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RESEARCH

Pitfalls in the management of induced seismicity

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Abstract Induced seismicity poses a potential threat to the viability of many energy-related projects involving injection or extraction of fluids. Important advances have been made in terms of protocols to manage induced seismicity in such projects, including guidelines for seismic monitoring and communications prior to operations and following the occurrence of seismic events. However, for such protocols to guarantee successful management of induced seismicity it may be necessary to include additional elements, that have not been explicitly addressed, in the mitigation strategy. These elements, identified from case histories in which induced earthquakes have led to interruption or suspension of operations, can be broadly grouped into two categories: quantification of the seismic risk due to induced earthquakes and effective and balanced risk-based regulation. While clear and effective communication of the risk to the public is often highlighted as a key factor, this requires that the risk is first correctly quantified, and secondly that the regulatory body takes at least partial responsibility for explaining the risk and providing assurance that it is acceptably low. Such action by the regulatory authority would be premised on the basis of the operator demonstrating compliance with risk-based targets, as is done in the nuclear industry. Potential pitfalls in the quantification of the physical risk from induced earthquakes include exaggeration of the impact of small-magnitude events, overly conservative values of the upper bound magnitudes, modelling choices that lead to biased estimates of the hazard due to induced seismicity relative to that from natural earthquakes, and the use of inappropriate risk metrics.

Keywords Induced seismicity · Protocols for induced seismicity · Seismic risk · Regulation · Risk quantification · Risk mitigation

1 Introduction

Induced seismicity poses a threat to many energy-related technologies that involve injection or extraction of fluids. Induced seismicity has also long been observed following the impounding of deep reservoirs (leading to fluid pressures increasing in the underlying rocks) and due to mining operations, but in recent years the focus has been very much on induced seismicity caused by the injection or extraction of fluids. Several energy-related operations have been diminished or suspended as a consequence of earthquakes caused by the changes in stress or pressure due to the fluid injection or extraction. As new technologies are developed, such as carbon capture and storage (CCS), which could involve very large injection volumes

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(albeit with different characteristics), the effective management of potential induced seismicity may be critical to their successful implementation.

To facilitate the effective management of induced seismicity in energy technologies, several proposals have been put forward for protocols designed to quantify the risk associated with potential induced earthquakes and to manage this risk to remain within tolerable limits (e.g., Myer and Daley 2011; Majer et al. 2012; White and Foxall 2014; Trutnevyte and Wiemer 2017; Templeton et al. 2023; Zhou et al. 2024; Grigoratos et al. 2025a). These proposals are all valuable contributions to the objective of successfully managing induced seismicity, although it can be noted that the focus is often very much on avoiding unacceptable levels of induced earthquake activity whereas truly successful management of induced seismicity would also ensure the continuation of the operations. Despite the obvious and valuable benefits of using the recommended protocols, the closure of several energy-related operations due to induced seismicity highlights that they may not guarantee a successful outcome (and there may also be cases where there is no way to avoid unacceptably large earthquakes except by abandoning the project). In some cases, the cessation of operations can be related to pitfalls that were not foreseen in the management protocols for handling induced earthquakes. These pitfalls may be encountered in the details of implementing the protocol (in particular, in quantifying the risk due to induced seismicity) or externally within the social and regulatory environments in which the project is being executed. The purpose of this article is in no way intended as a criticism of existing protocols, since an overarching scheme to manage the potential impact of induced earthquakes is vital and considerable work has been undertaken to develop the proposals that have been published. The focus of this article is complementary to the proposed protocols, having the express purpose of helping to identify where things can go wrong.

The reader may ask why the title of the paper does not end with a phrase such as "*and how they can be avoided*". The scope is limited to the identification of the pitfalls since solutions are often likely to be region- and/or application-specific, and operators, regulators and their technical advisers will be able to devise appropriate remedies. Some elements of addressing the potential pitfalls, however, could require significant legal and organisational adjustments. In some instances the article offers suggestions, but for many of the pitfalls, simple awareness of their existence may be sufficient to mitigate their impact.

Section 2 presents a brief review of some case histories where induced seismicity has interrupted or ended energy-related operations. The review focuses on the causes for the interruptions, especially highlighting those cases where the response does not seem to be justified by the occurrence of small earthquakes. These cases highlight several of the pitfalls that can lead to failure in the management of induced seismicity, even when following a well-formulated protocol. In Sect. 3, the magnitudes of induced earthquakes are discussed, with particular reference to how magnitude can influence both risk perception and risk quantification, addressing the influence of exaggerating the impact of small earthquakes and of issuing very large estimates of the largest possible induced event. Section 4 then addresses the many pitfalls that can lead to overestimation of the hazard and risk due to induced earthquakes, highlighting especially how the impact of induced earthquakes can be exaggerated relative to that of natural seismicity. Section 5 then addresses the critical question of regulation, highlighting the model of the nuclear industry as a framework from which lessons could be drawn to address some of the shortcomings in the regulation of induced earthquakes to date, while acknowledging the many challenges that stand in the way of a direct emulation of nuclear practice. The paper then closes with a brief statement of the key conclusions and a few recommendations.

2 Failures in the management of induced seismicity

The experience database of energy-related projects that have been disrupted by the occurrence of induced earthquakes provides insight into the factors that led to the decision to curtail or close the operations. The purpose of such a review is to identify whether those factors are addressed in strategies for the management of induced seismicity and, if not, to highlight these as pitfalls that could affect future projects. The review is not comprehensive both because of space limitations and by being limited to those cases for which detailed information is openly available. Nonetheless,

the examples covered are sufficient to highlight some of the most important pitfalls in managing induced seismicity.

The dramatic rise in earthquake activity in the US state of Oklahoma, historically a region of very low seismicity, since (Schultz, et al., 2007) has been well documented and clearly recognised as being primarily due to massive injections of wastewater from hydrocarbon extraction (Walsh and Zoback 2015; Grigoratos et al. 2025c). The induced (or triggered) events have included five earthquakes of **M** > 5, the largest being the 2011 Prague (**M** 5.7) and the 2016 Pawnee (**M** 5.8) events, both of which caused building damage. In response to the seismicity, from 2015 the Oklahoma Corporation Commission, the *de facto* regulator, imposed restrictions through a series of directives aimed at reducing the induced seismicity, both through significant reductions in the injected volumes of wastewater as well as through injecting into shallower formations that are farther from the crystalline basement (Skoumal et al. 2024). Similar regulatory measures were taken by the Kansas Corporation Commission in the neighbouring state, and these actions have resulted in an appreciable reduction in the levels of induced seismicity (Skoumal et al. 2024). In Texas, the Texas Railroad Commission has targeted individual areas and operators rather than imposing state-wide restrictions as in Oklahoma, although the operators have not always complied with the regulatory instructions and significant earthquakes (M 4.5–5) have still occurred. In such circumstances, with sustained and massive injections into seismically sensitive formations over a large area, there is probably no other feasible route to manage the induced seismicity other than reduction of injected volumes and depths. Unless alternative methods of disposing of the coproduced saltwater (such as treatment and release into rivers) are available, which could be very difficult at large scale, some reduction of the hydrocarbon extraction was inevitable.

A case history that can be classified as a clear failure, both in terms of not controlling the induced seismicity and not ensuring continued operation, was the November 2017 **M** 5.5 earthquake triggered by the Pohang enhanced geothermal project in South Korea, which resulted in widespread damage and 135 injuries (Lee et al. 2019). The earthquake is understood to have been triggered by increased pore pressures on a previously unknown west-dipping fault that was intersected by the injection well at a depth of about 4 km. This fault was favourably oriented for seismic slip within the regional tectonic stress regime. The **M** 5.5 earthquake occurred almost two months after the last fluid injections, but several indicators of the potential risk were available long before this time, including major mud losses during drilling of the injection borehole, assumed to have been associated with the fracture zone around the causative fault, and the location of smaller induced events associated with stimulations that began in early 2016 (Ellsworth et al. 2019). The focal mechanism of events that occurred prior to the main shock were consistent with the orientation of the causative fault plane. It may have been possible to detect this fault plane with geophysical investigations prior to the operations and with improved seismic monitoring during the injections. Magnetotelluric measurements at the Pohang site had revealed west-dipping features that were interpreted as fracture zones and potential geothermal targets, but the spatial resolution of these measurements was insufficient to reveal the presence of the fault plane (Ellsworth et al. 2019). In their analysis of the lessons learned from Pohang, Ellsworth et al. (2019) also highlight the fact that the project was effectively self-governing, with neither regulatory scrutiny nor independent peer review. Moreover, they also note that several national and foreign institutions were involved in the monitoring and analysis of the seismicity data, which did not favour rapid dissemination and integration of the available information.

The remainder of this section focuses on case histories that can be classified as failures to effectively manage induced seismicity in the sense that in each case the occurrence of induced earthquakes, with limited impact, led to closure of the projects. Others may take the view that the decisions were justifiably cautious, but my informed view is that the closures could have been avoided and that they have set unhelpful precedents rather than providing useful models for the management of induced seismicity. Most of these case histories are discussed in greater detail in Bommer (2022), with extensive source references, but herein focus is on the key features contributing to the failure of each project. The four case histories are discussed in order of increasing magnitude of the largest induced event.

In the UK, hydraulic fracturing for shale gas produced an earthquake of M_L 2.3 in April 2011, leading to suspension of operations. The injections were

resumed two months later, until an event of M_L 1.5 occurred, prompting the operator to suspend the operations again after discussions with the Department of Energy and Climate Change (DECC). DECC commissioned a scientific study of the project, which concluded that continued operations could result in an induced event of $M_L > 3$, proposing the implementation of a Traffic Light Scheme (TLS) with a red-light threshold at M_L 1.7. DECC then commissioned three UK scientists to conduct a review of this study, as a result of which an alternative TLS was proposed, with yellow- and red-light thresholds at M_L 0.0 and M_L 0.5. DECC adopted this recommendation. It then fell to the regulatory body, the Oil and Gas Authority (OGA) to implement when hydraulic fracturing in the UK recommenced in late 2018. Unsurprisingly, the operations were frequently stopped for at least 18 h following red-light triggers, leading to frequent news reports of induced earthquakes that were not even felt by anybody. Following an earthquake of M_L 2.9, the government ordered a moratorium on fracking. The OGA subsequently commissioned four studies examining different elements of the risk posed by continuation of such operations. While none of the studies concluded that the risk was unacceptable, the government announced, on the same day that the OGA studies were published, that the moratorium was to become permanent. In the UK fracking is very unpopular, at least as portrayed by the press, and there is little doubt that the government decision and its timing were motivated politically. Even though it became widely recognised (privately by some officials at the OGA and publicly by one of the authors of the DECC review) that the M_L 0.5 red-light threshold was absurdly low, there was no appetite to be seen as being responsible for raising it and thus facilitating the continued application of this technology. Schultz et al. (2023) have since proposed alternative TLS thresholds for the fracking in the UK. It is not known if continued operations would have induced unacceptably large earthquakes, but the fact is that fracking was permanently banned in the UK due to earthquakes that were felt by few people and for which there is no substantiated evidence these caused building damage.

Coincidentally, it was also a magnitude 2.9 event that ultimately led to abandonment of the Soultz-sous-Forêts enhanced geothermal system (EGS) project in Alsace, France. Begun in 1987, this was a research project funded by the European Commission that made several important contributions to the technology of fracturing hot dry rocks to create a geothermal reservoir. However, the injections at a depth greater than 4 km led to a number of earthquakes that were felt by the local population. The project operators were unable to reassure the local population, who had felt some of the shaking episodes, and the impasse led to greatly reduced injection rates and ultimately to the project being closed. Although the local population was unsettled by the induced earthquakes, the shaking did not cause any damage: insurance claims were submitted by some local residents, but these were declined following inspections (Majer et al. 2007).

