Induced Seismicity Hazards arising from Oil and Gas Operations – an October 2014 Perspective

Mahendra Samaroo, PEng, PGeol

Energy Technical Services, Resource Development Policy Division, Alberta Department of Energy

Root causes of induced seismicity[1]

Induced seismicity is a term given to earthquakes that are attributable to human activities. Induced seismic events generated by oil and gas operations are usually a consequence of fluid injections or withdrawals, which cause changes in pore fluid pressure, temperature and volume. These processes lead to stress state changes in the rock mass, and may lead to induced shear slip of critically stressed rocks or faults. Usually the hazard factors that have the most impact on induced seismicity are:

(i) The net fluid balance, i.e. the total balance of fluid injected into or removed from the subsurface, at any point in time, which is the volume change effect. The induced seismicity hazard typically increases with the net volume of fluid injected into (or withdrawn from) the subsurface.

   a. Large net fluid injections into the subsurface have the potential to alter stresses and pressures and facilitate movement of faults, thereby triggering sudden ground movement.
   b. Alternatively, large net fluid withdrawals from the subsurface have the potential to trigger reservoir compaction and associated ground subsidence (sinking) as a result of the increased matrix stress, and the large stress redistributions that accompany this process can also trigger sudden ground movement.

(ii) The presence of faults within range of the injection activities (i.e. within the radius of influence of the injection activities) and the stress state of any such faults are key aspects of induced seismicity. The existence of faults close to a critical stress state within the radius of influence of injection activities increases the associated seismic hazard.

(iii) The state of stress of the rock formations in the target (injection or withdrawal) zones affects induced seismicity. In particular. over-pressured or overstressed rocks, such as in a tectonic environment, typically present a higher risk of induced seismicity

(iv) The location of the target (injection) zone with respect to (hot, dry and fractured) crystalline basement rock will impact induced seismicity because of massive cooling of the rock from cold water injection, as in a waterflood into a hot reservoir.

(v) The magnitude of the temperature differential between the injected fluid and the target formation affects the induced stress state. Injection of a cold fluid into a hot, dry rock to extract heat will cause volume shrinkage from rock cooling, which could generate seismicity.

(vi) Steam injection into viscous oil reservoirs causes thermal expansion, which also triggers slip.

Many conventional oil extraction activities such as gas injection and water flooding are designed to maintain fluid pressure in underground reservoirs, in order to maximize hydrocarbon displacement from the pore spaces of the rock and enhance recovery. This is typically achieved by maintaining a balance between the volume of fluid extracted and the volume of fluid injected (usually achieved by monitoring the reservoir voidage replacement ratio). Therefore the seismic hazard potential of such conventional oil extraction activities is typically low.

However, extraction strategies without pressure maintenance injection usually involve reservoir pressure depletion, and this also generates volume changes and stress changes that may lead to shearing of the reservoir rock, usually involving slip along pre-existing weak surfaces such as joints,

[1] National Academy of Science, "Induced Seismicity Potential in Energy Technologies", 2012

faults or bedding planes. For example, gas extraction activities may inherently have a greater seismic hazard potential than conventional oil activities because pressure maintenance is never used as part of the operating strategy.

The occurrence of seismicity associated with gas reservoir depletion is well documented in existing case histories, such as that of the Groningen Gas Field in the Netherlands. Reservoir pressure depletion in this field because of gas production triggered differential compaction, which induced approximately 1000 seismic events of magnitude 1.5 to 3.6 (Richter magnitude) during the period 1986 – 2013 (Figure **1**). The largest seismic event experienced during this period was of magnitude 3.6 (August 2012), which resulted in 2,000 (non-structural) claim damages to (mainly) local residences. This event raised concern about the level of acceptability of damages and the possibility of future larger events and associated structural damage. The Dutch State Supervision of Mines' subsequent investigation[2] concluded that the frequency of occurrence of seismicity in the Groningen field had increased over time as a function of the gas production rate, and the increased frequency of seismic event occurrence increased the probability of larger magnitude events occurring (Figure 2). This showed that the volume of the affected zone and the magnitude of the depletion are important factors in both the rate of seismic event generation and their magnitudes.

