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Induced seismicity hazard and risk by enhanced geothermal systems: an expert elicitation approach

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Abstract

Induced seismicity is a concern for multiple geoenergy applications, including low-carbon enhanced geothermal systems (EGS). We present the results of an international expert elicitation (n = 14) on EGS induced seismicity hazard and risk. Using a hypothetical scenario of an EGS plant and its geological context, we show that expert best-guess estimates of annualized exceedance probabilities of an M ≥ 3 event range from 0.2%–95% during reservoir stimulation and 0.2%–100% during operation. Best-guess annualized exceedance probabilities of M ≥ 5 event span from 0.002%–2% during stimulation and 0.003%–3% during operation. Assuming that tectonic M7 events could occur, some experts do not exclude induced (triggered) events of up to M7 too. If an induced M = 3 event happens at 5 km depth beneath a town with 10 000 inhabitants, most experts estimate a 50% probability that the loss is contained within 500 000 USD without any injuries or fatalities. In the case of an induced M = 5 event, there is 50% chance that the loss is below 50 million USD with the most-likely outcome of 50 injuries and one fatality or none. As we observe a vast diversity in quantitative expert judgements and underlying mental models, we conclude with implications for induced seismicity risk governance. That is, we suggest documenting individual expert judgements in induced seismicity elicitations before proceeding to consensual judgements, to convene larger expert panels in order not to cherry-pick the experts, and to aim for multi-organization multi-model assessments of EGS induced seismicity hazard and risk.

Introduction

As a vast, low-carbon, locally available energy source [1], deep geothermal systems are part of the much-needed transition of the electricity and heating sector and feature in the energy strategies of the USA [2] and Switzerland [3]. Conventional deep geothermal systems extract hot water from natural aquifers at a depth of 2–5 km. If an aquifer with high enough water volumes and temperatures is not present, enhanced geothermal systems (EGS) can be deployed [4]. In EGS, a reservoir with sufficient permeability is engineered deep underground by injecting water at high pressures.

The deployment of EGS, while promising, leads to concerns over induced seismicity [5–7]. Many geoenergy applications, such as conventional oil and gas production, enhanced oil recovery, hydraulic fracturing, wastewater injection, or geological CO2 storage, carry the risk of induced seismicity [8, 9]. The USA [9], Canada [10] and the Netherlands [11] are already experiencing unprecedented levels of non-geothermal induced seismicity. For EGS, the seismicity is a particular constraint to unlocking the technology’s potential. Firstly, only a handful of EGS exist worldwide [12]. Empirical evidence of EGS seismicity is sparse, episodic uncertainties are ubiquitous, and the learning with every new plant is steep. Large research programs on EGS seismicity have been thus recently pursued [13, 14]. Secondly, several projects have already led to seismic events being felt during stimulation [15].
For example, in 2003, the EGS in Soultz-sous-Forêts (France) led to an event of M2.9 [16]. Similarly, in Basel (Switzerland) in 2006 there was an event of local magnitude $M_L$ 3.4 [17], and yet another of $M_L$ 4.4 in 2003 in Berlin (El Salvador) [18]. Public concerns arise when seismic events are felt, potentially leading to projects being abandoned or new projects being pushed back [6, 19, 20]. Thirdly, if EGS are to maximize their economic and environmental performance, there needs to be a use for their waste heat in addition to generating electricity [4]. However, EGS that are next to large heat consumers in densely populated areas also pose a higher seismic risk. Finally, despite the substantial uncertainties, ongoing and planned EGS require the use of good practice regarding induced seismicity assessment and management [21–25].

In order to inform timely assessment, management, and research on EGS induced seismicity, we present the results of an international expert elicitation.

### Methods

Expert elicitation techniques combine technical analyses with insights from behavioral science have proved advantageous for assessing new technologies and risks, when direct empirical evidence is scarce and significant epistemic uncertainties are involved [26–28]. Such expert elicitation can be used in combination with quantitative modeling, but they can also serve as independent characterizations of phenomenon of interest [26]. In either case, they do not replace basic science and modeller, but complement them from a different angle [27].

When experts are asked questions during the elicitation process, their answers may be biased due to cognitive heuristics, which every human is subject to. So-called overconfidence, when experts provide uncertainty bounds that are too narrow, is pervasive [26]. Availability heuristics lead to probability judgements, based on how easily an event comes to mind [29]. Anchoring and adjustment heuristics mean that experts could anchor on a number and would not be sufficiently flexible in adjusting it [29]. Group dynamics in workshops can lead to distorted judgements of both groups and individuals [30, 31]. Techniques are readily available to minimize such effects [31], but they have not been systematically used in seismicity-related expert elicitation.

