Induced Seismicity: Issues and Paths Forward

Ernest Majer
Lawrence Berkeley National Laboratory

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DOE Geothermal and NETL/Oil and Gas Program

( complied from many recent workshops, road mappings and conferences)
Definitions

• Triggered Seismicity
  – Causative activity accounts for only a small fraction of the stress change associated with the earthquakes.
  – Pre-existing tectonic stress plays the primary role

• Induced Seismicity
  – Causative activity accounts for most of the stress change or energy to produce the earthquakes
Induced Seismicity: Recent Issues

• High-profile press coverage and congressional/regulatory inquiries have focused attention on induced seismicity related to energy projects in the U.S. and Europe
  – The Geysers, CA; Basel, Switzerland; Soultz, France; Landau, Germany
  – Oil and gas: Texas, shale gas sites
  – CO₂ sequestration sites (various)

• However, industry has successfully dealt with induced seismicity issues for almost 100 years (mining, oil and gas, waste injections, reservoir impoundment, etc.)

• How does one assess hazard risk and economic risk
  – Investors want to know
  – Regulators want to know
  – Seismicity related to injection cannot be assessed the same as natural seismicity
  – Scale and distance of influence

• Seismicity is also be useful as a resource management tool
  – Geothermal, Oil and Gas, CO₂ Seq ??
# Examples (largest events)

<table>
<thead>
<tr>
<th>Type</th>
<th>Location</th>
<th>Magnitude</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir Impoundment</td>
<td>Hoover, USA</td>
<td>5.0</td>
<td>1939</td>
</tr>
<tr>
<td></td>
<td>Koyna, India</td>
<td>6.5</td>
<td>1967</td>
</tr>
<tr>
<td></td>
<td>Aswan, Egypt</td>
<td>5.3</td>
<td>1981</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mines and Quarries</td>
<td>Wappingers Falls, NY</td>
<td>3.3</td>
<td>1974</td>
</tr>
<tr>
<td></td>
<td>Reading, PA</td>
<td>4.3</td>
<td>1994</td>
</tr>
<tr>
<td></td>
<td>Belchatow, Poland</td>
<td>4.6</td>
<td>1980</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil and Gas fields</td>
<td>Long Beach, CA</td>
<td>5.2</td>
<td>1930’s</td>
</tr>
<tr>
<td></td>
<td>Dallas - Ft worth</td>
<td>3.4</td>
<td>2008</td>
</tr>
<tr>
<td></td>
<td>Lacq, France</td>
<td>~4</td>
<td>various</td>
</tr>
<tr>
<td></td>
<td>Gazli, Uzbekistan</td>
<td>~7</td>
<td>1976</td>
</tr>
<tr>
<td>Injection related</td>
<td>Denver</td>
<td>5.3</td>
<td>1960’s</td>
</tr>
<tr>
<td></td>
<td>Geothermal</td>
<td>4.6</td>
<td>1970’s</td>
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</table>
Accurate and Consistent Assessment of Risk is Essential for All Injection Technologies

- What is the largest earthquake expected?
- Will small earthquakes lead to bigger ones?
- Can induced seismicity cause bigger earthquakes on nearby and distant faults?
- Even small felt (micro)earthquakes are annoying.
- Can induced seismicity be controlled?
- What controls are (will be) in place to mitigate future induced seismicity?
- What is the plan if a large earthquake occurs?
- Long term response versus short term response
Importance of Understanding Induced Seismicity

• Technical
  – One of few means to understand volumetric permeability enhancement/fluid paths
  – Proper uses could optimize reservoir performance

• Policy/Regulatory
  – Potential to side track important energy supply
  – Technology must be put on a solid scientific basis to get public acceptance
  – Accurate risk assessment must be done to advance energy projects
Zone of influence from potential earthquakes in the US
Therefore

• Three main issues to address to advance Energy Applications
  – How does one assess risk
  – How does one minimize risk
  – How does one effectively utilize Induced seismicity
Small versus Large Earthquakes

- Earthquake magnitude determined by the size of the slipping fault
  - Small faults imply small earthquakes
  - Many more small faults than large faults
  - Many more small earthquakes than large earthquakes

- Most Large earthquakes start deep
  - Shallow injection implies small earthquakes
Causal Mechanisms

• Earthquakes (fault rupture) 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 rupture.
• This can result from either:
  – 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 (chemical changes)
    • Thermal stresses
    • Stress diffusion
    • Other
Elevated Fluid Pressure:

- Reduces effective normal stress on fault, lowering resistance to shearing. **Implies that if pressure balance can be maintained seismicity can be controlled**
The analysis indicates that induced seismicity would occur near the ground surface, close to the wells, and at depth below the wells.