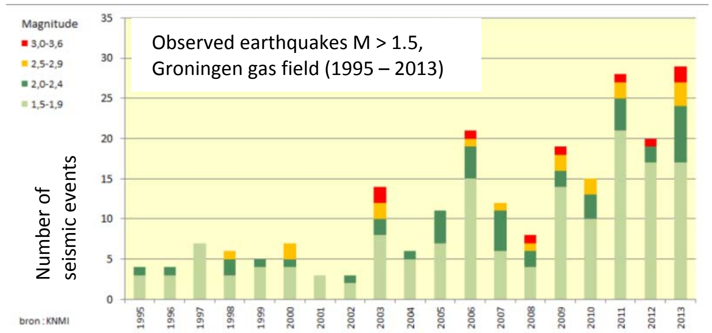

Figure 1 – induced seismicity rate and frequency in the Groningen Gas Field, Netherlands (After Muntendam-Bos, 2013)

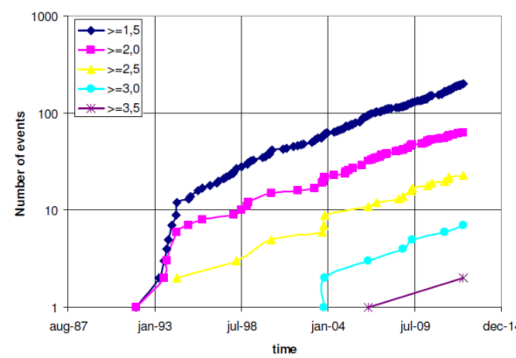

Figure 2 – Number of induced seismic events at Groningen Gas Field vs. time of occurrence. Note linear increase (log normal scale) in event rate over time (After Muntendam-Bos, 2013)

A low public tolerance for induced seismicity, even if the damage level is minimal or zero, coupled with uncertainty surrounding the maximum magnitude of future events, resulted in the Dutch Government reducing (in January 2014) gas production rates from the field by approximately 25%. This measure appears to have successfully mitigated seismicity through management of the reservoir pressure decline and rate of differential subsidence in the field.

Sustained large net balance fluid injection into the subsurface can occur during some non-oil and gas activities, such as liquid waste disposal (including oil and gas produced water and hydraulic fracture flowback fluids), carbon capture and storage (CCS), acid gas injection, and geothermal energy extraction. These activities consequently also present an associated seismic hazard potential. However, there has historically been a lack of reliable data to assess, quantify and predict the existence and nature of the hazard potential.

There are efforts underway to collect data to establish the nature of the relationship in the CCS field. The USGS and Schlumberger Carbon Services embarked on a comprehensive data collection program with the objective of building a monitoring, verification and accounting (MVA) program for CCS

[2] Muntendam-Bos, A., et al "Re-assessment of the probability of higher magnitude earthquakes in the Groningen gas field", Dutch State Supervision of Mines, January 16, 2013

systems. This program focuses mainly of microseismic data collection (along with pressure and temperature data) to demonstrate CO_2 containment of the Decatur (Illinois) CCS project and to validate and update predictive models. The data collected to date (September 2014) indicated that the low injection volume CCS project generated approximately 750 low magnitude events (- 2.14 to 1.14) per day, all below the human detection threshold. The learnings[3] generated from the data collected so far have helped the project proponents to adjust the location of the injection well perforations and the injection strategy to mitigate the frequency and magnitude of induced seismicity.

Seismic event magnitude and intensity

Seismic energy is released when rocks underground suddenly rupture or move, usually a process of shear slip along a predetermined plane of weakness. The amount of energy released during the rupture or slip event, at the point of the rupture or slip, is termed the magnitude (sometimes referred to as M). The amount of ground motion (i.e. "ground shaking") recorded at any location is termed the "intensity" of the seismic event. The magnitude and intensity of a seismic event are proportional to the size of the slip area and the stress level on the source fault. The potential for damage to surface infrastructure is directly related to the degree of ground surface shaking. The ground surface intensity of a seismic event of a given magnitude generally increases the closer the source event is to the ground surface, but because of variations in surface response (different soils, nature of the slip movement), the surface effects cannot be predicted by magnitude alone. Seismic events with a M < 2 generally do not have enough energy to produce ground shaking that can be felt, while shallow seismic events with a M > 2 can generally be felt at surface, although there are no cases known of surface damage for such low magnitude events.

Induced seismic events generally occur at depths that are significantly shallower than natural earthquakes (often referred to as tectonic events). A typical depth range for induced seismic events is between ~ 1 km to 6 km, while tectonic events generally occur at depths exceeding 10 km[4].

The shallower the induced event, the smaller the amount of energy that can be released for two reasons: natural earth stresses are smaller at shallow depths, and the rocks or faults are weaker, so that large stresses cannot be accumulated over large volumes. In these cases, many small events occur to relieve the induced stresses, but the probability of a large event may be vanishingly small. An example is the induced seismicity arising from thermal stimulation of shallow heavy oil deposits in Alberta, less than 800 m depth. Sensitive sensors record thousands of small events, but it is rare that an event is detected by humans at the ground surface.

