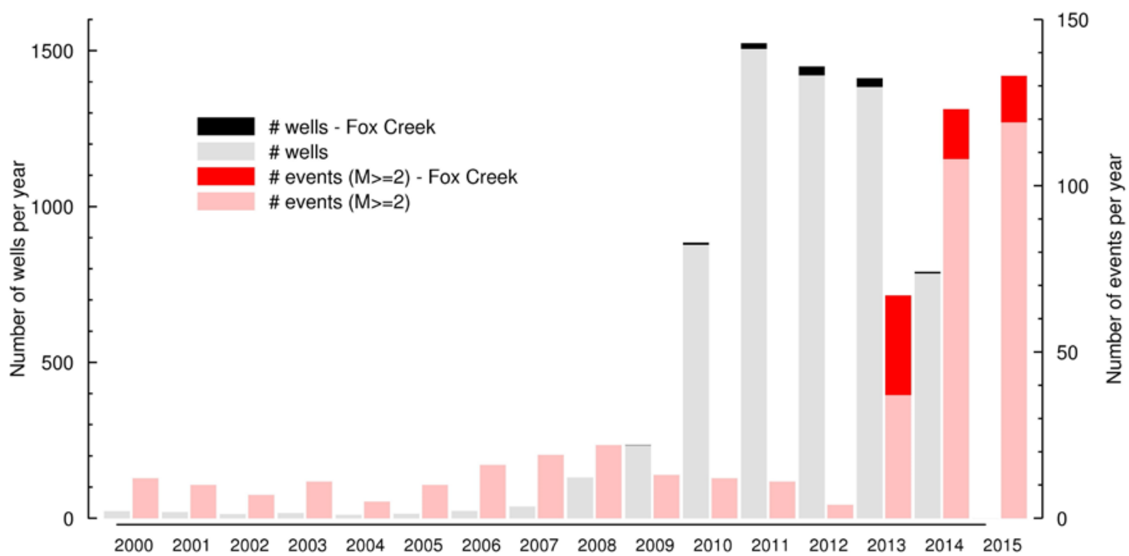

Fig. 2 – Number of seismic events of M>2 in comparison to the number of wells for the area shown in Fig. 1; the Fox Creek contributions are shown at the top of each bar.

The fact that both the number of HF wells and the number of earthquakes are increasing in time does not necessarily suggest any causal relationship. If the HF wells are inducing earthquakes, they must precede the earthquakes in time, and be closely related in space. We used a simple methodology to determine if there is a spatial and temporal correlation between oil and gas activity and seismic events. This involved scanning the well database from AER to count the number of HF wells with earthquakes of **M**>2, **M**>3, **M**>4 within a 20 km radius. The 20 km figure for potential spatial correlation, over the entire area of Fig. 1, was chosen as an upper bound on the likely correlation distance considering a number of factors. These factors include the following considerations: (i) the location uncertainty in events is typically 10 km in most areas and sometimes larger, as evidenced by differences in event locations quoted by different agencies (AGS, GSC) for the same events; (ii) events might be induced at distances up to a few km from the causative well, as the fluid pressures diffuse along local faults and fractures; and (iii) the HF wells may be several km in lateral extent. It should be noted that that we did not consider earthquake depth in this correlation check, because the large uncertainties in focal depths for the vast majority of events in the catalogue preclude such a check.

Once a potential spatial correlation was identified, a check was made for a temporal link. We considered that there is a potential temporal correlation if the event occurred within a window beginning with the date drilling was completed and ending ~1 month after the "on production" date. Previous studies suggested that triggered earthquakes usually occur either during or hours after hydraulic fracturing begins (Holland, 2011; BCOGC, 2012) but this appears to be changing. In particular, in Fox Creek some of the larger events have occurred during flowback operations after the completion of hydraulic fracturing (Schultz et al., 2015).