We apply an elicitation technique [26, 32] to evaluate EGS induced seismicity hazard and risk and characterize uncertainty, using individual judgements from knowledgeable experts. We aim to provide independently-standing hazard and risk estimates and highlight expert agreements and disagreements. We use a hypothetical scenario of an EGS plant, its geological context, exposed population and structures, shedding light on the consent and diversity in judgements.

In our expert elicitation, we define induced seismicity as all earthquakes that are related to EGS activity, including those that primarily release tectonic stress and those that primarily release stress created by EGS [9]. In other literature, such earthquakes are sometimes called man-made, anthropogenic, triggered, or induced in a narrower sense. We therefore do not explicitly investigate the share of risk that would be attributable to natural and manmade causes [33] and follow the current practice [9] in seismology of labeling all EGS-related earthquakes as induced.

We then distinguish between induced seismicity hazard at the source, e.g. probability and magnitude of induced earthquakes, and induced seismicity risk, which includes soil amplification effects, damage to buildings and infrastructures, economic loss, injuries, and fatalities. Risk is a composite of hazard at the source, soil amplification effects, secondary hazards, exposure and vulnerability of the buildings, infrastructure, and population [21, 24].

In section 1 of the supplementary information (SI) available at stacks.iop.org/ERL/13/034004/mmedia we provide the full interview protocol. The individual elicitation interviews took about 2 h and started with an introduction to the study objectives, rules of participation, and a request for consent to participate. The key terminology and units were then defined in order to prevent ambiguities. The experts’ attention was drawn to cognitive heuristics in order to increase self-awareness of these effects. Afterwards, the elicitation itself was conducted in two parts: induced seismicity hazard, and risk. In both cases, experts were first asked to rank by importance a list of factors that may influence their estimates (before introducing the hypothetical scenario) in order to help them retrieve their mental models.

The experts were then given a hypothetical scenario of an EGS plant, its geological context, exposed population and structures. In the hazard section, the experts estimated lower bound, upper bound, and best-guess (most-likely) exceedance probabilities of $M \geq 3$ and $M \geq 5$ events as well as the largest observed magnitude at extremely low probability during reservoir stimulation and operation. The largest magnitude question refers to the deterministic type of hazard assessment. While making judgements, the experts were asked additional questions in order to iteratively refine the judgements and reduce overconfidence. As hazard judgements involve very low probabilities, two scales have been included to facilitate working with very low probabilities: exceedance probabilities and return periods (frequencies). The interviewer repeatedly converted the experts’ judgements during the interview in order to sense-check the results and help the interviewers take into account natural seismicity information. In the risk part, the experts drew a probability distribution of economic loss due to building damage. For injuries and fatalities, only lower bound, upper bound, and best-guess estimates were elicited.
At the end of the hazard and risk sections, the experts were again given the list of factors that may influence their estimates. They rated these factors once more, based on how much they contribute to uncertainty in the final outcome and whether future research could reduce this uncertainty. The elicitation closed with the demographic questions and a brief open-ended discussion.

As this elicitation aims at better characterizing the experts’ agreements and disagreements for a hypothetical EGS scenario rather than eliciting consensual probability distributions, we have invited a diverse group of experts, varying by country, sector, discipline, and experience [34, 35]. Following the standard procedures of expert selection [26, 32, 34], we have first identified and approached the key academic experts that worked over the last several years on EGS induced seismicity hazard and risk in different countries. In the interviews with them, we used snowball sampling and asked them to identify others who have the relevant expertise, especially in other countries, disciplines and in industry or public administration. We have continued our process until we conducted 14 interviews because this number is generally sufficient to reveal the diversity [26]. The experts received no compensation for participating in the interviews. As they were from different backgrounds, we have asked them to self-report what they believe is their level of knowledge with respect to specific questions. Such an approach to documenting the confidence of the experts is not without its limitations as compared to empirical control and validation of expert judgements, which are problematic too [28, 36]. We found self-reporting of confidence appropriate for this elicitation because we have not aimed for consensual probability distributions anyway. In order to shed light on the diversity [26] and discuss induced seismicity risk governance implications for policy and regulation, we have not aggregated the expert judgements.