Instead of an energy emission measure such as the magnitude, engineers often use an empirical scale, called the Modified Mercalli Intensity (MMI) scale (Table 1), to specify the impact on the surface. This empirical scale gives a measure of the surface impact. For example, the seismicity induced in the Cold Lake region is only of MMI levels I or II, whereas the largest event at Groenigen was probably of MMI IV level, still not considered to be damaging to structures (although not comforting to those experiencing it).

It is interesting to note that one of the historically largest earthquakes in Alberta (apparently the second largest to date) was probably triggered by high-pressure water injection leading to movement of a pre-existing fault at the Snipe Lake oilfield in 1970[5]. This event was widely felt in the local region, and

[3] Couelesan, M., "Overview of induced microseismic activity in the Illinois Basin – Decatur Project", , paper presented at the SPE/SEG/ARMA Induced Seismicity Workshop, Banff, AB, Sept 16 – 18 2014

[4] Keranen, K.M et al, "Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection", Science, 345, 448 (July 2014)

[5] Milne, W.G., "The Snipe Lake, Alberta earthquake of March 8, 1970", Dept. of Energy, Mines and Resources, Victoria, BC, Canadian Journal of Earth Sciences, Vol. 7, 1970

had values of M = 5.1 and MMI of III (perhaps verging on IV). No significant recurrence took place.

Table 1 – Modified Mercalli Intensity Scale (After Wikipedia)

I. Instrumental	Generally not felt by people unless in favorable conditions.
II. Weak	Felt only by a couple people that are sensitive, especially on the upper floors of buildings. Delicately suspended objects (including chandeliers) may swing slightly.
III. Slight	Felt quite noticeably by people indoors, especially on the upper floors of buildings. Many do not recognize it as an earthquake. Standing automobiles may rock slightly. Vibration similar to the passing of a truck. Duration can be estimated. Indoor objects (including chandeliers) may shake.
IV. Moderate	Felt indoors by many to all people, and outdoors by few people. Some awakened. Dishes, windows, and doors disturbed, and walls make cracking sounds. Chandeliers and indoor objects shake noticeably. The sensation is more like a heavy truck striking building. Standing automobiles rock noticeably. Dishes and windows rattle alarmingly. Damage none.
V. Rather Strong	Felt inside by most or all, and outside. Dishes and windows may break and bells will ring. Vibrations are more like a large train passing close to a house. Possible slight damage to buildings. Liquids may spill out of glasses or open containers. None to a few people are frightened and run outdoors.
VI. Strong	Felt by everyone, outside or inside; many frightened and run outdoors, walk unsteadily. Windows, dishes, glassware broken; books fall off shelves; some heavy furniture moved or overturned; a few instances of fallen plaster. Damage slight to moderate to poorly designed buildings; all others receive none to slight damage.
VII. Very Strong	Difficult to stand. Furniture broken. Damage light in building of good design and construction; slight to moderate in ordinarily built structures; considerable damage in poorly built or badly designed structures; some chimneys broken or heavily damaged. Noticed by people driving automobiles.
VIII. Destructive	Damage slight in structures of good design, considerable in normal buildings with a possible partial collapse. Damage great in poorly built structures. Brick buildings easily receive moderate to extremely heavy damage. Possible fall of chimneys, factory stacks, columns, monuments, walls, etc. Heavy furniture moved.
IX. Violent	General panic. Damage slight to moderate (possibly heavy) in well-designed structures. Well-designed structures thrown out of plumb. Damage moderate to great in substantial buildings, with a possible partial collapse. Some buildings may be shifted off foundations. Walls can fall down or collapse.
X. Intense	Many well-built structures destroyed, collapsed, or moderately to severely damaged. Most other structures destroyed, possibly shifted off foundation. Large landslides.
XI. Extreme	Few, if any structures remain standing. Numerous landslides, cracks and deformation of the ground.
XII. Catastrophic	Total destruction – everything is destroyed. Lines of sight and level distorted. Objects thrown into the air. The ground moves in waves or ripples. Large amounts of rock move position. Landscape altered, or leveled by several meters. Even the routes of rivers can be changed.