Table 1 summarizes the number of wells that meet both the spatial and temporal correlation criteria, at each magnitude level, for the area of Fig. 1 as a whole, and also for the Fox Creek area (box on Fig. 1). From these statistics, we can make a rough initial estimate of what percentage of all wells fracked may result in at least one event, above each **M** level that we are considering. However, we must bear in mind that the count is incomplete at the **M**2 level due to the limited number of stations. Furthermore, of the 7102 total wells in our database, 397 wells are not considered in this study since the "on production" dates are not reported (thus they may not yet have been fracked). Finally, the well data are not complete for 2014 so we may be missing some wells that are potentially correlated with seismicity in 2014.

Table 1 – Number of horizontally-fractured wells in study region that may be associated with seismicity, at magnitude thresholds of 2, 3 and 4.

Year	M>=2	M>=3	M>=4	Whole region	M>=2	M>=3	M>=4	Fox Creek
				# wells fracked/yr				# wells fracked/yr
2006	0	0	0	25	0	0	0	0
2007	1	0	0	39	0	0	0	0
2008	1	0	0	131	0	0	0	0
2009	3	1	0	237	0	0	0	2
2010	6	1	0	903	0	0	0	7
2011	8	2	0	1526	0	0	0	19
2012	6	3	0	1436	0	0	0	29
2013	82	16	0	1402	4	3	0	28
2014	73	3	0	797	1	0	0	5

Based on Table 1, we see that there has been a significant rise in both the number of horizontal wells and those that may be associated with seismicity. If the relation is indeed causal, it appears that the rate of induced events at the **M**>3 level is of the order of 1/100 to 1/1000 on a per well basis in the region as a whole. In Fox Creek, the rate is higher, perhaps as high as 1/10. It is important to note that the record of **M**>2 events in the Fox Creek area is incomplete due to the sparse station coverage. We reiterate that there are no disposal wells or other suspected sources of induced seismicity in this area.

Figure 3 examines the wells in the Fox Creek area that appear to be correlated with seismicity in each year. Prior to 2012, there were no detected seismic events in the area. Over the period from 2009 to 2012, over 100 wells were hydraulically fractured in the area with no associated seismicity. Then in 2013 there was an abrupt acceleration of induced events, that continues to this day. The apparent association between the HF wells and seismicity is strong (see Schultz et al., 2015 for more details). About 1/10 to 1/100 wells in this area appear to trigger significant seismicity. By comparison, in western Alberta as a whole this rate appears to be an order of magnitude lower. In the following sections we examine the hazard implications of the observed rates of induced seismicity from hydraulic fracturing. We first look at the hazard from natural sources in the area, then examine how the additional events change that hazard. The focus is on the low probabilities that are of most concern to critical facilities.

