Technical Considerations Associated with Risk Management of Potential Induced Seismicity in Injection Operations

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Abstract

With growing public attention to the potential risk of seismicity induced by waste-water injection and hydraulic fracturing, there is a need for better understanding of the technical elements associated with induced seismicity and the subsequent implications associated with management of the potential risks.

In this paper, the technical elements of the risk are first examined including probability and consequence. Probability elements include volume of injected fluid, formation characteristics, tectonic/faulting environment and operating experience. Consequence elements include physical damage, environmental impact, economic disruption, social or community impact and public disturbance.

A potential approach for risk characterization is then presented and includes the definition of risk zones. The risk zones can be considered relative to potential "stoplight" approaches associated with risk mitigation. Various options of potential mitigation methods are discussed, such as well planning, design and ground shaking monitoring. The risk characterization framework is applied to recent well activities that have been the subject of studies by the United States Environmental Protection Agency and by regulators in Canada and the United Kingdom, and also applicable to hundreds of thousands of hydraulic fracture treatments and to tens of thousands of injection wells.

The results presented clearly delineate important seismicity drivers, demonstrate the extremely low likelihood associated with such events and are consistent with the major conclusions published in a recent United States National Academy of Science comprehensive report on the subject. The information presented in this paper will help to further inform policy makers, regulators, oil and gas companies, and service companies of the technical and operational elements to consider for assessing and/or managing the potential risks associated with induced seismicity from injection operations.

Introduction

Over the past few years, it has been reported that several states in the USA have seen an apparent increase in mild seismic activity in areas where unconventional gas development is occurring.[1,2] In addition, other reports have attributed seismicity to injection associated with hydraulic fracturing of shale gas wells in the Horn River Basin (Canada)[3] and the Bowland Shale (U.K).[4]

Seismic waves are generated when sudden slip occurs along a fault. This sudden slip can be due to release of strain accumulation from tectonic loading, stress changes and/or pore pressure changes. It has been previously reported that induced or triggered seismicity has occurred due to many industrial activities including reservoir impoundment, mining, construction, waste disposal, and oil and gas operations[5,6,7]. Many industries have dealt with induced seismicity for decades using sound engineering and controls although this knowledge has not always been widely reported or understood.

In response to the recently published reports and the public concerns, many regulatory and government agencies have recently reacted. For example, several local and state regulatory agencies in the USA have placed additional regulation on waste-water disposal wells, and in the United Kingdom and Canada additional regulations have been put in place for hydraulic fracturing operations.

The United States National Academy of Sciences (NAS) recently released the results of a comprehensive ~2-year study on induced seismicity across multiple energy sectors.[8] The three major conclusions reported by the NAS include:

1. The process of hydraulic fracturing a well as presently implemented for shale gas recovery does not pose a high risk for inducing felt seismic events;

2. Injection for disposal of waste water derived from energy technologies into the subsurface does pose some risk for induced seismicity; but very few events have been documented over the past several decades relative to the large number of disposal wells in operation; and

3. Carbon capture storage, due to the large net volumes of injected fluids, may have potential for inducing larger seismic events.

While providing a broad context for the risks associated with induced seismicity across multiple energy sectors, the NAS report does not provide risk assessment methods or mitigation approaches that may be practical, reasonable, or scalable across the diverse local conditions, geology, and operating practices that may be globally encountered.

Ultimately, the risk level is strongly coupled to the actual magnitude, frequency, and duration of ground shaking. Typically, reported cases of induced seismicity have been below Magnitude 4, a level having minor impact on primary structures and not considered for earthquake-resistant design. Humans and damage to "secondary" components can be more sensitive to these smaller level tremors. The local ground shaking is highly dependent on local soil conditions and in-structure local motion amplification.[9,10]

While there are many methods and measures for characterizing the size of a seismic event (e.g., Richter scale magnitude, local magnitude, body-wave magnitude, surface-wave magnitude, moment magnitude, etc.)[11,12] it is widely accepted that the "Modified Mercalli Index" (MMI), peak ground acceleration (PGA) measurements, and peak ground velocity (PGV) measurements provide the best representation for the potential damage that may occur from a given seismic event. Note the MMI is a qualitative measure based on human-felt ground shaking and observed damage in the vicinity of a seismic event.

Potential Damage	Modified Mercalli Intensity	Perceived Shaking	Approximate Magnitude*	Peak Acceleration (%g)	Peak Velocity (cm/s)	Description of Intensity Level
None	I	Not Felt	1.0 - 3.0	<0.17	<0.1	Not felt except by a very few under especially favorable conditions.
	II	Weak	3.0-3.9	0.17-1.4	0.1-1.1	Felt only by a few persons at rest, especially on upper floors of buildings.
	III					Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
	IV	Light	4.0-4.9	1.4-3.9	1.1-3.4	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
Very Light	V	Moderate	4.0-4.9	3.9-9.2	3.4-8.1	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
Light	VI	Strong	5.0-5.9	9.2-18	8.1-16	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
Moderate	VII	Very Strong	5.0-6.9	18-34	16-31	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
Moderate/ Heavy	VIII	Severe	6.0-6.9	34-65	31-60	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
Heavy	IX	Violent	6.0-6.9	65-124	60-116	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
Very Heavy	X	Extreme	>7.0	>124	>116	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.
	XI					Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.
	XII					Damage total. Lines of sight and level are distorted. Objects thrown into the air.

