CANADA'S OIL & NATURAL GAS PRODUCERS

Industry Shared Practices

Anomalous Induced Seismicity due to Fluid Disposal

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2021-0015

The Canadian Association of Petroleum Producers (CAPP) represents companies, large and small, that explore for, develop and produce natural gas and oil throughout Canada. CAPP's member companies produce about 80 per cent of Canada's natural gas and oil. CAPP's associate members provide a wide range of services that support the upstream oil and natural gas industry. Together CAPP's members and associate members are an important part of a national industry with revenues from oil and natural gas production of about $116 billion a year. CAPP's mission, on behalf of the Canadian upstream oil and natural gas industry, is to advocate for and enable economic competitiveness and safe, environmentally and socially responsible performance.

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Overview

As prudent and responsible operators active in the development and production of unconventional resources, it is important to gain a better understanding of the types and sources of seismic activity. By supporting research at universities, partnering with federal and provincial agencies, and conducting our own on-site research, we are contributing to a better understanding of seismicity and the potential impacts of our operations in each unique geological setting. Evidence suggests that any induced seismicity caused to date by fluid disposal in the Western Canadian Sedimentary Basin (WCSB), while occasionally felt, is generally deep, located in or near the disposal reservoir interval and poses no risk to health, safety or the environment.

CAPP and its member companies encourage approaches to managing potential induced seismic risk that are based on science, considering factors that include the local public's exposure to felt events, operational factors, geological setting and historical baseline seismicity levels. We also support the consideration of applicable engineering codes and standards related to seismic hazards and structural integrity. We take a diligent risk-based approach toward studying, managing and limiting the potential for induced seismicity associated with fluid disposal operations.

Induced seismicity is a rare aspect of fluid disposal in the WCSB, occurring in a small percentage of disposal wells. Typically, these are microseismic events, too small to be felt at the surface, but approximately one percent of disposal wells have generated events greater than magnitude 3 on the Richter scale[1]. These have not posed a threat to safety, structures, or the environment. Seismic events felt at the surface and linked to human activities are often referred to as anomalous induced seismicity. This is the case in some areas in Alberta and northeast British Columbia where incidents of felt seismic events associated with fluid disposal have been reported.

1 Hydraulic Fracturing and Seismicity in the Western Canada Sedimentary Basin by Gail M. Atkinson, David W. Eaton, Hadi Ghofrani, Dan Walker, Burns Cheadle, Ryan Schultz, Robert Shcherbakov, Kristy Tiampo, Jeff Gu, Rebecca M. Harrington, Yajing Liu, Mirko van der Baan, and Honn Kao, Seismological Research Letters Volume 87, Number 3 May/June 2016 631

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1 Purpose and Scope

Operators in CAPP's seismicity committees have shared their experiences and knowledge to produce this document. It is designed to serve as a guide and describes current practices for induced seismicity risk appraisal related to fluid disposal, risk mitigation approaches and key research and activities. These shared practices reflect the current state of knowledge and take into account ongoing research to improve understanding. This document is therefore described as a "shared" rather than "best" practice. Operators are encouraged to follow these shared practices voluntarily. Any recommendations herein are superseded by regulatory requirements that exist in specific areas of operations.

Seismicity is a common natural phenomenon which occurs deep below the ground near geologic faults. When linked to human activity, it is known as anomalous induced seismicity. Natural or industrial alterations to the environment that create or alter stresses in deep rock formations, such as glacial movement, volcanic activity, dams, mining, disposal, hydraulic fracturing and geothermal, all have the potential to induce seismicity.

The scope of this document is based on operator experience in the WCSB, where disposal is typically into geologic formations (such as reefs) capable of accepting large quantities of fluids. While deep, these formations are typically laterally constrained and are located hundreds of meters or more above basement rocks, and so the geologic situation differs to some extent from U.S. states such as Oklahoma, where disposal into laterally extensive formations immediately above basement rocks leads to seismicity that can be far from the disposal well. The scope of this document does not cover seismicity from hydraulic fracturing, as that is covered by CAPP's Anomalous Induced Seismicity due to Hydraulic Fracturing shared practice. Also, while its themes are broadly applicable to seismicity from any disposal operations, it does not specifically cover seismicity from disposal of CO_2 into deep saline aquifers, geothermal operations, hazardous waste disposal or acid gas disposal.