The role of insurance claims was markedly distinct following induced earthquakes caused by another EGS project in Basel, Switzerland, also injecting at depths of 4–5 km. The project was operated by GeoPower Basel on behalf of a consortium in which the majority shareholder was the city of Basel. The project appointed a rather loosely run Scientific Board to offer technical advice and adopted a TLS. Six days into the injections, a yellow-light event led to reductions in injection pressures but an M_L 2.6 earthquake in December 2006 exceeded the red light and led to immediate cessation of injections. A trailing event of M_L 3.4 (**M** 3.2) occurred a few hours later, which eventually led to the permanent closure of the project. The project lead from GeoPower Basel, Markus Häring, was escorted by police to a meeting with the City of Basel, who effectively placed all the responsibility on his shoulders (he was even put on trial some time afterwards, although the judge rapidly dismissed the ridiculous charges). The most important feature of the response to the largest earthquake was the active promotion via a radio station for people to submit damage claims and the insistence by the City of Basel that these claims be settled without on-site inspection. Despite there being no evidence for damage exceeding DS1 in the EMS-98 intensity scale (i.e., hairline cracks in walls; Grünthal 1998), which is encountered in most masonry buildings within a few years of construction, the total insurance pay-out reached US$ 9 million. The occurrence of a slightly larger earthquake generating slightly higher ground motions in another Swiss geothermal project in July 2013, which did not lead to any reports of damage or insurance claims, cast

further doubt on the extent to which the insurance claims in Basel reflected damage caused by ground shaking.

The closure of the very large Groningen gas field in the Netherlands in October 2024 probably represents the most spectacular failure in the management of induced seismicity, for three key reasons. Firstly, cutting off gas supply from the Groningen field has had serious consequences for the Netherlands in terms of lost revenue for the state and the need to create new supplies of low-calorific gas (with a high nitrogen content) and has possibly also had broader geopolitical implications (e.g., van der Beubel 2022). Secondly, the closure was imposed by the Dutch Ministry of Economic Affairs and Climate Policy (EZK), on the recommendation of the regulatory body, SodM (State Supervision of Mines), despite an unprecedented investment by the field operator, NAM, in data acquisition and the development of advanced risk models that would have allowed the design of optimal mitigation strategies comprising both production changes and the strengthening of the weakest buildings (van Elk et al. 2019). This is important to stress because it offers little encouragement to stakeholders in other situations to seek to build robust risk models and to seek rational risk management strategies if these have little or no impact on decision-making. Finally, gas production has been permanently suspended in response to earthquakes of magnitudes that would not be expected to cause any significant damage. An M_L 3.5 event in 2006 caused no major controversy, but following the 2012 Huizinge earthquake that was only fractionally larger (M_L 3.6, **M** 3.5), a crisis unfolded that culminated in the final decision to stop production. There were M_L 3.4 earthquakes in 2018 and 2019, but the impact of all the earthquakes was limited, not least because the levels of ground shaking generated by these events were rather low: abundant accelerograph recordings have shown that the amplitudes are substantially lower than those from earthquakes of comparable magnitude in California (Bommer et al. 2024) and also lower than those recorded in another gas field in the northern Netherlands (Bommer et al. 2022). The energy content of the motions, as represented by the Arias intensity, is also low, as can be observed from the residuals of the Groningen recordings with respect to a California-based predictive model (Fig. 1). Building damage in the region, especially where consistent with the upper end of DS2 and greater on the EMS-98 scale, is primarily due to differential settlements in soft soils, exacerbated by drought in recent years, a process that causes building damage in many parts of the Netherlands (e.g., Peduto et al. 2019). Nonetheless,

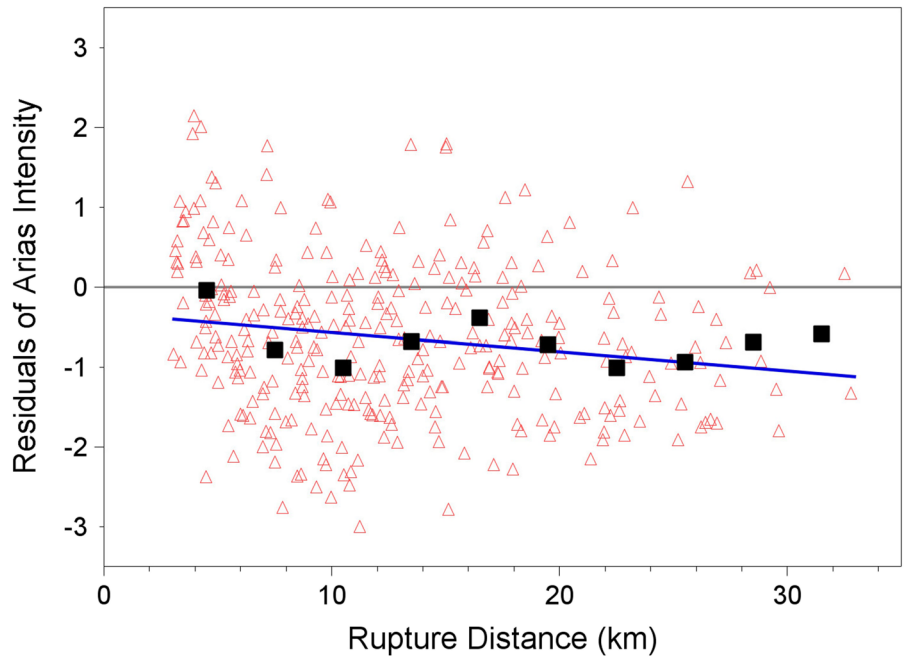


Fig. 1 Natural logarithmic residuals of Arias intensity from recordings of Groningen earthquakes with $\mathbf{M} \geq 3$ relative to the model of Campbell and Bozorgnia (2019) against distance. The straight line is the best fit through the mean residual in each 3 km distance bin, represented by the black squares. The average residual over the distance range of the data is −0.686, implying overestimation by a factor of ~ 2

enormous claims have been submitted for building damage attributed to earthquake shaking (see Sect. 4.6).

Unsurprisingly, given the small magnitudes and lower-than-average ground motions of the Groningen earthquakes, the justification for the field closure given by SodM alluded to the potential impact of larger earthquakes in the field if production continued. Whether earthquakes appreciably larger than those that have occurred to date would be physically feasible in Groningen is discussed in Sect. 3.2. There is no doubt that the initial denial of a link between gas production and the seismicity by the field operator (Bommer 2022) had a very negative and long-lasting impact on public trust, but the regulatory decision should have been based on quantified risk assessment rather than the sentiments of the exposed population. In view of the limited impact of the earthquakes that did occur and the very low probability of appreciably larger events occurring, the decision to close the gas field was questionable, especially when taking into account the far-reaching consequences of the decision.

The Castor project was intended to provide gas storage in a depleted oil reservoir located 20 km offshore from NE Spain. Injections began in June 2013 and were intensified in September, leading to many induced earthquakes, the largest of which had a magnitude of 2.7. Injection rates were reduced and then terminated on 17 September, with more intense seismicity then occurring between two and three weeks later, the largest event reaching **M** 4.2. The impact of the earthquakes was understandably limited, with the official seismological service (IGN) reporting maximum EMS-98 intensities of III (Weak. Felt by a few people indoors. No damage.) at coastal locations. The project was regulated by the General Directorate of Energy Policy and Mines (DGPEM), which had originally approved the project including geomechanical studies undertaken on behalf of the operating company, ESCAL. These studies were reviewed by the Spanish geological service, IGME, which did not raise concerns about induced seismicity. Following the trailing event of **M** 4.2 on 1st October 2013, DGPEM ordered the suspension of gas injections. This suspension was later made permanent following the publication of a report by US academics that assigned the earthquakes to a structure referred to as the Amposta fault. The same report stated that continued gas injections could trigger an earthquake as large as **M** 6.8 on this fault. There are doubts as to whether the Castor fault is a seismogenic structure, being a shallow listric structure more likely related to salt tectonics. Many papers have been published in the literature analysing and debating the mechanism of the earthquakes, including five cited in Bommer (2022) plus those by Vilarrasa et al. (2022) and Cesca et al. (2022), and the one point on which all the authors agree is that the earthquakes did not occur on the Amposta fault. The decision to permanently close the project has never been revisited, even after the lead author of the US study – which was never published in a peer-reviewed journal – appeared as a witness in criminal proceedings brought against two technical directors from ESCAL (in which they were both fully acquitted) and made the clear statement that the Amposta fault did not cause the seismic activity associated with Castor. This is a remarkable case in the sense that the earthquakes that did occur had no effect at all on the built environment and the threat used to justify the closure of the project was a hypothetical triggered earthquake on a geological structure, the dimensions of which were likely overestimated and for which there was no evidence of being seismogenic.

In summary, at least three common characteristics can be identified in these case histories. Firstly, exaggeration of the impact of small earthquakes, and secondly the prediction of potentially much larger earthquakes with severe consequences. The third factor is lack of a clear regulatory framework, which therefore left no clear mechanism for balancing the interests and concerns of different stakeholder groups, including broader societal benefits of the projects that were cancelled.

3 The magnitude of the problem

Magnitude is a convenient and universally recognised measure of earthquake size, but by virtue of being a logarithmic scale it can serve to conceal the real differences between earthquakes of different magnitude. This has implications when dealing with induced seismicity for two simple reasons. At the lower end, it can obscure just how small the earthquakes under

discussion may be: if, for example, a minimum threshold for damaging earthquakes at a given location were determined, an event 0.4 units below this threshold may seem uncomfortably close to the limits of acceptable, but in reality such an event would only be releasing one quarter of the seismic energy required to meet that threshold. At the upper end, what can be lost is the implications for how much the source dimensions need to increase the magnitude. Assume, for example, that it is proposed that fluid injections could trigger an earthquake of magnitude 6.0, it might be proposed to add a margin by assigning an upper magnitude of 6.3. However, according to the scaling relationships of Wells and Coppersmith (1994), this would require a fault rupture that would need to be increased by more than 80 km^2 despite the small increment in magnitude.

3.1 Exaggerating the impact of small earthquakes

The impact of an earthquake on the built environment depends not only on magnitude but also depth, distance, site conditions and the seismic fragility of the exposure. However, some general rules-of-thumb can be established in terms of the smallest earthquakes capable of causing damage, which indeed is the rationale behind the specification of the minimum magnitude, M_{min}, used in PSHA (Bommer and Crowley 2017). In the field of induced seismicity, defining this threshold magnitude can be complicated when insurance/compensation claims lead to consideration of DS1 (i.e., hairline cracks) that are ubiquitous and generally outside the realm of interest of earthquake engineering (since they routinely result from settlement, thermal effects, etc.); it is acknowledged, however, that such cracks may be noticed for the first time following an episode of earthquake shaking. For damage levels that exceed DS1, however, empirical evidence can provide insight into the smallest magnitudes capable of harming different types of structures. For the purpose of obtaining such insights, studies have been undertaken to determine at what magnitude levels earthquakes become potentially damaging. Green and Bommer (2019) established that liquefaction does not occur in soils capable of supporting construction during earthquakes of magnitude smaller than **M** 5. Nievas et al. (2020a) compiled a global database of earthquakes with magnitudes between 4 and 5.5 that have been reported to cause damage. In aiming for breadth of coverage – which facilitated a follow-up statistical study (Nievas et al. 2020b) – the primary sources were taken at face value. As a result, the paper is frequently cited to justify consideration of relatively small-magnitude earthquakes because of their potential risk impact. However, there are very few well substantiated cases of structural damage the specification of magnitude smaller than 4.5 and, as pointed out in Bommer (2022), events in this range that are reported to have caused fatalities are associated with mine collapses or landslides rather than building collapses. For older events, the lack of substantial proof for the reported damage remains a source of ambiguity, but for events in the last two decades, during which time smartphone ownership has become widespread and even the most banal experiences are recorded on social media, the absence of evidence can reasonably be interpreted as evidence of absence.