*Magnitudes correspond to intensities that are typically obsered at locations near the epicenter of earthquakes of different magnitudes

Table 1: Modified Mercalli Scale (Wood and Neumann, 1931[13]; Richter, 1958[14]) to describe the effect of an earthquake on the Earth's surface. Magnitudes correspond to intensities that are typically observed at locations near the epicenter of earthquakes of different magnitudes (http://earthquake.usgs.gov/learn/topics/mag_vs_int.php).

Magnitude and intensity are used to measure different seismic event characteristics. It is emphasized that use of Richter or other magnitude scales to classify an event does not lead directly to interpretation of actual ground shaking values, as magnitude is a measure of total energy release at the event epicenter, and ground shaking will clearly reflect the attenuation characteristics as a function of depth and distance from the source, with strong coupling influence from the local geologic setting and soil conditions.

Table 1 above summarizes the Modified Mercalli Intensity and damage levels associated with ground shaking of a given level is provided below and compiled from several public sources of information. In developing Table 1, two-word descriptions of both perceived shaking and potential damage levels were derived with consideration of the descriptions in the Modified Mercalli descriptions by Dengler and Dewey (1998, 2003).[15] For intensities greater than MMI V, a relationship between Modified Mercalli Index and peak ground acceleration or peak velocity was developed by Wald et al (Earthquake Spectra, 1999)[16] by comparing motions observed for intensities for eight significant California earthquakes. A relationship between lower intensities and peak ground acceleration was developed based on magnitude 3.5 to 5.0 earthquakes in California with intensities derived using voluntary responses from Internet users (Wald et al., Seismology Research Letters, 1999).[17]

These relationships are used by the USGS to generate maps of instrumental intensities following an earthquake. For additional information, see: Wald, D.J., Worden, B.C., Quitoriano, V., and Pankow, K.L., 2005, ShakeMap manual: technical manual, user's guide, and software guide.[15] The U.S. National Earthquake Hazards Reduction Program (NEHRP) has recommended additional measurements of PGA be obtained in the Midwest and East regions of the USA so that improved relationships can be developed to better correlate between magnitude and PGA for those regions.[18] There is emerging work to develop relationships between the magnitude and resulting ground motion for the lower magnitude events that are typically associated with induced seismicity (i.e., ML<4-5).[19,20] The large body of work on this subject has typically been for the larger magnitudes events that will cause significant damage.

Hydraulic fracturing treatments are generally performed in low permeability reservoirs (i.e., shale gas, tight oil), and at treatment pressures above fracturing pressure to create fractures in the reservoir. Fracturing operation in a specific location typically last hours and it may take several days to complete a single well with multiple stages. As such, in fracturing operations, the volume of fluid is typically substantially less than waste-water, and the local region where reservoir pressure and stress fields may be altered is substantially smaller than in waste-water injection.

Furthermore, following fracturing operations, the well is produced for recovery of fracturing fluid and to enable hydrocarbon production. Thus, the perturbation to the reservoir pressure and stress due to fluid injection is substantially reduced with the flowback period following the fracturing operation. Millions of fracturing treatments have been performed across the globe without any significant incident of a negative safety, health, or environmental consequence arising from induced seismicity.

With this background, subsequent approaches to assess and manage seismicity risk associated with injection operations should be clearly based on sound science, and take into account the local conditions, operational scope, geological setting, and historical baseline seismicity levels; furthermore, the approach should reflect reasonable and prudent consideration of engineering standards and codes related to seismicity structural health.

In establishing an a science-based risk management framework, cross-disciplinary expertise, as illustrated by Figure 1, is required to frame the range of technical factors that may affect the overall risk level, as well as to establish effective mitigation dependent on the risk level and local conditions.

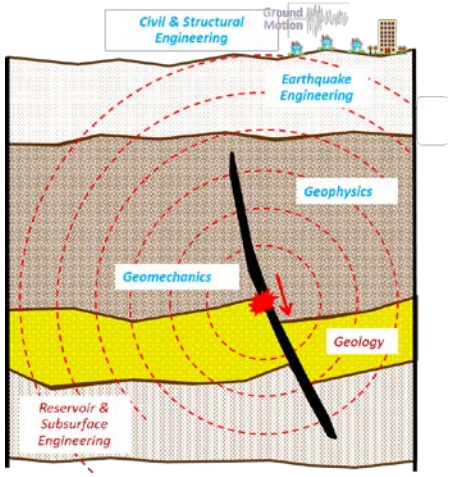

Figure1: Schematic of technical elements involved in examining risk of induced seismicity.