Seismicity and risk to surface infrastructure

The design specifications for surface infrastructure usually require consideration of reasonable hazards, and an assessment of the risks to society that may be posed by such hazards. These considerations generally include the potential for seismicity during the lifespan of the infrastructure, if the region in which the infrastructure is located has a recorded history of seismicity. Seismicity potential may not be considered in the design if the region is classified as having a low seismicity hazard during its design life. The typical design lifespan of a building is usually ≈ 50 years.

Earthquake hazard maps are used to show the potential for seismic activity in a specified location, and the degree or intensity of "ground shaking" that could be expected, based on historical data and trends. These maps generally show the expected magnitudes and frequencies of earthquakes, within a 50 year period, for specific areas, based on historical seismicity and its projected trends. These maps are used for a wide variety of purposes, including defining safe structural building codes (for residences, bridges, industrial facilities and structures including dams), pipelines, utilities, business and land use planning, slope and landslide potential and asset insurance rates. The US Earthquake Hazard Map is generated and maintained by the USGS, while the Canadian Earthquake Hazard Map is generated and maintained by Canadian Geological Surveys.

Historically, the frequency of occurrence of induced seismicity has been insignificant and consequently induced seismicity was previously excluded from the (Canadian and US) earthquake hazard maps generated and published to date. However, the USGS indicated in September 2014 that the 2015 iteration of the USGS Earthquake Hazard Map will, for the first time, include induced seismicity in the earthquake hazard assessment.

Surface infrastructure designed and built according to the relevant building codes are therefore safe for the degree of seismic risk presented in the hazard map existing at the time of the design of the structure. Specifically, such surface infrastructure can generally safely withstand seismic events, providing that[6]:

(i) None of the seismic events experienced by the infrastructure during its lifespan produces a ground motion intensity larger than that predicted by the hazard map (based on historical precedence)

(ii) Seismic events do not occur significantly more often than the frequency predicted by the hazard map

(iii) Ground shaking generated by seismic events does not last longer than the maximum duration of seismic event predicted by the hazard map

Therefore, a significant increase in the background seismicity of an area may present a hazard to surface infrastructure and facilities if the MMI magnitude is deemed greater than III, for example. Specifically, the hazard to surface infrastructure may be greater if the intensity, duration and frequency of seismic events that may be experienced by the structure during its design lifespan increases from those originally considered during the design.

This hazard potential may be especially relevant in areas that have not historically been seismically active but may experience induced seismicity because of a change of industrial activity. Typically, buildings in low hazard zones are not engineered for seismic hazards. Therefore an increase in the assessed level of seismic hazard, such as increasing hazard from none/low to medium, could trigger changes in building codes and design/construction requirements for infrastructure, as well as insurance rates and coverages. These changes, if triggered, could have measureable financial costs (construction and insurance costs).

However, the relationships between induced seismic event magnitude, ground shaking intensity and potential effects on surface infrastructure have not yet been established, and there is currently

[6] Atkinson, G.M., Confidential Report Feb 15, 2013

limited data to support any reliable conclusions. This is therefore an area in which the opportunity may exist to support collection of the relevant data and definition of the relationships, in order to assess and quantify the hazards, if any, to surface infrastructure and facilities.

Assessing the cause of a seismic event[7]

Existing seismological methods are not yet sufficiently evolved to differentiate the "signature" of a natural seismic event from that of an induced event. However, the source location of a seismic event can be accurately determined if there is an adequate array of sensitive instruments, a microseismic monitoring network, deployed within detection range of the source event. Seismic events are considered induced if there is a clear correlation of:

(i) The geographic location of the injection or production activity and the location of the seismic activity
(ii) The temporal occurrence of injection or production activity and the temporal occurrence of seismicity
(iii) The depth of injection and production activity and the depth of the induced seismicity
(iv) The timing of injection and production activity and the timing and frequency of seismic event occurrence

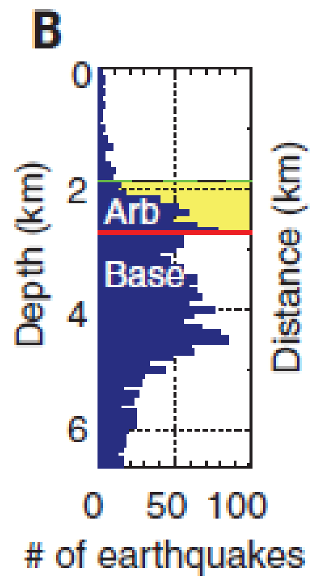

Figure 3 – Example of geolocation of a seismic event swarm in Oklahoma (after Kiranen et al, 2014)

Therefore, an extensive data collection infrastructure and program is a key requirement for assessing cases of induced seismicity and the probable causes. The deployment and monitoring of dense arrays of sensitive seismic instruments is costly, and these arrays have traditionally only been installed in areas with high tectonic risk, such as central and southern California. Therefore there has traditionally been a lack of data collection capability and consequently a lack of high resolution seismic data for other historically aseismic areas.