Anecdotal reports of damage due to small-magnitude events are frequently encountered, but their investigation rarely leads to substantiation. A recent example is shown in Fig. 2, which is taken from a paper exploring the lessons learned from a quarter century of *Did You Feel It?* data in California. From the perspective of the current discussion, the feature that jumps out is the data point highlighted by an arrow, which implies shaking with a Modified Mercalli intensity of VIII caused by an earthquake of magnitude 3.1. An MMI of VIII implies "*slight to moderate damage in well-built ordinary structures and considerable damage in poorly built or badly designed structures*". The data point corresponds to an aftershock of an M 5.1 earthquake near Brea, California, on 29 March 2014. Since the aftershock occurred on the same day, the most likely explanation is that the reporting of the felt effects of the mainshock was erroneously attributed to the much smaller aftershock (J.K. Saunders, *personal communication*, 2025).

To the best of my knowledge, there is little or no substantiated evidence (beyond hairline cracks that will often be of indeterminate origin) of shaking damage to properly constructed buildings due to earthquakes smaller than about magnitude 4.5. An assertion that is often made is that nonetheless induced earthquakes of small magnitude can be damaging by virtue of their shallower depths leading to stronger surface motions. This argument does not stand up,

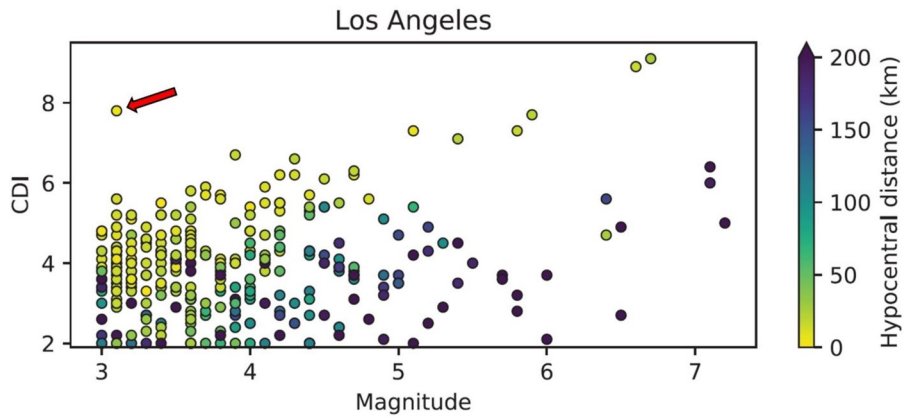


Fig. 2 Community decimal intensities (CDI) in Los Angeles as a function of magnitude and hypocentral distance (modified from Chaffeur et al. 2025). The arrow highlights the data point discussed in the text

however, for two key reasons, the first being that the smaller Brune stress parameter for shallow events, which largely offsets the effects of the shorter travel paths (e.g., Hough 2014; Atkinson et al. 2018). Abercrombie et al. (2021) have noted that the apparent depth dependence of stress drop is not seen when the variation of propagation velocity with depth is taken into account, which means that the lower motions may be related to path rather than source effects, but in most ground-motion modelling the effect can be captured through a depth-dependent stress parameter. The second reason is that whether or not motions are damaging does not depend exclusively on the amplitude of the motion – the specific purpose of M_{min} in PSHA is to exclude hazard contributions from high-amplitude, short-duration, low-energy ground motions that would not contribute to risk.

Justification for considering the potential impact of small-magnitude induced earthquakes is also frequently based on citing the case histories reviewed in Sect. 2. The Basel earthquake is repeatedly referred to as 'damaging' despite the lack of evidence for anything beyond hairline cracks, which in many cases could have been caused by a variety of other mechanisms. By way of an illustrative example, Kivi et al. (2023) state that "*Earthquakes induced by these geoenergy activities were occasionally felt by the local population and even resulted in injuries to people and damage to buildings and infrastructure, causing early termination of projects and loss of investment*", followed by references to papers on Basel, Castor and Pohang. The only common factors in these cases were that they generated felt shaking and that they were terminated, while only the Pohang event caused structural damage and injury, but their grouping in this way could convey to the reader that such consequences were common to all cases. It is perhaps understandable that authors will make such statements repeating unsubstantiated claims rather than seeking substantiation for the reported damage; after all, if there was not substantial damage due to these induced earthquakes, why would major resources such as the Basel EGS, the Castor gas storage and the Groningen gas field have been closed down? However, if rational risk-informed approaches to managing induced seismicity are going to be adopted for future energy projects, it is critical to separate substantiated fact from fiction in these case histories.

3.2 Estimations of the largest possible induced earthquake

A recurring feature of the case histories reviewed in Sect. 2 is the final justification for closing down energy-related projects being premised on the largest earthquakes that are estimated to be possible if operations were to continue.

A great deal of attention has been given to the estimation of the largest possible earthquake magnitude, M_{max}, to be considered in PSHA for natural seismicity. It is common practice to develop a logic-tree node for M_{max} with all branches carrying large values, often far in excess of the largest observed event in the region. For the most recent seismic hazard maps for the UK, for example, Mosca et al. (2022) assigned the following values, with their associated weights in parentheses: 6.5 (0.5), 6.7 (0.2), 6.9 (0.2) and 7.1 (0.1). The use of such values causes no concern – there have been no calls to strengthen UK buildings to resist the effects of a magnitude 7 earthquake – and

disaggregations show that magnitudes in this range have little impact on the hazard estimates. The lower end of the distribution is sometimes extended down to the largest observed magnitude, when the Bayesian updating of global priors often used in stable regions (e.g., USNRC 2012), if one ignores the assertion of Vanneste et al. (2016) that a global distribution should be used everywhere because local regional catalogues simply reflect an incomplete record. The Bayesian approach is more likely to capture the full distribution of uncertainty on M_{max} since it addresses the questions of both how small and how large the biggest earthquake could be. When the broader distributions obtained with the Bayesian approach are used, hazard results become more sensitive to M_{max}. Although the upper end of the distributions has limited impact on the results, the use of these values implies that there are active but undetected faults with lengths of tens of kilometres throughout the region, as confirmed by the virtual fault ruptures that must be generated to calculate the distances required for the hazard calculations (Bommer et al. 2023).

In general, it is very likely that M_{max} distributions adopted in PSHA for natural seismicity are often biased high (Bommer and Verdon 2024). This is important because there is little doubt that the practice of seismic hazard assessment for natural earthquakes has influenced the assessment of induced seismic hazard. However, it is important to note that M_{max} estimates tend to have far greater influence when dealing with induced seismicity, both in terms of the perception of the risk and the quantification of the risk. With regard to risk perception, it is not uncommon for M_{max} estimates for induced earthquakes to be interpreted by the public not as limiting upper bounds but rather as predictions, and for their branch weights to be viewed as probabilities of their occurrence. This is not to say that such misconceptions should influence the objective estimation of M_{max}, but it perhaps should give pause to exercise greater scrutiny to the specification of large values than is generally the case in standard PSHA practice.

Changes in stress or fluid pressures due to anthropogenic operations can lead to the occurrence of incipient tectonic earthquakes. Such events are referred to as triggered earthquakes or runaway ruptures, the energy released by the fault rupture being tectonic strain energy stored in the crust. The upper bound on the magnitude of induced earthquakes is therefore the same as M_{max} for tectonic earthquakes, but there are several reasons why the distribution of maximum magnitudes for induced earthquakes will be shifted to lower values than that for tectonic earthquakes. Firstly, the operations would need to be in close proximity to a favourably oriented and critically stressed fault, with a mechanism for the transfer of stress or fluid pressure from the injection well to the seismogenic fault, the dimensions of which will control the largest possible magnitude. In the absence of such faults in the vicinity of the operations, large tectonic earthquakes cannot be triggered. Another very important consideration is the depth of the injections, since large tectonic earthquakes that initiate at shallow depths are rare, and if the injections are into formations appreciably above the crystalline basement, then large runaway ruptures are also unlikely. Induced earthquakes, in the purer sense of the term – which is confusing nomenclature, for which reason Bommer and Verdon (2024) proposed that these be referred to as (anthropogenically) driven events – can still occur. The energy released in such events is related to the energy input by the operations. In setting up a logic-tree for M_{max} for induced seismicity, therefore, it is advisable to include a first node that assigns probabilities to only driven earthquakes occurring and to the possibility of triggering tectonic earthquakes and then developing the branches for M_{max} for these two separate options on a second node (see, for example, Fig. 2 in Zhou et al. 2024).

Many papers have been published proposing approaches to the estimation of M_{max} for induced seismicity, including all those cited in Bommer and Verdon (2024) and more recent contributions (Drif et al. 2024; Langenbruch et al. 2024; Verdon and Eisner 2024; Im and Avouac 2025; Schultz et al. 2025). Within the literature of the last decade, several papers have challenged models such as that of McGarr (2014) which relate the maximum earthquake magnitude to operational parameters, such as the total injected volume. Even though the dataset used for verification in McGarr (2014) includes some triggered earthquakes of moderate magnitude, the available evidence would seem to support the notion that the size of induced (i.e., driven) earthquakes is controlled by operational parameters and such magnitude limits can be exceeded if runaway ruptures are triggered (the magnitudes then depending on tectonic stresses and fault dimensions). This is precisely why

distinguishing between driven and triggered earthquakes is advisable, facilitating consideration of the likelihood of the latter occurring in light of the depth of injections and the presence, or otherwise, of susceptible faults. The maximum magnitudes of the triggered earthquakes then can be assessed in the same way as is done for tectonic seismicity, with the focus on the local geological structures, but should bear in the mind the observations presented above as to why current practice is likely to often produce distributions that are biased high.

M_{max} distributions for induced seismicity will inevitably be specific to each region and also to the particular operation being considered, but the process – and the consequences for risk estimates – can be illustrated for the case of the Groningen gas field. Given the sensitivities surrounding the question of the largest earthquake that could occur in Groningen, NAM commissioned an international panel of experts to make the assessment, informed by presentations on all aspects of the gas field and the observed seismicity at a multi-day workshop (Bommer and van Elk 2017). The outcome is shown in the top left-hand corner of Fig. 3. Six years later, it was decided that the additional information available justified a new assessment, for which the same panel was convened and a new international workshop conducted in 2022, including presentations of several proponent models for the maximum earthquake magnitude in the Groningen field. This resulted in a new M_{max} distribution, shown in the middle left-hand panel of Fig. 3. As can be appreciated from the figure, a key change from 2016 was a reduction in the magnitudes and associated weights of triggered earthquakes, the highest values in the original distribution being based on cases previously considered to be analogues for Groningen. Nonetheless, the changes to the upper end of the M_{max} distribution had a modest impact on seismic risk estimates for Groningen, as shown by the corresponding plots on the right-hand side of Fig. 3, since the risk estimates are driven by earthquakes of magnitude 4.5–5.5, where the weights did not change significantly.

