ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

USYS TdLab

SCCER SoE
SWISS COMPETENCE CENTER for ENERGY RESEARCH
SUPPLY of ELECTRICITY

Expert agreements and disagreements on induced seismicity by Enhanced Geothermal Systems (EGS)

Evelina Trutnevyte (ETH Zurich, Switzerland)

Ines L. Azevedo (Carnegie Mellon University, USA)

Second Schatzalp Workshop on Induced Seismicity, 17 March 2016, Davos

Goal

- Evaluate induced seismicity hazard (and risk) for EGS, using expert judgments
- Characterize uncertainty
- Complement timely assessment (not substitute basic science)

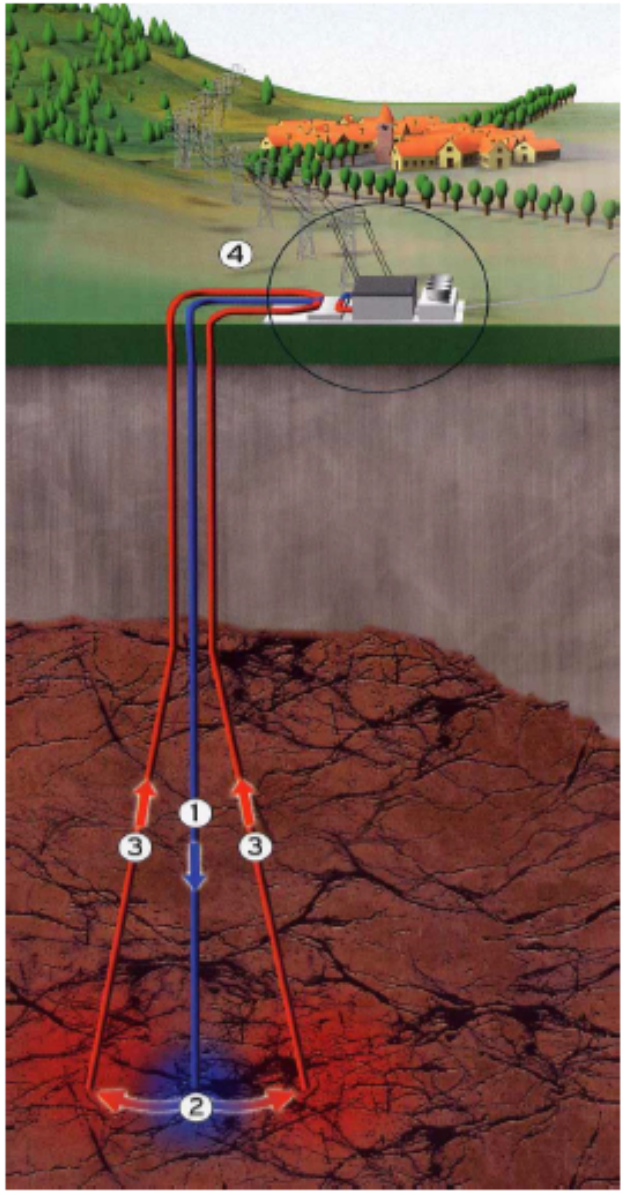


Figure: SCCER-SoE

Why expert elicitation?

Direct empirical evidence
(direct measurement)
⇐Basel, Geysers, Soultz etc.

Semi-empirical evidence
(direct measurement under other conditions)
⇐Grimsel lab

Empirical correlations
(measurement of other effects)

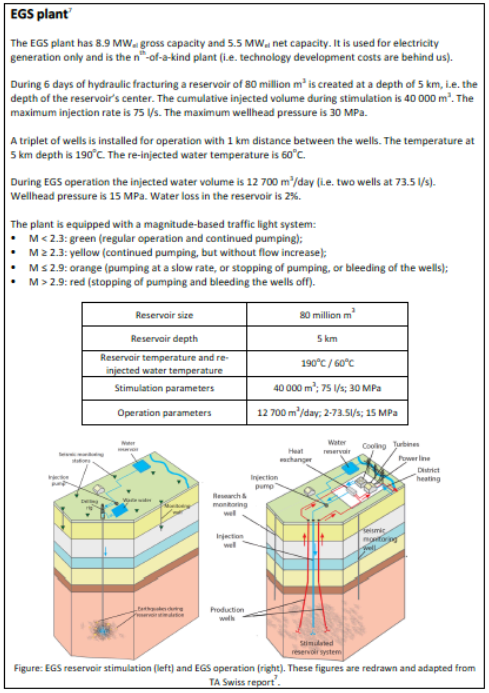
Theory-based inference
(modelling)
⇐Probabilistic seismic hazard/risk modelling

