Induced Seismicity Associated with Energy Applications
Issues, Status, Challenges, Needs

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April 26, 2011
Acknowledgements

David Oppenheimer (USGS), Bill Leith (USGS)
Art McGarr (USGS), David Simpson (IRIS)
Steve Hickman (USGS) Bill Ellsworth, Nick Beeler (USGS), Jon Ake (NRC)
Mark Walters (Calpine) Bill Smith (NCPA) Paul Segall (Stanford), Mark Zoback (Stanford) plus many more
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 ??
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
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
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 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
# Examples (largest events)

<table>
<thead>
<tr>
<th>Type</th>
<th>Location</th>
<th>Magnitude</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reservoir Impoundment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hoover, USA</td>
<td>5.0</td>
<td>1939</td>
</tr>
<tr>
<td></td>
<td>最早认可的RIS案例</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Koyna, India</td>
<td>6.5</td>
<td>1967</td>
</tr>
<tr>
<td></td>
<td>structural damage, 200 killed</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aswan, Egypt</td>
<td>5.3</td>
<td>1981</td>
</tr>
<tr>
<td></td>
<td>largest reservoir, deep seismicity</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mines and Quarries</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></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 (coal)</td>
<td>4.6</td>
<td>1980</td>
</tr>
<tr>
<td><strong>Oil and Gas fields</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></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>Gas extraction</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gazli, Uzbekistan</td>
<td>~7</td>
<td>1976</td>
</tr>
<tr>
<td></td>
<td>Previously aseismic region, three M7 events</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Injection related</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></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>
</tr>
</tbody>
</table>
Small versus Large Earthquakes

• Earthquake magnitude determined by the size of the slipping fault
  - Small faults = small earthquakes
  - Many more small faults than large faults
  - Many more small earthquakes than large earthquakes
• Large earthquakes start deep (>10 km)
  - Shallow injection implies small earthquakes
• Small or moderate (M<5) induced earthquakes are extremely unlikely to remotely trigger large events on major faults even close by
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**

For a microearthquake to occur one must exceed the critical shear stress on the fault:

\[ \tau = c + \mu(\sigma_n - p) \]

- Water/fluid pressure in fault = p
- \( \mu \) = coefficient of friction on fault
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
    - Thermal stresses
    - Stress diffusion
    - Other
Examples - Reservoir Impoundment

Reservoir

+ΔVertical Stress
+ΔPore Pressure
Examples - Injection and Extraction

Fluid Injection (e.g., water disposal)
Fluid Extraction (e.g., petroleum production)

+ΔPore Pressure

-ΔVertical Stress
-ΔPore Pressure

Aquifer
Fault
Petroleum Reservoir
Zone of influence from potential earthquakes in the US

Map showing the zone of influence from potential earthquakes in the US, with areas shaded to indicate shaking felt and areas of damage, including specific magnitudes and years of occurrence.
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

**Empirical “Attenuation Relationships”**

**Physics-based “Waveform Modeling”**

![Map of California with seismic activity and a graph showing PGA vs distance with a magnitude of 6.0](image)
Earthquake Risk

• Risk in this context can be thought of as:

\[ R = AF(a \mid eq) \times \Pr(f \mid a) \times C(\$;LL \mid f) \]

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)
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

- Oil and Gas
  - Hydrofracture
  - Secondary recovery
  - Waste water disposal
- 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**
The Geysers Seismicity, 1965 to Present  (Smith, 2006)
Northern California Historical Seismicity (M 3.5 to 5.0) 1900-2005

The Geysers
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
Oil and Gas
Oil and Gas Injection seismicity

- Hydrofracture operations pose very low seismic risk
  - Disposal of waste water is most significant risk
  - Most hydrofracture operations have been in low seismic risk areas (may not be true of natural gas applications)
  - Hazard is in inducing permeability that may cause “leakage” (control of whole process)

- “Traditional” oil and gas induced seismicity cases have well known mitigation strategies (fluid balance)
Gas Shale Reservoirs