Bommer et al. (2024) made a critical assessment of the results from the second M_{max} workshop, recognising the observation by the expert panel regarding the limited time that they were given to digest a very large body of information and to make their assessment. It is probably fair to say that the assessment was influenced by the established practice in estimation of maximum magnitude discussed above. A key focus of the review by Bommer et al. (2024) was to challenge the branch for triggered tectonic earthquakes, especially in view of the absence of any instrumental or historical record of natural earthquakes in the northern Netherlands.[1] Additional reasons why the triggering of tectonic earthquakes was considered unlikely were based on stress considerations, which have been strengthened by work conducted at Utrecht University (van Dinther et al. 2025; Li et al. 2025a) in which geomechanical simulations have been unable to generate runaway ruptures that propagate into the Carboniferous formation below the gas reservoir (upwards propagation would not cause large earthquakes because the reservoir is overlain by the Zechstein salt formation). In 2,000 simulations, Li et al. (2025b) only managed to make a single runaway rupture, using parameter combinations that the authors considered to be outside the range of realistic values. In the simplest interpretation, this would lead to a weight on the branch for triggered earthquakes being 0.005; if weights were applied to the input parameters to the simulations, this branch weight would be even smaller. Boitz et al. (2024) also pointed out that the recurrence rates of smaller earthquakes are such that if larger triggered earthquakes were possible, such an event would already have occurred. We also note that most of the proponent expert models presented at the workshop did not include the possibility of runaway ruptures and the only model that did include this possibility assigned a rather low weight to this possibility. All these considerations led us to conclude that the triggering of tectonic earthquakes is extremely unlikely; rather than assign a vanishingly small weight to this possibility in the logic-tree, it is more appropriate to remove this branch altogether.

As far as the driven (induced) earthquakes are concerned, it seems entirely appropriate for the distribution to begin at the largest observed magnitude, especially in view of the number of events of $M \geq 3.0$ that have occurred without the magnitude of the 2012 Huizinge earthquake being exceeded (while

[1] Despite the apparently aseismic nature of the region, for the 2020 European Seismic Hazard Model (Danciu et al. 2024), M_{max} in the zone containing the northern Netherlands was defined by the following branches (with weights in brackets): 6.3 (0.5), 6.6 (0.4), 6.9 (0.1).

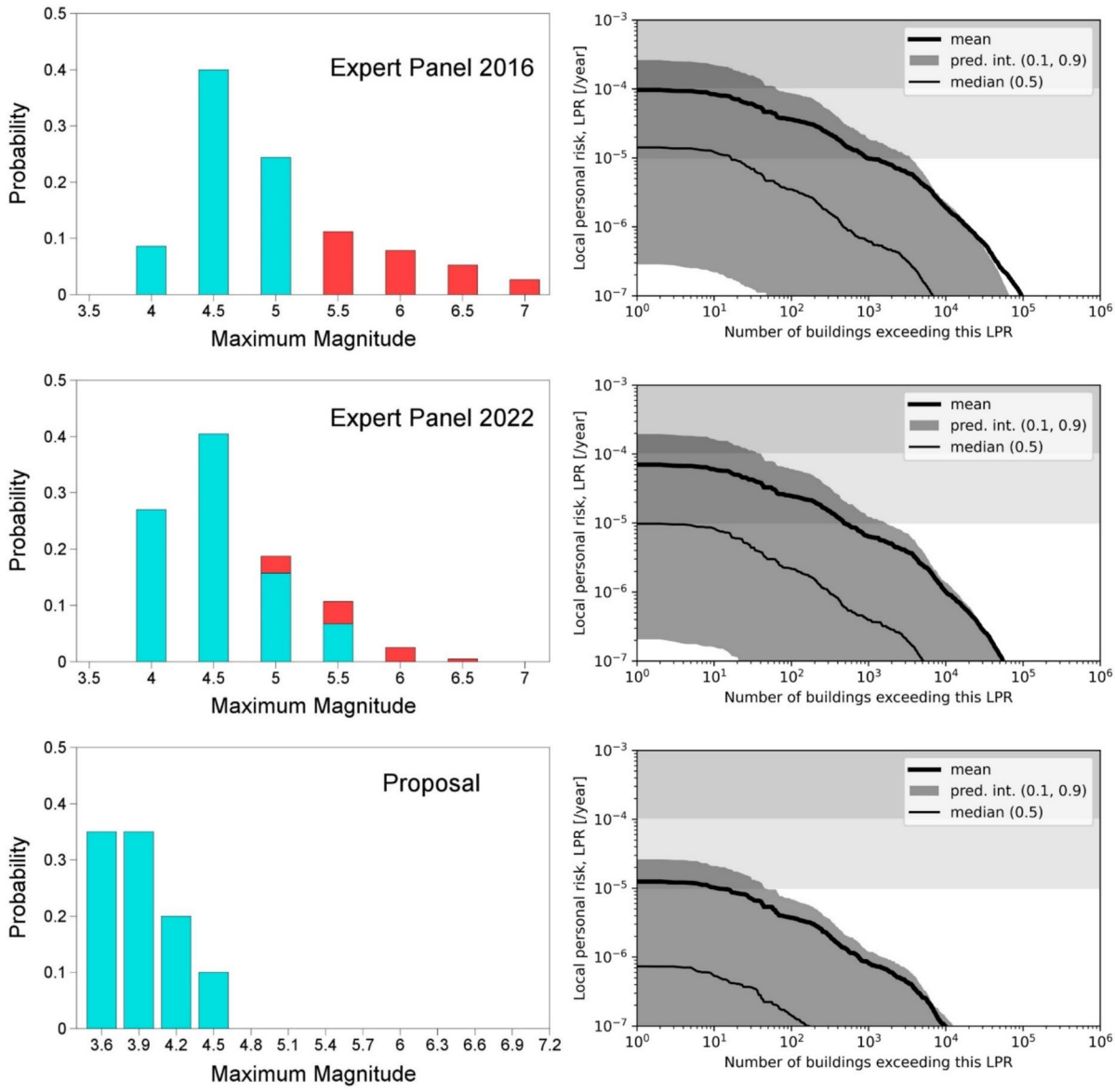


Fig. 3 Logic-tree distribution of M_{max} for Groningen *(left)* and resulting risk estimates in terms of local personal risk (LPR) and number of effected buildings for the period from 2016 to 2031 for an annual production rate of 33 bcm (*right*), showing median (*thin line*), and mean (*thick line*) risk estimates, together with the 10% to 90%c confidence interval (*shaded area*). The horizontal shading reflects the specifications of Dutch safety legislation. The same seismicity, ground motion, exposure, fragility and consequence models are used in each case. The upper and middle rows are for the M_{max} distributions proposed by the Expert Panel in 2016 and 2022, respectively; the bottom row is a tentative alternative distribution proposed by the author and based on the deliberations of Bommer et al. (2024). The cyan bars correspond to induced (anthropogenically driven) earthquakes, the red bars to triggered tectonic earthquakes

this paper was under review, a third earthquake of M_L 3.4 occurred in Groningen). In some cases, it may be appropriate to also allow for uncertainty in the magnitude of the largest observed earthquake, depending on when and how this value was determined. The maximum size of induced earthquakes will be controlled by the possible rupture dimensions of the faults within the thin sandstone

formation containing the gas reservoir, within which all events have been located. The maximum thickness available for rupture is therefore on the order of 300 m, hence induced earthquakes appreciably larger than those that have occurred to date would require ruptures with unusually (and probably unrealisable) aspect ratios. The M_{max} models presented at the 2022 workshop, all of which started the distribution above the largest observed event, proposed values in the range 4.0 to 4.5. On the basis of all these considerations, I have put forward a tentative (although, in my view, entirely defensible) proposal for an alternative distribution that is shown in the bottom left-hand corner of Fig. 3. The distribution eliminates the possibility of triggering runaway ruptures releasing tectonic strain energy, allowing only for induced (driven) earthquakes. The greatest weight is assigned to the maximum observed earthquake and slightly larger magnitudes, and lower weights on events that would require ruptures with large length–width ratios. As the corresponding plot in the second column of the figure shows, when such an M_{max} distribution is adopted, the estimated risk is dramatically reduced.

4 Overestimation of induced seismic risk

Quantification of the risk posed by potential induced earthquakes is central to successful management of induced seismicity in energy projects. There are many ways that estimates of the induced seismic risk can be inflated, especially if the induced seismic hazard and risk are being compared to the effects of natural seismicity. There are a few published studies that directly compare hazard due to natural and induced earthquakes (the latter due to hydraulic fracturing) in the Western Canadian Sedimentary Basin, all of which find very large increases of hazard due to induced seismicity (Atkinson et al. 2015; Ghofrani et al. 2019; Reyes Canales et al. 2022; Babaie Mahani et al. 2025). The intention here is not specifically to critique these studies but rather to use them to illustrate some of the ways that hazard (and hence risk) can be overestimated for induced earthquakes. These studies have the merit of being openly published and therefore conveniently highlight issues that are very likely encountered in many unpublished studies conducted for energy projects. I focus here on the first and last of these studies, which focus on individual locations, and which are therefore easier to interpret. In the earlier of these, Atkinson et al. (2015) assessed the hazard at Fox Creek in Alberta, finding that the induced hazard was many times larger than that due to natural earthquakes, the 2,475-year accelerations increasing by more than an order of magnitude (Fig. 4). The study recognises that not all fracking operations lead to induced seismicity – globally, the rate is about 1% (Schulz et al., 2020a) – which is incorporated as an activation probability. The preferred value for this probability chosen by Atkinson et al. (2015) is 0.01 hence the comparison of relevance in Fig. 4 is the difference between the thick black line (natural seismicity) and the upper end of the grey shaded area (induced seismicity). In the most recent of these studies, Babaie Mahani et al. (2025) find that during the year with greatest induced seismicity (2022), the 2,475-year seismic hazard near Fort St John in British Columbia increased by a factor of ~ 12 for PGA and bya factor of ~ 5 for PGV.

Induced earthquakes will always lead to an increase in the seismic hazard, at least in the short-term, and Atkinson et al. (2015) make the point that their study area is of relatively low natural seismicity and hence elsewhere relative increases may not be so pronounced. However, there are features of both the Atkinson et al. (2015) and Babaie Mahani et al. (2025) studies that may well have exaggerated the relative impact of induced seismicity through choices made regarding input parameters, particularly the choice of minimum magnitude (Sect. 4.4) and GMPEs (Sect. 4.5), as well as the seismic source model in the case of the earlier study (Sect. 4.2).