Experiential insight
(experience-based opinions)
⇐Expert elicitation

Adapted from: US EPA (2011)

Expert elicitation method

- A combination of technical analysis and expert judgement (Morgan, 2014)
- Individual structured 2-hour interviews
- Techniques to minimize behavioral effects and subjectivities, such as overconfidence, availability bias, or anchoring and adjustment bias **(new!)**



EGS plant[7]

The EGS plant has 8.9 MW_{el} gross capacity and 5.5 MW_{el} net capacity. It is used for electricity generation only and is the nth-of-a-kind plant (i.e. technology development costs are behind us).

During 6 days of hydraulic fracturing a reservoir of 80 million m^3 is created at a depth of 5 km, i.e. the depth of the reservoir's center. The cumulative injected volume during stimulation is 40 000 m^3. The maximum injection rate is 75 l/s. The maximum wellhead pressure is 30 MPa.

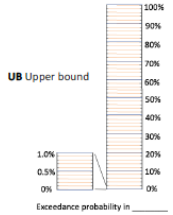
A triplet of wells is installed for operation with 1 km distance between the wells. The temperature at 5 km depth is 190°C. The re-injected water temperature is 60°C.

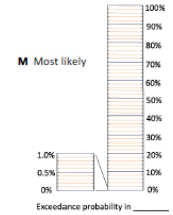
During EGS operation the injected water volume is 12 700 m^3/day (i.e. two wells at 73.5 l/s). Wellhead pressure is 15 MPa. Water loss in the reservoir is 2%.

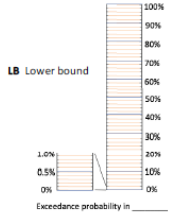
The plant is equipped with a magnitude-based traffic light system:
- M < 2.3: green (regular operation and continued pumping);
- M ≥ 2.3: yellow (continued pumping, but without flow increase);
- M ≤ 2.9: orange (pumping at a slow rate, or stopping of pumping, or bleeding of the wells);
- M > 2.9: red (stopping of pumping and bleeding the wells off).

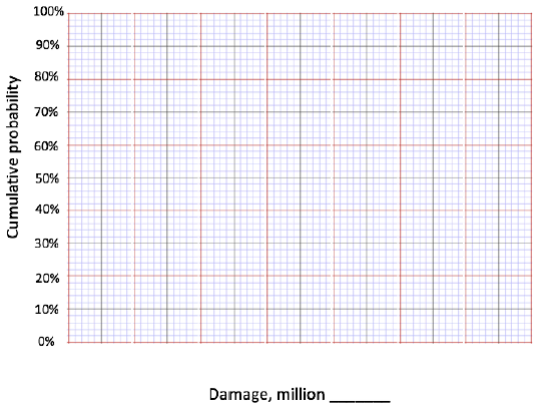
Reservoir size	80 million m^3
Reservoir depth	5 km
Reservoir temperature and re-injected water temperature	190°C / 60°C
Stimulation parameters	40 000 m^3; 75 l/s; 30 MPa
Operation parameters	12 700 m^3/day; 2-73.5l/s; 15 MPa

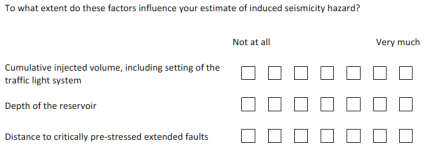
Figure: EGS reservoir stimulation (left) and EGS operation (right). These figures are redrawn and adapted from TA Swiss report[7].











