Understanding and Managing the Potential for Induced Seismicity in CO₂ Storage Projects

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Outline

- Introduction
- Some observations, general characteristics of induced seismicity
- Managing the risks of induced seismicity
- Some remaining questions
- Summary
Induced Seismicity is Common in Subsurface Activities

- Seismicity has been associated with reservoir impoundment, mining, fluid injection
- Characteristically many more small events than large ones; once in awhile a large one has occurred.
- Seismicity not all bad – useful for imaging subsurface

Koyna reservoir dam, India, (above) and damage from 1967 M6.5 earthquake (below) (www.indianetzone.com and www.timescontent.com)

Seismicity at Geysers geothermal area (courtesy E Majer, LBNL)
Causal Mechanisms

- Earthquakes (fault slip) occur when the shear stress along a fault is greater than the strength of the fault.

- Induced or triggered earthquakes occur when human activity causes changes in stresses within the Earth that are sufficient to produce slip.

This can result from:

- An increase in shear stress along the fault
- A decrease in strength of the fault
- Decrease the normal stress across the fault
- Increase the pore pressure within the fault
- Decrease in cohesion on fault
- Thermal stresses
### Historical Data: “Felt-Earthquakes” “Likely” Related to Energy Technologies in US

<table>
<thead>
<tr>
<th>Energy Technology</th>
<th>Number of Projects</th>
<th>Number of Felt Induced Events</th>
<th>Maximum Magnitude of Felt Events</th>
<th>Number of Events M≥4.0°</th>
<th>Net Reservoir Pressure Change</th>
<th>Mechanism for Induced Seismicity</th>
<th>Location of M≥2.0 Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapor-dominated geothermal</td>
<td>1</td>
<td>300-400 per year since 2005</td>
<td>4.6</td>
<td>1 to 3 per year</td>
<td>Attempt to maintain balance</td>
<td>Temperature change between injectate and reservoir</td>
<td>CA (The Geysers)</td>
</tr>
<tr>
<td>Liquid-dominated geothermal</td>
<td>23</td>
<td>10-40 per year</td>
<td>4.1°</td>
<td>Possibly one</td>
<td>Attempt to maintain balance</td>
<td>Pore pressure increase</td>
<td>CA</td>
</tr>
<tr>
<td>Enhanced geothermal systems</td>
<td>~8 pilot projects</td>
<td>2-10 per year</td>
<td>2.6</td>
<td>0</td>
<td>Attempt to maintain balance</td>
<td>Pore pressure increase and cooling</td>
<td>CA, NV</td>
</tr>
<tr>
<td>Secondary oil and gas recovery (waterflooding)</td>
<td>~108,000 (wells)</td>
<td>One or more events at 18 sites across the country</td>
<td>4.9</td>
<td>3</td>
<td>Attempt to maintain balance</td>
<td>Pore pressure increase</td>
<td>AL, CA, CO, MS, OK, TX</td>
</tr>
<tr>
<td>Tertiary oil and gas recovery (EOR)</td>
<td>~13,000</td>
<td>None known</td>
<td>None known</td>
<td>0</td>
<td>Attempt to maintain balance</td>
<td>Pore pressure increase (likely mechanism)</td>
<td>None known</td>
</tr>
<tr>
<td>Hydraulic fracturing for shale gas production</td>
<td>35,000 wells total</td>
<td>1</td>
<td>2.8</td>
<td>0</td>
<td>Initial positive; then withdraw</td>
<td>Pore pressure increase</td>
<td>OK</td>
</tr>
<tr>
<td>Hydrocarbon withdrawal</td>
<td>~6,000 fields</td>
<td>20 sites</td>
<td>6.5</td>
<td>5</td>
<td>Withdrawal</td>
<td>Pore pressure decrease</td>
<td>CA, IL, NB, OK, TX</td>
</tr>
<tr>
<td>Waste water disposal wells</td>
<td>~30,000</td>
<td>8</td>
<td>4.8°</td>
<td>7</td>
<td>Addition</td>
<td>Pore pressure increase</td>
<td>AR, CO, OH</td>
</tr>
<tr>
<td>Carbon capture and storage, small scale</td>
<td>1</td>
<td>None known</td>
<td>None known</td>
<td>0</td>
<td>Addition</td>
<td>Pore pressure increase</td>
<td>IL</td>
</tr>
<tr>
<td>Carbon capture and storage, large scale</td>
<td>0</td>
<td>None</td>
<td>None</td>
<td>0</td>
<td>Addition</td>
<td>Pore pressure increase</td>
<td>None yet in operation</td>
</tr>
</tbody>
</table>

