Rock Fracture Dynamics and Induced Seismicity

Paul Young, Professor of Seismology and Rock Mechanics, University of Toronto, Canada.

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Overview

• Induced Seismicity (Field)
  - Imaging the subsurface
  - State of the art, challenges and opportunities

• Rock Fracture Dynamics and Induced Seismicity (Lab)
  - Some previous research, standing on the shoulders of giants
  - True-Triaxial lab experiments, induced seismicity and geophysical imaging
  - Seismicity, velocity and permeability

• Conclusions and Future Potential for Induced Seismicity
Seismicity: Natural and human sources

- When a material (e.g. rock) undergoes brittle failure, elastic energy is radiated from the point of failure (or slip) into the surrounding medium.
Imaging the Earth with Seismicity

- S-Wave
- P-Wave

10 seconds
Seismic Signals

- The signal recorded at any one sensor is the convolution of the source magnitude and other properties, $M(t)$, the transmission media, $G(t)$, and the sensitivity of the instrument, $S(t)$.

- Understanding the effect of each is key to understanding seismicity.

The “instrument” includes the seismic transducer and all electronics that combine to record the waveform.
Induced or Triggered Seismicity

• There are many examples where human activity causes perturbations of the Earth’s crust that lead directly or indirectly to seismicity.

• Studies of such ‘stimulated’ seismicity provide important insights into the factors controlling crustal seismicity, both natural and ‘artificial’.

• Monitoring of stimulated seismicity can provide critical feedback on the engineering performance of a particular site or infrastructure.

• **Induced**
  Where the causative activity can account for most of the stress change or energy required to produce the seismicity

• **Triggered**
  Where the causative activity accounts for only a fraction of the stress change or energy associated with the seismicity (i.e. tectonic loading plays a primary role)

(after McGarr & Simpson, 1997)
Induced MicroSeismicity (MS) and Scaling

Km & 100s Hz

0.1m & 100s kHz

100m & kHz

10m & 10s kHz

MS Locations and Hydraulic Fracturing

- The analysis of the spatial distribution of induced MS events provide critical information of the fracture network stimulated through hydraulic treatments:
  - Fracturing extent and geometry
  - Quantification of the stimulated rock volume

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Wing Breakthrough</td>
<td>Yes</td>
</tr>
<tr>
<td>Fracture Network Wing Length</td>
<td>173 m</td>
</tr>
<tr>
<td>Fracture Network Half Length</td>
<td>133 m (E-wing)</td>
</tr>
<tr>
<td>Fracture Network Height</td>
<td>26 m</td>
</tr>
<tr>
<td>Fracture Network Width</td>
<td>18 m</td>
</tr>
<tr>
<td>Fracture Network Top</td>
<td>3,976 m (TVD SS)</td>
</tr>
<tr>
<td>Fracture Network Bottom</td>
<td>4,002 m (TVD SS)</td>
</tr>
<tr>
<td>Fracture Network Azimuth</td>
<td>97 degrees E of N</td>
</tr>
<tr>
<td>Fracture Network Plunge</td>
<td>90 degrees</td>
</tr>
</tbody>
</table>
Challenges and Opportunities

- S-wave Location Methods
- Relative Location
- Source Mechanisms
- Analysis of the Continuous Data Streams
- Enhanced Velocity Models
- Synthetic Seismicity Modelling
Increasing MS locations

- The success of MS monitoring relies on the accurate location of the highest number of events. Low signal-to-noise ratios are often experienced in many engineering environments. This has the effect of causing difficulties in the identification and picking of waveform phases, required to obtain source vectors for a successful location from arrays with limited geometry. Different approaches can be used to enhance the number and accuracy of located events:
  - Increasing the number of events with identified phase arrivals.
  - Using a location algorithm independent of the availability of both P and S wave arrivals and source vector information.
S-wave Polarization Methods

• A significant number of seismic events recorded during a hydrofracture treatment display a high energy S-wave arrival but have a P-wave that is close to or below the ambient noise level. Traditional location methods, relying on P-wave polarization information to determine the source vector, therefore fail to determine a source location for these events.

