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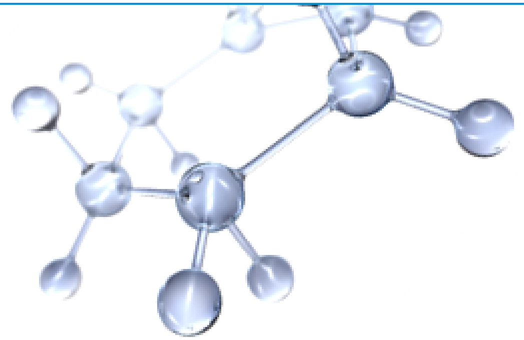
Technical Considerations Associated with Risk Management of Induced Seismicity in Waste-Water Disposal & Hydraulic Fracturing Operations



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ExxonMobil Production Company

Groundwater Protection Council Annual Forum

St. Louis, Missouri

September 23-25, 2013

Background

- **Seismicity can be induced or triggered when stress or pore pressure changes promote slip along a fault.**
- **These changes can be due to:**
  - **Geothermal energy**
  - **Carbon Capture Storage**
  - **Mining**
  - **Dam/reservoir impoundment**
  - **Waste water disposal wells**
  - **O&G injection/extraction**
  - **Hydraulic fracturing**

National Academy of Sciences Report **Major Findings**
NAS has recently examined induced seismicity across multiple energy sectors. Three major findings were published from this study[(1)] :
1. "The process of hydraulic fracturing a well as presently implemented for shale gas recover does not pose a high risk for inducing felt seismic events 2. Injection of 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. CCS, due to the large net volumes of injected fluids, may have potential for inducing larger seismic events."
(*1) NAS (June 2012), "Induced Seismicity Potential in Energy Technologies", http://www.nap.edu/catalog.php?record_id=13355*

Historical Examples

- Documented examples of seismic activity that have been linked to human activities include:
  - 70 hydrocarbon fields with unusually large seismic activity; primarily in 2 basins[2]
  - 95 artificial water reservoirs with reported reservoir triggered seismicity[3]
  - 26 sites in the US with mining related seismicity events larger than Magnitude 2.6[4]
  - 25 geothermal energy sites with injection related events larger than Magnitude 0[1]
- Understanding whether individual events are triggered, induced, or naturally occurring can be challenging
- Although the study of induced seismicity has been ongoing since the 1960s, many questions still remain

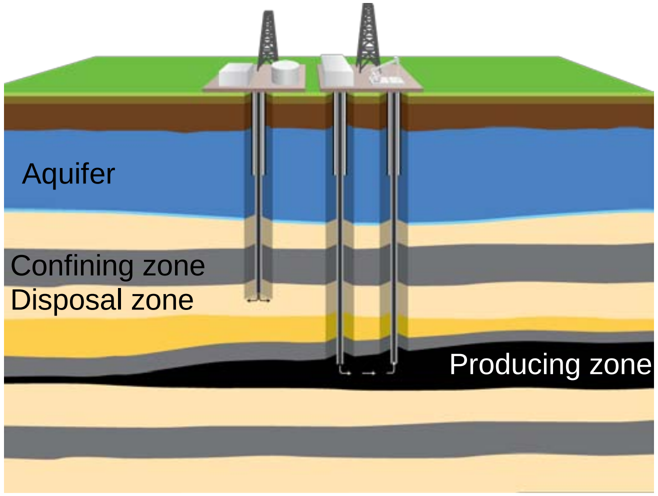
References:

2. Jenny Suckale, Chapter 2 - Induced Seismicity in Hydrocarbon Fields, In: Renata Dmowska, Editor(s), Advances in Geophysics, Elsevier, 2009, Volume 51, Pages 55-106, ISSN 0065-2687, ISBN 9780123749116, 10.1016/S0065-2687(09)05107-3. http://www.sciencedirect.com/science/article/pii/S0065268709051073
3. Gupta, H. K., A review of recent studies of triggered earthquakes by artificial water reservoirs with special emphasis on earthquakes in Koyna, India, Earth-Science Reviews 58 (2002) 279–310.
4. Routine United States Mining Seismicity, State-By-State List of Mining Regions, USGS Earthquake Hazard Program, http://earthquake.usgs.gov/earthquakes/eqarchives/mineblast/sources.php