The interviews were conducted by the same interviewer in order guarantee coherence among the experts in the interview procedure, given the information and questions posed. The interviews took place in spring 2016 via telephone (n = 6), conferencing (n = 5), and face to face (n = 3). The interviews were audio-recorded, transcribed, and audio records were destroyed to protect anonymity.

Results

Interviewed experts. We elicited the judgements of 14 experts from 12 organizations in six countries (see SI section 2). Nine experts work in science, five in consultancy, four in public administration, and two in industry. They have an average of 23 years of professional experience with natural seismicity hazard (SD = 15 years; MIN = 0 years for two experts, who reported ≥ 0 years expertise in induced seismicity hazard and/or risk), an average of 17 years with induced seismicity hazard (SD = 15 years; MIN = 0 years for one expert, who reported ≥ 0 years expertise in induced seismicity risk), and an average of 11 years with seismic risk (SD = 8 years; MIN = 0 years for two experts, who reported ≥ 0 years expertise in natural or induced seismicity hazard). We were able to engage more experts on hazard than risk, possibly because induced seismicity is a topic of key relevance for seismologists [9]. The experts reported their primary or secondary disciplines as seismology (n = 8), engineering geology, geotechnical engineering, mining engineering, structural engineering, structural geology (n = 2 each), earthquake engineering, geophysics, mineralogy, petroleum engineering, production engineering, rock physics, and seismic exploration (n = 1 each). They worked with induced seismicity related to EGS (n = 11), conventional oil and gas, shale oil and gas, wastewater injection (n = 10 each), other deep geothermal systems (n = 8), carbon capture and storage, hydroelectric dams (n = 4 each), mining (n = 3), other unconventional oil, and ice quakes (n = 1 each).

Induced seismicity hazard at the source. Our elicited subjective probabilities are conditional to the hypothetical scenario of an EGS plant and its geological context (see SI section 1). In brief, the scenario describes a plant with an 80 million m$^3$ reservoir at 5 km depth. The experts were asked to assume that during 6 d of reservoir stimulation 40 000 m$^3$ cumulative volume is injected at a maximum rate of 751 s$^{-1}$ and 30 MPa wellhead pressure. During 30 years of operation, the volume of 12 700 m$^3$ day$^{-3}$ (two wells at 73.51 s$^{-1}$) is injected at 15 MPa wellhead pressure. The plant is equipped with a conventional magnitude-based traffic light system, where earthquakes of M2.3 or higher do not allow the pumping to increase, and M2.9 events require stopping and bleeding the wells off. The EGS plant is located in a non-volcanic area with granite at the reservoir depth and no known critically prestressed extended faults. The annualized exceedance probabilities of natural M6 and M7 earthquakes within a 50 km diameter are 0.1% and 0.01% respectively. All magnitudes in this elicitation refer to generic magnitudes. The natural seismicity level as well as the limited information on existence of critically prestressed faults is compatible with the situation that EGS projects face in Switzerland.

We report expert judgements using annualized exceedance probabilities, i.e. probabilities during a year, of an event that is larger or equal to a predefined threshold. As shown in figure 1, during stimulation the expert best-guess (most likely) estimates of annualized exceedance probabilities for an M ≥ 3 event show an enormous variability within the experts’ opinions, ranging from 0.2%–95%. The lower and upper bounds are 0.08% and 99.8% respectively. Ten out of 13 experts rate their best-guess probability below or equal to 50%, but a significant disparity in judgements is observed. Specifically, Expert A assumes that an M ≥ 3 event is
very likely or virtually certain at 86.5%–99.8% annualized probability. In contrast, Expert L expects it only at a very low probability of 0.8%–6%. Exceedance probabilities for an M ≥ 5 event during stimulation are just as diverse. The best-guess annualized estimates range from 0.002%–2% with uncertainty bounds from 0%–20% across the experts. In fact, their judgements are so diverse that not even clusters of opinions can be observed.

After the experts were told that no M ≥ 2.3 earthquakes occurred during the stimulation, their best-guess annualized exceedance probabilities during a 30 year EGS operation range from 0.2%–100% for M ≥ 3 and 0.003%–3% for an M ≥ 5 event. Uncertainty bounds vary from 0.02%–100% for M ≥ 3 and 0%–18% for an M ≥ 5 event. Ten out of 13 experts think that an M ≥ 3 event has the best-guess probability of 1% or higher. Seven out of 13 experts rate the probability of an M ≥ 5 event to be 0.1% or higher, but less than 10%.