Risk Management Considerations

Seismicity monitoring and mitigation may be considered in local areas where induced seismicity is of significant risk. For instance, in areas where significant seismicity above historical baseline levels has been observed and sound technical assessment indicates that the seismicity is likely associated with fluid injection operations or, alternatively, in areas where a risk screening identifies significant risk associated with potential induced seismicity. One possible framework for addressing the risk of induced seismicity is described below:

1. An understanding of historical baseline seismicity in region can be developed and evaluated to assess if seismicity has been generally "naturally" occurring, or if speculation or public reports suggest abnormal seismicity may have been induced by human activity. For example, in the USA, various resources such as the USGS website are available to identify the historical seismicity data; and many countries outside the USA have similar resources.
2. Regulations related to underground injection operations and induced seismicity should be reviewed, and plans developed ensuring compliance with all regulations.
3. Readily available data associated with the key factors that affect the probability of occurrence of an induced seismic event can be collected, including proximity of any known faults to injection location, volume of fluid to be injected, formation characteristics, tectonic/faulting environment, operating experience, public sensitivity/tolerance, and local construction standards.
4. A preliminary injection plan based on the technical objectives can be developed, and can consider the initial understanding of the local geology, operating experience in the region, public sensitivity/tolerance to nuisance seismicity, and awareness of local construction standards and historical architecture designs and structures. Include in the preliminary plan any induced seismicity mitigation methods and procedures that would be put in place for the base design.
5. An "Initial Risk Screening" to evaluate the potential risk level can be performed.
6. Based on the potential risk level, the potential desire for additional monitoring and/or mitigation can be assessed and may be implemented as prudent to manage and/or reduce the risk, and finalize design plan.
7. If the Initial Risk Screening identifies the activity as potentially higher risk, a "Stoplight System" could be considered, defining the monitoring procedures and the seismicity thresholds based on local conditions where operations may be modified or suspended if anomalous seismicity is encountered in proximity to the operations.
8. The injection plan may then be finalized, including, if appropriate, any monitoring and mitigation requirements for potential induced seismicity.
9. Based on the final injection plan, site personnel can be trained for awareness of induced seismicity risk, and as appropriate, in the operation and implementation of the Stoplight System if increased levels of anomalous seismicity were to actually be observed.
10. The project then proceeds with the injection plan implemented based on the risk assessment.
11. The injection program may then be operated within the appropriate parameter space and monitoring performed if appropriate for anomalous seismicity.
12. Should unacceptable levels of anomalous seismicity be observed, the injection operations may be modified or suspended; and the operator would engage the appropriate regulatory bodies and local community.

Induced Seismicity Risk Assessment

A key element of an effective risk management framework is the identification of the risk level (e.g., as considered by the "Initial Risk Screening" listed in point 5 above). In identifying the risk level, it is important to establish a consistent definition of risk and a sound basis for establishing the level of risk. A widely used tool in risk management is the "Risk Matrix".

As indicated in Figure 2, risk is a combination of probabilities and consequences. A high risk activity is an activity that can frequently result in significant safety, security, health, or environmental ("SSHE") consequences; while a very low risk activity is an activity that can result very minor consequences on a very infrequent basis, or even negligible consequences on a frequent basis.

With the risk level identified, then opportunities to mitigate the potential risk can be considered relative to the overall risk level, local conditions, and project commercial considerations. For example, for a low or very low risk project, additional

mitigation may not be necessary; while for a higher risk project, additional mitigation may be considered appropriate to reduce the risk level.

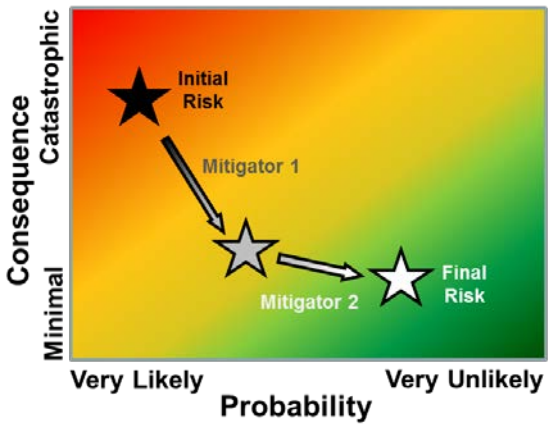

Figure 2: A generic example of a risk matrix illustrating the potential range of negative SSHE outcomes based on probability of event occurrence and significance level of consequence.

With respect to the issue of induced seismicity, the probability of negative consequence arising from an induced seismic event can be strongly influenced by the injected fluid volume and formation characteristics, including tectonic, faulting and soil conditions. In addition, past operating experience and potential occurrence of seismicity should be considered. Another element to consider may be public sensitivity to seismicity. Local construction standards and historical construction or significant architectural elements may also enter into consideration. These elements, as summarized in Table 2, provide a qualitative frame of reference for characterizing induced seismicity probability of occurrence.