Near the wells stress reduction due to cooling shrinkage causes seismicity.

Near the ground surface and at depth below the wells induced seismicity is caused by stress redistribution from the shrinking reservoir.
PSInSAR from ERS satellite track 113
Average velocities 1992-2000
Seismic Hazard Analysis

Two main model components:

1) Earthquake **Rupture** Forecast

   Gives the probability of all possible earthquake ruptures (fault offsets) throughout the region and over a specified time span.

2) Earthquake **Shaking** model

   For a given earthquake rupture, this gives the probability that an intensity-measure type will exceed some level of concern.

**Physics-based**

"Waveform Modeling"

**Empirical**

"Attenuation Relationships"
PSHA Basics

• Probabilistic Seismic Hazard Analysis (PSHA) integrates the hazard from all sources and includes the effect of uncertainty explicitly
• State of Practice for Critical Facilities
• Required for any Risk Informed Assessment
Earthquake Risk

- Risk in this context can be thought of as:
  \[ R = AF(a \mid eq) \cdot Pr(f \mid a) \cdot C(\$; LL \mid f) \]

Where \( R = \) “risk”, \( AF = \) annual frequency of ground motion \( a \), given occurrence of an earthquake(s), \( Pr(f \mid a) = \) probability of failure of something of interest given ground motion \( a \), and \( C = \) consequences (dollars, or any metric of interest).

AF developed using Probabilistic Seismic Hazard Analysis (PSHA)
Components of the Uniform California Earthquake Rupture Forecast 2

- **Fault Models**: Specifies the spatial geometry of larger, more active faults.
- **Deformation Models**: Provides fault slip rates used to calculate seismic moment release.
- **Earthquake-Rate Models**: Gives the long-term rate of all possible damaging earthquakes throughout a region.
- **Probability Models**: Gives the probability that each earthquake in the given Earthquake Rate Model will occur during a specified time span.

Components (??) of an Induced Seismicity Rupture Forecast

- **Fault Models**: Specifies the spatial geometry of faults in reservoir.
- **Stress Models**: Specifies the magnitude and orientation of stress in reservoir.
- **Earthquake-Rate Models**: Gives the rate of earthquake on each fault as a function of the perturbing pore pressure.
- **Probability Models**: Gives the probability that each earthquake will occur during a specific time span.
Examples

- Geothermal
  - EGS
  - Hydrothermal
- Carbon Sequestration
  - Saline formations
  - Tight formations
Geothermal
Enhanced Geothermal Systems

- Located at depths of 3-10 km
- It requires increasing permeability by stimulating fracturing and shearing of fractures through fluid/propant injection
- Fluid circulated between injection and production wells to capture and extract heat from system
- i.e. Requires creating controlled seismicity
Northern California Historical Seismicity (M 3.5 to 5.0)
1900-2005

The Geysers
Figure 1. Location of USGS stations, Current Calpine array, and the new LBNL stations. Also shown are the locations of the pipelines used for the water from Santa Rosa. (from Calpine)
Water injection wells

Injection related EQs
Geysers Annual Steam Production, Water Injection and Seismicity  (Smith 2011)

- Seismic Events of M>=1.5
- Earthquake Count M>=3.0
- Earthquake M>=4.0
- Steam Production
- Water Injection

Annual Number of Seismic Events

Steam Production and Water Injection (billion lbs)

Time Period:
- 1965
- 1970
- 1975
- 1980
- 1985
- 1990
- 1995
- 2000
- 2005
- 2010

Events:
- 25
- 32
- 31
- 29
- 25
- 24

Values:
- 1,384
Seismic moment & Injection Rate

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

- Total Seismic Moment
- Fluid injected

\( K \sim 0.5 \)

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

McGarr (1976)
Volume change for Geysers

- Total volume change = $1.42 \times 10^9$ meters cubed (over 35 Years)

- Sum Moments = $1.85 \times 10^{18}$ N-m
  - 1 Mag 6.2
  - 10 Mag 5.2
  - 100 Mag 4.2
  - 1,000 Mag 3.2
  - 10,000 Mag 2.2
  - etc.