The elicitation was also repeated for a scenario, where the experts were asked to assume that an M = 2.3 event occurred during the stimulation and triggered the yellow light of the traffic light system (continue pumping without increase) and later an M = 2.9 triggered the red light and the pumping was stopped. The results annualized exceedance probabilities during a 30 year EGS operation after this complicated stimulation are reported in SI section 4.

At an extremely low annualized probability of 0.0002% during the stimulation, 11 of 13 experts believe that the largest events between M5 and M6 could be observed. Two experts judge the maximum observed magnitude as M7, but both have made a remark that such a high-magnitude event would be triggered, i.e. primarily release tectonic stress. During operation, the maximum observed magnitude at 0.01% annualized probability is estimated between M5 and M6 by ten out of 13 experts and as M7 by another three experts.

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**Figure 1.** Experts’ annualized exceedance probabilities of induced M ≥ 3 and M ≥ 5 events. These estimates are conditional to the given scenario of an EGS plant and its geological context (see SI section 1). For M ≥ 3 (red circles) and M ≥ 5 (blue circles), experts provide their lower bound, upper bound and best-guess estimates. The annualized probability values for reservoir stimulation are identical to probability values during 6 d of stimulation; the probability values for 30 year operation are annualized using the Poisson law. The uncertainty is shown as a solid line for experts that self-report their knowledge as ‘I am an expert,’ as dotted lines if they self-report as ‘I know a lot,’ and light shaded lines if they state ‘I have some limited knowledge’ (SI section 3 provides the individual values). Asterisks (*) mark the experts that make judgements using return periods as the primary metric; the rest of the experts provide exceedance probabilities directly. We have also asked the experts to estimate the maximum observed magnitude (M) that would correspond to a 0.0002% annualized probability for stimulation and to a 0.01% annualized probability for operation. The resulting M estimates are shown in the horizontal dashed line and are reported just below or above it.
Economic loss, injuries, and fatalities. We have elicited estimates of economic loss, injuries, and fatalities that are also conditional to the hypothetical scenario of exposed population and structures (see SI section 1). In brief, the EGS plant is assumed to be in a town in Western Europe or the USA with 10 000 inhabitants, 3000 buildings, minor industrial activity, and without infrastructure of high importance. Granite rock dominates under 5 m of soil cover, leading to low soil amplification. The experts were asked to consider the real damage, not the damage to insured property or submitted insurance claims.

As shown in figure 2, all nine experts that provided judgements on economic loss think that in the case of an M = 3 induced event at 5 km depth beneath the town, no economic loss occurs. The estimates of the upper bound range from 100 000 USD to 20 million USD. With 50% probability, 500 000 USD loss is not exceeded in the view of seven out of nine experts. In the case of an M = 5 event, the economic loss that is sure to occur is from 0–10 million USD across the experts. The upper bound varies from 10 million USD to 500 million USD. Eight out of nine experts believe that at 50% probability the loss is contained within 50 million USD.

As depicted in figure 3, in the case of an M = 3 induced event at 5 km depth, the expert best-guess (most likely) number of injuries varies from zero to five injuries with uncertainty bounds from 0–100 injuries. Seven out of ten experts judge their best-guess number of injuries as zero. The best-guess number of fatalities for an M = 3 event is unanimously seen as zero. For the upper bound, four out of nine experts think that up to five fatalities could happen in an extreme case, when
Table 1. Experts’ ratings for different factors that influence induced seismicity hazard and risk in general, as well as the contribution of these factors to uncertainty. We also show the potential to reduce this uncertainty as a function of future research and data collection. Only the judgements of experts that have self-reported their knowledge as ‘I am an expert’ or ‘I know a lot’ are reported (n = 13 on hazard; n = 9 on risk; SI section 3 provides the individual values of self-reported knowledge). In SI section 5 we list additional factors, suggested by some experts.

<table>
<thead>
<tr>
<th>Influence on the final hazard or risk outcome</th>
<th>Contribution to uncertainty</th>
<th>Uncertainty reduction with future research and data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not at all</td>
<td>Very high</td>
<td>Not at all</td>
</tr>
<tr>
<td>Distance to extended faults</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cumulative injected volume</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Depth of the reservoir</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Wellhead pressure</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Injection rate</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Tectonic stress regime</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Natural seismicity</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Type of injection fluid</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Local site amplification</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Exposed population</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Quality of construction</td>
<td>0</td>
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<tr>
<td>Exposed critical infrastructure</td>
<td>0</td>
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<tr>
<td>Exposed building stock</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Value of exposed property</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Earthquake preparedness</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Secondary hazards</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

* given good engineering design  ** exposure and vulnerability

simple structures collapse or heavy objects fall. For an M = 5 event at 5 km depth, the best-guess estimates of injuries range from 1–200 with eight out of 11 experts foreseeing less than 50 injuries. The best-guess number of fatalities spans from zero to five and four out of ten experts estimate them as zero and another three experts as one fatality.