Probability	Fluid Volume	Formation Characteristics	Tectonic / Faulting / Soil Conditions	Operating Experience	Public Sensitivity & Tolerance	Local Construction Standards
A Very Likely	Large volumes of injection in immediate or close proximity to active faults	Deeper injection horizon; highly consolidated formations	Large-scale developed/active faults are present at depths that could be influenced by pressure / fluid communication associated with injection; strongly consolidated formation; soil conditions amplify vibrational modes	Past injection experience in region with damaging levels of ground shaking	High population density & historically low background seismicity	Primitive construction and limited/no engineering applied for earthquake resistant designs
B Somewhat Likely	Large or moderate volumes of fluid injected in proximity to active faults	Moderate depth injection horizons; highly consolidated formations	Large-scale developed/active faults may possibly be present, but not identified; strongly consolidated formation, soil conditions may amplify vibrational modes	Limited injection experience historically in region	Moderate / high population density and/or historically low / moderate background seismicity	Sound construction practices, but age/vintage of building construction pre-dates earthquake engineering design principles.
C Unlikely	Moderate fluid volume of injection; remote from any active fault	Shallow injection horizon; highly consolidated formations	Faults well identified, and unlikely to be in influenced by pressure / fluid associated with injection; moderately consolidated formation	Significant injection experience historically in region with no damaging levels of ground shaking	Moderate population density and historically moderate / high background seismicity	Ground vibration and seismic activity routinely considered in civil / structural designs and routinely implemented in majority of buildings
D Very Unlikely	Small fluid volume of injection; remote from any active fault	Shallow injection horizon; weakly consolidated formations	Stable stress environment; minimal faulting; if faults present, too small to induce any surface felt seismicity; weakly consolidated or unconsolidated formation, soil conditions may dampen vibrational modes	Significant injection experience historically in region with no surface felt ground shaking	Low population density & historically moderate background seismicity	Rigorous earthquake engineering civil / structural designs routinely implemented and required
E Very Highly Unlikely	Small fluid volume of injection; remote from any active faults	Shallow injection horizon, Poorly consolidated formations	Stable stress environment; no significant faults, weakly consolidated or unconsolidated formation, soil conditions may dampen vibrational modes	Significant injection experience historically across wide geographic region with no surface felt ground shaking	Low population density & historically high background seismicity	Rigorous earthquake engineering civil / structural designs routinely implemented and required

Table 2: Technical factors associated with assessing probability of adverse seismicity due to injection operations.

With respect to qualitative assessment of potential consequences, it is widely accepted that the "Modified Mercalli Index" (MMI), peak ground acceleration (PGA) measurements, and/or peak ground velocity (PGV) measurements will provide the

best representation for the potential damages that may occur from a given seismic event. Note the MMI is a qualitative measure based on human felt ground shaking and observed damage in the vicinity of the seismic event.

Table 3, based in part on the ground shaking data contained on damage potential in Table 1, provides a means to establish a qualitative assessment of the potential consequences associated with an induced seismic event which is directly influenced by the potential level of ground shaking observed at the surface and considering the safety and health impact, environmental impact, public impact, and financial impact.

Consequence	Safety / Health Impact	Environmental Impact	Public Impact	Financial Impact
1 *MMI > VIII* *PGA>0.34g*	Potential fatalities and serious injuries; building structural damage.	Potential widespread long-term significant adverse affects. Possible release of potentially hazardous compounds – extended duration &/or large volumes in affected area (large chemical static / transport vessels and pipelines break).	Ground shaking felt in large region. Possible extensive mobilization of emergency 1st responders. Possible disruption of community services for extended time.	$$$$
2 *MMI: VI – VII* *0.092g<PGA<0.34g*	Potential serious injuries; building cosmetic & secondary building content damage.	Potential localized medium term significant adverse effects. Possible release of potentially hazardous compounds short-duration &/or limited volumes (large vessels break).	Ground shaking felt by all in local area. Possible mobilization of emergency 1st responders. Possible disruption of community services for brief time.	$$$
3 *MMI: V – VI* *0.039g<PGA<0.092g*	Potential minor injuries in isolated circumstances; building secondary content damage.	Possible release of potentially hazardous compounds in limited volumes (e.g., containers break).	Ground shaking possibly felt by sensitive few at site. Possible limited site impact and possible limited mobilization of 1st responder(s).	$$
4 *MMI < V* *PGA<0.039g*	Potential first aid in isolated circumstances; isolated secondary building content damage.	Possible release of potentially hazardous compounds in very small volumes (e.g., small containers break).	Possible minor public complaints.	$

Table 3. Factors influencing consequences of an induced seismic event.

An "Induced Seismicity Risk Matrix" can then be constructed based on the probabilities and consequences as described in the tables above, and is shown in Figure 3 below.

CONSEQUENCE	PROBABILITY				
	Very Likely	Somewhat Likely	Unlikely	Somewhat Unlikely	Very Unlikely
1 MMI > VIII PGA > ~0.34g	High	High	High	Medium	Low
2 MMI : VI - VII PGA > ~0.092g	High	High	Medium	Low	Very Low
3 MMI: V-VI PGA > ~0.039g	Medium	Medium	Low	Very Low	Very Low
4 MMI: II-V PGA < ~0.039g	Low	Very Low	Very Low	Very Low	Very Low

Figure 3: A generic example of a risk matrix for induced seismicity.

The Initial Risk Screening of a specific project can then involve a qualitative assessment of the probability and consequences and qualitative evaluation of the risk level using Tables 2 and 3 and Figure 3; with the goal of identifying whether the project may include potentially higher risk activities. Then, with evaluation of risk level, the potential application of various risk mitigation strategies can be considered relative to the potential risk level, considering local conditions, and reflecting project operability considerations.

Risk Assessment Case Examples

A seismicity risk assessment for injection operations can be performed on example cases based on the above definitions. The cases selected for demonstration of this approach have been the subject of various public reports and studies suggesting that injection activities associated with these wells were responsible for inducing seismicity. These examples are extensively reported in the public literature, including detailed information on injected fluid volume and formation characteristics, including tectonic, faulting, and soil conditions. In addition, information on historical seismicity, public sensitivity, and local construction is available. The specific examples selected include waste-water injection wells in the USA that have been subject to recent study by the USA Environmental Protection Agency and hydraulically fractured wells in Canada and the United Kingdom that have been subject to regulatory reviews. The specific operations and wells are summarized in Table 4, along with a brief description of the observed seismicity and the references that were examined to perform the risk assessment.