Injection Operations
Waste Water Disposal & Hydraulic Fracturing

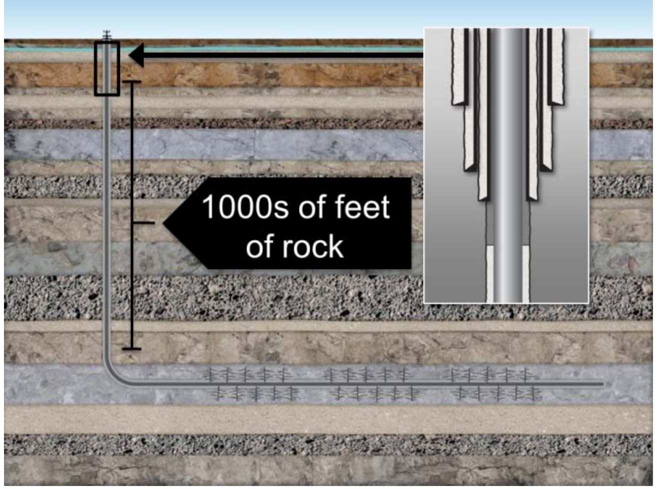
Disposal Operations

- Injection into non-productive intervals to dispose of produced water and cuttings
- Pressure of injection typically below frac pressure
- Injection operations continue for months to years
- Volumes ~ 100,000–1,000,000 barrels/year
- Injected fluids can reach ~1000s ft from injection
- ~140,000 Class II injection wells operating in US



Hydraulic Fracturing Operations

- Stimulation treatment for low permeability reservoirs (i.e., shale gas, tight oil)
- Treatment pressures above fracturing pressure to create fractures in the reservoir
- Stimulation operations typically last hours; for multiple stages it can take several days to complete a single well
- Volumes ~ 1000s of barrels per stage
- Fracture length created ~100s ft from wellbore



Event Impact
Ground Motion and Potential Damage

Primary Structure

- Design fundamentally based on probabilistic seismic analysis defined by a hazard curve:
  - Defines the probability of exceeding spectral acceleration at a specified structural period
  - Analysis based on seismic sources with associated activities probabilistically defined
  - Lower limit for earthquakes < Mag. 4
- Induced seismicity, typically below Mag. 4, likely to have little to no impact on primary structure

Humans & Secondary Components

- Likely to be more sensitive to small tremors
- Highly dependent on
  - Local soil conditions
  - In-structure local motion amplification
- Best monitored via ground motions
- Effects described by Modified Mercalli Intensity (MMI)

Potential Damage	MMI	Perceived Shaking	Description of Intensity Level
None	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		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.
Very Light	V	Moderate	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
Light	VI	Strong	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
Moderate	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.
Moderate/ Heavy	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.
Heavy	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.
Very Heavy	X	Extreme	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.

Wald, D.J., Worden, B.C., Quitoriano, V., and Pankow, K.L., 2005, ShakeMap manual: technical manual, user's guide, and software guide: U.S. Geological Survey, 132 p.
Wald, D.J., Quitoriano, V., Heaton, T.H., and Kanamori, H., 1999, Relationship between Peak Ground Acceleration, Peak Ground Velocity, and Modified Mercalli Intensity in California: Earthquake Spectra, v. 15, no. 3, p. 557-564.

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  - Local soil conditions
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- Best monitored via ground motions
- Effects described by Modified Mercalli Intensity (MMI)

Potential Damage	MMI	Perceived Shaking	Approximate Magnitude*	Peak Acceleration (%g)	Peak Velocity (cm/s)
None	I	Not Felt	1.0 - 3.0	<0.17	<0.1
	II	Weak	3.0-3.9	0.17-1.4	0.1-1.1
	III				
	IV	Light	4.0-4.9	1.4-3.9	1.1-3.4
Very Light	V	Moderate	4.0-4.9	3.9-9.2	3.4-8.1
Light	VI	Strong	5.0-5.9	9.2-18	8.1-16
Moderate	VII	Very Strong	5.0-6.9	18-34	16-31
Moderate/ Heavy	VIII	Severe	6.0-6.9	34-65	31-60
Heavy	IX	Violent	6.0-6.9	65-124	60-116
Very Heavy	X	Extreme	>7.0	>124	>116
	XI				
	XII				