4.1 Probabilistic and scenario-based estimates

Probabilistic approaches to the assessment of seismic hazard and risk have become standard practice and they offer many advantages, especially if risk thresholds are defined in terms of tolerable annual frequencies for undesirable outcomes. Fundamental to any probabilistic seismic hazard analysis is a model for the average rates of earthquakes of different magnitudes. For assessments made prior to the start of operations, information on rates is likely to be lacking unless previous injection operations have been carried out in the same region and formation. A comprehensive seismic risk assessment for potential induced

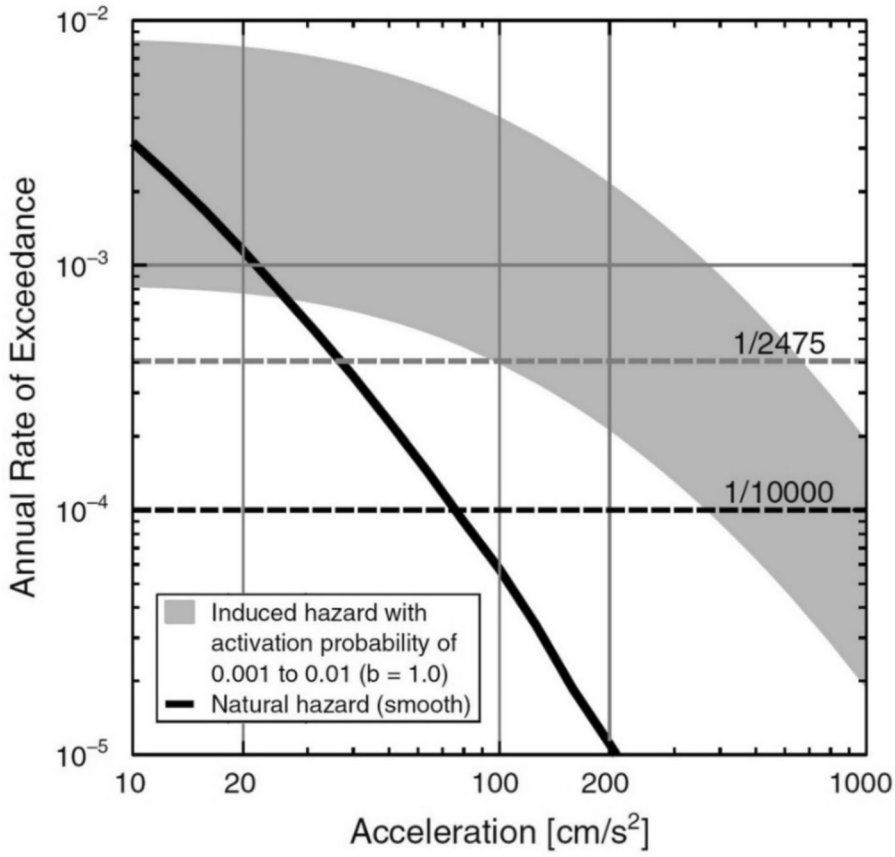


Fig. 4 Seismic hazard curves for Fox Creek obtained by Atkinson et al. (2015) for natural earthquakes and induced seismicity associated with hydraulic fracturing. The hazard curves for induced seismicity are plotted for a *b*-value of 1, a minimum magnitude of 4.0, and probabilities of activation ranging from 0.0001 to 0.01; the preferred value in the study is 0.01 hence the representative induced seismic hazard is the upper bound of the grey shaded area

seismicity that could be caused by future fracking operations in Manaus, Brazil, was performed by Silva et al. (2021). With no prior observations to inform the model, the logic-tree included two nodes for recurrence rates, the first for the *b*-value of the recurrence relationship and the second for the seismogenic index (Shapiro et al. 2010), which is a measure of the level of seismicity caused as a function of the injected volume of fluid. The ranges of values adopted for these two parameters reflect the uncertainty in the recurrence characteristics prior to injection, and in the absence of any basis for a correlation between the two parameters, their inclusion on separate logic-tree nodes is appropriate. The resulting range of possible recurrence rates for earthquakes is shown in Fig. 5.

The actual range of recurrence levels is even greater than illustrated in Fig. 5 since Silva et al. (2021) also include a node for the possibility that the hydraulic fracturing would not produce any seismicity (with a weight of 0.997). This is a perfectly reasonable representation of the epistemic uncertainty, but it renders any ensuing risk estimates uninformative. Even with a probability of 0.3% of seismicity being induced, the higher levels of possible earthquake activity could cause regulatory concern.

In such cases, a preferable approach may be to perform risk assessments for possible induced earthquake scenarios of different magnitudes. Such scenario-based assessments can still include probabilistic elements, including the sampling of the ground-motion field (e.g., Edwards et al. 2021; Schultz et al. 2021a). Such risk simulations, with appropriate characterisation of the exposed building stock and its fragility, enable determination of the magnitude levels that would lead to unacceptable consequences, which in turn can then inform the design of TLS (see Sect. 4.3), taking account of potential magnitude increases associated with trailing events (e.g., Verdon and Bommer 2021; Schultz et al. 2022). However, one should be wary of comparing scenario-based ground motions with those obtained from probabilistic analyses (for example, for natural

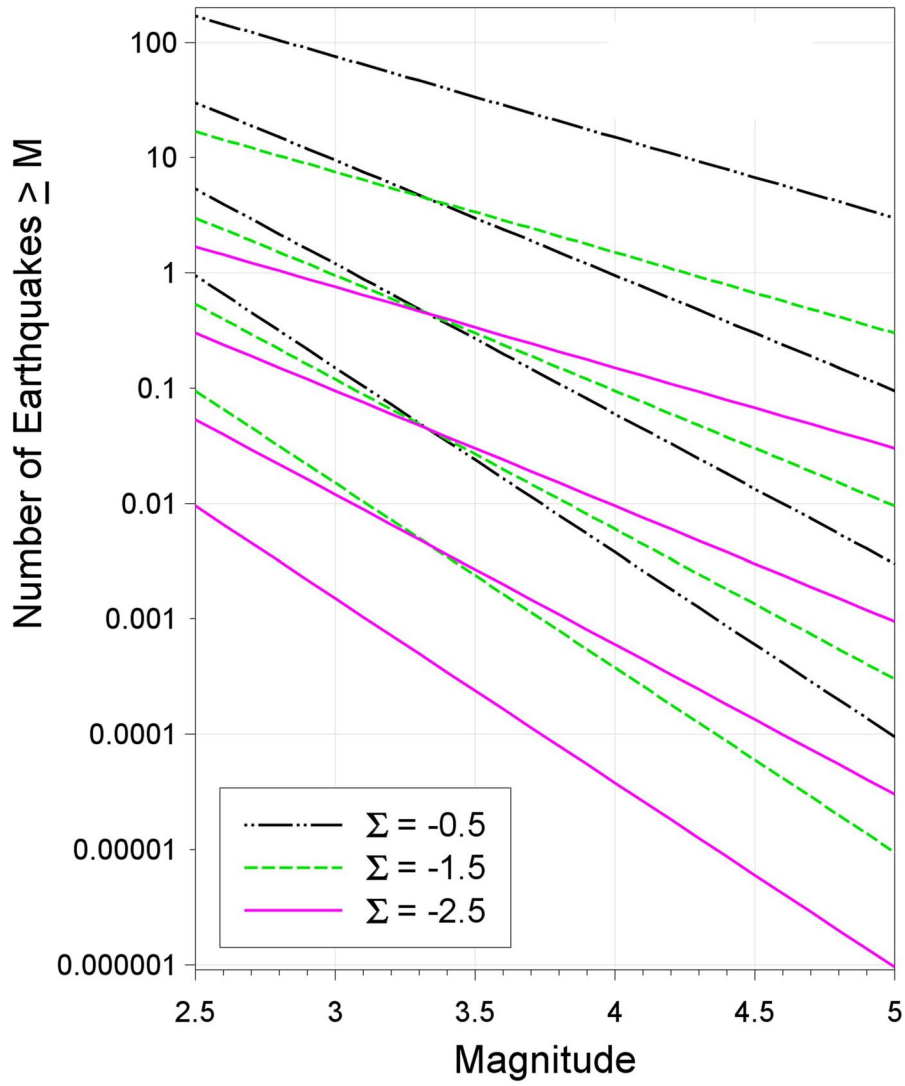


Fig. 5 Recurrence relationships in the logic-tree developed by Silva et al. (2021) in a probabilistic risk analysis for a potential fracking project in Manaus, Brazil, assuming a total injected volume of 30,000 m^3 (the use of an alternative volume would scale all the curves up or down by the same factor)

seismicity) for the same reasons that ground motions from PSHA should not be assessed by comparison with individual ground-motion recordings (e.g., Iervolino 2013).

4.2 Seismicity models and maximum magnitudes

For a probabilistic seismic hazard analysis, the most fundamental input is a seismicity model defining the locations and average annual frequencies of future earthquakes. If such models are to be derived from observations of induced earthquakes, it is important that only induced events are included in the earthquake catalogue. In any location where multiple injection operations are active, such a hydraulic fracturing and wastewater disposal, it is equally important to ensure a correct correlation between the induced events and the causative injections (e.g., Grigoratos et al. 2022). Incorrect association of events with industrial processes can be a pitfall in several ways – denial of causality on the part of an operator that is later disproven will seriously undermine public trust and regulatory assurance.

Standard practice is to normalise seismicity rates to average annual values, which will particularly be required if comparisons are to be made between hazard contributions from induced and natural earthquakes. Careful consideration needs to be given, however, to short periods of elevated induced seismicity and the risk posed over the project duration. Atkinson

et al. (2015) propose rates based on the assumption that future fracking operations would continue to generate induced earthquakes at the same rate as during the preceding six months. However, it should be borne in mind that each individual fracking operation will have a duration of a few weeks.

Another potential pitfall lies in extrapolating earthquake recurrence models from initial observations of small-magnitude earthquakes. In many cases, it has been observed that subsequently *b*-values may decrease hence the rate of larger earthquakes will be much greater than predicted from the early extrapolations. Unless potential changes in the *b*-value are taken into account, this can result in serious underestimation of the hazard and risk.

Defining the spatial distribution of induced seismicity can be challenging and will depend very much on the geographical extent of the specific process generating the seismicity. For an individual hydraulic fracturing well, most seismicity will tend to occur in close proximity to the injection wells, usually within 1–2 km (Schultz et al. 2020a; Zhou et al. 2024), although there can, very rarely, be greater separation (e.g., Schmittbuhl et al. 2021). With other technologies and larger injected volumes, greater distances may need to be considered.

With the foregoing in mind, the modelling of the source of induced earthquakes in Fox Creek by Atkinson et al. (2015) provides the first insight as to why such high hazard estimates were obtained. In their Fig. 2, they show a square within which the 2013–2014 induced seismic sequence at Fox Creek occurred, which is the basis for the recurrence relationship. The source zone, however, is defined by an area of ~ 10 × 10 km at the centre of the first square, with an area about six or seven times smaller, into which all the induced earthquakes are concentrated. The hazard is then calculated at the centre of the smaller source area, a location that in the model is thus exposed to sustained induced seismicity with a much higher spatial density of earthquakes than almost any location in the Fox Creek region. The authors note that the results will only be applicable to a site in very close proximity to fracking operations, but it also needs to be noted that the sites correspond to an enhanced spatial density of earthquake activity and that the actual operations at any given location are relatively short-lived.

The final element of the seismicity model is the maximum magnitude at which the recurrence relationship is truncated, which has already been discussed at some length in Sect. 3.2. The M_{max} model for induced earthquakes in Fox Creek is not unreasonable, comprising the following branches and weights: 4.5 (0.4), 5.0 (0.3), 5.5 (0.2) and 6.5 (0.1). The lower bound appropriately reflects the largest observed earthquake induced by fracking in this region, but the upper bound is questionable since there is no precedent for such large earthquakes being initiated at such shallow depths (the M_{max} distribution and focal depth distributions are independent, so the model envisages a magnitude 6.5 earthquake initiating at 2 km). These M_{max} values are, however, markedly smaller than those adopted in the PSHA for natural seismicity in the source zone hosting Fox Creek, namely 6.9, 7.0 and 7.5 (Halchuk et al. 2014), hence this parameter choice is not likely to have been an important contributor to the dominance of induced seismic hazard indicated in Fig. 4. A similar conclusion may be drawn regarding the Babaie Mahani et al. (2025) study.