Waste-Water Injection Wells	***Description of Seismicity***	***References***
Dallas Ft. Worth Airport, TX USA	2008-2009 with maximum 3.3M event	Frolich & Potter (*BSSA*, 2011)[21]
Dallas Ft. Worth Area, Cleburne TX USA	2009 with maximum 2.8M event	Howe, et. Al. (SRL, 2010)[22]
Braxton, West Virginia USA	2008-2010 with maximum 3.4M event	Bass (UIC GWPC 2013)[23]
Guy-Greenbriar, Arkansas USA	2011 with maximum 4.7M event	Horton (SRL, 2013)[25]
General Case (100,000+ wells in USA operation)	None felt at surface	National Academy of Sciences Report[8]
Hydraulic Fracturing Operations		
Horn River Basin, British Colombia, Canada	2009-2011 with maximum 3.8M event	BCOGC Report[3]
Bowland Shale, United Kingdom	2011 with maximum 2.3M event	Preese Hall Report[4]
General case (millions of fracture stimulations)	Events typically less than 1M	Warpinski (SPE, 2013) [26]

Table 4: Case examples for illustrating risk assessment of various injection and hydraulically fractured wells, based on publicly reported information

The example case of the Braxton, West Virginia injection well is first considered. Central West Virginia in the USA has had very little historical seismicity – there is a larger catalogue of events in the southern part of the state. Between April and September of 2010, there were eight recorded events in Braxton County. Injection into a well for disposal began in April 2009. Following the observed seismicity, permitted maximum injection pressures were lowered (from 2100 to 200 psi) and there were no further seismic events until early 2012 after the injection pressures were permitted to increase again. Recently, another event (M_L=2.7) occurred in March 2013.

There is a faulted structure near the well, the Gassaway Dome – a fan-like distribution of faults characteristic of a "positive flower structure". Based on the publically available information, specifically an analysis of that feature in 1999, 10 years prior to the injection activities,[24] the site may be assessed as having a higher probability for occurrence of an induced seismic event. The M3.4 event did not create any significant damage, but was felt locally by the residents of the area. Based on the available information, this example is considered a "Low" risk situation (Figure 5).

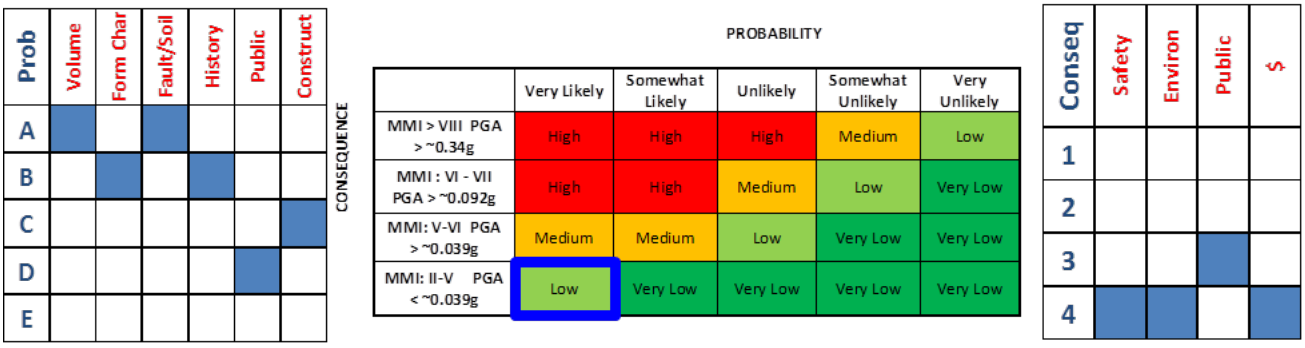

Figure 5. Risk assessment methodology applied to the example of the Braxton West Virginia injection well

The second example considered is the case of hydraulic fracturing operations in the Horn River Basin located in British Colombia, Canada.[3] Shale gas development in the Etsho area of Horn River began in February 2007. Through July of 2011,

14 pads had been used to drill 90 wells and approximately 1,600 hydraulic fractures were conducted. This area of British Colombia apparently has not any had significant recorded seismicity (going back to 1985), with the closest previous event being 160 km away. The western part of British Colombia has considerable seismicity, but this northeastern part of British Colombia is not prone to natural seismic events. The NRCAN (Natural Resources Canada) seismic network recorded 38 events in Horn River between April 2009 and December 2011 ranging in magnitude from M_L 2.2 to 3.8.

Dense seismic arrays were subsequently installed and recorded hundreds of smaller additional events that were not picked up by the NRCAN national array. Reported work by the British Colombia Oil and Gas Commission (BCOGC) suggests these events may be attributable the hydraulic fracture operations in Horn River, with the depth of the seismic events seemingly correlated with the deeper fracturing operations. Twelve faults were identified in the area of the hydraulic fracturing operations (five of the seven wells traversed faults) but the report suggested only one appeared to be activated during the recorded events.