The document provides information of use to operators in managing the risk of induced seismicity from fluid disposal. The shared practices are general in nature. Operators will need to adapt the shared practices to their specific situation. It is the responsibility of each operator to conduct their operations safely and in accordance with the circumstances of the particular operation.

2 Risk Appraisal and Mitigation

The key planning activities that guide the design and implementation of fluid disposal operations, where induced seismicity has been identified as a potential risk, should be influenced by a structured hazard assessment and a corresponding risk management plan appropriate to the specific surface location and geologic formation.

What follows is a discussion that will help lead to a substantiated and logical pre-operations risk assessment, and a presentation of recommendations for monitoring and appropriate operational responses.

2.1 Pre-Operations Risk Assessment for Anomalous Induced Seismicity Due to Fluid Disposal

While most fluid disposal operations do not trigger induced seismicity, anomalous induced seismicity has occurred under certain conditions. This section highlights some of the factors that should be considered when designing and assessing risk associated with fluid disposal operations. As with all aspects of oil and gas operations, hazards exist and should be evaluated/assessed to manage and mitigate the potential associated risks.

A hazard is considered any source of potential damage or harm to people or property. The risk associated with a hazard is understood to be the product of the likelihood of the hazard to occur and its consequence, as presented in Figure 1. That is,

Risk = Likelihood x Consequence

The consequence of a hazard is a measure of its severity or impact. For anomalous induced seismicity, the measured risk is directly related to a seismic event's resulting ground motion. This is primarily governed by the event's magnitude[2], near-surface geological conditions, ground motion generated at various epicentral distances and the effects of the ground motion on nearby infrastructure and/or the public.

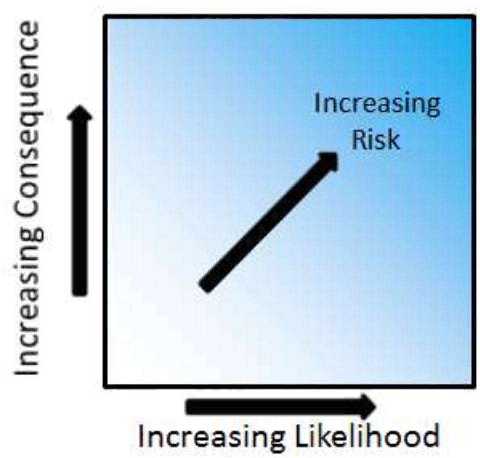

Figure 1: Risk Matrix

[2] Although ground motion is the key concern, the most commonly used measure of seismic event size is the magnitude scale. As such, most industry and regulatory traffic light/stop light approaches still use magnitudes as thresholds in their response plans. The magnitude value calculated depends on whether moment or local magnitudes are used, what phase is analysed and how the equations are parameterized. In this document, magnitude is used to refer to any of these methods of calculating the size of a seismic event.

For decades, seismologists have struggled to predict when and where seismicity will occur in long-standing geological systems with well known, essentially steady-state, tectonic stress. Natural seismicity is typically characterized based on historically observed seismicity and the assumption of a power law (Gutenberg-Richter) relationship between event magnitude and its frequency of occurrence that is normally derived over a significant period of time (years to decades) as shown in Figure 2.