Influencing factors, uncertainties, and future research. We asked the experts to rank eight factors that influence induced seismicity hazard and eight other factors that influence risk in terms of their importance, contribution to uncertainty, and potential to reduce the uncertainty with future research and data collection (table 1). The list of factors was compiled from the literature review on induced seismicity hazard [9, 24, 37–39] and on risk [21, 24, 40]. The experts’ judgements here were elicited for induced seismicity more generally and not for the given hypothetical scenario. For induced seismicity hazard, the distance of EGS plants to critically pre-stressed extended faults is judged as having the highest importance. Distance to faults is also rated as having the highest influence on uncertainty. The experts, however, are split on whether this uncertainty could be realistically reduced through future research. EGS design and operational factors, including cumulative injected volume, depth of the reservoir, wellhead pressure, and injection rate, are also perceived to be important and follow the distance to faults in terms of influence on the level of induced seismicity hazard. The contribution of these factors to uncertainty is considered as medium to low by the majority of experts with further splits apparent on the views about the gains of future research. Importance and uncertainty contribution of the natural factors, such as the tectonic stress regime and especially natural seismicity, are ranked the most diversely, hinting at disagreement in the community. The experts believe that future research on the role of natural seismicity has a medium to very high potential to reduce uncertainty, but a comparatively low potential to reduce uncertainty about the role of tectonic stress regimes. The fluid type is rated as the least important overall to the final outcome and uncertainty.

We have also found that there were divided opinions regarding traffic light systems. Some experts had in principle confidence in them, arguing that the traffic light system in our hypothetical scenario is outdated compared to the best systems today, or that the magnitude thresholds are too low. Other experts have expressed cautiousness due to post-shut-in response and have not lowered their probability judgements in figure 1 due to the traffic light system.

When a hazard at the source is known, the experts consider local site amplification to be of the highest importance to the risk outcome (in general, not for the given hypothetical scenario). The contribution of local site amplification to uncertainty and future research potential are, however, judged from low to very high. The size of the exposed population, quality of construction (given good building codes and engineering design), value per unit of exposed property, presence and seismic characteristics of critical infrastructures and building stock are all ranked as having a high influence by the majority of experts. The contribution of these factors to uncertainty and future research gains are also judged very diversely. The judgement of the importance of the population’s earthquake preparedness ranges from very low to high. Most experts think that preparedness, especially without physical measures, adds relatively little to uncertainty. Similar judgements are made on the role of secondary hazards, such as landslides or fires.
In SI section 6 we list key future research questions for induced seismicity hazard and risk assessment and management suggested by the experts.

Discussion

Our elicited subjective probabilities of induced seismicity in the future EGS plant scenario are broadly consistent with the observed seismicity. Our plant has comparatively large injected volumes during stimulation (40 000 m$^3$ in 6 d) and operation (12 700 m$^3$ d$^{-3}$) as well as high wellhead pressure of 15 MPa. In the Basel EGS project with 11 500 m$^3$ during stimulation, events of M$≥$2.5, M$≥$2.7, and M$≥$3.4 have been recorded [17]. In the EGS project in Soultz-sous-Forêts with 37 000 m$^3$ during stimulation in the GPK3 well, seismicity of up to M2.9 has occurred [41]. In The Geysers deep geothermal site in California with 95 000 m$^3$ injection and no stimulation performed, multiple M$≥$3 events and several M$≥$4 events are observed every year and the largest observed event has been M4.6 [4, 5]. In fact, The Geysers is the only deep geothermal site that has been operating for several decades now, like in the scenario that our experts reviewed. Other EGS projects have exhibited microseismicity only [12, 15]. Our experts also rate M$≥$3 events as likely, but not necessarily a given. With the exception of M5.1 in the deep non-EGS Salton Sea geothermal field in California [7], no M$≥$5 induced events have been observed in EGS plants. As such events are also seen very rarely by our experts, it is not surprising that they have not occurred in the handful of EGS sites that exist today. As our scenario assumes that tectonic M7 events can happen, many of the experts interviewed agree with the recent evidence that the maximum magnitude is bound by tectonics [42].