Based on the available information, this example is considered a "Very Low" risk situation (Figure 6). This designation is influenced by the very remote nature of the location and extremely low population density with little exposure to negative consequences for the actual level of ground shaking that was encountered.

Prob	Volume	Form Char	Fault/Soil	History	Public	Construct
A				■		
B	■	■	■			
C					■	■
D						
E						

CONSEQUENCE

PROBABILITY

	Very Likely	Somewhat Likely	Unlikely	Somewhat Unlikely	Very Unlikely
MMI > VIII PGA > ~0.34g	High	High	High	Medium	Low
MMI : VI - VII PGA > ~0.092g	High	High	Medium	Low	Very Low
MMI: V-VI PGA > ~0.039g	Medium	Medium	Low	Very Low	Very Low
MMI: II-V PGA < ~0.039g	Low	Very Low	Very Low	Very Low	Very Low

Conseq	Safety	Environ	Public	$
1				
2				
3				
4	■	■	■	■

Figure 6. Risk assessment methodology applied to the example of the Horn River fracturing operation.

This assessment methodology can be applied to the various examples listed in Table 4, with the results of the assessments summarized in Figure 7 below.

Disposal

1. Dallas-Forth Worth Airport, Texas
2. Dallas-Fort Worth, Cleburne, TX
3. Braxton, West Virginia
4. Guy-Greenbriar, Arkansas
5. General Case – Injection Well

Hydraulic Fracturing

6. Horn River Basin, Canada
   a) Etsho
   b) Tattoo
7. Bowland Shale, UK
8. General Case – HF Well
   - *Microseisms always created*

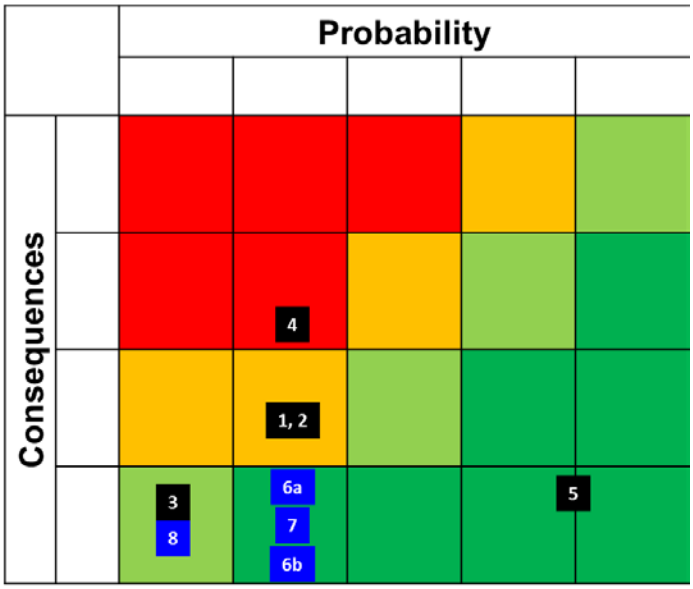

Figure 7: Risk assessments associated with selected publicly reported examples.

Key observations that are suggested from this assessment methodology include:

1. *hydraulic fracturing is clearly a very low risk activity* relative to inducing adverse seismicity (consistent with the conclusions provided in the recent USA National Academy of Sciences report); and that
2. *it may be possible that under very rare and unique geologic circumstances, waste-water injection operations may pose an elavated risk*; and risk mitigation may be considered in these rare instances to futher reduce the overall risk level.

The observed ground shaking levels in the Dallas Ft. Worth examples, and in Guy Arkansas example suggest an elevated potential risk level as indicated in Figure 7. In the Guy Arkansas example, significant ground shaking was observed over a large region, creating a higher risk exposure.[25]

Potential Mitigation of Higher Risk Scenarios

For medium or higher risk situations, depending on the local conditions, it may be appropriate to consider mitigation options that could reduce the overall risk level. Such mitigation options could consider local factors and available monitoring options and suitable "Stoplight Systems". For example, various mitigation options that could be considered include possibly implementing one or more of the following elements:

- Identifying the location of faults in vicinity of project area based on seismic survey data and/or surface expressions;
- Placing the well outside of the "at-risk" area where injected fluid volume will not significantly and adversely perturb the pressure/stress state at identified fault locations;
- Monitoring for presence of any previously unidentified faults during drilling could be considered, and location noted if a fault encounter;
- Avoiding perforating or completing the well directly in contact or immediately adjacent to identified and significant faults could be considered;
- Avoiding direct injection of fluids into a known significant fault(s);
- Implementation of a fit-for-purpose monitoring and notification system based on local conditions, and including possible implementation of a "Stoplight System" could be considered; with a possible plan to adjust operations if anomalous seismicity occurs (such monitoring could be human observation or electronic systems on a periodic or near-real time basis depending on risk level and local conditions; and
- Providing education and training of well-site personnel regarding the potential for induced seismicity and awareness of ground vibration / shaking beyond baseline pumping / site noise could be considered.

Stoplight Systems

Stoplight systems have been broadly discussed and implemented in risk management protocols associated with geothermal projects,[27] and the possibility for the application in injection operations has also been raised.[28] The specific design and operation of the Stoplight System would be appropriately considered in the context of the risk level and local conditions associated with a specific injection operation.