In 2008 the USGS commenced deploying transportable seismograph array systems (the USArray, NetQuake and Earthscope Array systems) in areas that had experienced shale gas development. This system has been continuously expanded since, and has been able to collect high resolution, high density data which has helped to identify induced seismicity trends and causal factors in the USA.

In 2009 Natural Resources Canada's existing regional seismic network commenced detecting anomalous seismicity in northeast BC, in an area in which seismicity had not previously been detected. Natural Resources Canada has subsequently expanded its seismic monitoring network in this region and its data collection capabilities have since been supplemented by networks installed by the UofA, UofC and various industry operators.

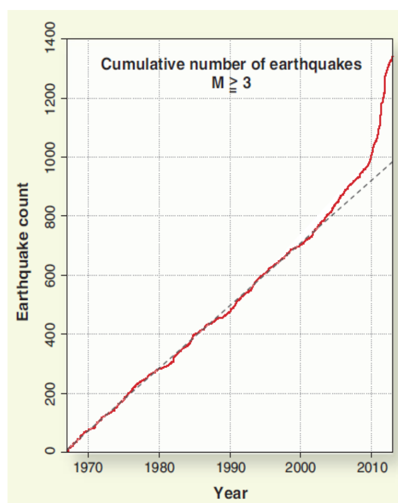

Figure 4 – Earthquakes with M ≥ 3 in the US mid-continent, 1967 - 2012 (after Ellsworth, W., Science 341, 2013)

Current understanding of induced seismic hazard in the USA

After observing a trend of (detectable) earthquakes in unusual locations in 2008/2009, the USGS expanded its data collection capability in aseismic locations by using various

[7] Ellsworth, William L., " Injection Induced Earthquakes, Science 341 (July 2013)

(transportable) dense array seismograph network systems (such as the USArray & EarthScope systems). These systems are portable and were deployed in mainly in Texas and Oklahoma to investigate the occurrence and causes of induced seismicity in mid-central USA.

The data collected from this investigation was first published in the USGS's July 2013 paper titled "Injection-Induced Earthquakes". This paper showed that the rate of occurrence of earthquakes of M ≥ 3 was steady during the period 1970 - 2005, but then increased significantly in ≈2005 and continued to increase since (Figure 4). The central/eastern USA earthquake count for the period 1967 – 2000 was 21 events per year, while the earthquake count for the same area for 2010 - 2012 was 300. This increase triggered the USGS to review the 2008 US National Seismic Hazard Map (NSHM), because an increase in the rate of earthquake occurrence potentially increases the hazard of damaging ground shaking. The USGS's 2014 release of its NSHM[8] identified and delineated areas in which swarms of earthquakes potentially induced by fluid injections had occurred, and advised users that the earthquake hazards within these areas may be higher than that shown on the present map (Figure 5).

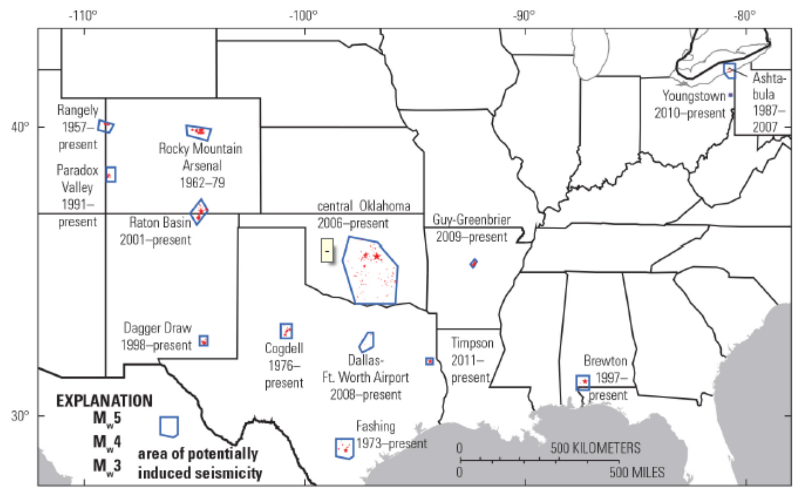

Figure 5 – USGS's 2014 NSHM showing areas of potentially induced seismicity in the Central and Eastern USA

The areas shown in this map correspond to the areas in which high volume (shale gas development derived) waste water injection has been occurring. Recent data analysis[9] links 20% of the Oklahoma induced seismic events (with M ≥ 3.0) to the operation of four high-rate wastewater disposal wells, each injecting around 4 million barrels of wastewater per month, and allocated 45% of the induced seismicity in Oklahoma to waste water injection operations in a specific geographical region. The USGS has since also shown that, if the induced seismic events correlated to injection activities in mid-continent USA are subtracted from the earthquake count, the earthquake occurrence rate returns to the historical (normal) trend line[10].