There will, however, be cases where overestimation of the maximum magnitude of induced earthquakes will lead to inflation of the assessed hazard due to induced seismicity. By way of a clear example, let us return for a moment to Fig. 3. The M_{max} histogram in the bottom row will no doubt surprise many readers since we are all used to distributions that start appreciably above the largest observed event and extend to significant magnitudes. A paradigm shift is required here: rather than including large values of M_{max} on the basis of it not being possible to definitively rule out the possibility of such events occurring (which is tantamount to invoking the precautionary principle), large M_{max} should only be included if there is a clear physical basis for such events to be induced or triggered. For Groningen, multiple lines of evidence strongly indicate that triggering of tectonic earthquakes in this environment is extremely unlikely (as summarised in Sect. 3.2), hence the size of induced earthquakes will be controlled by the available fault rupture areas within the gas-bearing Rotliegend sandstone. In view of the maximum thickness of this formation not exceeding 300 m and also taking into account limiting aspect ratios for the ruptures, the proposed M_{max} distribution very likely captures the range of possibilities. If this is the case, the risk estimates in the upper and

middle plots on the right-hand side of the figure are grossly overestimated. As a footnote to this discussion, an assessment of liquefaction triggering in the most susceptible soils in the Groningen region found this hazard to be very low (Green et al. 2020), with only minor surficial manifestations at a return period of 2,475 years. However, these results were entirely driven by the larger magnitudes – adopting the M_{max} distribution proposed in this paper, the liquefaction triggering hazard is null.

4.3 Risk metrics

A rational approach to managing induced seismicity will necessarily focus on risk (i.e., the potential consequences of shaking) rather than seismic hazard (i.e., the intensity of shaking) alone. This allows the thresholds on a TLS to calibrated to the exposure, and its seismic fragility, at the location of the project, thus providing for more stringent controls in proximity to vulnerable buildings and allowing greater leeway for operations in uninhabited areas (e.g., Schultz et al. 2020b). Risk targets were implicit in the first TLS, developed for an EGS in El Salvador, which first defined PGV thresholds that could be potentially damaging to local buildings, and then converting these to equivalent magnitudes using the focal depth and the ground-motion prediction model (Bommer et al. 2006). Schultz et al. (2021a) developed this further using comprehensive risk assessments to calibrate the TLS threshold magnitudes. As noted previously, the TLS thresholds can be fixed to avoid reaching the magnitude levels that would produce unacceptable consequences by accounting for magnitude jumps observed in induced seismic sequences (Verdon and Bommer 2021; Watkins et al. 2023; Schultz et al. 2022). Clearly, the selection of TLS thresholds without accounting for magnitude jumps or larger trailing events is a pitfall that should be avoided. On a related point, it is worth emphasising that even if thresholds are established in terms of ground-motion levels (or even loss estimates), there are several compelling reasons to calibrate the TLS levels in terms of magnitude (e.g., Ader et al. 2020). Ideally, both the risk metric and the associated thresholds would be defined by the regulatory authority.

Once a risk-based framework is adopted, the key question is the risk metric that will control the thresholds of tolerable induced seismicity. Several researchers have proposed thresholds related to disturbance, which essentially means avoiding levels of shaking that could be felt by the exposed population (e.g., Douglas and Aochi 2014; Cremen and Werner 2020; Schultz et al. 2021b). While I fully agree that any disturbance to the local population should be taken seriously, especially if it occurs repeatedly, not least because it will generally raise concerns regarding the possibility of stronger shaking episodes, I would always counsel against defining tolerable risk thresholds on the basis of felt shaking on the simple basis that it will always create very narrow margins within which operations can continue. If one looks at the empirical relationships between MMI and PGV of Worden et al. (2012), the median PGV for shaking that is clearly felt by some people (III) is just 1 mm/s; for shaking at which slight damage can occur (VI), the corresponding PGV is almost two orders of magnitude larger (96 mm/s). Using thresholds related to physical damage, even if it set well below these thresholds to create margins of safety, provides much greater possibilities of being able to continue operations without interruption. The disturbance to the exposed population through induced shaking can be handled in many other ways, as discussed in Sect. 5.3.

Risk thresholds may also be expressed in terms of potential injuries to building inhabitants or in terms of costs to repair building damage. In such cases, it is recommended to first use fragility functions to estimate building damage and then to use consequence functions to transform the damage into the selected metric. The use of vulnerability functions, which directly predict consequences as a function of shaking levels, will make it more difficult to interpret the results and identify contributors to high risk estimates. In particular, cost estimates based directly on past costs inferred from damage claims should be avoided (see Sect. 4.6).

4.4 Minimum magnitude

The purpose of M_{min} in PSHA is to prevent inflation of the hazard estimates by large-amplitude contributions from short-duration, low-energy ground motions that would not contribute to risk (Bommer and Crowley 2017). M_{min} is therefore an engineering parameter rather than a seismological parameter, and its value primarily reflects the seismic fragility of

the structures for which the ground motions are being assessed.

A key question in the context of this discussion is whether M_{min} should be smaller when considering induced earthquakes as a result of their shallower depth. This point was already discussed in Sect. 3.1 and can be succinctly summarised by the following conclusion from the study by Atkinson et al. (2018): "*The intensity signature of induced events has important implications for seismic hazard. For moderate earthquakes (M~ 4:0–5:5), induced and natural events have similar intensities, and thus equivalent damage potential, at distances close to the epicenter (< 10 km); however, induced events have lower intensity at regional distances*." The lower intensities from induced events at regional distances are also due to faster attenuation within the low-velocity layers at the top of the crust. The fact that the damage potential of shaking at the epicentre of both induced and natural earthquakes is broadly the same, irrespective of the differences in average focal depths, means that the M_{min} used in PSHA for both natural and induced earthquakes in a given location should be the same. However, in the Fox Creek study, Atkinson et al. (2018) used a minimum magnitude of 4.0 in the PSHA for induced seismicity "*based on observations that induced events of M 3.5 have caused damage to vulnerable structures*", referring to the case of the Basel earthquake that was discussed in Sect. 2. As illustrated in Fig. 6, their hazard estimates are very sensitive to this parameter, especially for larger *b*-values. By contrast, Halchuk et al. (2014) specified a minimum magnitude of **M** 4.8 in the PSHA for natural seismicity against which the induced seismic hazard results are compared. Although not shown, it can be inferred that using $M_{min} = 4.8$ in the PSHA for induced earthquakes would have lowered the hazard estimates appreciably, hence this would appear to be one of the important contributors to the stark difference between the natural and induced hazard seen in Fig. 4.

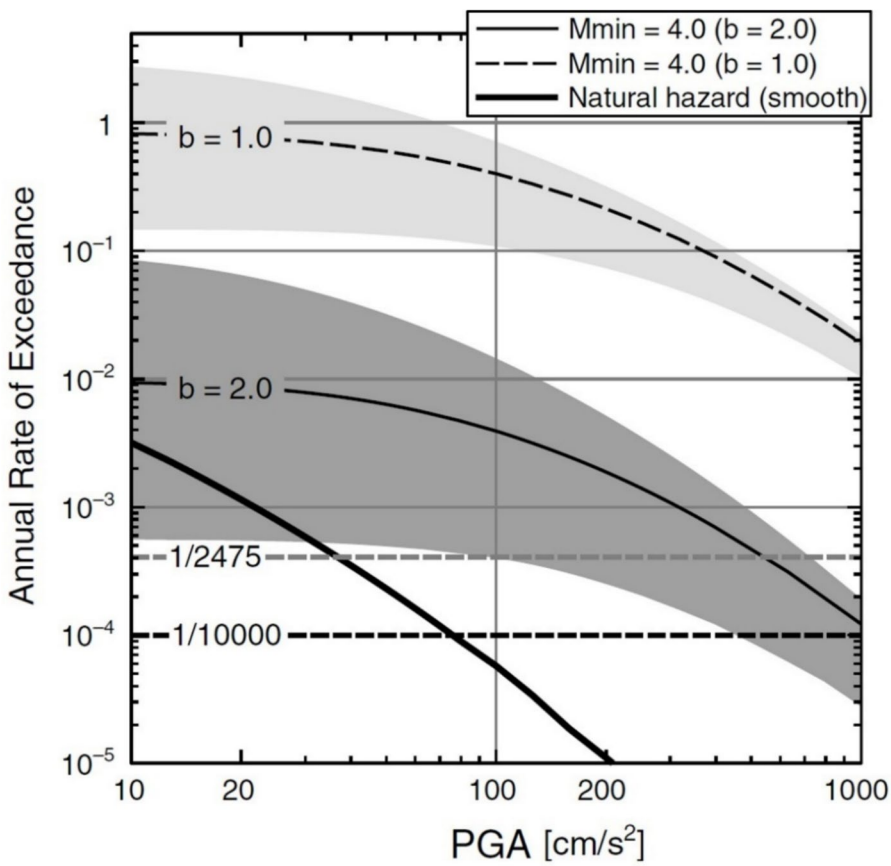


Fig. 6 Seismic hazard curves for Fox Creek obtained by Atkinson et al. (2015) for natural earthquakes and induced seismicity associated with hydraulic fracturing, assuming a probability of activation of 1. The hazard curves for induced seismicity are plotted for two *b*-values and a minimum magnitude of 4.0, with the shaded areas indicating the sensitivity to M_{min} values ranging from 3.5 to 4.5

In the study of Babaie Mahani et al. (2025), M_{min} is likely to have had an even more pronounced effect since the value of **M** 4.8 was retained for natural seismicity while **M** 3.0 was adopted for induced earthquakes. This very low value was justified by comparisons of intensities from shallow and deeper crustal earthquakes (Babaie Mahani et al. 2021), noting higher values for the former in contrast to the findings of Hough (2014) and Atkinson et al. (2018) cited earlier. However, the data used for these comparisons also come from different regions, which may well mask the counteracting effects of shallow focal depths (i.e., shorter travel paths and lower stress drops). Justification is also given on the basis of shaking of Modified Mercalli intensity VI – which corresponds to the onset of damage – from an induced earthquake of M ~ 3 south of Fort St John (Babaie Mahani and Kao 2018). However, this is inferred from the PGA value of a single recording and comparison with the lower bound (mean-minus-one-standard-deviation) of PGA for this intensity from the empirical relations of Worden et al. (2012); the PGA is below the median value for intensity VI and the corresponding PGV value does not even reach even the lower bound threshold. It is quite an extrapolation to infer from this single exceedance of a necessary but insufficient lower bound threshold for MMI VI to concluding that earthquakes of **M** 3 can be damaging (for which there is no empirical evidence, as discussed in Sect. 3.1). As explained in Sect. 4.5 below, the GMPEs used by Babaie Mahani et al. (2025) will have exacerbated the impact of the large difference in M_{min} values for natural and induced earthquakes.

There may be cases of hazard and risk assessments for induced seismicity where lower values of M_{min} are adopted, either because of very vulnerable building stock and/or because of risk thresholds related to very low levels of damage. If the hazard calculated in this way is to be compared with that due to tectonic earthquakes, then the latter must first be recalculated using the same M_{min} value, otherwise the comparison will be misleading. The minimum magnitude will always depend on both the exposure and the risk metric, and would, for example, be considerably lower if considering nuisance from shaking as opposed to physical damage (Grigoratos et al. 2025b).

A final point to make here is that the determination of M_{min} is entirely independent from the estimation of M_{max} discussed in the previous section. Consequently, it is perfectly feasible that the M_{min} value may be higher than the lower limit of the M_{max} distribution defined for induced seismicity. If this is the case, it would be entirely incorrect to adjust either the M_{min} value or the M_{max} distribution; it will simply be the case that the branches for values of $M_{max} \leq M_{min}$ will not contribute to the hazard estimates. The basis for determining M_{min} means that PSHA is always risk-related and consequently it is possible for there to be null contributions (in the extreme case, for an M_{max} distribution such as shown in the lower left-hand corner of Fig. 3 and structures engineered for lateral resistance, it would be possible to have null hazard).