There are four key elements to consider in establishing the Stoplight System: (a) monitoring methods/equipment; (b) monitoring frequency; (c) the threshold parameters for the "yellow" and "red" trigger points where operations would be modified or suspended; and (d) reaction time needed to implement operational adjustments if required.

For example, when considering a Low Risk or Very Low Risk activity, it may be reasonable for only occasional monitoring, or monitoring provided by on-site personnel via "human-based" observation of any noticeable or unusual ground shaking; without need for any specialized seismicity monitoring capability. Conversely for a High Risk activity, it may be appropriate to implement specialized monitoring that could, for example, provides real-time notification if anomalous seismicity were to occur, and a mechanism to make real-time or near-real-time adjustment to the operations (such as has been done in some geothermal projects such as the Geysers project[29] in California).

The equipment, procedures, and resource requirements for the Stoplight System could be substantially different depending on the risk level and local conditions. Similarly the precision, accuracy, and sensitivity could be selected based on the level of risk and local conditions. For example, in many instances the current USGS (USA) or NRCAN (Canada) regional monitoring system may be a suitable monitoring system for the vast majority of applications in the N. America.

Figure 8 highlights the conceptual approach and options to consider when evaluating the specific design requirements for a Stoplight Procedure based on risk level. This approach provides a rational basis for defining and selecting monitoring requirements; for example, there is little benefit to mandating specialized and expensive automated monitoring systems for clearly low risk activities that can be monitored effectively by on-site personnel (e.g., via human observation or low-cost PC-based accelerometer systems). When selecting a measurement system for implementation, there are certainly many elements to consider in the design, and special consideration must be given to the frequency content relationship and corner frequency for a given magnitude.

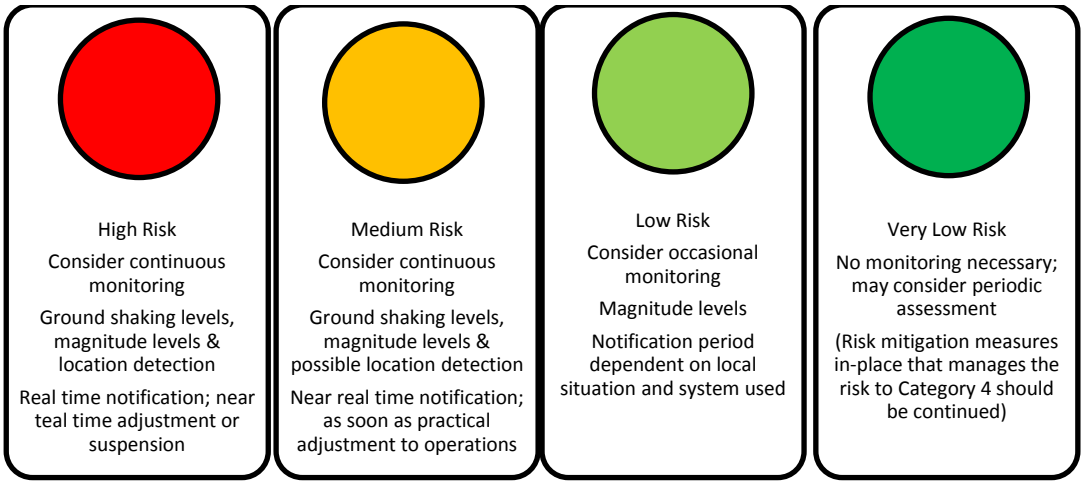

Figure 8: Conceptual approach for selection of "Stoplight System" monitoring equipment, methods, and procedures

There are many different options for the monitoring approach to use with the Stoplight System that may be considered. Several typical options are summarized below. Definition and selection of any specific approach would consider the risk level and the local situation. There are many options that could be considered for monitoring methods in a Stoplight System, such as:

1. Human-observation of ground-shaking at location
   - Easily implemented; requires on-site personnel; near real-time reaction; sensitive to MMI > II-III, low-cost, but would not provide hypocenter or epicenter event location.
2. Regional monitoring arrays
   - Available in many countries, broad regional coverage; post-event reaction; capable of measuring M1.0+, precision of location measurements may be issue; 24/7 monitoring remotely; does not report directly ground-shaking value, low cost if regional monitoring already in place.
   - As an example, the USGS has available a free real-time monitoring service that sends automated notification emails when earthquakes happen in a local area.
3. Accelerometer-based "strong shaking" systems
   - Readily implemented; near real-time reaction; can tailor sensitivity of detector for local conditions and slightly perceptible ground shaking levels, relatively moderate cost, but would not provide hypocenter or epicenter event location.
4. Local surface arrays
   - Readily implemented; near real-time reaction; requires high level technical expertise for event location and on-site staffing continuously for operations, relatively high cost, but may provide event location.
5. Local buried near-surface receivers
   - Readily implemented; near real-time reaction; requires high level technical expertise for event location and on-site staffing continuously for operations, relatively high cost, and may provide event location.

6. Local borehole installed systems

   - Readily implemented; near real-time reaction; requires high level technical expertise for event location and on-site staffing continuously for operations, relatively high cost, and may provide event location.

Stoplight Systems – Contrasting Approaches

Recently, regulators in Canada and in the United Kingdom have put in place regulations for use of Stoplight Systems and mitigation methods to address the risk of induced seismicity associated with hydraulic fracturing operations.