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

Wald, D.J., Worden, B.C., Quitoriano, V., and Pankow, K.L., 2005, ShakeMap manual: technical manual, user's guide, and software guide: U.S. Geological Survey, 132 p.
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Risk Management
Probability and Consequences

- Risk is the combination of *Probabilities* and *Consequences*
- A standard tool used in risk assessment is a risk matrix approach to identify risk level
- With risk level identified, possible risk mitigation approaches can be evaluated

Probability

Consequence	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

A Generic Example of a Possible Risk Matrix

Potential Probability Considerations

Probability	Fluid Volume	Formation Character	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. Reservoir pressure rising and approaching fracture pressure	Deeper injection horizon; highly consolidated formations. Low KH sand of limited lateral continuity	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. Reservoir pressure rising above initial pressure	Moderate depth injection horizons; highly consolidated formations. Marginal KH sand of marginal lateral continuity	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. Reservoir pressure is near initial reservoir pressure	Shallow injection horizon; highly consolidated formations. Moderate KH sand with moderate lateral continuity	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. Reservoir pressure is constant below initial pressure	Shallow injection horizon; weakly consolidated formations. Good KH sand with good lateral continuity	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. Reservoir pressure is constant below initial pressure	Shallow injection horizon, Poorly consolidated formations. High KH sand of extensive lateral continuity	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

Potential Probability Considerations

Probability	Fluid Volume	Operating Experience	Local Construction Standards
A **Very Likely**	Large volumes of injection in immediate or close proximity to active faults. Reservoir pressure rising and approaching fracture pressure	**Past injection experience in region with damaging levels of ground shaking**	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. Reservoir pressure rising above initial pressure	**Limited injection experience historically in region**	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. Reservoir pressure is near initial reservoir pressure	**Significant injection experience historically in region with no damaging levels of ground shaking**	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. Reservoir pressure is constant below initial pressure	**Significant injection experience historically in region with no surface felt ground shaking**	Rigorous earthquake engineering civil / structural designs routinely implemented and required
E **Very Highly Unlikely**	Small fluid volume of injection; remote from any active faults. Reservoir pressure is constant below initial pressure	**Significant injection experience historically across wide geographic region with no surface felt ground shaking**	Rigorous earthquake engineering civil / structural designs routinely implemented and required

Potential Probability Considerations

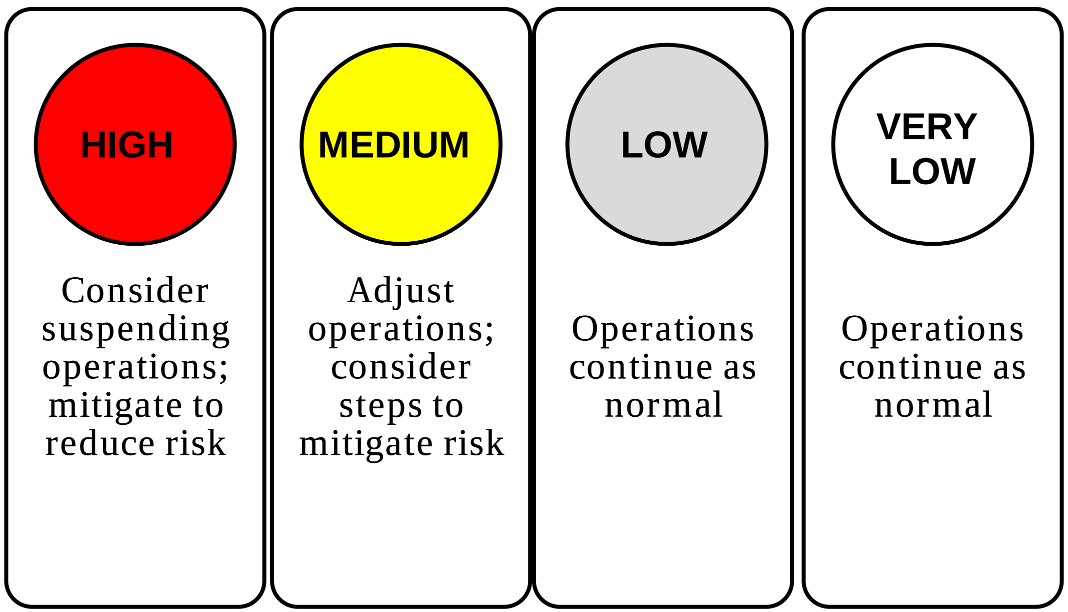
Probability		Tectonic / Faulting / Soil Conditions	l tion rds
A Very Likely	La injec or c Re appr	Large-scale developed/active faults are present at depths that could be influenced by pressure / fluid communication associated with injection; strongly consolidated formation; soil conditions amplify vibrational modes	uction lied for stant
B Somewhat Likely	La ve inje to Re ris	Large-scale developed/active faults may possibly be present, but not identified; strongly consolidated formation, soil conditions may amplify vibrational modes	tion uilding -dates neering s.
C Unlikely	Mode of i from Res nea	Faults well identified, and unlikely to be in influenced by pressure / fluid associated with injection; moderately consolidated formation	n and routinely vil / ns and nented ildings
D Very Unlikely	Sma injec a Res cons	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	uake / ns nented
E Very Highly Unlikely	Sma injec ar Res cons	Stable stress environment; no significant faults, weakly consolidated or unconsolidated formation, soil conditions may dampen vibrational modes	uake / ns nented