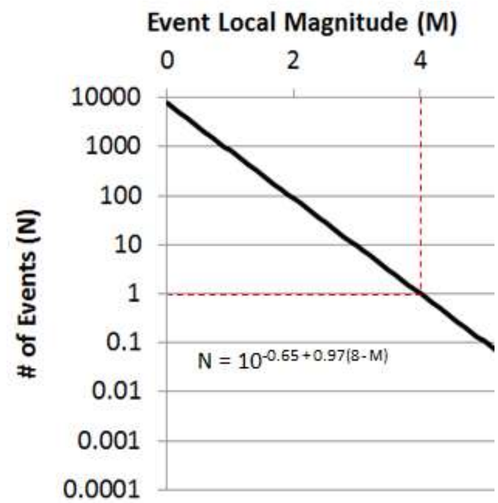

Figure 2: Gutenberg-Richter plot normalized for a single M=4.0 event

When short-term human activity, such as fluid disposal, impacts a geological system, our ability to predict the number and magnitude of seismic events is challenged. However, there are factors we can consider when assessing the risk of induced seismicity caused by fluid disposal, as identified in the following subsections.

2.1.1 Historical Seismicity

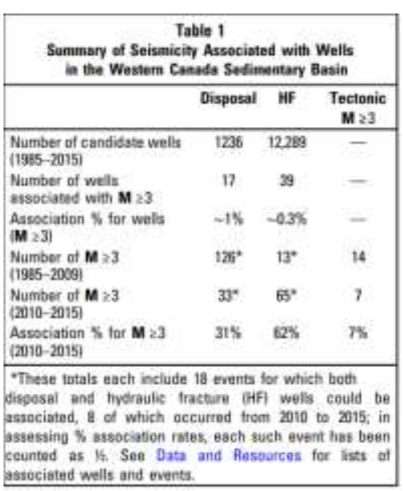
Table 1
Summary of Seismicity Associated with Wells in the Western Canada Sedimentary Basin

	Disposal	HF	Tectonic **M** ≥3
Number of candidate wells (1985–2015)	1236	12,289	—
Number of wells associated with **M** ≥3	17	39	—
Association % for wells (**M** ≥3)	~1%	~0.3%	—
Number of **M** ≥3 (1985–2009)	126*	13*	14
Number of **M** ≥3 (2010–2015)	33*	65*	7
Association % for **M** ≥3 (2010–2015)	31%	62%	7%

*These totals each include 18 events for which both disposal and hydraulic fracture (HF) wells could be associated, 8 of which occurred from 2010 to 2015; in assessing % association rates, each such event has been counted as ½. See Data and Resources for lists of associated wells and events.

Table 1: WCSB Seismicity Summary from Atkinson et al, 2016

Checking historical seismicity data within 20 km will help identify whether there has been natural or induced seismic activity near an area of operations. The occurrence of previous seismic activity indicates the geologic system may be critically stressed. This may raise the likelihood of seismic activity resulting from fluid disposal, particularly if the historical seismicity is known to come from the depth near that of planned disposal operations. In addition to the occurrence of seismicity, it is useful to identify the locations, spatial clustering/trends, focal mechanisms and the maximum magnitude that has occurred. These attributes provide further insight into the seismogenic character of the area. A useful academic resource for identification of fluid disposal related seismicity in the WCSB can be found courtesy of the Canadian Induced Seismicity Collaboration[3].

The absence of seismic activity does not necessarily mean the geologic system is not critically stressed, as the historical seismicity dataset may suffer from poor or sparse array monitoring and may not have been capable of detecting low magnitude seismicity. If an area has not been previously targeted for development, fluid disposal operations may induce events for the first time as natural seismicity often occurs on larger time scales that may not yet have been captured during any monitoring. Data should be analyzed from longer historical records and collected from higher-quality arrays when available. For a field/play scale perspective of the historical seismicity, it is helpful to first review the data (e.g., Natural Resources Canada, U.S. Geological Survey, Alberta Geological Survey) on a regional scale around operations to put the planned operation into the correct context.

2.1.2 In-situ Stresses

The subsurface stress state is a key factor in assessing the likelihood of seismicity in a region, in particular S_{Hmin}. Activation of pre-existing faults only occurs under very specific stress states of the geological system. Local estimates of the in-situ stress magnitudes and azimuths (principal stresses S_V, S_{Hmax}, S_{Hmin}[4] and pore pressure) at the target level should be made using available data. This may provide insight into how close the system is to failure for an optimally orientated fault and for any other fault orientations identified.