• The S-wave polarization can be investigated using similar methods as those used to analyze the P-wave polarization. Depending upon the nature of the S-wave polarization due to transmission effects, either the full source vector or the plane containing the source vector can be estimated.

• The use of this additional information in the standard location algorithm has been applied in field operations, increasing up to 8-fold the number of located events.

a) MS events located using source vector orientations from P-wave polarization.
b) MS events located using source vector orientations from S-wave polarization
Relative Location

- Relative location methods (master event or double difference) is based on the use of travel time differences between events, being more robust against uncertainties in the velocity model of the larger rock volume between the events and the sensor array.
- The method can provide successful location for microseismicity using a single phase and no polarization information on the target events.
- The technique provides a means to increase location efficiency and thus provide greater information on the fracture network.
- A stepwise approach is used over a lattice of master events to overcome the requirement of close separation between target and master events.
- The technique means that a simpler velocity model can be used for the target events.
Fracture Network Engineering

Interpreting fracture diagnostics from microseismic data:

- Numerical PFC models can simulate the evolution of fracture volume change and network connectivity and perform simulated fluid circulation;
- Feedback information between observed and simulated data provide Fracture Network Engineering (FNE).
- Synthetic seismicity, calculated within the modelled Discrete Fracture Network (DFN), can be compared with that observed during monitoring to relate microseismicity to fracture growth.
**MS from Bonded Particle Models and Synthetic Rocks**

\[
\begin{array}{|c|c|c|}
\hline
\sigma_1/\sigma_3 & \text{MPa} & 9/3 \\
q_i & \text{m}^3/\text{s} & 2 \times 10^{-3} \\
\hline
\end{array}
\]

Similar MS propagating patterns between field and model:
- Event locations with time
- Linear orientations
- Truncation or arrest of events in the N-E and S-W directions

* Zhao et al., 2011, GRC Annual Meeting
Continuous Record Analysis

- The continuous microseismic record can be used for investigating the fracture network growth and mechanics of hydrofracture data when no MS are induced or identified.
- It provides a means for diagnosing the quality of a data set and then optimizing the processing of discrete microseismic events.
- Continuous records could be used to better understand the fundamental hydrofracture propagation mechanics in different geological and treatment scenarios – by directly correlating with scaled laboratory experiments and dynamic numerical models in which seismic energy release is also mapped.
Natural Hazards
Application to Volcanic Seismicity

Benson PM, Viciguerra S, Meredith PG and Young RP (2008), Laboratory Simulation of Volcano Seismicity, Science, Vol 322.
Rock Fracture Dynamics Facility (RFDF)
True-Triaxial Geophysical Imaging Cell and Polyaxial Testing Machine

- Polyaxial servo-controlled loading system; 6800 kN axial, 3400 kN lateral
- Polyaxial (true triaxial) and triaxial geophysical imaging cells
- Temp. up to 200 °C
- Full waveform continuous Acoustic Emission (18 sensor 3D array sampled at 10MHz – up to 8hrs)
- 3D velocity measurement system (including 6P and 12S axial sensors)
- Pore pressure control and 3D permeability along independently controlled axes
True-Triaxial Geophysical Imaging Cell

One of the few *True Triaxial Rock Deformation Facilities with Integral Geophysical Imaging* for laboratory experiments and modelling of rock fracture:

- 3D geophysical measurements provide data to validate models
- 3D directional permeability measurements
- Coupled hydraulic, stress, and thermal conditions
- Laboratory simulation of the engineered subsurface environment of the Earth
Some Citations for True-Triaxial Experiments


Research Objectives of Current Study

1. Effect of intermediate stress on seismic and transport properties of rocks (here some results for Fontainebleau Sandstone)

2. Evolution of velocity and acoustic emission for imaging fracture growth within a true triaxial system

3. Permeability measurements along three independent orthogonal axes and application of effective medium theory and numerical methods
Results: Effect of TT Stress on 3D deformation and $V_p$

