Technical Elements to Consider in a Risk Management Framework for Induced Seismicity

Presentation to

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Ground Water Protection Council

by

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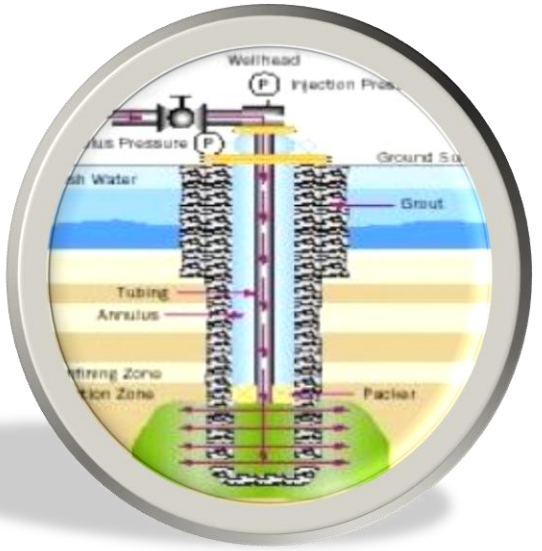

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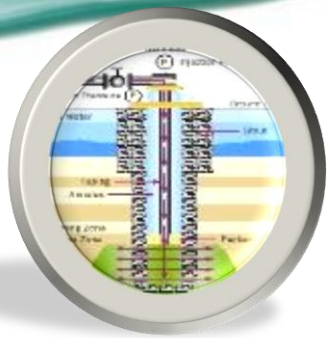
Background



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

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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

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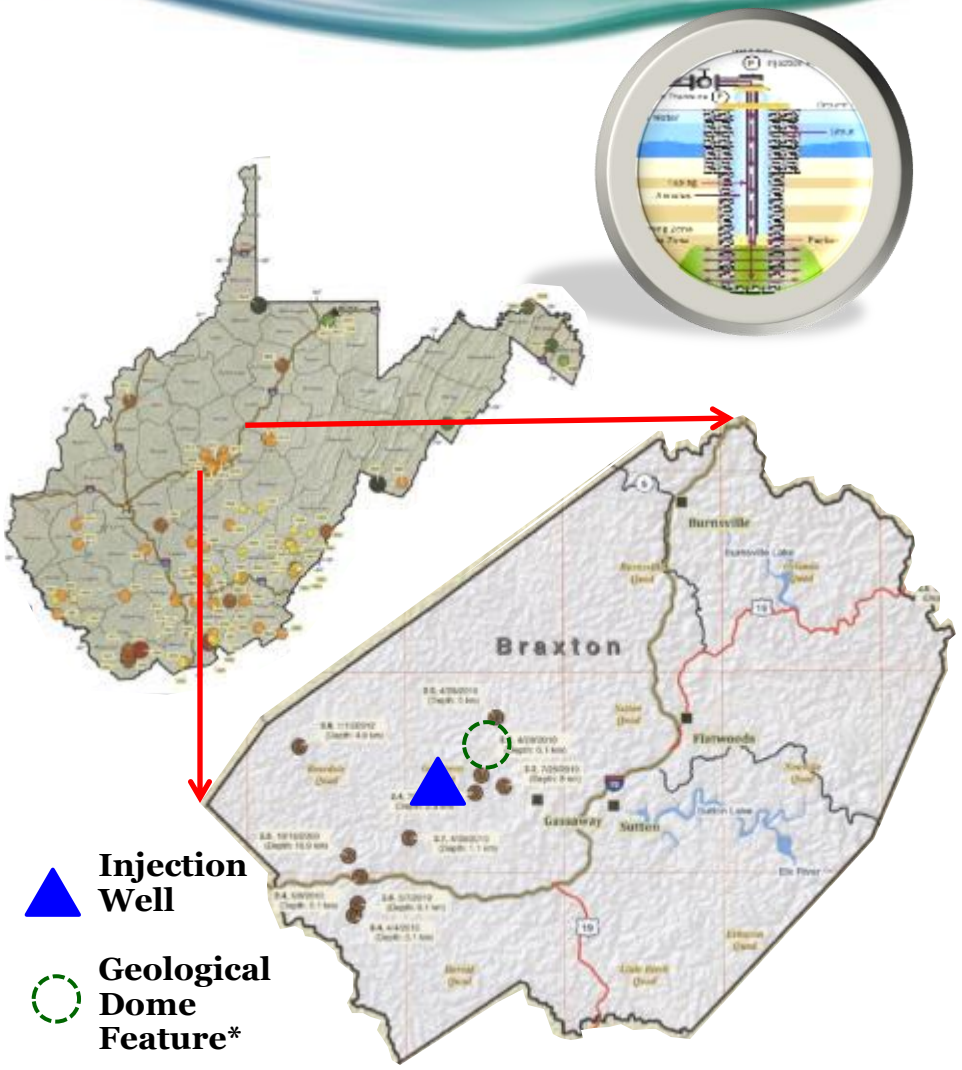
Case Studies