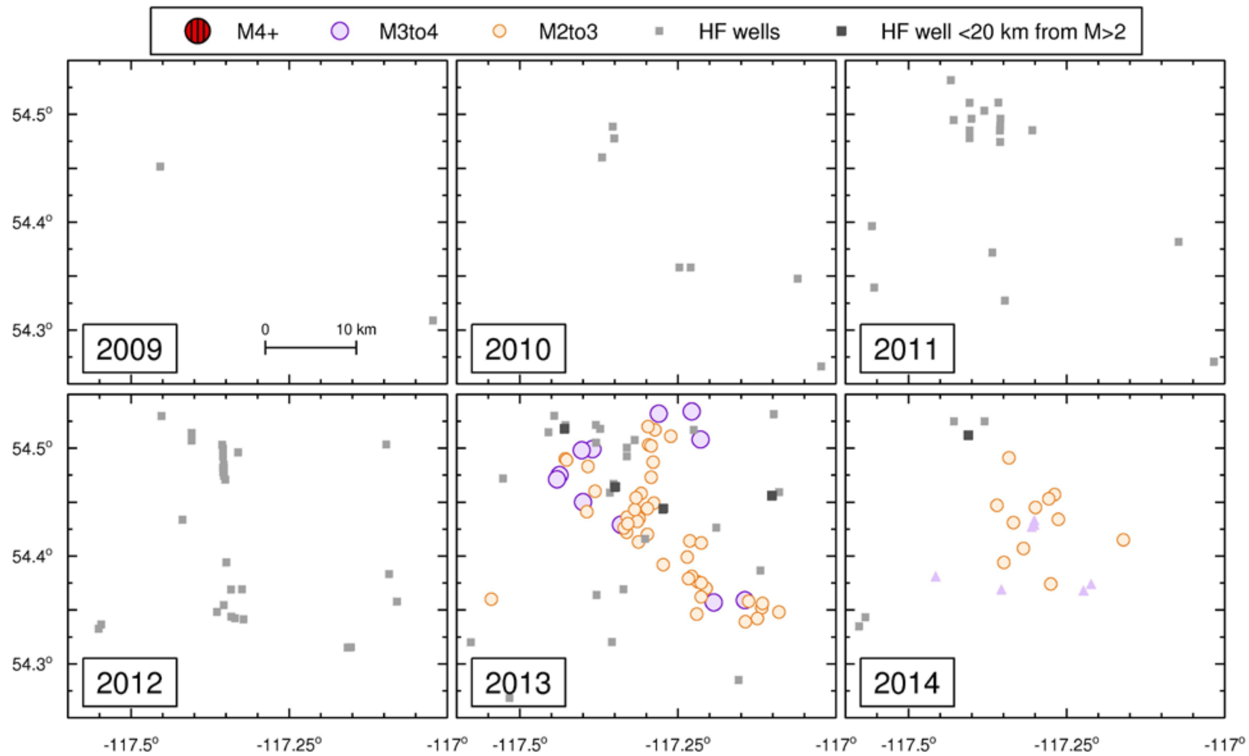

Fig. 3 – Seismicity (circles) and HF wells (squares) in the Fox Creek area in each year since 2009. Darker squares are wells that satisfy the potential correlation criteria at the M>2 level. The triangles in the panel for 2014 show M>3 events that have occurred in the first 3 months of 2015 (no well information yet available for 2015).

3. Seismic Hazard at Fox Creek from Natural Sources (2013)

We use the national seismic hazard model of the Geological Survey of Canada (GSC), developed in 2013 for the 2015 National Building Code of Canada (Halchuk et al., 2014) as the benchmark for the hazard prior to the commencement of the induced seismicity near Fox Creek. For this exercise, we follow the classic probabilistic seismic hazard analysis (PSHA) methodology as originally developed by Cornell and McGuire, using the EQHAZ software (Assatourians and Atkinson, 2013) for the calculations. We select a site in the middle of the area that is currently active (small box shown in Fig. 1). The baseline model from GSC, assuming uniform seismicity distributed over a broad regional zone, is adopted without modifications, and does not reflect any of the induced seismicity from 2013 to the present. Therefore our calculations will mirror those of the GSC for the 2015 hazard maps (as given in Halchuk et al., 2014). We note that some of the regional events in the baseline seismicity prior to 2013 may have been induced, and therefore the "natural seismicity hazard" may have some influence from induced events that have occurred in the past in the region. However, there are no previous historical seismicity clusters anywhere near Fox Creek, and thus any contributions to hazard from induced seismicity can be assumed negligible prior to 2013.

We adopt the GSC magnitude-recurrence parameters and uncertainty estimates as given in Halchuk et al. (2014). The ground motion model, also adopted directly from the GSC national hazard model, is a three-equation suite that represents median motions and their epistemic uncertainty, for B/C site conditions (shear-wave velocity of 760 m/s), as described by Atkinson and Adams (2013). Aleatory variability is also included as specified in the GSC model. The Fox Creek site is near the boundary between active tectonics in western North America (WNA), and stable craton tectonics in eastern North America (ENA); this roughly follows the deformation front indicated on Fig. 1. There are thus two ground motion models employed in this region, one for shallow crustal earthquakes west of the deformation front (WNA) and one for events to the east (ENA). The zone in which the site is located draws from the western model, while the less-active regions to the east use the eastern model; the reader is referred to Halchuk et al. (2014) for details.