Interviewed experts

- 14 experts:
  - Natural seismicity, M=23 years of experience, SD=15 years
  - Induced seismicity, M=17 years, SD=15 years
  - Seismic risk, M=11 years, SD=8 years
  - Seismologists (n=8); engineering geologists, geotechnical engineers, mining engineers, structural engineers, structural geologist (2 each), and other
  - Worked on EGS (11), conventional oil and gas, shale oil and gas, wastewater injection (10 each), other deep geothermal systems (8), carbon capture and storage, hydro dams (4 each), and other
- 6 countries: France, German, Netherlands, Switzerland, UK, USA
- 12 organizations: 9 experts are active in science, 5 in consultancy, 4 in public administrations, and 2 in industry

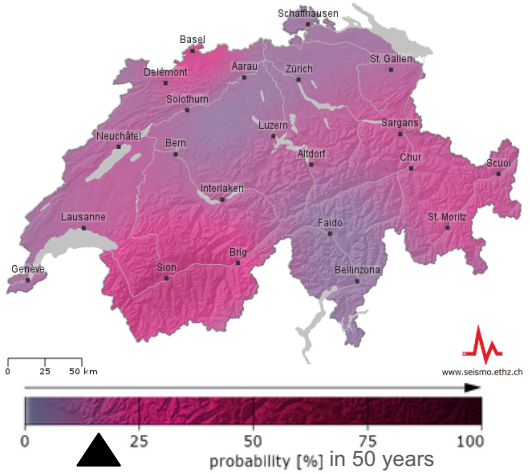
A hypothetical case

EGS plant

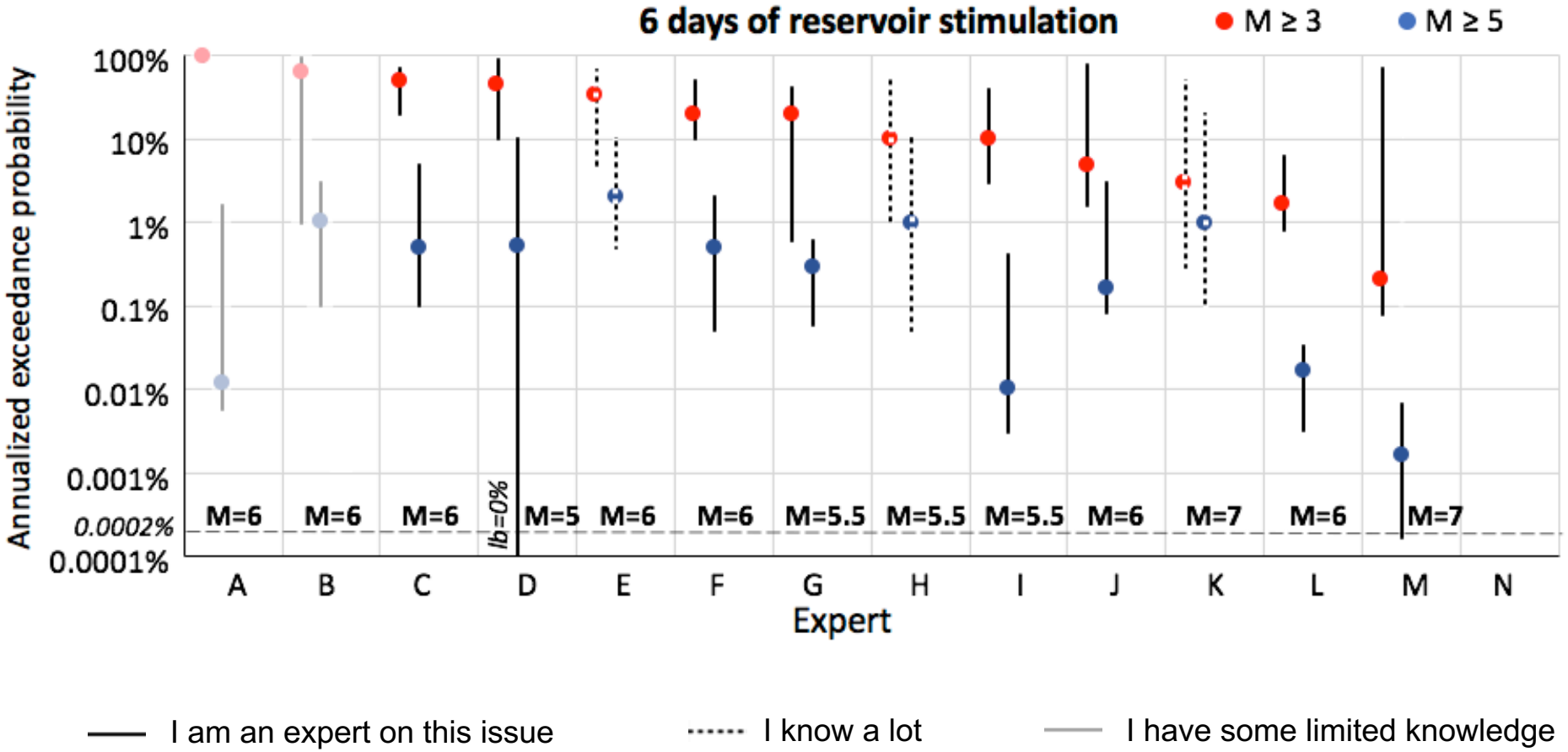
- 8.9 MW_{el} gross
- 5 km depth, 80 million m^3 reservoir
- 6-day stimulation: 40 thousand m^3, 75 l/s, 30 MPa
- 30-year operation: 2 x 73.5 l/s, 15 MPa, 190°C/60°C, 2% water loss
- Magnitude-based traffic light system (red at M>2.9)