Industry Data

1. DFW – Airport (Disposal)
2. DFW – Cleburne (Disposal)
3. Braxton WV (Disposal)
4. Arkansas (Disposal)
5. General Case of Injection Wells
6. Horn River Basin
   a) Etsho
   b) Tattoo
7. U.K. Bowland Shale
8. General HF Wells:

   microseisms always created



Seismic Epicenters of West Virginia (1824-2012) & Braxton County (2000-2012). (Images from West Virginia Geological and Economic Survey)

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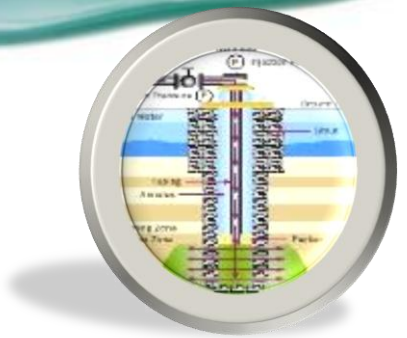
Shaking Impact



Primary Structure

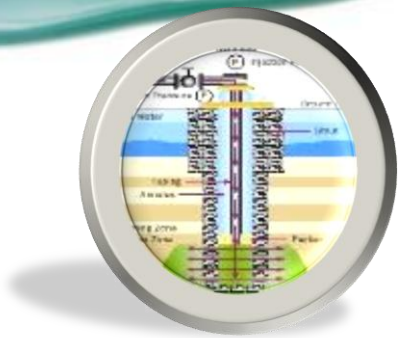
- Design is fundamentally based on probabilistic seismic analysis defined by a hazard curve:
  - This defines the probability of exceeding a spectral acceleration at a specified structural period;
  - Analysis is based on seismic sources with associated activities probabilistically defined;
  - Lower limit of earthquakes < M4
- Induced seismicity, typically below M4, is 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 ; and
  - In-structure local motion amplification
- Best monitored via surface acceleration, e.g. Modified Mercalli Intensity (MMI)

MMI	Magnitude	Acc. (g)	Description of Intensity Level
I	1.0-3.0	<0.0017	Not felt except by a very few under especially favorable circumstances.
II	3.0-3.9	0.0017	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
III	4.0-4.9	0.014	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an arthquake. Standing motor cars may rock slightly. Vibration similar to the passing of a truck. Duration estimated.
IV	5.0-5.9	0.014-0.039	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	6.0-6.9	0.039-0.092	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI	7.0 and higher	0.092-0.18	Felt by all; many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII	7.0 and higher	0.18-0.34	Damage negligible in building 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. Noticed by persons driving motorcars.
VIII	7.0 and higher	0.34-0.65	Damage slight in specially designed structures; considerable 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	7.0 and higher	0.65-1.24	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		>1.24	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.
XI		>1.24	Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.
XII		>1.24	Damage total. Lines of sight and level distorted. Objects thrown into the air.