Qualitative and quantitative methods to help characterize the local stresses include:

- Density log data.
- Multi-arm caliper and FMI/OBMI log data.
- Initial reservoir pressure.
- Formation integrity tests, or formation fracture pressure based on ISIP.
- Step rate injectivity test or diagnostic fracture injection tests (DFIT).
- Microseismic data, if available.
- Attributes that include advanced pre-stack seismic attributes to predict zones of elevated local stresses from a combined mapping of 3D inversion for highly brittle zones with low minimum closure stress with 3D azimuthal differential shear anisotropy to assess elevated strain energy.
- Disposal and injection fracture gradient maps for the formation fluids are being disposed into. This can be found in various data services and for B.C. can be found online from the BC Oil and Gas Commission.

3 Overview – Canadian Induced Seismicity Collaboration

4 M.D. Zoback, et al, Determination of stress orientation and magnitude in deep wells, International Journal of Rock Mechanics and Mining Sciences, 2003, https://doi.org/10.1016/j.ijrmms.2003.07.001.

2.1.3 Geological Fault Mapping

It is broadly understood that seismic events induced by human activity occur on previously existing faults in the subsurface. Faults provide a pathway between the disposal formation and brittle overlying or underlying formations.

It can be challenging to identify existing faults, particularly faults with small offsets, vertical dip, or a strike-slip sense of motion. However, there are several technologies and methods available to industry that may be useful. These include:

- FMI/OBMI log data and cross dipole shear logging.
- Drilling cuttings or core sample data.
- Gamma ray logs from the horizontal well section (may detect vertical offsets of bedding).
- Microseismic data (may highlight minor fault re-activation trends).
- 2D/3D surface seismic data for fault identification within 20 km.
- To assist in identifying subtle faults, it is helpful to use seismic attributes such as curvature, semblance and coherence to highlight structural features in the seismic data.

Faults and structural features should be mapped within the target formation, as well as above and below the area of planned fluid disposal. It may also be useful to map faults at deeper levels (e.g., crystalline basement). Basement features may help to identify controlling faults that have been nearly healed at the reservoir depth but may still exert a local influence. Gravity and magnetic data can be useful in identifying some of these larger-scale basement features that may be difficult to resolve on most industry surface seismic data.

Although identifying faults near the area of fluid disposal operations is good practice, industry experience on the use of fault mapping in B.C. and Alberta has been mixed. Seismicity with anomalous magnitudes tends to appear or cluster in zones. These zones may not correlate to areas of mapped faults, suggesting a pre-existing fault exists but is not easily discernable.

2.1.4 Operational Risk Factors

Operational risk factors in known areas of seismicity should be evaluated to capture historical experience. This knowledge can be used to determine whether the planned disposal activities pose an operational risk. Examples of operational fluid disposal parameters that may affect the risk of seismicity are:

- Initial reservoir pressure (Pi), and the associated wellhead and bottom hole injection pressure.

- Injection volumes and injection rate, injection rate variability[5], maximum limiting injection pressure (e.g., 120 per cent Pi[6], MWHIP as prescribed by regulation[7], or established practices[8]).
- Alterations in in pumping rates that may lead to abrupt changes in injection rate and well pressure[9].
- Operational factors, such as the frequency and length of maintenance downtime, which could alter pore pressure and differential stress[10].
- Injection fluid characteristics such as viscosity and density.
- Available voidage capacity based on reservoir characteristics.
- Caprock formation fracture pressure, if known.
- Cumulative effects from disposal operations in the local area that may influence fault slip potential.

2.2 Consequence

Although rare, anomalous induced seismic events can sometimes be reported as felt by the public at the surface. Such events are also referred to as anomalous induced seismicity. As such, it is important to identify any communities near the area of operations and be prepared to respond to local concerns regarding felt events in addition to regulatory requirements.