Therefore, existing published data from the USA indicates that the seismic hazard potential has been confined to sustained high rate injections. Hydraulic fracturing has not (as yet) been linked to the

[8] Petersen, M.D. et al, "Documentation for the 2014 Update of the United States National Seismic Hazard Maps", USGS Open File Report 2014-1091 (pgs. 22 & 23) http://pubs.usgs.gov/of/2014/1091/

[9] K.M Keranen et al, "Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection", Science, 345, 448 (July 2014)

[10] Llenos, A. & Rubenstein, J., "Increased earthquake rates in central and eastern USA portend higher earthquake hazards", paper presented at the SPE/SEG/ARMA Induced Seismicity Workshop, Banff, AB, Sept 16 – 18 2014

occurrence of seismicity with M ≥ 3[11] in the USA, and has consequently not been considered to be a major factor in the NSHM map update. However, it is important to note that hydraulic fracturing has been linked to the triggering of induced seismicity with M ≥ 3 in British Columbia [12]and Alberta[13], although with only a MMI value of II.

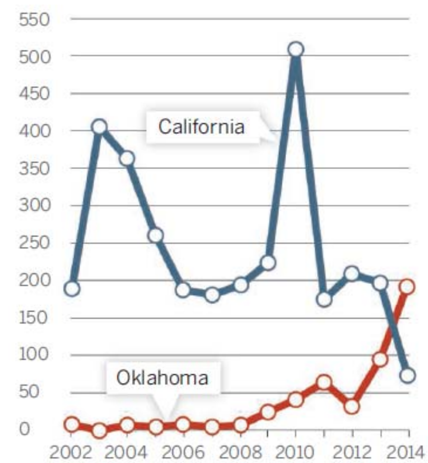

Figure 6 – Number of earthquakes M 3 or greater (Hand, E., Science Vol. 345 Issue 6192, pg. 13)

While the current 2014 version of the USGS's NSHM states that injection induced seismicity poses an anomalous seismic hazard, it does not quantify the hazard, because of the lack of appropriate data and models to estimate the future Ms and frequency of occurrence. Current predictive seismic models are considered inadequate because they are based on a historically observed empirical relationship between the number of tectonic earthquakes and the expected M (seismic event M-frequency models). These are rules of thumb, such as, for every 1000 M-4 quakes there may be 100 M-5 quakes, 10 M-6 quakes and so on.

The validity of the use of this relationship to assess induced seismicity and to predict ground motion is unknown. However, there is sufficient data to show that the frequency of occurrence of detectable seismic events in Oklahoma in 2014 exceeded the frequency of occurrence of comparable seismic events in California for the same time period[14] (Figure 6).

The USGS has since used the data it has collected to date to develop several induced seismicity models, in order to quantify the seismic hazard posed by induced seismic events. These models will form the basis for future quantification of induced seismicity hazards, and will be presented at a USGS workshop in Oklahoma on November 17, 2014. A preliminary draft of the model options, presented by the USGS at the SPE/SEG/ARMA Injection Induced Seismicity Workshop (Banff, AB, September 16 – 18 2014) suggest that the seismic hazard potential for areas that have experienced high levels of induced seismicity (such as Oklahoma and Texas) could be rated as equivalent to tectonically active areas, such as California.

Current understanding of induced seismic hazard in Canada

The Geological Survey of Canada (GSC), an arm of Natural Resources Canada (NRCan) is the federal agency responsible for the assessment and quantification of seismic risk in Canada. The GSC is responsible for preparing and publishing seismic hazard maps for all of Canada. The most recent seismic hazard map of Canada was published in 2010, and is provided in Figure 7. This map was prepared on the basis of data obtained pre-2009, and indicates that the seismic risk for northern Alberta is low.