(Source: NRC report on induced seismicity)
Induced Seismicity Not Always in Tectonically Active Areas

Approximate location of recent induced seismicity associated with natural gas development activities
Induced Seismicity Commonly Occurs on Pre-existing Faults

Induced seismicity on Guy-Greenbrier fault, due to fluid Injection activities (maximum event M4.7). (S. Horton, U. Memphis)
The Potential for Induced Seismicity Can Be Managed Using Best Practice Approaches

- Site selection and characterization
- Risk assessment
- Managing reservoir pressures during operation
- Monitoring
- Public outreach
- Event response procedures
Site Characterization Provides Essential Data on Geology, Hydrology, etc

- Develop 3-D geologic model
  - Identify faults
- Determine in-situ stress state
- Determine in-situ fluid pressures; regional hydrologic boundary conditions
- Review historical seismicity – magnitude, location, frequency
- Perform social characterization

Geologic model and historical seismicity in vicinity of WESTCARB proposed pilot CO₂ injection test in northern California
Identify and Analyze Risks, Develop and Implement Risk Response

- Project risk assessment includes induced seismicity along with other potential risks
- Review, consider update of natural seismic hazard assessment of site
- Consider induced seismicity probabilistic hazard analysis
Managing Reservoir Pressures: Determine Max Allowable Pressure on Faults

- “Coulomb criterion”: faults slip when frictional resistance (allowable shear stress) is exceeded
- Input data: in-situ stress state and coefficient of friction, $\mu$, of fault
- Determine $P$, the maximum allowable fluid pressure on fault

Use of “Mohr circles” to evaluate potential for fault slip
Managing Reservoir Pressures: Design of Injection Operations

- Model reservoir pressures – operational period and post-injection
  - Incorporate actual hydrologic boundary conditions

- Consider pressure limits in location and number of injection wells
  - Site injection wells far from faults

- For depleted oil and gas reservoirs, consider setting original reservoir pressure as a limit

- Consider brine extraction for pressure management
Monitoring for Induced Seismicity

- Reservoir pore pressures
  - Direct measurements
  - Indirect: surface displacements, seismic

- Microseismic measurements
  - Permanent sensors; integrate with regional network
  - Integrated with overall seismic monitoring scheme
  - One year or 6 month baseline

- Monitoring need follow from risk assessment – technical risks and social attitudes

Schematic of wells and wellbore monitoring at Decatur RCSP project
Incorporating Induced Seismicity into Public Outreach Programs

- Characterize local attitudes toward seismicity
- Incorporate discussion of seismicity, natural and induced, into project outreach plan
  - Account for technical risk and local attitudes
- Consider making seismic data available to public in “real time”
- Plan ahead for complaints
Establish Procedures for Responding to Events

- Work with regional authorities to establish protocols
- Set thresholds for a range of actions depending on magnitude of event (where magnitude is tied to shaking potential)
  - Eg., no action if events smaller than M2; suspend injection if >M4
  - Take into consideration natural seismicity and location of event
- Consider vibration monitoring of some structures in cultural areas
Some Remaining Questions
Total Seismic Moment May Be Correlated With Injected Volume

\[ \sum M_0 = K \mu |\Delta V| \]

McGarr (1976)

Volume added to region in expansion in direction NW/SE (\(\sigma_2\)) and NE-SW (\(\sigma_3\))

\[ K \approx 0.5 \]

Correlation of total seismic moment and injected volume at Geysers (E Majer, LBNL)
Are Injected CCS Injected Volumes Unprecedented?

(NRC Induced Seismicity Report)

(Wilson 2003)
“b” Values For Induced and Natural Seismicity May Be Different

Gutenberg-Richter relationship: $\log_{10} N = a - bM$

Induced seismicity from salt water injection in Paradox Valley, Colorado. “b” values have changed over time. (Ake, US Bureau of Reclamation, NRC)
Summary

- Induced seismicity represents a potential risk for CCS, though it also has potential as a reservoir monitoring tool
  - Very little induced seismicity in CCS projects to date
- Observations indicate induced seismicity very often associated with pre-existing faults, but attributes of induced events may differ from natural seismicity
- Induced seismicity should be addressed as part of the risk assessment carried out for CCS projects; results of risk assessment inform project operations
- The potential for induced seismicity can be managed using best practice approaches in site characterization, monitoring, injection operations and public outreach