Earthquake magnitude measures the seismic energy released and earthquake intensity estimates the degree to which the energy released is felt at surface as ground motion. The intensity of ground shaking is defined by the Modified Mercalli Intensity Scale (MMI). In the rare cases where induced seismic events are felt, intensities may range from II (up to 30 km away) to V (close to the epicenter). Table 2 shows the MMI scale NRCAN and the USGS use to quantify felt events.

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5 Understanding rate effects in injection-induced earthquakes | Nature Communications

6Application-Guideline-for-Deep-Well-Disposal-of-Produced-Water-Non-Hazardous-Waste-March-Release-2021.pdf (bcogc.ca)

7 Directive 065: Resources Applications for Oil and Gas Reservoirs (aer.ca)

8 Systematic Design and Analysis of Step-Rate Tests To Determine Formation Parting Pressure | SPE Annual Technical Conference and Exhibition | OnePetro

9 Seismicity Induced by Simultaneous Abrupt Changes of Injection Rate and Well Pressure in Hutubi Gas Field, Lanlan Tang, Zhou Lu, Miao Zhang, Li Sun, Lianxing Wen

10 Mehrabifard, A. and Eberhardt, E. (2021): Investigation of the dependence of induced seismicity magnitudes on differential stress and pore pressure using supervised machine learning, northeastern British Columbia (NTS 093, 094A, B, G, H) and globally; in Geoscience, BC Summary of Activities 2020: Energy and Water, Geoscience BC, Report 2021-02, p. 57–66

Table 2: Description of the levels of Modified Mercalli Intensity (source USGS).

Intensity	Shaking	Description/ Damage
I	Not felt	Not felt except by a very few under especially favorable conditions.
II	Weak	Felt only by a few persons at rest, especially on upper floors of buildings.
III	Weak	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	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.
V	Moderate	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI	Strong	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII	Very strong	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.
VIII	Severe	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.
IX	Violent	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.
X	Extreme	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.

In addition to magnitude, intensity is determined by distance and depth, site amplification effects and source radiation pattern. Site amplification effects due to site class vary considerably. A magnitude 4 event may not be felt at all on hard rock (Class A) soil, whereas the same event may be felt a considerable distance away on soft (Class E) soil. Ground motion is described by both peak ground acceleration (PGA) and peak ground velocity (PGV). Table 3 relates PGA and PGV to Mercalli Intensity.

Table 3: Relationship between PGA, PGV, Damage Potential and Intensity (source USGS[11])

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	*<0.02*	*0.1*	*1.4*	*4.7*	*9.6*	*20*	*41*	*86*	*>178*
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2012)

Through 2015, there were nine induced seismic events due to fluid disposal in Western Canada greater than magnitude 4.0, with the largest being 4.4[12], with little to no impact on infrastructure, or on health and safety. However, as part of a field-level risk assessment, it may be prudent to identify potentially susceptible critical infrastructure[13] such as, but not limited to, dams, gas plants, power facilities, water towers, etc. Where warranted by risk such as proximity to population centers, operators may consider use of a Ground Motion Prediction Equation (GMPE) that relates earthquake magnitude to ground motion vs. distance for a given region. This allows operators to set magnitude thresholds appropriate to the risk associated with the disposal well, along with those required by regulation.

11 Shakemap 3.5 Manual, Chapter 2.6.1, USGS

12 Hydraulic Fracturing and Seismicity in the Western Canada Sedimentary Basin by Gail M. Atkinson, David W. Eaton, Hadi Ghofrani, Dan Walker, Burns Cheadle, Ryan Schultz, Robert Shcherbakov, Kristy Tiampo, Jeff Gu, Rebecca M. Harrington, Yajing Liu, Mirko van der Baan, and Honn Kao, Seismological Research Letters Volume 87, Number 3 May/June 2016 631

