Quantifying Changes in Site Hazard for Induced Seismicity through Bayesian Inference

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• Probabilistic seismic hazard analysis (PSHA) is used worldwide to assess risk from natural seismicity

• Its application to induced seismicity is nontrivial
  – Detecting changes in seismicity is important for PSHA (and other decision support—traffic lights)
  – Common assumptions in natural-seismicity hazard analysis may not be appropriate
Change Point detection illustrated with simulated seismicity data

This example data comes from a Poisson process, where the rate of events triples at a known point in time. Can we detect this Change Point using only the observed data?

Bayes Factor: $B_{01} = \frac{p(t \mid H_0)}{p(t \mid H_1)}$ ← Likelihood assuming a constant rate
← Likelihood assuming a rate change in the data
Change-Point results: time of change

We can also calculate the probability of the Change Point being at time $t$
Change-Point results: event rates

Estimated pre-change rate

Estimated post-change rate

Known input rates

Rate (Events/day)
Change Point detection for Oklahoma seismicity

Cumulative number of events with $M \geq 3$
Change Point detection for Oklahoma

From declustered catalog of M≥3 earthquakes (Oklahoma Geological Survey)

From seismicity through 2010

Regions with detected Change Points

Spatial sampling radius
Change Point detection for Oklahoma

From declustered catalog of M\(\geq3\) earthquakes (Oklahoma Geological Survey)

From seismicity through 2014

Regions with detected Change Points
Change Point detection for Oklahoma

From declustered catalog of M≥3 earthquakes (Oklahoma Geological Survey)

From seismicity through 2014

USGS regions of suspected induced seismicity

Spatial sampling radius
Increases in seismicity rates

The seismicity rate is increased in many regions by a factor of 100
Effect of seismicity models on seismic hazard

Base model
- Areal source (25 km radius considered)
- Gutenberg-Richter recurrence model
  - one $M=3$ earthquake per year
  - $b=1$, $M_{\text{min}} = 3$, $M_{\text{max}} = 7$
- Atkinson (2015) ground motion prediction model (calibrated for induced seismicity)

$$
\lambda(PGV > x) = \sum_{\text{sources}} \left[ \lambda(m_{\text{min}}) \sum_{M} \sum_{R} P(PGV > x \mid m, r) P(M = m) P(R = r) \right]
$$
Impact of seismicity rate on PSHA results

Earthquake rates

\[
\lambda(PGV > x) = \sum_{\text{sources}} \left[ \lambda(m_{\text{min}}) \cdot \sum_{M} \sum_{R} P(PGV > x \mid m, r) P(M = m) P(R = r) \right]
\]

Ground motion hazard

Seismicity rate
Impact of $M_{\text{max}}$ on PSHA results

**Earthquake rates**

![Graph showing earthquake rates with different $M_{\text{max}}$ values.](image)

**Ground motion hazard**

![Graph showing ground motion hazard with different $M_{\text{max}}$ values.](image)
Impact of $M_{\text{min}}$ and $M_{\text{max}}$ on PSHA results

Varying $M_{\text{min}}$

Varying $M_{\text{max}}$
Impact of ground motion prediction model on PSHA results

Ground motion predictions (M=5)

- Atkinson (2015)
- Atkinson (2015), eff. depth = 9km
- Boore et al. (2014)
- Atkinson and Boore (2006)

Ground motion hazard

- Atkinson (2015) induced seismicity
- Boore et al. (2014)
- Atkinson and Boore (2006)

Effects of ground motion on damage:
- Felt
- Light damage
- Moderate damage
Potential risk management actions

- Simpler to make decisions or rules (fewer models required)
- Poor link to risk (ground motions cause damage, not earthquakes)

- Most direct measure of risk
- Requires more models

Diagram:

- Earthquake occurrence
- Ground motion
- Consequences
Conclusions

• Seismicity rates are a key input to seismic hazard analysis, and changes in seismicity rates can be detected and quantified using the Bayesian Change-Point calculations.

• The results have relevance to seismic calculations and stop-light systems for risk management.

• Traditional intuition regarding PSHA important parameters for PSHA calculations may not apply when considering frequent low-amplitude events.

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