Potential Consequence Considerations

Consequence	Safety / Health	Environmental	Public	Financial
1 *Mod. Merc. Ind.* *> VIII*	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.	$$$$
2 *Mod. Merc. Ind.* *VI – VII*	Potential serious injuries; building cosmetic & secondary building content damage.	Potential localized medium term significant adverse effects. Possible release of potentially hazardous compounds short-duration &/or limited volumes (large vessels break).	Ground shaking felt by all in local area. Possible mobilization of emergency 1st responders. Possible disruption of community services for brief time.	$$$
3 *Mod. Merc. Ind.* *V – VI*	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 *Mod. Merc. Ind.* *< V*	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.	$

Potential Stoplight Systems and Mitigation Approaches

- **With risk level identified, possible risk mitigation approaches can be evaluated (effectiveness / cost)**
- **A stoplight approach is prudent and reasonable in high seismicity risk areas**
- **Options for monitoring systems can include human observation, use of existing regional array, local surface arrays, or downhole arrays; and can be selected based on considering specific local conditions**



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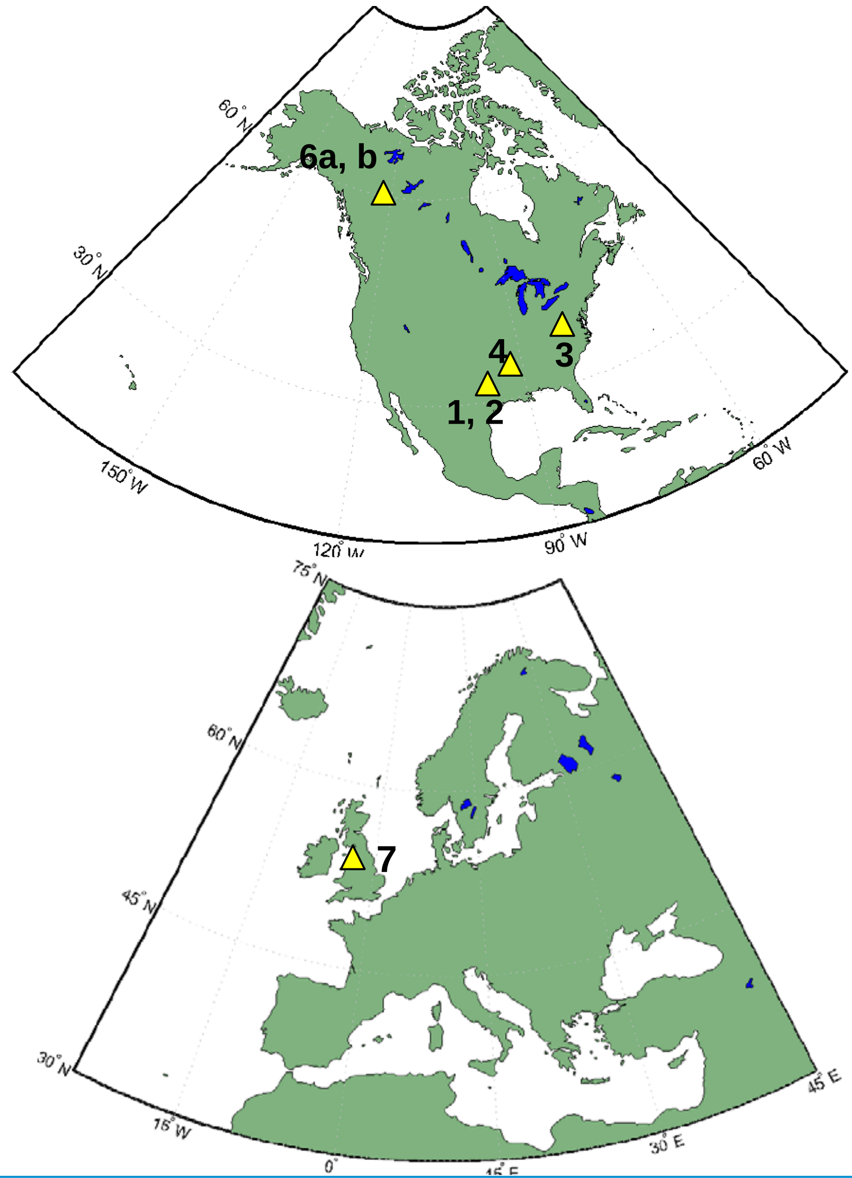
Industry Data