- Not Far Off!!
Determination of Max Magnitude  
(Shapario 2011, 2010)

Assumptions/Hypothesis/Observations

1. Large events are under represented in fluid stimulated volume 
2. Geometry of a stimulated volume influences frequency magnitude relation 
3. Seismicity cloud defines the volume of fluid pressure increase 
4. Majority of area of slip (fault) must be pressurized to fail 
5. Therefore, minimum principle axis of a fluid stimulated rock volume controls size of “largest events”

$$2 \log \cdot L_{\text{min}} - 1 = \text{Max Magnitude}$$

ie, rupture of fluid induced events is only probable along a surface mainly inside a stimulated volume

$$L_{\text{min}} = \text{min axis of stimulated volume (in meters)}$$
One year of data
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</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>184.884</td>
<td>316.944</td>
<td>396.18</td>
<td>3.53379865723046</td>
<td>4.001965069</td>
<td>4.195785095</td>
</tr>
<tr>
<td>B</td>
<td>264.12</td>
<td>528.24</td>
<td>660.3</td>
<td>3.84360257720195</td>
<td>4.445662569</td>
<td>4.639482595</td>
</tr>
<tr>
<td>C</td>
<td>158.472</td>
<td>396.18</td>
<td>528.24</td>
<td>3.39990507796923</td>
<td>4.195785095</td>
<td>4.445662569</td>
</tr>
</tbody>
</table>
Interesting Observations
(Geothermal)

- Large events happen (sometimes) at the edges of the reservoir/after the injection stops
  - Implication of diffusion processes
- Variable rate dependency of injection versus seismicity
  - Sometimes anti-correlation between injection and seismicity
- Seismicity reaches an equilibrium (in certain magnitude ranges)
- Seismicity does not follow normal aftershock patterns
- Close relation between seismicity and volume balance
  - Implies volume change not volume injected is important
- Variable relation between foreshocks, aftershocks, b-values, etc.
- Induced seismicity appears to change mechanisms (triggering) over magnitude ranges
Carbon Sequestration
CO₂ Sequestration

Overview of Geological Storage Options
1. Depleted oil and gas reservoirs
2. Use of CO₂ in enhanced oil and gas recovery
3. Deep saline formations — (a) offshore (b) onshore
4. Use of CO₂ in enhanced coal bed methane recovery

IPCC (2005)
Deep Well Injection-Hazards

• Three types:
• (1) Loss of integrity of “capping layer” degradation of water supply (EPA)
• (2) Physical Damage due to induced/triggered seismicity
• (3) Loss of public trust/confidence
Regional Seismicity: 1960-present

Perry Nuclear Power Plant
- January 31, 1986
- $M_b$ 5.0 Event
- Pressures in nearby deep injection wells reached 11.2 MPa above ambient
- Pressure increase may have been responsible for triggering the event

Mountaineer Power Plant
- State of stress: Strike-slip frictional equilibrium
- Small pressure increases could result in reactivation
CO$_2$ Sources in the Illinois Basin

Annual CO$_2$ Emissions from Stationary Sources
300 million tons (MT)

Midwest Geological Sequestration Consortium (MGSC)
Basin-Scale Pressure Buildup (bar)

Cutoff Pressure: 0.1 bar
Fig. 2. Relation between $S$ (fault surface area) and $M_o$ (seismic moment). The straight lines give the relations for circular cracks with constant $\Delta \sigma$ (stress drop). The numbers attached to each event correspond to those in Table 1.
Example for CO2 sequestration, 1 million tons/yr of injection

Also, assume that the relation between volume injected and seismicity is similar as in geothermal case (let $K = 1$)

$$\sum M_0 = K \mu |\Delta V|$$

Assuming normal magnitude: moment relations
Then one could expect total Magnitude = 4.6
(Also works out for stress drop of 50 bars and fault radius of 500 meters)

Also assumes b value of 1

Or

<table>
<thead>
<tr>
<th>$V$ (tons/yr)</th>
<th>$M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>3.6</td>
</tr>
<tr>
<td>100</td>
<td>2.6</td>
</tr>
</tbody>
</table>
| 1000          | 1.6 | etc
Recent and Current DOE Activities for Geothermal Induced Seismicity