Geological context

- Non-volcanic area, granite rock
- No known critically pre-stressed faults
- Tectonic M≥7 at 0.01% in 1 year, Ø50km
- Tectonic M≥5 at 0.4% in 1 year, Ø30km

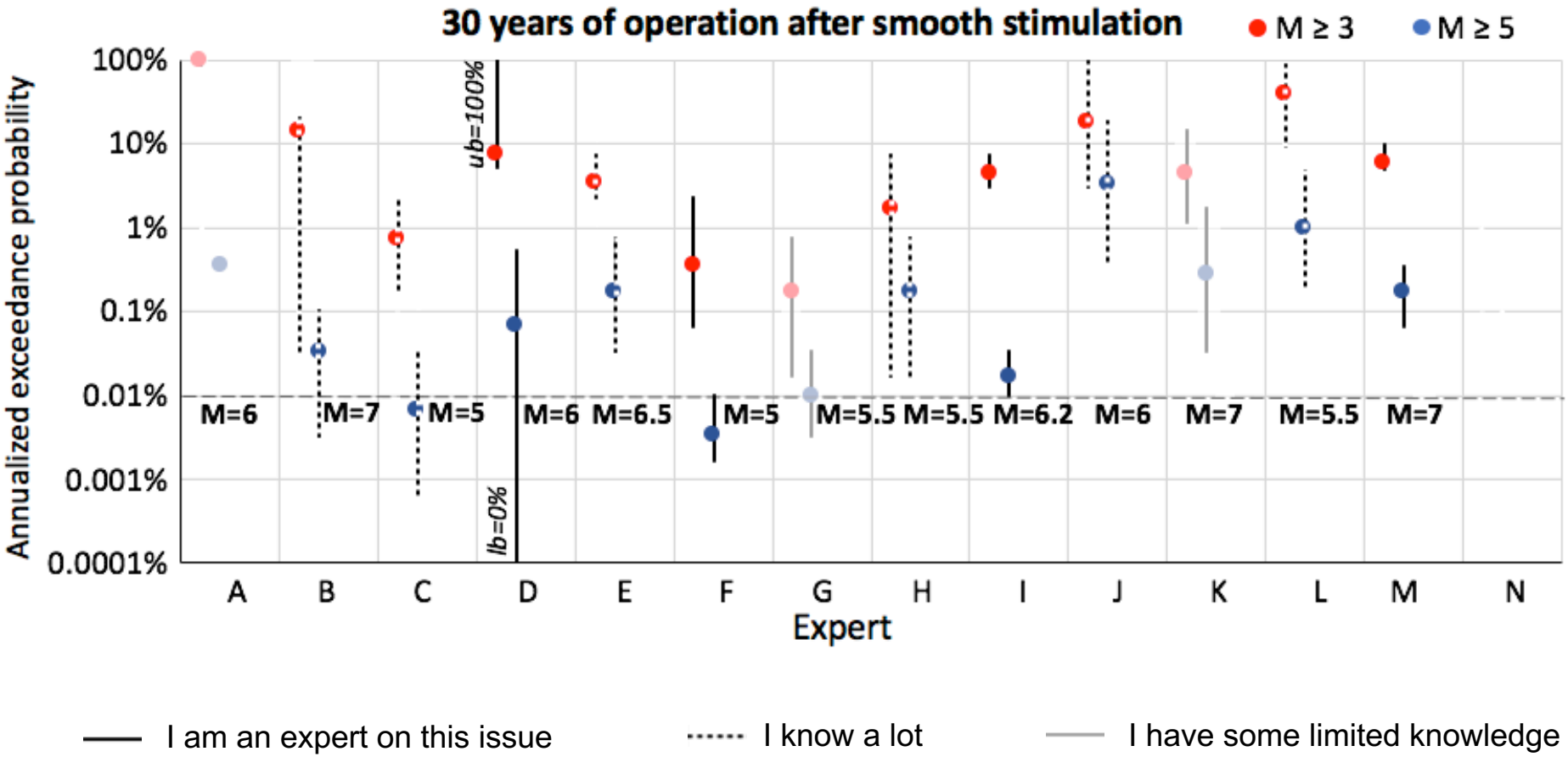


Exceedance probabilities of EGS induced earthquakes



Source: Trutnevyte & Azevedo. 2017. Under review.

Exceedance probabilities of EGS induced earthquakes



Source: Trutnevyte & Azevedo. 2017. Under review.

Influencing factors, uncertainty, and gains through future research

		Influence on the final hazard outcome							Contribution to uncertainty							Uncertainty reduction due to future research and data collection						
		↓ Not at all			↓			Very high ↓	↓ Not at all			↓			Very high ↓	↓ Not at all			↓			Very high ↓