Risk Management



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

HIGH	MEDIUM	LOW	VERY LOW
Consider suspending operations; mitigate to reduce risk	Adjust operations; consider steps to mitigate risk	Operations continue as normal	Operations continue as normal

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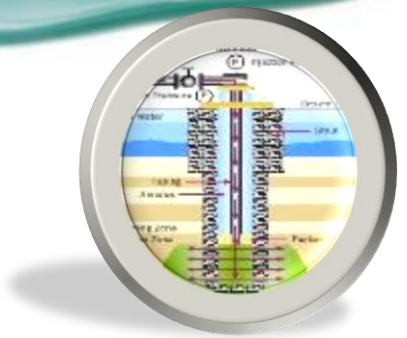
Risk Management



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Consequence	Probability A	B	C	D	E
1	HIGH	HIGH	HIGH	MEDIUM	LOW
2	HIGH	HIGH	MEDIUM	LOW	VERY LOW
3	MEDIUM	MEDIUM	LOW	VERY LOW	VERY LOW
4	LOW	VERY LOW	VERY LOW	VERY LOW	VERY LOW
5	VERY LOW	VERY LOW	VERY LOW	VERY LOW	VERY LOW

Added "V" consequence for normal HF operations, micro-seisms created all the time with no consequence

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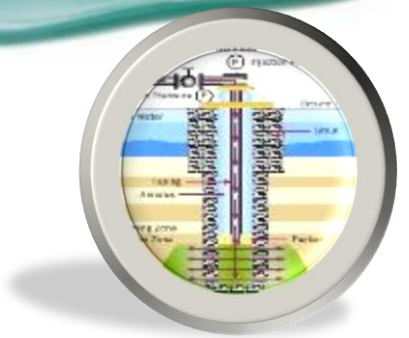
Risk Management



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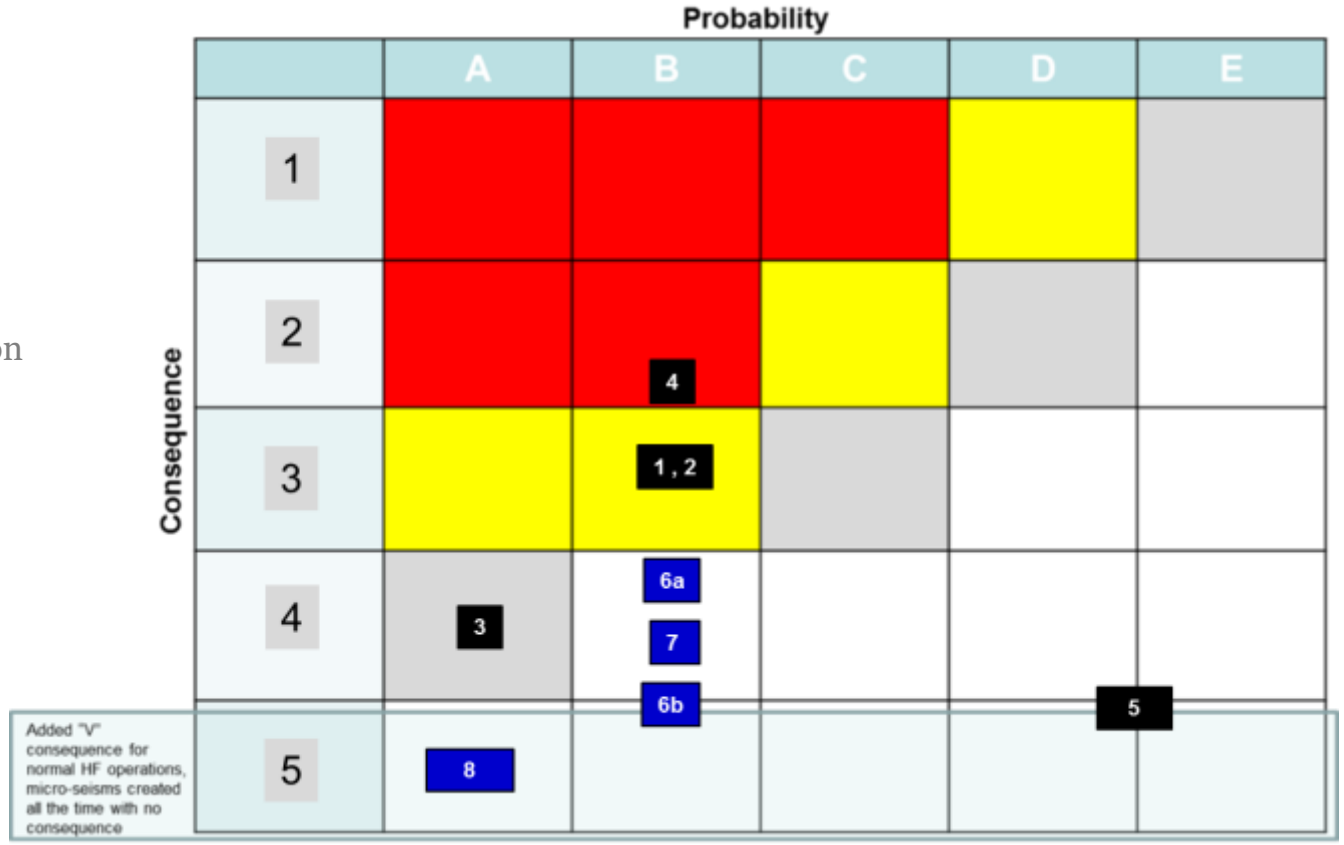