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*



Example Assessments
Waste-Water Disposal & Hydraulic Fracturing

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

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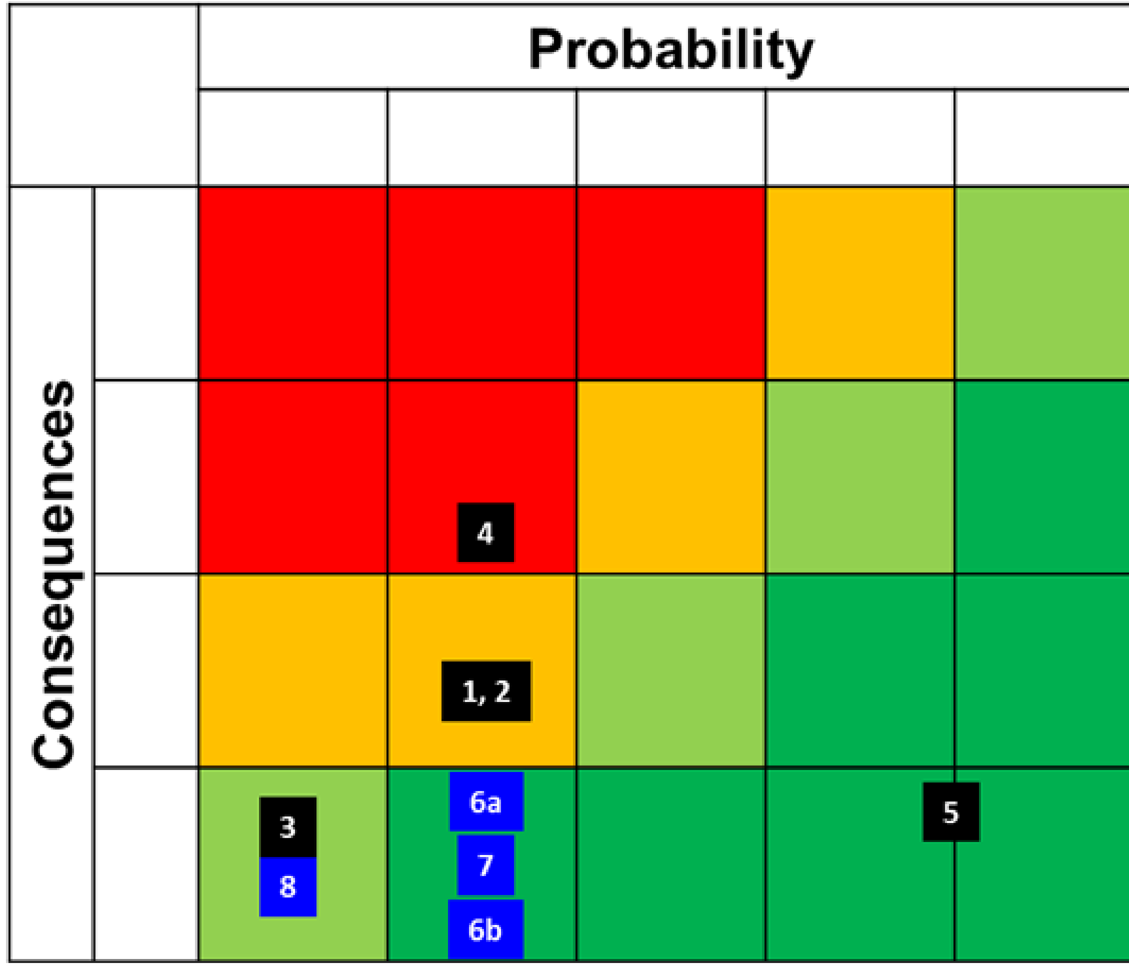
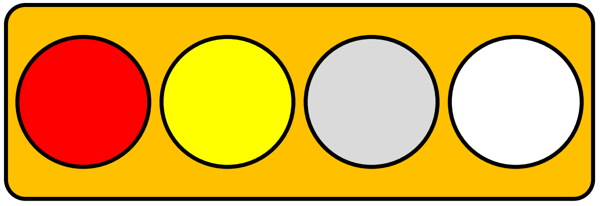


