Development of microseismic analysis method with multidisciplinary geophysical data

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Background
**Beyond the dots**

**More Information from Induced Seismicity/Microseismicity**

**Measurement of induced seismicity/microseismicity**
- Hypocenter location (dots)
- Indicator of pore pressure increase
- Enhancement of permeability/Stimulated rock volume

**Fracture orientation in reservoir**
- Geometry of existing fractures in reservoir tells us
  - *Flow path*
  - *Orientation of enhanced permeability*
  - *Fracture network system in the reservoir*
- Optimize energy extraction system

**Microseismic distribution @ Basel**
Constraining focal mechanism

**METHOD TO ESTIMATE FOCAL MECHANISM**

- **Centroid Moment Tensor (CMT)**
  The best moment tensors to explain waveforms
  - High SNR signal
  - Good coverage of stations

- **First motion information**
  The best focal mechanism to explain observed first motion data (compression or dilatation)
  - Good coverage of stations
  - + Waveform information
    e.g. Hardebeck and Shearer, 2003; Kraft et al., 2006

**Principle of first motion method**

First motion data for a hypothetical earthquake from various seismograph stations

Nodal planes and N, P & T axes fitted to the data
Focal mechanism estimation in microseismic monitoring

REALITY OF MICROSEISMIC MONITORING

Microseismic monitoring
- First objective of microseismic monitoring is hypocenter location
- Cost limit to install more stations (more boreholes)
- Not all microseismicity has enough SNR to apply CMT or other waveform based method

Focal mechanisms of induced seismicity are not well constrained in these situations

Example of focal mechanisms using only first motions
Polarity consistent focal mechanisms

Lower hemisphere pole plot
Introduction of multidisciplinary geophysical data
Introduction of multidisciplinary geophysical information

<table>
<thead>
<tr>
<th>SEISMIC INFORMATION</th>
<th>NON-SEISMIC INFORMATION</th>
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<tbody>
<tr>
<td>• Hypocenter location</td>
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<tr>
<td>• Velocity model</td>
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<td>• Polarization</td>
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<td>• Other geophysical information related to induced seismicity</td>
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<td>• In-situ stress state</td>
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<td>• Existing fractures</td>
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<td>• Injection pressure</td>
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<td>• Friction coefficient</td>
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<td>• Thermal stress</td>
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<td>• Poroelastic stress</td>
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ADDITIONAL GEOPHYSICAL INFO. CAN PROVIDE MORE CONSTRAINT ON THE RANGE OF FOCAL MECHANISMS
Mechanism of induced seismicity

**Geomechanical Theory of Induced Seismicity**

![Diagram](image)

**Coulomb failure criterion**

\[ \tau \geq \mu (\sigma - P) \]

- \( \tau \): Shear stress
- \( \mu \): Friction coefficient
- \( \sigma \): Normal stress
- \( P \): Pore pressure

We can evaluate the stability of each fracture under given stress state and injection pressure (we can estimate critical pore pressure):

- \( P_c > \) injection pressure: stable
- \( P_c < \) injection pressure: slip

\( P_c \): Pore pressure increase necessary for shear slip

Existing fracture distribution
Geomechanical constraint on fault orientation

In-situ stress information provide constraint of focal mechanism

Critical pore pressure for slip along arbitrary fault

\[ \tau = \mu \sigma \]

Fractures with shear slip

\[ \tau \geq \mu (\sigma - P) \]

Critical pore pressure
Constraining focal mechanism by multidisciplinary geophysical data

INTRODUCTION OF IN-SITU STRESS DATA TO CONSTRAIN SOURCE PARAMETER

Focal mechanism from microseismic information

Focal mechanism from stress information

Focal mechanism from combined information

Polarity consistent focal mechanism
Application to field data
Microseismic monitoring at Basel Switzerland

MICROSEISMIC MONITORING

- 6 downhole stations with 3C sensors
- 1 temporal station in injection well for velocity model calibration

BENCHMARK FOCAL MECHANISMS

- Well constrained focal mechanisms have previously been estimated for larger events

IN-SITU STRESS

- *In-situ* stress is estimated from borehole logging and hydraulic testing
Example of the results

**Slip-index:**

The ease with which fracture can have shear slip. Poles to focal mechanisms cannot exist in area of slip index=0

\[
\text{slip index} = \frac{\text{WHP}-\Delta P}{\text{WHP}-\Delta P_{\text{min}}} \quad (\text{for WHP} > \Delta P)
\]

\[
\text{slip index} = 0 \quad (\text{for WHP} < \Delta P)
\]

**Note:** Higher slip index does not mean higher probability/plausibility of the best focal mechanism

- **First motion info.**
  - ●: Compression
  - ○: Dilatation

- **Benchmark focal mechanisms**
  - ◇: Slipped fault plane
  - □: Nodal plane

- **After introduction of stress info.**
Example of the results

OBSERVATIONS: GROUP 1

- Integration of induced seismicity data and multidisciplinary geophysical data is significantly improves result
- Many polarity consistent focal mechanisms are eliminated
- Nonzero slip index area becomes larger with time (e.g. increased WHP)
- For first 4 events, one of the poles of benchmark focal mechanism falls in nonzero slip index region
- For the others, both of the poles fall in nonzero slip index area
Conclusions and future studies

CONCLUSIONS

• Integration of induced seismicity data and multidisciplinary geophysical data is crucially important for better understanding reservoir physics and further development of the reservoir.