- Large, Unconventional Natural Gas Resources
- Organic-rich, low porosity, very low permeability
- Diverse Composition, Organic Content, Maturity, Depth, Temperature and Pressure
Drilling/Completion Technology Key To Natural Gas Development

Horizontal Drilling and Multi-Stage *Slick-Water* Hydraulic Fracturing Induces Microearthquakes (M ~ -0 to M ~ -3) To Create a Permeable Fracture Network

Courtesy of Schlumberger
Differences Between Oilfield/Gas and Geothermal

• The volumes injected and length of injections are significantly greater in geothermal, because of the limited nature of the hydrocarbon-bearing strata relative to the presumably much larger target volume for Geothermal; (not true for CCS)
  – Except for secondary recovery (water and CO2 floods, etc)

• Igneous rock is stronger than oilfield rock (however, while at first glance it may seem that stronger geothermal rock is more difficult to fracture, it is actually more likely to benefit from natural fractures or other pre-existing weaknesses, as compared to weaker oilfield rock, due to fracture shearing combined with propping of asperities);

• Most of the geothermal developments have a more or less hydrostatic pressure gradient, in contrast to oilfield reservoirs (of which some can be over- or under-pressurized, although many are at or near hydrostatic pressure).
Carbon Sequestration
CO$_2$ Sequestration

Overview of Geological Storage Options

1. Depleted oil and gas reservoirs
2. Use of CO$_2$ in enhanced oil and gas recovery
3. Deep saline formations — (a) offshore (b) onshore
4. Use of CO$_2$ in enhanced coal bed methane recovery

IPCC (2005)
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
Basin-Scale Pressure Buildup (bar)

Cutoff Pressure: 0.1 bar
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
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
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
Backup slides
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?
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!!
• **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
Summary/“Products”

- Supplying seismicity data needs for understanding relations between injection and induced seismicity
  - Source mechanism studies
  - Energy release rates and distributions
  - High precision locations
  - Correlation of injection data with MEQ attributes
- Data/Results for developing “best practices/protocol”
- Other needs (for successful/efficient implementation)
  - Geologic characterization (structure, lithology, faults, velocity models)
  - Subsurface stress (magnitude and orientation as a function of time)
  - Controlled field tests (manipulation experiments)
  - Borehole monitoring
- Upgrade and continue operation of high resolution seismic arrays to record seismicity from any new additional DOE EGS sites as they come on line.
- The data will be archived and made available to the public through the USGS Northern California Data Center (NCDC).
PSInSAR from ERS satellite track 113
Average velocities 1992-2000
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)
Aidlin
Prati
Calpine EGS Well

The Geysers
2009 - 2010

32,000 high quality events/

Latitude
Longitude
Well
LBNL Recording Station
Doughnut Hole Study Area
Potential for Intraplate Seismicity Limits Injection Pressures

Brittle Failure in Critically-Stressed Crust Results From Creep in Lower Crust and Upper Mantle

\[ \dot{\epsilon} = Ae^{Q/RT}(S_1 - S_3)^n_{brittle} \]

Seismogenic Zone  \( \tau = \mu \sigma_n \)

Brittle  \( \sim 16 \text{ km} \)

Ductile  \( \sim 40 \text{ km} \)

Moho

Plate-driving forces  \( \sim 3 \times 10^{12} \text{Nr} \)

\[ \text{Differential Stress Magnitudes} \quad (0.6 < \mu < 0.7) \]

\[ \text{Stress Orientation} \]

\[ \text{Number of induced Earthquakes} \]

\[ \text{Brittle-Ductile Transition ?} \]
CO$_2$ Sources in the Illinois Basin

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

Midwest Geological Sequestration Consortium (MGSC)
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.
Seismic moment & Injection Rate

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

Total Seismic Moment

Fluid injected

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

\(K \sim 0.5\)

McGarr (1976)
Volume change for Geysers

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

• Sum Moments = $10^{18.45}$ 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!!
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

\begin{align*}
10 & \quad M = 3.6 \\
100 & \quad M = 2.6 \\
1000 & \quad M = 1.6 \quad \text{etc}
\end{align*}