The uniform hazard spectrum (UHS) for Fox Creek, calculated using EQHAZ and the GSC hazard model, considering natural seismicity as of 2013, is shown on Figure 4 for a probability of exceedance of 1/10,000 per annum (p.a.). This probability is commonly used to check the seismic resistance of critical structures such as dams and nuclear power plants. The UHS plots the mean-hazard values of the response spectrum (5% damped pseudo-spectral acceleration, horizontal component, on B/C site conditions) for the stated annual probability, at selected frequencies of vibration. Fig. 4 also shows the UHS that results from the potential for induced seismicity from hydraulic fracturing, which will be described in more detail in the next section.

To place the UHS in context, we show a few scenario events, drawn from the median branch of the WNA ground-motion prediction equation (GMPE) suite, with one standard deviation added, in comparison to the UHS. We choose a median-plus-sigma GMPE level as this is typically a strong contributor to hazard. It is observed that the 1/10,000 motions from the natural-seismicity hazard are similar to those expected from events of **M**~6.75 at distances ~80 km. By comparison, moderate events (**M**~5) at close distances may cause stronger motions than these scenarios at high frequencies, but much weaker motions at low frequencies (<1 Hz). As we show next, these are the type of motions expected from potential induced seismicity sources.

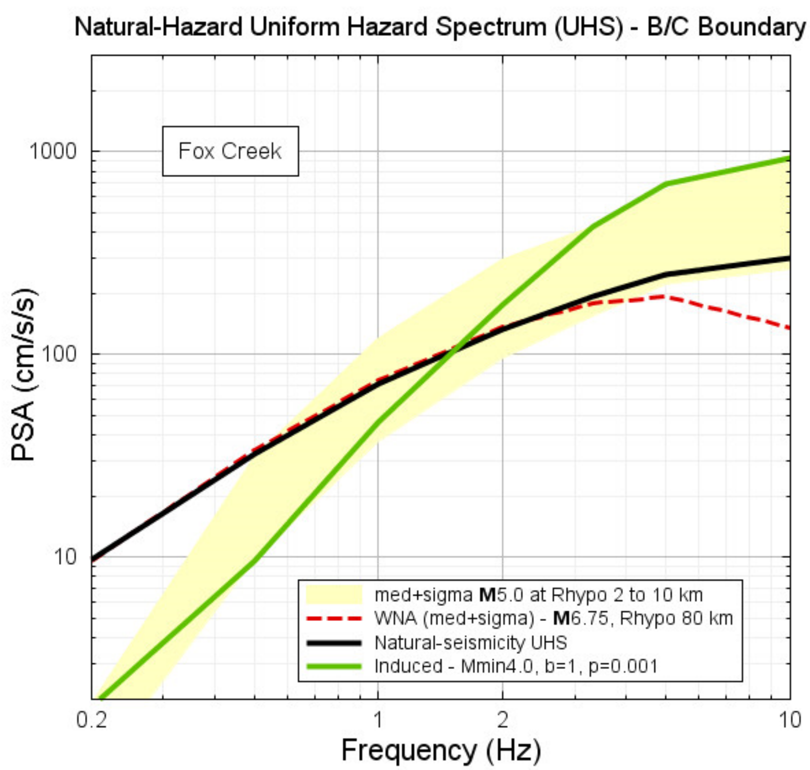

Fig. 4 – The UHS for Fox Creek at 1/10,000 p.a. as of 2013 due to natural seismicity. The corresponding UHS for induced seismicity (described in the next section) is also shown. Expected motions (medium GMPE plus sigma) for several scenario events are shown for comparison: M6.75 at 80 km (hypocentral distance), and M5.0 at 2 to 10 km.