$\sigma_3=10$, $\sigma_2=20$ MPa

$\sigma_3=10$, $\sigma_2=50$ MPa
Imaging Velocity Structure

- \( \sigma_3 = 2.5, \sigma_2 = 50, \sigma_1 = 550 \) MPa
- \( \sigma_3 = 10, \sigma_2 = 50, \sigma_1 = 50 \) MPa
- \( \sigma_3 = 10, \sigma_2 = 50, \sigma_1 = 100 \) MPa
- \( \sigma_3 = 10, \sigma_2 = 50, \sigma_1 = 300 \) MPa
- \( \sigma_3 = 10, \sigma_2 = 50, \sigma_1 = 400 \) MPa
- \( \sigma_3 = 10, \sigma_2 = 50, \sigma_1 = 500 \) MPa
- \( \sigma_3 = 10, \sigma_2 = 50, \sigma_1 = 550 \) MPa

4400 m/s 4625 4850 5073 5300
Acoustic Emission Evolution (Induced Seismicity in the Lab)
ARMA Plenary Lecture, Chicago, June, 2012

UNIVERSITY OF TORONTO

C4

AE Hits/s

Time [seconds]

Cumulative AE

σ₁

σ₂

σ₃

σ₂

σ₃

σ₃

σ₂

σ₃

ARMA I
Fracture Pattern Under True-Triaxial Testing

\[ \sigma_3 = 10, \sigma_2 = 50, \sigma_1 = 550 \text{ MPa} \]

Side view parallel to \( \sigma_2 \)
Top view parallel to \( \sigma_1 \)
Deformed Pore space

Polarized light
Epi-fluorescent

1 mm
AE Location and Failure Planes

\[ \sigma_3 = 10, \sigma_2 = 50, \sigma_1 = 550 \text{ MPa} \]
3D Directional Permeability under Sealed Edges
Evolution of 3D Permeability Experimental Data

\[ \sigma_3 = 10, \sigma_2 = 20 \text{ MPa} \]

\[ \sigma_3 = 10, \sigma_2 = 50 \text{ MPa} \]
3D Compressional and Shear wave velocities

\( \sigma_3 = 10, \ \sigma_2 = 20 \text{ MPa} \)

\( \sigma_3 = 10, \ \sigma_2 = 50 \text{ MPa} \)

(a) depicts variation of \( V_P \) and \( V_{S1} \) along three principal stress axes as a function of \( \sigma_1 \) stress while \( \sigma_2 \) and \( \sigma_3 \) was kept at 20 and 10 MPa, b) shows similar variation while \( \sigma_2 \) and \( \sigma_3 \) was kept at 50 and 10 MPa.
Permeability Prediction, Statistical Approach

\[ \sigma_3 = 10, \ \sigma_2 = 50 \text{ MPa} \]

Crack density from inversion of seismic wave velocities

After Gueguen and Dienes (89)
Summary of True-Triaxial Results and Future work

- 3D velocity shows the effect of unequal stresses causing global compaction prior to fracture development when preferred tension cracks were formed parallel to the $\sigma_1$ and $\sigma_2$ plane.
- Evolution of AE events confirm progressive development of such planes parallel to $\sigma_1$ and $\sigma_2$ plane.
- 3D permeability is achievable within our TTT cell and satisfies Darcy’s law.
- Inherent fabric orientation and initial 3D fracture networking was not the same between the two samples.
- Increments of axial stress and compaction in the $\sigma_1$ direction did influence the transport properties in the other two horizontal directions. 3D fracture networking affects lateral $K$ values when axial stress is increased.
- Predicted values using both methods (statistical and numerical) captured the overall trend of the 3D permeability variations as a function of axial stress increments.
- Further development of platens underway for simultaneous resistivity, permeability and compliance. Initial tests are with machinable ceramics and non conductive coatings.
- Future work on lab hydraulic fracturing under true-triaxial conditions to help validate Bonded Particle and Synthetic Rock numerical models for true-triaxial conditions at elevated temperatures.
Future Potential for Induced Seismicity Monitoring

- Reservoir Stimulation via Hydraulic Fracturing
- Shale Gas
- Mass Mining
- Geothermal
- CO2 Sequestration
- Deep Geological Disposal of Radioactive Waste
- Laboratory Investigations
Thank you