4.5 Ground-motion prediction models

Assessing the potential impact of induced earthquakes requires ground-motion prediction equations (GMPE) calibrated for conditions rarely considered in standard earthquake engineering practice for natural seismicity. Firstly, ground motions may be calculated for earthquakes of magnitude smaller than the lower limit for which many GMPEs are derived, and the application of such models to such small events will lead to overestimation of the shaking levels (e.g., Bommer et al. 2007; Atkinson and Morrison 2009; Chiou et al. 2010). Secondly, the GMPEs will often be applied to much shallower focal depths that are typically represented in databases of ground-motion recordings from tectonic earthquakes; if the models do not account for the reduction of stress drop with focal depth, the application of models using hypocentral or rupture distance to very shallow earthquakes will also lead to overestimation of the ground motions. Moreover, the source and attenuation characteristics for shallow induced earthquakes are controlled by the structure and properties of the uppermost part of the crust, which is far more heterogeneous than the lower portions in which most tectonic earthquakes nucleate and through which the radiated seismic waves propagate. Consequently, there are compelling reasons for developing GMPEs specific to induced earthquakes in a particular region (Bommer et al. 2016). This statement is supported by the work of Douglas et al. (2013) to develop generic GMPEs for induced earthquakes by combining multiple sets of recordings from different regions: their Fig. 5 shows residuals grouped by region, displaying very distinct trends.

For the Fox Creek hazard study, Atkinson et al. (2015) adopted the GMPE of Atkinson (2015), derived from recordings obtained within 60 km of Californian (tectonic) earthquakes of magnitude **M** between 3 and 6, but intended explicitly for application to induced seismicity. The model uses hypocentral depth without any adjustment for stress-drop scaling and hence is likely to be conservative when applied to very shallow events. The logic-tree was comprised of the two versions of the model with a lower branch obtained by dividing the less conservative version (greater near-source saturation) by an uncertainty factor and an upper branch obtained by multiplying the more conservative version (low saturation) by the same factor (which ranged between 1.4 and 2 depending on distance). In contrast, the natural seismic hazard was calculated using the model proposed by Atkinson and Adams (2013) for eastern Canada, as used in the national seismic hazard mapping by the Geological Survey of Canada (Halchuk et al. 2014). Figure 7 compares the median spectra obtained at the epicentre for an earthquake scenario common to the PSHAs for both natural and induced earthquakes: an earthquake of **M** 5.5 at a depth of 5 km (the induced seismicity model assigned depths of 2, 3 and 5 km, whereas the natural seismicity model assigned depths of 5, 10 and 15 km). The plot also includes the mean and upper bound spectra for induced seismicity at the shallower depths.

Figure 7 shows that for the common scenario and for periods < 0.1 s, the weighted mean models for induced and tectonic earthquakes are broadly consistent; for periods ≥ 0.2 s, the mean induced model matches the upper bound spectrum for natural earthquakes (40–60% higher than the mean spectrum for the tectonic scenarios). For the shallower scenarios at

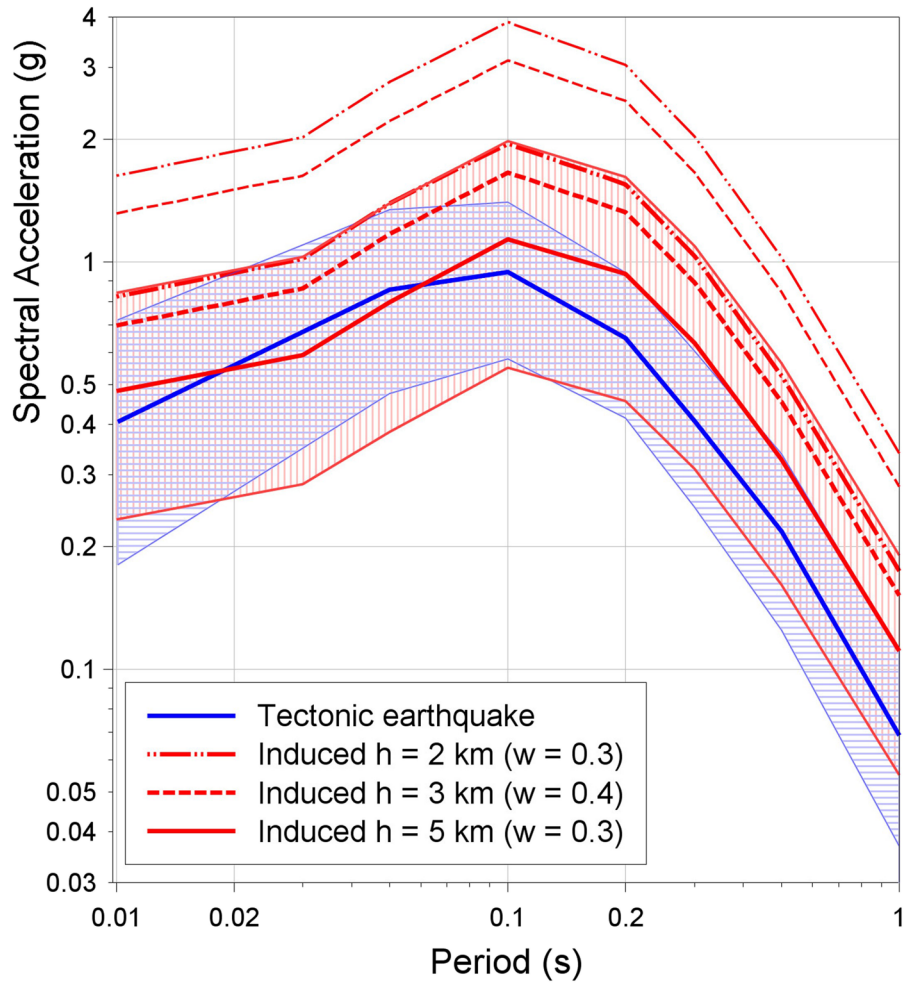


Fig. 7 Comparison of the median spectral ordinates predicted for a rock site (V_{S30} 760 m/s) at the epicentre of a magnitude 5.5 at a depth of 5 km using the GMPEs deployed by Atkinson et al. (2015) in their PSHA for induced earthquakes (*red*) and the GMPEs proposed by Atkinson and Adams (2013) for eastern Canada and used by Halchuk et al. (2015) for the national hazard maps and by Atkinson et al. (2015) (*blue*). In both cases, the shaded region indicates the range of predictions from the respective logic-tree branches and the solid lines are the weighted mean spectral ordinates. The dashed red lines shown the mean (*thick lines*) and upper bound (*thinner lines*) response spectrum for depths of 2 and 3 km, for which the ground motions from the corresponding tectonic earthquake would still be represented by the blue lines

2 and 3 km depth, which account for 70% of the simulated events in the PSHA calculations for induced earthquakes, it can be seen that the predicted motions are extremely high, the upper bounds indicating PGA values well in excess of 1 *g* (and these are only the median motions, on top of which there would be integration over the variability). Over the period range plotted, the mean spectral ordinates at these shallower depths are 1.9 and 2.2 times higher than the mean ordinates for the natural scenario. These motions result from the use of a GMPE (Atkinson 2015) which does not account for the reduction of stress drop at shallower depths, in addition to which the upper branches correspond to a version of the model with very little near-source saturation – although subsequent work concluded that the model with greater saturation, used for the lower branches, was to be preferred (Atkinson et al. 2016). Moreover, for the upper branch this doubly conservative model was scaled by a factor of 1.8 at 3 km and 1.86 at 2 km. Together with the artificially condensed seismicity activity (Sect. 4.2) and the large differences in M_{min} values (Sect. 4.4), these extreme ground-motion predictions are another factor likely to have contributed to the extreme dominance of induced seismic hazard shown in Fig. 4.

A clear pitfall exists therefore in potentially predicting excessively high amplitudes for shallow induced earthquake scenarios. As a general rule, if the seismic hazard contributions from natural and induced earthquakes are to be compared, ground-motion predictions for common scenarios should be the same. Some may not consider differences in predicted motions for shallow-focus induced and natural earthquakes of moderate magnitude as being of major consequence since tectonic earthquakes at such shallow depths and adjacent to the site will not usually be major contributors to the hazard estimate. Caution should be applied here because if the same ground-motion model was applied to such tectonic earthquakes, then these scenarios could become more significant hazard contributors. The more important point, however, is whether the differences indicate underestimation of the ground motions for such tectonic earthquakes or overestimation of the motions expected from an induced earthquake of the same magnitude and with the same hypocentre.

Achieving full consistency between the GMPEs applied to hazard assessments for natural and induced may be quite challenging, but as a minimum, comparisons should be made between the predicted response spectra for earthquake scenarios common to both seismic source models. The easiest way to achieve consistency, of course, is to use the same GMPEs for both induced and natural earthquakes. The key would be select GMPEs that are calibrated for the appropriate magnitude range and include an appropriate scaling with focal depth (that counteracts the effect of shorter travel paths). Such a feature is included, for example, in the NGA-West2 models as a function of depth-to-top-of-rupture (Abrahamson et al. 2014; Chiou and Youngs 2014) or hypocentral depth (Campbell and Bozorgnia 2014), although the degree of depth scaling varies appreciably among these models. The Boore et al. (2014) model, like any GMPE based on the Joyner-Boore distance metric, effectively models the effect of shorter travel path being completely cancelled by the stress drop reduction. In the NGA-East project, simulations identified a very strong depth dependence, similar to that proposed by Yenier and Atkinson (2015) in their ground-motion model for central and eastern North America (CENA), but the final NGA-East models (Goulet et al. 2021) adopted a weaker depth scaling based on the NGA-West2 models and a Fourier spectra model developed for CENA. The following text is worth of note: "*there is a significant depth dependence to ground motions for depths less than 10 km that is not captured in the NGA-East ground-motion models. On the other hand, this depth dependence might only be of practical importance for shallow, small-magnitude events. Most natural events occur at depths greater than 10 km, even those with small magnitudes. For this reason, although the effect of the depth variation on ground motions is substantial, it is primarily of importance mostly for PIEs* [potentially induced earthquakes]" (PEER 2015). In this regard it is notable that comparisons between the NGA-East model predictions and ground-motion recordings from induced earthquakes in Oklahoma, Kansas and Texas reveal systematic differences (Li et al. 2025c). The ideal approach may be to use the backbone GMPE approach for the constructing the logic-tree (Atkinson et al. 2014), selecting the backbone model on the basis of appropriate depth scaling. The construction of the full logic-tree through host-to-target adjustments (e.g., Boore et al. 2022) could then capture specific features of the shallower

induced earthquakes, such as more rapid attenuation with distance, while ensuring broad consistency in predictions for scenarios common to both the natural and induced seismicity models.

In the study of Babaie Mahani et al. (2025), the same GMPEs were adopted for both induced and natural seismicity, which addresses the issue of compatibility given that the uniform depth distributions assumed for natural (0–25 km) and induced (0–5 km) earthquakes clearly include overlapping scenarios. However, this consistency is undermined by the very different M_{min} values used; 4.8 for natural earthquakes and 3.0 for induced earthquakes. The adopted GMPEs – the eastern Canadian model proposed by Atkinson and Adams (2013) – is only calibrated for $M \geq 4.5$, so for the smaller induced earthquakes, the model had to be extrapolated to lower magnitudes. This was done by applying the average magnitude scaling in the range 4.5–8.0, which ignores both the steep scaling at lower magnitudes and the tendency to saturate at higher magnitudes (e.g., Douglas and Jousset 2011; Baltay and Hanks 2014). The resulting models for PGA and PGV are compared with those from empirical GMPEs derived for applicability from magnitude 3 and greater in Fig. 8.