During April 2009 - July 2011 the GSC detected 31 anomalous seismic events with magnitudes between 2.2 and 3.8 in the Horn River Basin of BC. This was an area in which no previous seismic events had been previously detected, and in which hydraulic fracturing development had been initiated. The BC Oil and Gas Commission's subsequent investigation on the causes of the observed seismicity

[11] Ellsworth, W., "injection induced earthquakes", Science Vol. 341, July 12, 2013

[12] Farahbod, A.M. et al, "investigation of regional seismicity before and after hydraulic fracturing in the Horn River Basin, northeast British Columbia", Canadian Journal of Earth Sciences, September 2014

[13] Novakovic, M. et al, "Investigation of observed seismicity in the Crooked Lake Region of Alberta" CGU-CSSS 2014 Annual Meeting, Banff AB, May 6, 2014

[14] Hand, E., "Injection wells blamed in Oklahoma earthquakes", Science Vol. 345 Issue 6192, July 4, 2014

concluded[15] that the observed seismicity was triggered by hydraulic fracturing being conducted in the area, on the basis of source location and activities being conducted in the area at the time. The operation of disposal wells was ruled out as a potential cause of the seismic events (based on a mismatch between the location of the events and the location of the injection target zone). This was essentially the first episode in which hydraulic fracturing had been known to generate induced seismicity with M ≥ 3. The largest (3.8 M) event was reported to be "felt by workers in the bush" and there were no reports or damages or injuries.

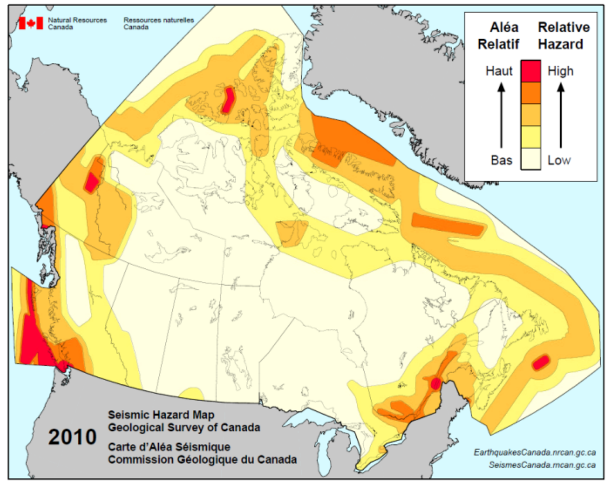

Figure 7 - Most recent (2010) version of Canadian seismic hazard map. Note northeastern BC and northwestern Alberta are classified as low seismic hazard areas

This experience prompted the GSC and various other entities (Geoscience BC, CAPP, BC Oil and Gas Commission and NRCan) to increase their data collection capabilities in the area. This included the installation of dense arrays, to triangulate the source location of seismic events, as well as ground motion sensors to detect and quantify ground acceleration (seismic hazard to infrastructure).

Additionally, Natural Resources Canada, in collaboration with the BC Oil and Gas Commission, during this period initiated[16] a project to investigate the "Potential links between shale gas fracking and induced seismicity for sustainable development and improved regulatory performance". This project is expected to run from April 2012 to March 2016 and its objectives are to provide answers to the following questions:

(i) Can the practice of fracking alter the local or even regional pattern of background seismicity?
(ii) What is the relationship between how fracking is performed and the maximum M of induced earthquakes?
(iii) What is the timescale of the interaction between fracking events and induced seismicity
(iv) Are there clear scientific evidences, from a seismic hazard point of view, to suggest imposing different fracking regulations for shale gas basins under different tectonic/geological conditions?

As a component of this project, the GSC has since been collecting, analyzing and (reanalyzing) data from these networks, and has published (September 2014) its most recent findings[17]. These findings are that:

(i) There was a high likelihood that hydraulic fracturing had caused the induced seismic events in the Horn River Basin
(ii) The number of seismic events in the Etsho area showed an increasing trend, from 24 in the 2002 – 2003 period (prior to commencement of hydraulic fracturing operations in the region) to 131 in 2012 (peak period of hydraulic fracturing tin the area)

[15] BC Oil and Gas Commission, "Investigation of Observed Seismicity in the Horn River Basin", August 2012
[16] Annex B: Shale Resources Compendium, Energy & Mines Minister's Conference, Yellowknife, NWT, August 2013, pg. 73
[17] Farahbod et al, "Investigation of regional seismicity before and after hydraulic fracturing in the Horn River Basin, northeast BC", Canadian Journal of Earth Sciences, September 2014 (*Pre-Print*)

(iii) The seismic event magnitude increased as the scale of hydraulic fracturing expanded in the area. The maximum event magnitude increased from 2.9 in 2006/2006 to 3.6 in 2011