• Three international workshops (2005-2009)
  – Peer reviewed white paper (IEA Report, Majer et al., 2007)
  – Protocol for the development of geothermal sites and good practice guidelines (IEA 2009)

Current Activities 2010-2011

• Establish induced seismicity website for scientific collaboration and community outreach – includes CO₂ and oil & gas
• Instrument all DOE EGS projects to monitor, analyze, and learn from induced seismicity
• Require all DOE EGS projects to follow Induced Seismicity Protocol
• Establish additional international scientific collaborations
• Ensure that real-time seismic data is available to public in community gathering spots near EGS project sites
• Hold series of workshops to address research/technical needs and establish risk assessment and updated Protocol and best practices for industry
• Updated protocol and best practices guide for US
Path Forward/Current Needs

• Technical Issues

• Regulatory/Risk Issues/Community Interaction
Technical Issues/Needs

Further understanding of complex interactions among stress, temperature, rock and fluid properties

• Alternative methods for creating reservoirs/injection volume
• Adaptive seismic hazard estimation
• Leverage existing expertise and capabilities to address technical issues common to all injection applications
Policy Needs

- Supply stakeholders with guidelines (protocols/best practices)
  - Update as technology progresses
  - Follow technical and community/regulator interaction
- Community Interaction
  - Supply timely, open, and complete information
  - Educate operators on importance of public outreach
  - Technical based risk analysis
- Develop risk based procedure for estimating potential mitigation requirements (Adapt Seismic hazard analysis for induced seismicity applications)
  - Probabilistic
  - Physics based
What should/could be done? – Research Needs

• Quantify relation between seismicity and permeability enhancement

• Improve means to quantify the relation between stress change and seismicity rate?

• Is there time dependence or stressing rate dependence in stress-seismicity rate changes/ or is the theory of effective stress all we need to know?

• Determine the role of slip-dilatancy (slip-permeability) in fault zones in EQ generation?

• Determine role of mechanical processes (fault healing, permeability reduction) versus other changes in the induced seismicity generation
  
  – What do we need to know about fault zone poroelasticity?
  
  – What do we need to know about chemical processes?

• Do induced earthquakes follow the same decay relations as tectonic earthquakes in the same province? (why or why not)

• Active experiments to manipulate seismicity without compromising production
  
  – reservoir performance assessment
  
  – integrated reservoir analysis

Dedicated test sites for exploring research issues?
• **Technical issues**
  – Further understanding of complex interaction between stress, temperature, rock and fluid properties (we do not fully understand the linkage between all of the subsurface parameters)

• **Community Interaction/Regulatory**
  – Supply timely, open, and complete information
  – Consistent science based “rules”
• Modeling/Theory needs
  – Fully coupled thermo-mechanical-chemical codes
    • Stress, temp, and chemical effects
    • Dynamic fracture codes in 3-D
  – Joint inversion of EM/seismic data
    • Links fluid and matrix properties
  – Full anisotropic 3-d models
    • Fracture imaging at different scales
• Data needs
  – Improved high pressure-high temperature rock physics data
    • Rock physics measurements
      – Coupled chem/mechanical
  – High resolution field measurements
    • Wide band
    • Dynamic fracture imaging
    • High res MEQ
What could/should we do?- Operational

• Deploy advanced monitoring systems
  – experimental data
  – continuous data-stream as basis for operational control decisions during development and long-term operation

• Risk-based decision making for operational control
  – adapt probabilistic seismic hazard/risk method coupled with physics-based approach incorporating uncertainty

• Mitigation and Control Procedures
  – Site characterization and selection; faults, communities
  – Engineering design – well locations, injection pressures, etc.
  – Data-driven operational control

• Establish a best practices/protocol based on accepted scientific knowledge in order to allow implementation of energy projects – i.e set out the rules!!
Summary

- If not addressed properly induced seismicity could unduly delay and cancel important energy applications
- Induced seismicity issues are not new (over 50 yrs)
- Generally, causes are known and have been mitigated
- Induced seismicity risk cannot be calculated in the same manner as “natural” seismicity
- New EGS protocol developed for US could serve as a model for other injection related technologies (with best practices “handbook”)
- Key research has the potential to lower the uncertainty associated with induced seismicity
- Causes and effects of induced seismicity associated with energy applications must be placed on a solid scientific basis for:
  - Optimizing energy applications
  - Convincing public and regulators that it is a viable (safe) energy resource