13 Gail M. Atkinson. Strategies to prevent damage to critical infrastructure due to induced seismicity. FACETS. 2(): 374-394. https://doi.org/10.1139/facets-2017-0013

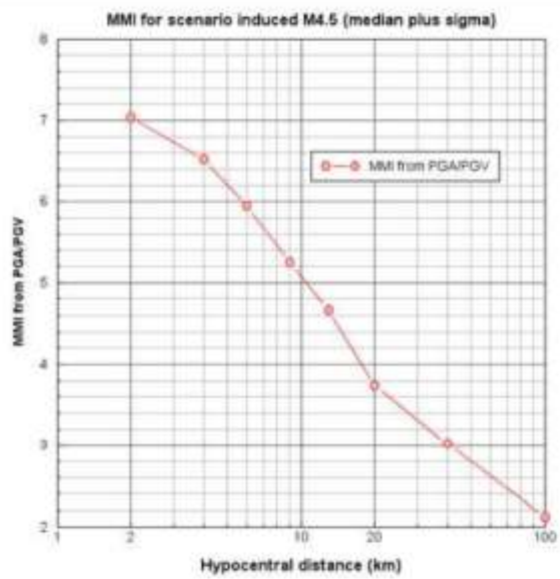

Figure 3: Expected intensity of motion for an induced scenario event of M4.5, for ground motions at the median plus one standard deviation level. The intensity is calculated as the average value predicted from the PGA and PGV (from Atkinson, 2017)

2.3 Final Risk Assessment

The overall risk associated with induced seismicity due to fluid disposal operations is the result of a reasonable aggregation and evaluation of all hazards and associated risks, weighted appropriately for the area of operations. The combined effect of identified hazards and risk factors discussed above should result in risk categories based on how they rank. The responsibility of how to assess and aggregate the risk from each of these should be passed on to operators.

In summary, total risk increases with the following:

- Historical seismicity
- In situ stresses
- Discernible faults from geological mapping
- Operation risk factors due to activities on site and adjacent operations
- Consequence

2.3.1 Operations Risk Review

Prior to initiating fluid disposal operations and depending on the results of the fluid disposal project risk assessment, it is good practice to hold a seismicity risk and seismicity mitigation planning review with key subsurface, technical and operational staff, and decision makers. The review can align understanding of the risks and associated response protocols for the fluid disposal well or wells, and should:

- Review and document hazards, risk factors and their characteristics for the upcoming area of operations.

- Finalize and document the prioritized risk mitigation response plan for consideration if seismicity events or trends occur.
- Use the results of the risk review to finalize seismicity monitoring and response protocols for that operation.

2.4 Seismic Monitoring and Response during Fluid Disposal Operations

In areas of higher risk, it is important to establish an appropriate seismic monitoring plan based on the risk assessment for anomalous induced seismicity. Options for monitoring span publicly available regional data and a spectrum of local private monitoring solutions. Prior to fluid disposal operations, the risk assessment should be incorporated into a documented monitoring and response plan. Below are suggestions for such a plan.

2.4.1 Monitoring System

Monitoring for induced seismicity serves three main purposes:

- Provides the operator with an opportunity to identify elevated levels of seismic activity or clustering before an anomalous event occurs so that proactive operational adjustments can be implemented to mitigate risk.
- Allows the operator to implement reactive operational changes quickly, if an anomalous seismic event occurs.
- Allows operators to learn more about the occurrence and behavior of anomalous induced seismicity to improve mitigation measures.

Monitoring will often use a national seismic network for detection and location of seismic events. In some cases, it may be preferred to supplement with a local private network installed to have same-day or near real-time notification of seismic activity. Furthermore, several applications are available for devices that provide real-time notifications of events that can be used to monitor the public arrays.

If an event is detected as part of a real-time seismic monitoring program within an agreed area surrounding the disposal well, the service provider should contact the agreed representative, consistent with their response protocol.

For fluid disposal wells in areas where seismicity has been demonstrated and the operator chooses to monitor, it is recommended to monitor prior and during disposal operations, and for a period of time thereafter.