Faults	Distance to extended faults	0	0	0	0	2	5	6	0	1	0	1	2	3	4	0	3	0	1	0	3	4
EGS design and operation	Cumulative injected volume	0	2	0	0	3	5	3	0	1	6	1	2	0	1	0	1	3	1	1	2	3
	Depth of the reservoir	0	0	1	5	3	4	0	0	3	4	1	2	1	0	1	3	2	0	3	2	0
	Wellhead pressure	0	1	2	2	4	3	1	0	2	0	6	1	2	0	1	0	1	4	4	1	0
	Injection rate	0	1	4	0	5	2	1	0	1	3	5	1	1	0	0	2	2	2	3	2	0
Tectonics	Tectonic stress regime	2	0	2	2	2	4	1	0	2	2	1	3	2	1	0	1	5	1	0	2	2
	Natural seismicity	1	1	3	2	2	3	1	0	0	2	2	4	2	1	0	0	1	2	4	3	1
Fluid	Type of injection fluid	2	5	2	3	1	0	0	1	6	1	2	0	1	0	1	3	5	2	0	0	0

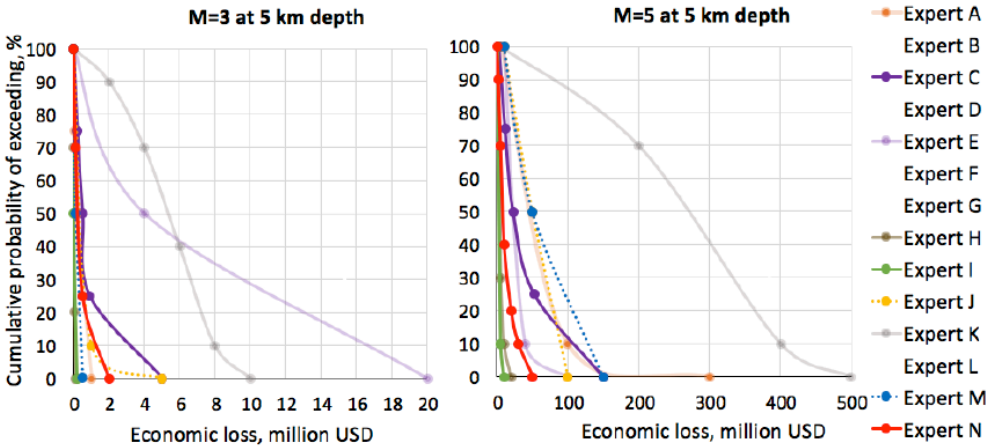
Source: Trutnevyte & Azevedo. 2017. Under review.