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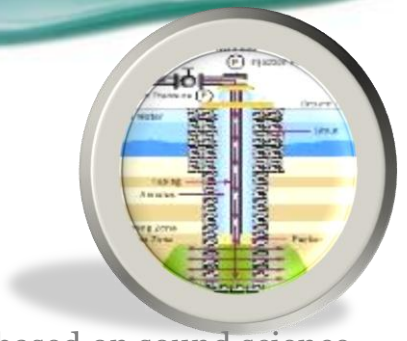
Perspective



- Approaches to assess and manage seismicity risk should be encouraged, should 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:
  a) significant seismicity (above historical baseline levels) has actually occurred and sound technical assessment indicates that the seismicity is associated with fluid injection operations, or
  b) 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) a mechanism to alert the operator in near real-time to the occurrence of seismicity significantly above local historical baseline levels, and
  b) 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

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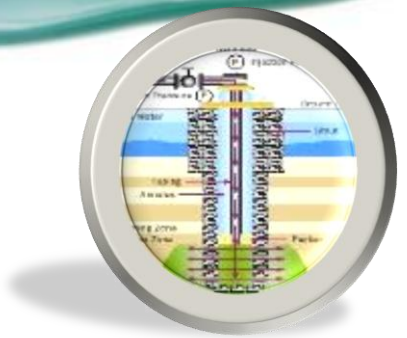

Back Up

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Probability Considerations

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

Consequence Considerations

Consequence Considerations	Safety / Health Impact	Environmental Impact	Public Impact	Financial Impact
1 *(MMI: > VIII)*	Fatalities and serious injuries; building structural damage.	Potential widespread long-term significant adverse affects. 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. Extensive mobilization of emergency 1st responders. Disruption of community services for extended time.	$$$$
2 *(MMI: VI - VII)*	Serious injuries; building cosmetic & secondary building content damage.	Potential localized medium term significant adverse effects. Release of potentially hazardous compounds short-duration &/or limited volumes (large vessels break).	Ground shaking felt by all in local area. Mobilization of emergency 1st responders. Disruption of community services for brief time.	$$$
3 *(MMI: V – VI)*	Minor injuries in isolated circumstances; building secondary content damage.	Release of potentially hazardous compounds in limited volumes (e.g., containers break).	Ground shaking felt by sensitive few at site. Limited site impact and limited mobilization of 1st responder(s).	$$
4 *(MMI: IV – V)*	First aid in isolated circumstances; isolated secondary building content damage.	Release of potentially hazardous compounds in very small volumes (e.g., small containers break).	Minor public complaints.	$
5 *(MMI: I – IV)*	None	None	None	None