4. Seismic Hazard Model at Fox Creek from Induced Seismicity (2014-2015)

In December of 2013, the seismicity rate at Fox Creek changed dramatically when a sequence of events of **M**>3 was apparently initiated by hydraulic fracturing. The hydraulic fracturing took place at a depth of about 2 km, which is the presumed depth of the seismic activity; this also agrees with estimated depths from preliminary regional moment tensor analyses (A. Babaie Mahani, pers. Comm., 2015; W. Greig, pers. Comm., 2015). The details of the operations that induced the seismicity are just now starting to be released (information on hydraulic fracturing locations and volumes becomes public about 1 year later). However, the sequence is known to have been frack-induced, in part because there are no disposal wells or other plausible sources nearby, and in part by the information currently available on the timing of the events in relation to hydraulic fracture operations that were taking place in the area (Schultz et al., 2015). Moreover, in Jan. 2015, there were an additional 24 events of **M**≥2 in the same area, six of which had **M**>3. The largest event, which occurred Jan. 23, 2015, had an estimated **M**=3.9 (Novakovik and Atkinson, 2015), though its local magnitude was significantly higher: ML=4.4; the estimated depth is 2.1 km. The events were all located in a small area near Fox Creek, which we have represented as a new seismic source zone, whose extent is given approximately by the small (~10×10 km) inner square in Figure 1 (latitude 54.355° to 54.445°, longitude -117.377° to -117.223°). We are considering the hazard for a site in the center of this activity. Thus it is important to recognize that the results will apply only to sites in very close proximity (within a few km) to such operations.

In the following we describe briefly the parameters used in the PSHA calculations for the induced-seismicity source. We are guided by the Fox Creek example, but the approach is quite generic and could be applied to other cases of induced seismicity. Further information and sensitivity analyses are provided in Atkinson et al. (2015).

4.1. Magnitude-recurrence parameters

The rate of events that contribute to the hazard will be controlled by the rate and slope parameters of the Gutenberg-Richter relation, and the minimum and maximum magnitudes over which the contributions to hazard are integrated. We use a truncated-exponential Gutenberg-Richter relation to characterize the magnitude recurrence parameters for the induced-seismicity source. We assume an event rate of ~10 **M**≥3 events in a year. This might be the applicable rate, in the short term, if frequent operations are expected to continue inducing seismicity at the rates observed at Fox Creek in the last year or so. We assume a typical regional b-value (slope of the Gutenberg-Richter relation) of 1.0 (Adams and Halchuk, 2014). This rate appears to be consistent with observed rates in the Fox Creek area (Atkinson et al., 2015).

The minimum magnitude considering in the hazard analysis, **M**min, is an important parameter that exerts significant influence on the results. Induced events are much shallower than natural events on average, and may thus cause strong ground motions at close epicentral distances (Atkinson, 2015; Hough, 2014). Moreover, it has been observed that induced events of **M**3.5 have caused some damage to vulnerable structures (Giardini, 2009). For natural events, of average focal depth (10 km), **M**min=4.75 is typically used (e.g. Adams and Halchuk, 2014), as smaller events have not generally been observed to cause damage to well-engineered structures. One approach to estimate the appropriate **M**min for induced events is to calculate the magnitude that produces the same amplitude of ground shaking as that produced by **M**=4.75, assuming the focal depth is 2 km instead of 10 km. If we use peak ground velocity as an index parameter for damaging ground motion, we would infer that an appropriate **M**min for events at 2 km focal depth is **M**=3.6 (i.e. an event of **M**3.6 at R=2 km produces the same PGV as an event of **M**4.75 at R=10 km, according to the GMPE of Atkinson, 2015). However, the **M**3.6 event may be less damaging due to its very short duration and high-frequency nature. To consider this, we adopt a value of **M**min=4.0 for this exploratory analysis.