Therefore, the September 2014 paper appears to have provided answers to some of the research question posed by NRCan's project. Since the objectives of the NRCan study are similar to those of the analogous USGS project[18], the USGS' experience in assessing and quantifying seismic hazard in mid-central USA may provide background and case histories for the other objectives of NRCan's project. The ultimate result of the NRCan project may be similar to that of the USGS', which is to generate a probabilistic seismic hazard analysis that includes induced seismicity hazards. There is a possibility that the seismic hazard may be increased in areas in which hydraulic fracturing is expected to occur, such as the Horn River and Montney shale gas plays. This possibility is based on the recent work by the GSC that has successfully linked hydraulic fracturing in the Horn River Basin to the triggering of seismicity with M ≥ 3 and the elevated risk that the shallow location (< 5 km deep) of these events could generate levels of ground shaking that could be strong enough to cause surface damage[19] (i.e. MMI value of V).

Recent data suggests that the profile of seismic activity in the northeastern BC - northwestern Alberta shale gas development basins may become elevated, if the pattern of seismicity with M ≥ 3 continues to occur. Two events with M ≥ 4 were recorded in 2014 in these areas, and both were correlated to hydraulic fracturing activities. The M 4 event occurred on July 30, 2014 and the larger M 4.2 event occurred on August 4, 2014. The M 4.2 event, believed to have been induced by hydraulic fracturing in the Montney, "…had the potential to cause surface infrastructure damage, based on the strong recorded ground acceleration an shallow location[20]…" This statement was also supported by the GSC, which stated[21] that "…the M 4 event(s) in the Horn River Basin had presented a risk to infrastructure, because of the strong recorded ground acceleration…"

Management Systems and Protocols Employed by Industry

Management systems and mitigation protocols utilized by operators all have some elements in common. These elements include:

(i) Understanding, in detail, the geology, geomechanics and hydrogeology of the entire basin in which the target reservoir is located
   a. Includes generating and validating geological, hydrogeological and geomechanical models for expected risk and receptor (people and environment) exposure

(ii) Identifying areas (i.e. on an area or basin basis) with high risk potential. The biggest risk factors typically include:
   a. Permeable or over-pressured zones close to basement
   b. Formations with faults close to their critical stress state (i.e. loaded faults that are ready to slip)
   c. Basement faults
   d. Sensitive public receptors

---

[18] Ellsworth, W., "Understanding the anomalous seismicity in the Central USA – brick by brick", paper presented at the SPE/SEG/ARMA Induced Seismicity Workshop, Banff, AB, Sept 16 – 18 2014

[19] Kao, H., "Investigation into regional seismicity before and after hydraulic fracturing in the Horn River Basin, northeastern BC", paper presented at the SPE/SEG/ARMA Induced Seismicity Workshop, Banff, AB, Sept 16 – 18 2014

[20] Atkinson, G & Eaton, D., "Source and attenuation parameters for seismicity in the Crooked Lake Region of Alberta", paper presented at the SPE/SEG/ARMA Induced Seismicity Workshop, Banff, AB, Sept 16 – 18 2014

[21] Kao, H., "Investigation into regional seismicity before and after hydraulic fracturing in the Horn River Basin, northeastern BC", paper presented at the SPE/SEG/ARMA Induced Seismicity Workshop, Banff, AB, Sept 16 – 18 2014

(iii) Instituting an appropriate management system

a. Assign, manage and audit/quality control risk management responsibilities (and accountabilities) of all members of operator, contractor and subcontractor teams
b. Reduce injection volumes, evaluate reservoir response and calibrate/validate geomechanical models
c. Conduct initial stages in wells with low injection rates and low stage volumes until the stress states and seismic response are well understood and can be modeled/predicted
d. Slow ramp up and ramp down of injection rates until stress states are well understood

However, a critical component of any management system is a comprehensive seismic data collection system that is robust enough to collect and record data at a frequency and resolution that enables the identification of source event locations, ground intensities and correlations to potential causal factors, on a basin-wide basis. Ideally, such a system would aggregate and make available data collected by private and public networks, and would be designed such that it could be used by operators as a process control [22]and hazard-mitigation tool. This data could help in the development and validation of reliable predictive models that would further enable operators to assess the potential for (and magnitude of) seismic event occurrence and best means of mitigation, prior to commencing development.

[22] Dusseault, M.B. et al, "Numerical investigation of seismic events associated with hydraulic fracturing", pre-print of paper to be presented/published at the ISRM International Conference of May 2015