Induced seismicity risk mitigation: An actuarial approach
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The challenge of mitigating induced seismicity

- Central United States (ANSS, magnitude 3 and above)
- Groningen gas field, Netherlands (KNMI, magnitude 1 and above)

Cumulative number of earthquakes

- Fracking wastewater disposal
- Tectonic activity
- Gas extraction

Year

Disposal wells to shut down after Oklahoma earthquakes

Shored-up homes are a common sight in earthquake-hit Groningen

Source: FOX 23 News

Source: Dutch News
Traffic-Light Systems (TLS) as a solution

✓ Consists in minimizing induced seismicity based on:
  ➢ **Decision variable** (e.g., earthquake magnitude, peak ground velocity)
  ➢ **Threshold value** above which actions are taken (e.g., reduction or stopping of injection)

✓ Tools **still inherently heuristic & mostly based on expert elicitation**
  ➢ Different regulations in different regions
  ➢ How are those magnitude thresholds chosen?
  ➢ How do they relate to risk? (risk-based safety norms in other hazardous industries, e.g., chemical plants)

source: Bosman et al. (2016)
Traffic-Light Systems (TLS) as a solution

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- One of the goals of T4.1 “Risk, safety & public acceptance” is to propose an actuarial approach to this problem in the scope of a TLS-based induced seismicity risk governance framework

source: Bosman et al. (2016)
A closer look at what happened in Basel, 2006

2006 Basel EGS data sources:
Häring et al. (2008);
Kraft & Deichmann (2014)

source: modified from Mignan (2016)
Induced seismicity rate model

✓ Linear relationship between flow rate $\Delta V(t)$ and induced seismicity rate $\lambda(t)$

✓ Overall activity or “underground feedback” represented by $a_{fb}$

✓ Normal diffusion in post-injection phase with mean relaxation time $\tau$

$$\lambda(t, m \geq m_0; \theta) = \begin{cases} 10^{a_{fb} - bm_0} \dot{V}(t) & ; t \leq t_{shut-in} \\ 10^{a_{fb} - bm_0} \dot{V}(t_{shut-in}) \exp \left( -\frac{t-t_{shut-in}}{\tau} \right) & ; t > t_{shut-in} \end{cases}$$

2006 Basel EGS data sources:
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source: modified from Mignan (2016)
Deep fluid injections around the world

- Simple model fits reasonably well most of the sequences (based on MLE & KS test)

- High variability of underground feedback
  - $-2.8 \leq a_{fb} \leq 0.1 \text{ m}^{-3}$
  - $0.8 \leq b \leq 1.6$
  - $0.2 \leq \tau \leq 20 \text{ days}$

- Second-order deviations from model still to be understood
  - Missing on-site data?
  - Second-order physics?

source: Mignan et al. (in rev., Sci. Rep.)
Let us define a risk-based safety norm

- Fixed to $\Pr(\text{fatality}) = Y = 10^{-6}$
- Risk of earthquake damage assumed to be insured

Can be mapped into magnitude space

- Poisson process with $\Pr(\geq m_{saf}) = 1 - \exp N(\geq m_{saf})$
- Total number $N$ obtained by integrating rate model

Closed-form means

- Almost instantaneous computation
- Robust & transparent

$$\Pr(m \geq m_{saf}) = 1 - \exp\{-10^{a_{fb} - bm_{saf}}[V(t_{shut-in}) + \tau\dot{V}(t_{shut-in})]\} = Y$$

modified from Mignan et al. (in rev., Sci. Rep.)
(for $V=10,000m^3$, 4km depth, $d=0km$ from borehole)
Developing a TLS based on the rate-model (2/2)

- a. Simulation of 2006 Basel time series
  - Stochastic process based on rate model

- b. Temporal evolution of \((a_{fb}, b)\)
  - Risk evolves with time
  - Adaptive TLS (ATLS)

- c. TLS definition
  - Stop injecting above \(m_{th}\)

- d. TLS validation
  - Over millions of simulations, we observe that the safety norm is respected in average

\[
m_{th} = \frac{1}{b} \log_{10} \left[ Y - 10^{a_{fb}} - b m_{saf} \tau \dot{V}(t_{shut-in}) \right] + m_{saf}
\]
Hierarchical Bayesian forecasting

- Bayesian online updating, including uncertainty quantification
- Predicts both the number of events & the expected maximum magnitude
- See SCCER-SoE T4.1 poster by Broccardo et al.

source: Broccardo et al. (submitted)
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Next steps

- Consider the impact of a TLS on the EGS business (see poster "The price of public safety in EGS projects")
  - Seismic risk turned into increased price/kWh
  - Decision-making under uncertainty to quantify stakeholders’ behaviour

- Improved physical model of induced seismicity
  - Changes of injectivity; pressure minimum threshold? (insights from DUG-Lab)
  - Could provide smarter strategies, e.g., modifying injection profile instead of brutal stop

- TLS in legislations & public acceptance (SoE-CREST JA)
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On induced seismicity risk analysis (for magnitude-risk mapping)

On induced seismicity modelling & forecasting
- Mignan, A. (2016), Static behaviour of induced seismicity, Nonlin. Processes Geophys. 23

On traffic light systems & safety norms

SCCER SoE posters
- Broccardo, M., A. Mignan, B. Stojadinovic, S. Wiemer, D. Giardini, Hierarchical Bayesian modelling for fluid-induced seismicity