The maximum magnitude (**M**max) for hydraulic-fracture-induced events is not known, but the largest observed event has increased over time, and thus any absolute maximum that may exist has probably not yet occurred. In this study we take a value of **M**=4.5 as a lower bound on Mmax. For the upper bound on **M**max, we assume an event that is somewhat smaller than the maximum magnitude for natural events and weight the distribution towards low to moderate values of **M**max. We use a logic-tree format to represent the assumed probability distribution of **M**max to input to the PSHA, with branch weights (w_i) as follows: **M**max=4.5 (w_i =0.4); **M**max=5.0 (w_i =0.3); **M**max=5.5 (w_i =0.2); **M**max=6.5 (w_i =0.1). We note that more extreme scenarios for **M**max have not been considered here - we are placing most of the weight towards the low end of the distribution, while allowing for some possibility that **M**max could be as large as 6.5. A more conservative approach would be to consider that the distribution of **M**max is the same for natural and induced seismicity sources (e.g. Petersen et al., 2015). Sensitivity tests have shown that the results are not very sensitive to the distribution of **M**max (e.g. see Atkinson et al., 2015). For example, if we halved the weight given to the two larger values of **M**max, redistributing that weight onto the lower two values, our conclusions would not change significantly.

4.2. Ground-Motion Prediction Equations (GMPEs) for induced seismicity source

Most GMPEs are not well suited for induced seismicity applications, as they were not derived to adequately model amplitudes for moderate events at the very close hypocentral distances that result for shallow events. Specifically, for this exercise, we consider that the source depth will be in the range of 2 to 5 km, weighted as follows: h=2 km (w_i =0.3), h=3 km (w_i =0.4), h=5 km (w_i =0.3). This depth range is consistent with induced seismicity in the Fox Creek area. Thus the GMPE needs to be applicable for small to moderate events at hypocentral distances as small as 2 km.

We adopt the Atkinson (2015) GMPE developed for **M**<6 events at distances < 40km, parameterized in hypocentral distance (Rhypo), as a representative model for induced-event ground motions. We construct upper and lower branch models to model its epistemic uncertainty, in an analogous approach to that taken by Atkinson and Adams (2013) for the GSC national model. This will provide a simple three-branch ground-motion model, consisting of a central, lower and upper GMPE for median motions. The epistemic uncertainty is very significant at close distances (Atkinson, 2015), and thus the lower and upper GMPE curves will spread widely. At larger distances (where focal depth is unimportant) the amount of epistemic uncertainty should converge to that in the Atkinson and Adams (2013) uncertainty model. It should be further noted that aleatory uncertainty is larger for induced events than for natural events, as discussed in Atkinson (2015) and Douglas et al. (2013). The GMPE model and its uncertainty is of critical importance to the seismic hazard result, which is why we focus explicitly on the magnitude-distance range of interest, and consider the implications of large epistemic uncertainty at short hypocentral distances.

5. Comparison of Induced-Seismicity to Natural-Seismicity Hazards

Figure 5 provides an overview of the induced-hazard curves in comparison to the corresponding curve for the natural-seismicity hazard. Here we have assumed that the probability of inducing a sequence characterized by a rate of 10 **M**≥3 events p.a. is in the range of 0.01 to 0.001. Therefore the assumed rate of **M**≥3 events is effectively 0.01 to 0.1 on a per well basis (the product of the rate and the activation probability). The other parameters of the PSHA are as given in Section 4. Figure 5 shows that the ground motions attributeable to the induced-seismicity hazard clearly exceed those from the natural-seismicity hazard at all probability levels of interest, at least for frequencies of 1 Hz and greater, PGA (peak ground acceleration) and PGV. We caution that this statement is heavily conditioned upon the fact that this region has a low background level of natural seismicity. In areas of high natural seismicity, the relative impact of the induced seismicity source would be much less, because the natural-hazard curves would be at a much higher level.