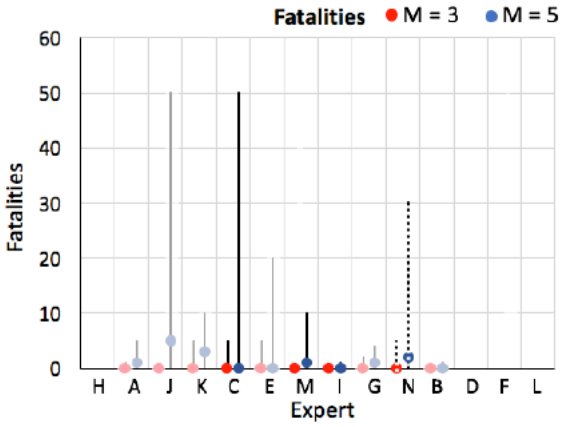
Examples of most promising research directions

General
• Proceed with more EGS projects and field experiments to get empirical data. • Validate all components of hazard and risk knowledge, including hazard at the source, ground motions, building response, and mitigation strategies. • Perform controlled experiments on induced seismicity, especially with control on many different variables, instead of observing commercial operations. • Enable open experiments and open-source data that everybody in the World could run their model on. • Improve the conceptual model of deep geothermal resource in order to know how to stimulate when. • Educate citizens and pupils on geothermal resource, induced seismicity, and geoscience.
Hazard assessment at the source
• Understand the physics of earthquakes, not only induced, but also natural. • Understand the difference between inducing processes for natural and artificial seismicity. • Develop a better source model how earthquakes are induced. • Develop geo-mechanical models that include more complete physics of induced seismicity.

Source: Trutnevyte & Azevedo. 2017. Under review.

EGS induced seismicity risk





Influence on the final hazard outcome

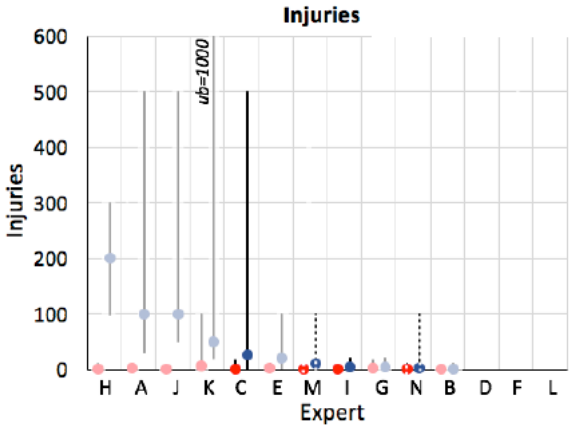
	Not at all						Very high
Local site amplification	0	0	0	1	1	2	5
Exposed population	0	1	0	0	2	2	4
Quality of construction	0	0	1	2	1	1	4
Exposed critical infrastructures	0	0	1	2	1	2	3
Exposed building stock	0	0	1	2	2	1	3
Value of exposed property	0	1	0	1	4	1	2
Earthquake preparedness	0	4	0	0	1	3	1
Secondary hazards	0	2	1	2	3	0	1

Contribution to uncertainty

	Not at all						Very high
Local site amplification	0	0	3	0	3	2	1
Exposed population	1	3	0	1	2	2	0
Quality of construction	0	2	2	0	3	1	1
Exposed critical infrastructures	0	3	0	2	1	3	0
Exposed building stock	1	0	1	2	1	2	2
Value of exposed property	1	3	1	2	2	0	0
Earthquake preparedness	0	5	0	1	2	1	0
Secondary hazards	0	1	3	3	1	1	0