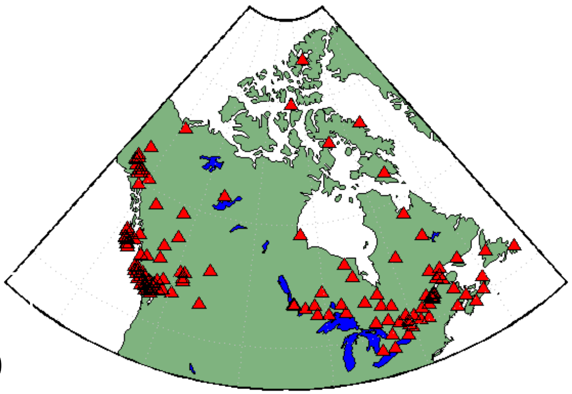
Note: assessment of probability & consequence for the specific examples based on hindcast evaluation of observed seismicity and publicly-reported information.

Recent Examples of Hydraulic Fracturing Related Stoplight Systems and Monitoring Approaches

Horn River, Canada



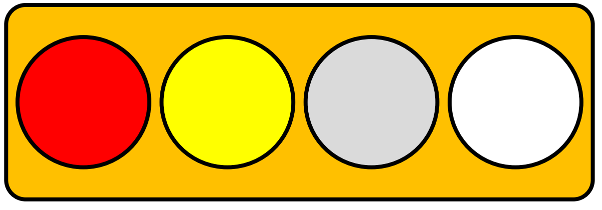
Suspend Operations	**$M_L \geq 4.0$**
Proceed with Caution	**$2.0 \leq M_L \leq 4.0$**
Proceed as Planned	**$M_L \leq 2.0$**



Canadian National Seismograph Network, Active Stations, 2/6/13

- Regional monitoring system
- Events should be reliably detected and reported at M_L 2.0
- Commission contacts operator if seismicity detected; at M_L 2.0, mitigation discussions begin
- Unique response for each case
- Operations temporarily suspended for $M_L \geq 4.0$

Bowland Shale, UK



Suspend Operations	**$M_L \geq 0.5$**
Continue with Recommended Operations and Monitoring	**$M_L \leq 0.5$**

"The controls are not at this stage to be regarded as definitive, but as appropriate precautionary measures for our present state of knowledge"

-Ministry Statement*

- Additional controls required as part of standard operating procedure
- Flow-back between frac stages required to relieve pressure
- Background and real-time seismic monitoring required, with detection $-1.0 \leq M_L \leq 1.0$
- Flow-back requirement creates operational complexity

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*https://www.gov.uk/government/speeches/written-ministerial-statement-by-edward-davey-exploration-for-shale-gas

Perspectives

- 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.
- Seismicity monitoring and mitigation should 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 is of significant risk, appropriate monitoring and mitigation should include:
  - A mechanism to alert the operator in near real-time 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
- Mitigation controls, if implemented, should consider completion practices and operational complexity