In conclusion, for a reasonable range of input parameters to a PSHA, the seismic hazard from an induced-seismicity source representing hydraulic fracturing at close proximity can greatly exceed the hazard from natural seismicity, in settings where the natural hazard is low. This is because the induced seismicity source presents the potential for significant events at very close distances, which can cause large ground motions. This issue is particularly important for critical infrastructure, for which the target reliability levels are high. Further research is required to understand the parameters that control the hazard, and to develop approaches for hazard mitigation.

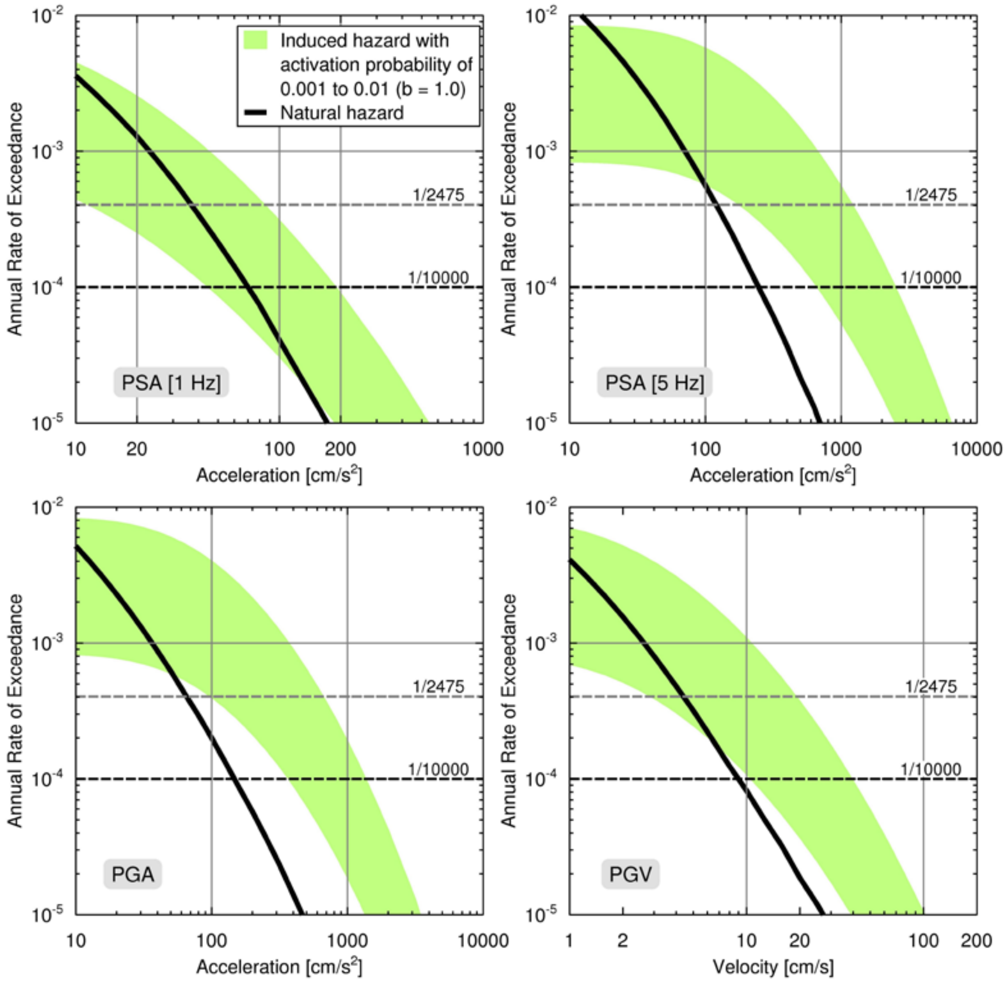

Fig. 5 – Induced-seismicity hazard curves at Fox Creek showing effect of activation probability in the range from 0.01 to 0.001 p.a., for an assumed rate of 10 M>3 p.a. with a b-value of 1. (Mmin=4.0, Mmax is a distribution from 4.5 to 6.5).

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