We observe a vast spread in probability estimates. Although probabilistic and logic tree-based hazard assessments also cover a vast spectrum of hazard outcomes, our elicitation reveals even wider uncertainties (e.g. compared with [43]). The experts stretch the probability distributions towards low-probability higher-magnitude events in particular. Some experts also envision cases where M$≥$3 events are very rare—a view that is consistent with empirical evidence [15], but may be underrepresented in some of the current assessments.

Our elicited estimates of economic loss, injuries, and fatalities are also consistent with the existing evidence. The M3.4 event at less than 5 km depth in the Basel EGS led to 7.5 million USD of damage claims [44]. The M3.5 event in the hydrothermal project in the Swiss city of St. Gallen caused almost no damage [44]. Both cities are more populous than our scenario. The Soultz-sous-Forêts project in France with up to an M2.9 event has faced only minor claims for broken mirrors [45]. None of these and other EGS projects have led to injuries or fatalities. The best understanding of economic loss, injuries, and fatalities at higher magnitudes exists for tectonic earthquakes that are also deeper and longer. Examples of shallow earthquakes that could be characteristic to induced seismicity are: M5.6 in Prague, Oklahoma, with two injuries, 14 houses destroyed and many damaged [46], and M$≥$3.1 at 3 km depth in Lorca, Spain, with nine fatalities, hundreds injured, and significant property damage [47]. The elicited judgments are thus consistent with current evidence, but again stretch the probability distributions towards low-probability higher-consequence events that might have not yet happened.

Research on existing faults is a high-risk high-gain direction: promising, but could be challenging to deliver. Research on EGS design and operational characteristics, e.g. cumulative volume, wellhead pressure, injection rate, and reservoir depth, is important too, but secondary to reducing the uncertainties. Although operational parameters are also part of traffic light systems, not all experts currently share confidence in effectiveness of these systems. Better understanding of the role of natural seismicity could resolve some uncertainties and expert disagreements. Future research on ground motion prediction equations and the seismic response of exposed structures are most valuable for assessing induced seismicity risk.

Conclusions

Using a hypothetical future EGS plant, its geological context, exposed population and structures, we have revealed a vast diversity and some disagreements among international experts about quantitative estimates of EGS induced seismicity hazard and risk. Not only quantitative probability estimates diverge, but so do expert mental models on what influences induced seismicity and how it could be better assessed and managed. Such diversity is not unusual when assessing the risks of new technologies [26, 48]. In fact, it is exactly in these cases that a structured expert elicitation that does not immediately aim for consensual opinion, but systematically opens up to the diversity of arguments, is key [26, 48, 49]. Thus, when our findings are interpreted, ‘it is always important to remember that science is not a matter of majority vote. Sometimes it is the minority outlier who ultimately turns out to have been correct’ (page 7183, 26).

This diversity in quantitative expert judgements and underlying mental models carries significant implications for the EGS induced seismicity risk governance process. For example, when expert elicitations are set up, we recommend that this diversity is always transparently documented in individual expert interviews, instead of proceeding directly to consensual expert answers. Elicitation techniques that emphasize minimization of cognitive and behavioral fallacies are key here for gathering good quality judgements. Only after such individual elicitations, aggregation of expert
judgements into consensual probability distributions should be attempted, possibly by also calibrating and weighing expert opinions [26, 36, 50].

When expert panels are set up for a specific EGS project, small panels should be avoided because it can happen that only some expert viewpoints are represented. It is therefore important not to cherry-pick, intentionally or unintentionally, experts with particular views. Diversity is best revealed by varying disciplinary backgrounds, experiences, and countries of experts. As convening large expert panels can come with significant costs and difficulties, the results of this expert elicitation can be at least used as a benchmark for which types of views need to be represented in smaller panels.

As these expert judgements are influenced by the experts’ individual experiences with induced seismicity hazard and risk assessments, the revealed diversity indicates that the induced seismicity field is still at the stage where multi-organization multi-model assessments of the EGS plants are adequate. As the emphasis on the diversity of expert judgements will be demonstrated through expert elicitation, expert panels, and hazard and risk assessments, wide uncertainties and expert disagreements will be inevitably revealed. Future work is thus needed on decision making and regulatory practices for induced seismicity in face of this diversity. Thoughtful ways of communicating this expert diversity to the public should also be explored [51].

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