In Canada, the British Colombia Oil and Gas Commission (BCOGC) has put in place a stoplight system based on use of the existing regional monitoring network. The BCOGC will contact the operator if anomalous seismicity is detected at a measured magnitude 2.0 or above, mitigation discussions begin with a unique response considered as appropriate for each case. If a larger magnitude event, M > 4.0, is detected, the operations are temporarily suspended and the data further evaluated. A re-start of operations would be considered pending the review and agreement of the BCOGC.

In the United Kingdom, the Department of Energy and Climate Change (DECC) has put in place a stoplight system that requires use of high resolution local monitoring systems. Additional controls required as part of standard operating procedure. Background and real-time seismic monitoring is required, and the systems must be capable of detection of micro-seismic events between -1.0 < M < 1.0.

Furthermore, as an added precaution, flowback is required after each fracture stage to relieve the system pressure. The flowback requirement in practice will provide additional operational complexity that must be considered by the operator in the establishment of the completion operations.

For example, it is a common practice in North America to implement a “Perf-and-Plug” or “Sliding-Sleeve External Packer” system for executing multi-stage fracturing operations during the stimulation of horizontal wells. These two approaches are not directly amenable to flowback; as during flowback, some proppant associated with the fracturing operation will flow back into the horizontal casing string, creating significant difficulty to run tools in the well or reliably initiate pumping in the next stage.

Effectively addressing this flowback requirement in the case of a horizontal well will likely require the operator to deploy alternate stimulation methods, for example using coiled tubing, to provide an ability to circulate clean the horizontal sections and enable reliable fracture initiation of the next stage. The impact of mandated operational requirements should be fully considered relative to the intended scope of operations, considering the broad well construction process, and incremental mechanical risk and cost that may be incurred with alternate approaches that may be required.

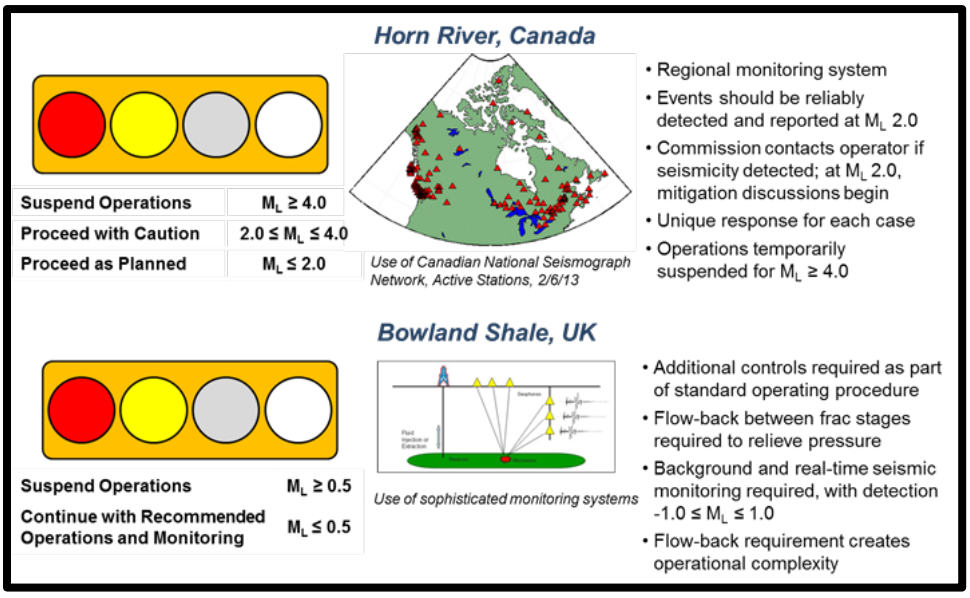

Figure 9: Some industry examples of induced seismicity mitigation for hydraulic fracturing operations

Summary

Approaches to assess and manage seismicity risk should be encouraged, be based on sound science, and take into account the local conditions, operational scope, geological setting, historical baseline seismicity levels and reflect reasonable and prudent consideration of engineering standards and codes related to seismicity structural health.

Based on significant industry experience with injection operations on a global basis, the science-based risk assessment methodology presented in this paper suggests that:

- hydraulic fracturing is clearly a very low risk activity relative to potentially inducing negative consequence seismicity; and
- under very rare and unique geologic circumstances, waste-water injection (disposal) operations may be identified as a elevated risk; and risk mitigation could be considered in these rare instances to futher reduce the overall risk level.

Seismicity monitoring and mitigation could be considered in local areas where induced seismicity is of significant risk, such as in areas where:

- Significant seismicity (above historical baseline levels) has actually occurred and sound technical assessment indicates that the seismicity is associated with fluid injection operations, or
- If sound technical assessment indicates the local area may possess significant risk associated with potential induced seismicity.

In local areas where induced seismicity may be of significant risk, appropriate monitoring and mitigation could include:

- A mechanism to alert the operator in an appropriate timeframe to the occurrence of seismicity significantly above local historical baseline levels, and
- A procedure to modify and/or suspend operations if seismicity levels increase above threshold values for maintaining local structural health integrity and minimizing secondary damage

Stoplight systems and operational mitigators, if implemented, would appropriately consider completion practices and operational complexity, and the actual level of risk associated with the local conditions.

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