• Integrated analysis of induced seismicity data and other geophysical data (multidisciplinary approach) will be a key approach for problems associated with subsurface development.

POSSIBLE FUTURE STUDY

• Introduction of realistic hydrological model
• Statistical model using existing fracture information
• Bayesian inversion to evaluate the uncertainties from multiple data
Acknowledgement

- We thank Geopower Basel AG/Geo Explorer Ltd. for providing the microseismic data set and for approving the publication of these results.

- This study was supported by Grant-in-Aid for JSPS Overseas Research Fellow (20160228) and ERL, MIT.

- The contents of this talk will be published in Mukuhira et al., 2018 GJI in the near future.

Thank you for your kind attention
Back up slides
Benchmark focal mechanisms by SED/ETH

- Focal mechanisms for relatively larger events (around 100 events)
- Surface natural seismic network over Switzerland
- Microseismic network at Basel (Deichmann and Giardini, 2009)

- Failure plane from each focal mechanisms was identified by comparison with neighboring events (Mukuhira et al., 2016)
### Groups having different first motion information

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1: compression, -1: dilatation

**Focal mechanism inversion**
- First motion info. from 6 sta.
- Grid search approach.
- 5 degree increment of strike/dip/rake.
- No weighting
In-situ stress information of Basel EGS reservoir

IN-SITU STRESS PROFILE IN DIFFERENT WAYS

- Orientation of SHmax: N144E±14°
- Borehole analysis (Valley and Evans, 2009)

- Stress magnitude
- SHmax & Shmin: Borehole breakout width
- Sv: density logging (Valley and Evans, 2015)

- Stress state transition from strike slip to normal fault type with depth
Example of the results

OBSERVATIONS: GROUP 1

• Integration of induced seismicity data and multidisciplinary geophysical data is significantly improves result
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• For first 4 events, one of the poles of benchmark focal mechanism falls in nonzero slip index region
• For the others, both of the poles fall in nonzero slip index area
Example of the results

OBSERVATIONS: GROUP 6

• Several dilatational first motions in the middle of the focal sphere lead to normal fault type focal mechanism
• Many poles of polarity consistent focal mechanisms having wide range of azimuth are eliminated
• In this case, poles of bench mark focal mechanisms are found in the nonzero slip index area
Example of the results

OBSERVATIONS: GROUP 2

- Introduction of our method helps to constrain strike of polarity consistent focal mechanism
- One of the poles of benchmark focal mechanism was in nonzero slip index area

OBSERVATIONS: GROUP 3

- Polarity consistent focal mechanism are well constrained already
- Still introduction our our method helps to constrain the focal mechanism region
**Example of the results**

**OBSERVATIONS: GROUP 4 & 5**

- Group 4 and 5 have similar distribution of polarity consistent focal mechanisms.
- In both cases, poles plotted in the center of the focal sphere are eliminated by introduction of out method.
- Poles of failure plane are always in the nonzero slip index area.

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In-situ stress information of Basel EGS reservoir

• First bullet point
  • Second bullet point
    • Etc.

• First bullet point
  • Second bullet point
    • Etc.
Geomechanics of induced seismicity

Objective
Constraining focal mechanisms under poor monitoring situations by introducing *in-situ* stress and injection pressure information
Quantitative evaluations

Elimination rate:

Num. of eliminated focal mechanisms

Num. of all polarity consistent focal mechanisms

Relative metric of constraining focal mechanism by introducing in-situ stress and wellhead pressure info.

Hit rate:
- Bootstrapping test: 1000 realization of in-situ stress models with uncertainties
- Count the number of tests where bench mark focal mechanism matches nonzero slip index region
- Hit rate = the number of hit count/the number of effective trial
Performance of our method
- Very good when wellhead pressure is low
  ➔ initial stage of stimulation
  ➔ near field of injection well
Good for evaluation of fracture system near the injection well
- Performance depends on initial distribution of polarity consistent focal mechanism
  ➔ Even all cases, we can constrain the range of focal mechanisms
- Overlapping area between polarity consistent focal mechanism and nonzero slip index determines elimination rate