2.4.2 Operational Response: Roles/Responsibilities/Communications

Personnel who are key to the seismicity response system should be documented and their roles and responsibilities described. The generic roles and responsibilities below are a guideline and can be modified and/or superseded by applicable regulations, company policies, etc.

Examples of important roles to identify:

- Seismic monitoring representative

    - Usually a member of a seismic monitoring service provider
    - May be on call to respond to large seismic events detected in proximity to known well operations
    - Confirms the occurrence, magnitude and determined location of an event of concern
- Operator technical staff (usually a geophysicist or engineer based in the office)
    - Typically on-call during operations
    - Regularly checks the seismicity recorded by the national network or by a local network, and when feasible, correlates observed seismicity to injection rate or pressure
    - Initiates communication protocols (e.g., contacting the regulator and the field operations) and organizes an investigation into seismic events of concern
    - If warranted by ground motion and fragility functions[14], initiate integrity assurance programs such as LDAR and pipeline inspections
    - Collaborates with an interdisciplinary team, develops a response / mitigation plan for submission and approval by the regulator (if required)
    - Communicates the approved mitigation plan to the field operations engineer
- Field supervisor/production superintendent
    - Based in the field and oversees well site operations
    - Executes the well operational responses/interventions and startup if operations were stopped during the investigation of an event of concern.
    - Responds to felt events by immediately assessing site and personnel safety followed by inspection for environmental impacts
- External communications focal
    - Operating company staff
    - Communicates with the public and media.
- Decision maker(s)
    - Identifies who has the key decision-making role for yellow- and red-light situations
- Regulator
    - Liaises with the regulator authority for well activities

2.4.3 Example Operational Response System

Table 4 provides an example Operational Response System for seismicity detected in the vicinity of fluid disposal well operations. Operators may modify their thresholds and metrics (e.g., ground motion) to suit local operations.

14 Seismic Damage Estimation for Buried Pipelines: Challenges after Three Decades of Progress Omar Pineda-Porras, Ph.D.1 ; and Mohammad Najafi, Ph.D., M.ASCE

Table 4: Example Operational Responses to Observed Seismicity based on AER's Subsurface Order No.2 in High to Moderate Risk Areas

Response Level	Observed Seismicity[15]	Recommended Operational Response
Level A	Local conditions may vary, but typically the seismicity would be less than magnitude 2.	• Continue with regular operations and initiate monitoring. • Track potential trends in the location and magnitude of events. • Consider initiation of yellow light mitigations if trends indicate the potential for higher risk.
Level B	Seismic events between magnitudes 2 and 4 are being observed, or there is a trend toward events of larger magnitude with time.	• A response plan on-site prior to continuing operations. • Meet with engineers and subsurface geological and geophysical staff to evaluate forward steps. The urgency on meeting with the team is subject to the level of seismicity observed. • Consider making operational changes to mitigate further seismicity. These include, but are not limited to: ○ Reducing the injection rate or pressure ○ Moving to another disposal well to allow time for gradual pressure depletion (returning at a later time) and conducting an analysis of seismic event magnitude or location trends near the problematic well.
Level C	Seismic events greater than magnitude 4 are observed, or ground motion is felt at the surface.	• Execute a controlled well shutdown and suspend further operations until an appropriate course of action is determined and approved by the operating company decision maker and the regulator as required.

3 Areas of Active Research

The science of anomalous induced seismicity is complex. Research and understanding are evolving rapidly among operators, academia and regulators. Operators are engaged in a wide range of research in Canada and globally. As the scientific community learns more, it is expected new avenues of research will emerge.

[15] The seismicity levels in this table are provided as an example. At this time, there are four traffic light protocols in Western Canada, two in B.C. and two in Alberta, with shutdown magnitudes of either 4.0 M_L or 3.0 M_L, depending on the specifics of the given area. Special regulations are also in place for some hydroelectric dams and gas storage facilities. If regulations are not already in place, operators are encouraged to consult with regulators and other operators regarding appropriate magnitude thresholds for a given region. Operators should set their response levels based on local operational conditions, regulatory requirements and internal protocols.