Uncertainty reduction due to future research and data collection

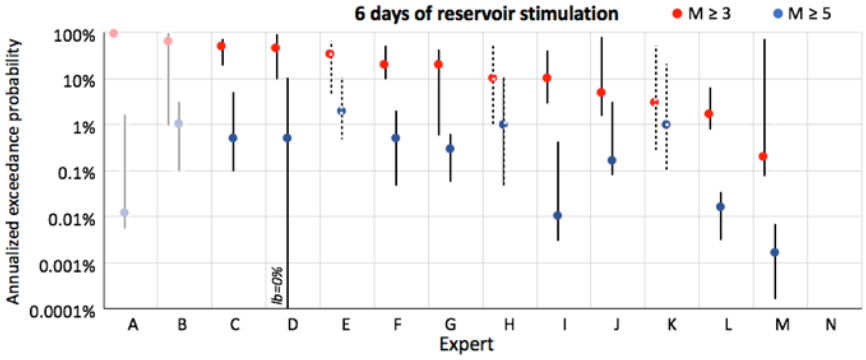
	Not at all						Very high
Local site amplification	0	2	0	3	2	2	0
Exposed population	0	3	2	3	1	0	0
Quality of construction	0	2	1	2	2	2	0
Exposed critical infrastructures	1	1	2	3	1	1	0
Exposed building stock	0	2	1	4	0	1	1
Value of exposed property	1	3	3	0	2	0	0
Earthquake preparedness	1	3	1	2	2	0	0
Secondary hazards	0	1	4	3	1	0	0



Source: Trutnevyte & Azevedo. 2017. Under review.

Summary

- We have observed a **vast diversity in quantitative expert judgements** about the probabilities of felt and damaging EGS induced earthquakes and magnitudes of the largest events



- Expert **mental models** of what influences induced seismicity hazard, related uncertainties, and what future research could achieve diverge too

	Influence on the final hazard outcome							Contribution to uncertainty							Uncertainty reduction due to future research and data collection						
	↓ Not at all			↓			Very high ↓	↓ Not at all			↓			Very high ↓	↓ Not at all			↓			Very high ↓
Distance to extended faults	0	0	0	0	2	5	6	0	1	0	1	2	3	4	0	3	0	1	0	3	4
Cumulative injected volume	0	2	0	0	3	5	3	0	1	6	1	2	0	1	0	1	3	1	1	2	3
Depth of the reservoir	0	0	1	5	3	4	0	0	3	4	1	2	1	0	1	3	2	0	3	2	0
Wellhead pressure	0	1	2	2	4	3	1	0	2	0	6	1	2	0	1	0	1	4	4	1	0
Injection rate	0	1	4	0	5	2	1	0	1	3	5	1	1	0	0	2	2	2	3	2	0
Tectonic stress regime	2	0	2	2	2	4	1	0	2	2	1	3	2	1	0	1	5	1	0	2	2
Natural seismicity	1	1	3	2	2	3	1	0	0	2	2	4	2	1	0	0	1	2	4	3	1
Type of injection fluid	2	5	2	3	1	0	0	1	6	1	2	0	1	0	1	3	5	2	0	0	0

Implications for risk governance processes

- **For expert elicitations:**
  - Be cautious with consensus-based elicitations
  - At least document individual judgements before and after
  - Do it in a structured and transparent manner, minimizing subjectivities and behavioral effects
- **For expert panels:**
  - Avoid small panels or select experts to represent the full spectrum of views
  - Ensure that experts with particular views are not cherry-picked
  - Involve experts with various backgrounds, experiences, and countries of origin
- **For hazard (and risk) assessments:**
  - Aim for multi-organization, multi-method hazard (and risk) assessments
  - Use techniques for decision making under deep uncertainty and diversity of expert views

“Science is not a matter of majority vote.

Sometimes it is the minority outlier who ultimately turns out to have been correct.”

Granger M. Morgan (2014) PNAS

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

USYSTdLab

SCCER SoE
SWISS COMPETENCE CENTER for ENERGY RESEARCH
SUPPLY of ELECTRICITY

Please get in touch with questions and comments!

Evelina Trutnevyte, ETH Zurich
tevelina@ethz.ch