CAPP members are conducting and supporting several research efforts to improve how risk from anomalous seismicity is identified and mitigated. Work is undertaken through research organizations and academic/industry consortia. CAPP member companies also contribute data and technical knowledge to support academic research. It is important to understand and identify knowledge gaps and demonstrate to regulators how operators are supporting consortium research on anomalous induced seismicity. The list below mentions some of the universities, academic consortia and other organizations industry works with to further understanding of induced seismicity.

Collaborative research on induced seismicity is conducted under the leadership of:

- Microseismic Industry Consortium (Universities of Alberta and Calgary)
- Canadian Induced Seismicity Collaboration
- Center for Integrated Seismicity Research (University of Texas Bureau of Economic Geology)
- Stanford Center for Induced and Triggered Seismicity (Stanford University)
- Massachusetts Institute of Technology
- Southern Methodist University
- Miami University
- Geoscience BC

While the geomechanics of natural seismicity are generally understood, induced seismicity from fluid disposal requires further research. Establishing linkages from operational activity to geomechanics is in its early stages. Ideally, deterministic models could be built from the mechanisms of induced seismicity that would predict when and where an anomalous induced seismic event will occur. This is unlikely in the near term.

CAPP members, in collaboration with academia, have identified these research priorities:

- Magnitude standardization.
- Subsurface characterization.
- Understanding seismicity effects at surface (e.g., shake maps).
- Relationship of ground motion to magnitude and effects on infrastructure
- Establishing effective operational mitigations

4 Industry and Regulator Interactions

Effective interactions between operators as well as between operators and the regulator are essential to the successful development of resources in an economic and socially responsible manner. This section highlights the various interfaces when dealing with anomalous induced seismicity due to fluid disposal.

4.1 Industry/Regulator Interface

The regulator's role includes ensuring industry compliance with provincial legislation to protect the public interest.

Industry's goal is to manage and continue operations safely and effectively while reducing the risks associated with anomalous induced seismicity. Operators who are disposing of produced water and other fluids should follow these guidelines, comply with regulations[16], relevant technical practices [17], and proactively communicate clearly and directly with the regulator.

When interacting with the regulator, industry operators should:

- Be professional and objective.
- Listen to requests and provide appropriate responses in a timely manner.
- Respect public concerns about anomalous induced seismicity.
- Provide accurate, clear and concise information.
- Be clear on what is considered fact, being evaluated or investigated, and what is not known at that time.
- Proactively provide the regulator with local surface array information, located event information and reports of felt seismic events to assist with anomalous induced seismicity event analysis.
- Ensure permissions and confidentiality agreements exist to share information.
- Incorporate lessons learned into future plans, which includes understanding how communication takes place.

4.2 Industry/Industry Interface

Operators new to an area are encouraged to speak with other operators nearby who have experience with and knowledge of fluid disposal and induced seismicity in the area. Operators are encouraged to share experiences and provide information about practices. Methods to build this working relationship could include:

- Sharing information to better understand the mechanisms of anomalous induced seismicity and mitigate risk.
- Sharing information on the levels of ground motion experienced by nearby populations and any impacts on infrastructure.
- Communicating new research findings and experiential learnings.
- Communicating the uncertainty that exists in relevant research areas.

16 Regulations regarding Class II disposal wells in British Columbia can be found at Subsurface Disposal | BC Oil and Gas Commission (bcogc.ca), while for Alberta relevant regulations for Class II disposal wells can be found at Directive 051 | Alberta Energy Regulator (aer.ca), and Directive 065: Resources Applications for Oil and Gas Reservoirs.

17 Systematic Design and Analysis of Step-Rate Tests To Determine Formation Parting Pressure | SPE Annual Technical Conference and Exhibition | OnePetro