The curves in Fig. 8 have been normalised to the predictions at **M** 4.8, which is the M_{min} applied in the PSHA for natural seismicity. As can be seen, the extrapolation by Babaie Mahani et al. (2025) leads to gross overestimation of the amplitudes at lower magnitudes. In light of the relatively weak scaling with magnitudes above **M** 4.8, that control the natural seismic hazard, and the very high recurrence rates of the smaller earthquakes included in the PSHA integrations, the combination of these two factors could explain a large part of the high ratios of induced to natural seismic hazard found in that study.

4.6 Fragility and consequence models

As noted previously, the first step in transforming hazard to risk should always be the application of fragility functions, calibrated to the characteristics of the exposed building stock, to estimate building damage. For higher damage states, and especially collapse, the duration of the shaking is likely to have some influence on the fragility, even though fragility functions are generally expressed in terms of the ground-motion or response spectral amplitude. Therefore, caution must be exercised in adopting fragility functions derived for larger magnitude tectonic earthquakes since these may lead to overestimation of the damage. To the extent possible, the risk model should be tested against observations, even if these are limiting to ensuring that the model does not predict extensive damage for scenarios in which damage was not observed. If the risk mitigation strategy for any project includes strengthening of the most vulnerable or most at-risk structures (Sect. 5.3), the fragility functions should reflect the seismic resistance of the retrofitted buildings.

Once building damage estimates are available, these can be transformed to other risk metrics using appropriate consequence functions. For many cases of induced seismicity, the focus is likely to be on the cost of damage and costs for repair and/or replacement should be calibrated to local building practices. A pitfall to be avoided is to project future costs from potential induced earthquakes on the basis of damage or insurance claims following previous events. The Basel EGS was finally closed down by a seismic risk assessment in which it was first estimated that continued operations could trigger an earthquake of M_L 4.5 and then estimated the impact of such an event by scaling from the insurance claims paid out following the M_L 3.4 event in December 2006 (see Sect. 2).

Another clear example of damage claims clearly exaggerating the physical impact of induced earthquakes is the Groningen gas field, also discussed in Sect. 2. The evolution of damage claims in Groningen, and the multiple factors influencing their exponential rise, is discussed in Bommer (2022). Figure 9 shows the value of the total damage claims in Groningen up to January 2025 compared with the economic losses reported for natural earthquakes of somewhat larger magnitude in comparable environments. The losses plotted for Groningen assume that 40% of the total claims are related to the largest (M_L 3.6) earthquake, which is potentially an underestimation. Given the relatively weak ground motions in Groningen (Fig. 1), there is no rational explanation for the impact implied by these damage claims, other than the damage being primarily due to other causes, such as differential settlement in soft soils.

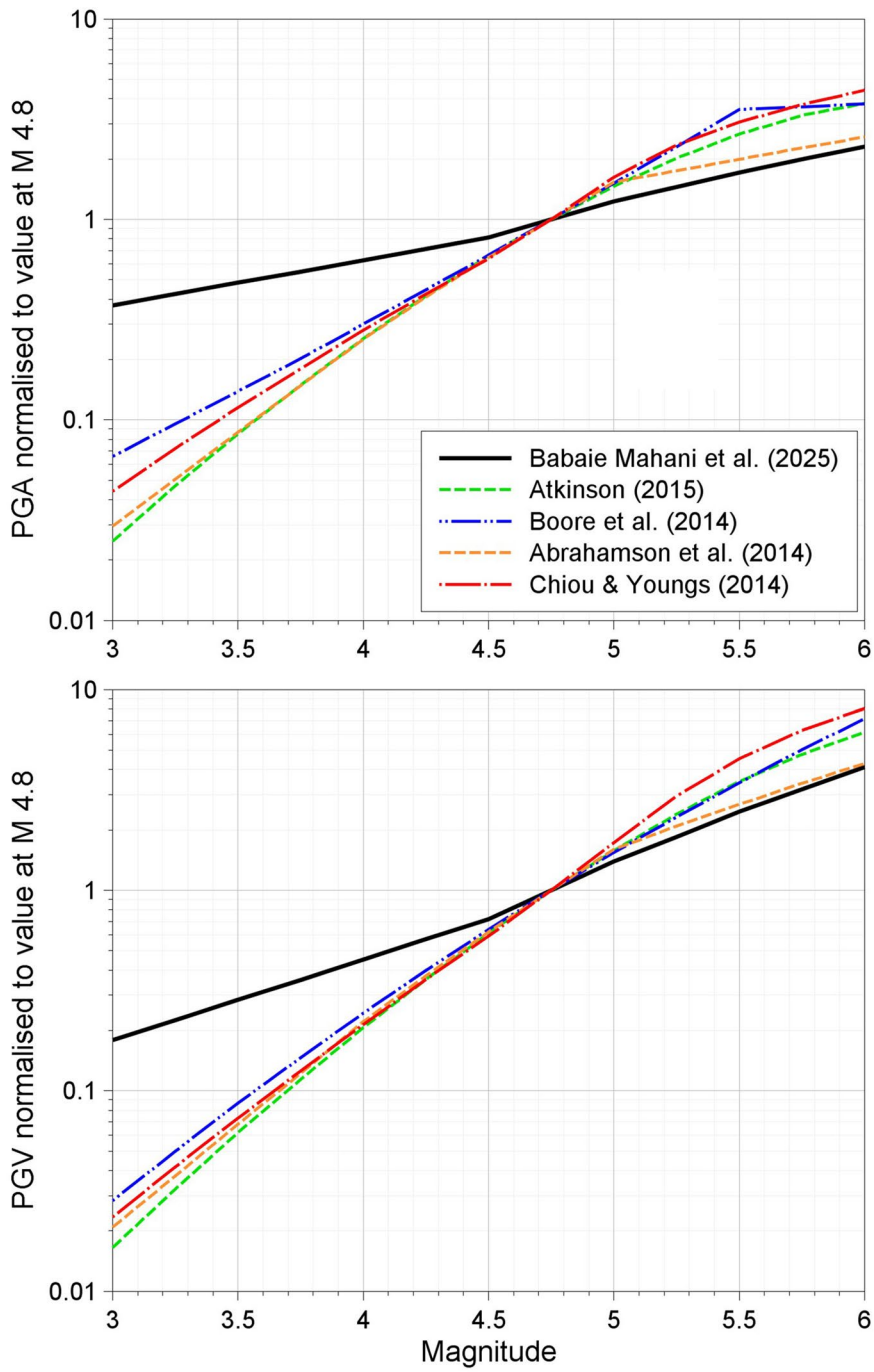


Fig. 8 Comparison of the magnitude scaling of PGA (*upper*) and PGV (*lower*) at short distances from the central GMPE of Babaie Mahani et al. (2025) with the scaling in the Atkinson (2015) model and the NGA-West2 models of Abrahamson et al. (2014), Boore et al. (2014) and Chiou and Youngs (2014)

5 Regulation of induced seismicity

Avoiding the pitfalls outlined in Sects. 3 and 4 goes a long way towards successful management of induced seismicity, but ultimately success depends on implementing effective measures within a clear regulatory framework. Whereas one might imagine that the most attractive situation for operators would be very lax or even absent regulation, there are several reasons why rigorous regulation by an empowered authority is in everyone's interest.

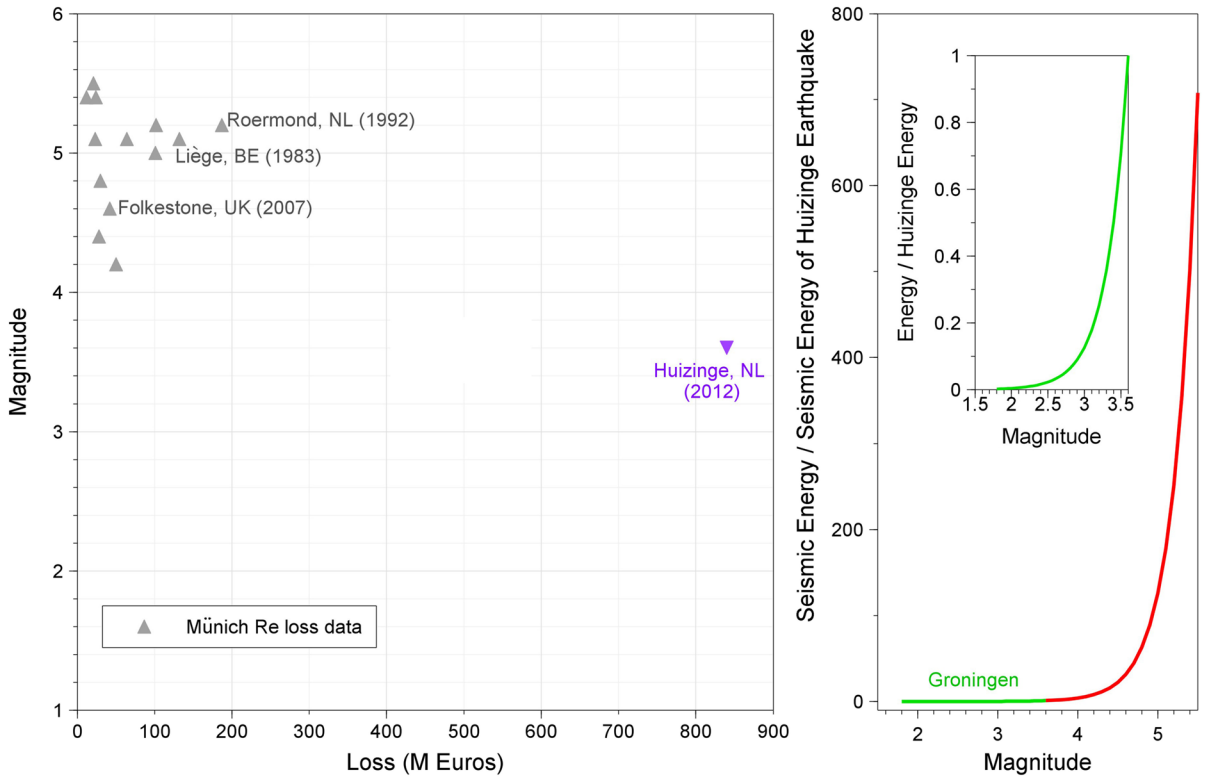


Fig. 9 *Left*: Economic losses due to earthquakes in countries with both GDP and construction practices comparable to the Netherlands (Australia, Belgium, France, Germany, US and UK), normalised to 2017 values using the national Consumer Price Index in order to account for inflation between the time of the earthquake and 2017, and the total damage claims attributed to the 2012 Huizinge earthquake in Groningen. *Right*: Seismic energy released by earthquakes as a function of magnitude, expressed as a ratio of the energy released by the Huizinge earthquake, with the smaller plot showing the same information for the range of magnitudes induced earthquakes in Groningen.

5.1 Experience of regulating induced seismicity

The case histories reviewed in Sect. 2 reflect a very heterogeneous approach to the regulation of induced seismicity. At one end, there are the actions taken by regulators in Oklahoma and other states to reduce the levels of induced earthquake activity (Davis and Fisk 2017; Stewart and Ingelson 2017), although these have not been entirely successful and it is worth noting that the Pawnee earthquake occurred five years after the Prague earthquake and was of even greater magnitude, suggesting that more could have been done earlier. There is also a very informative body of experience in the regulation of induced seismicity in western Canada (e.g., Shipman et al. 2018). At the other end there are projects that effectively operated without regulation, such as Pohang. In Basel, the project owner effectively turned into the regulator following the occurrence of induced earthquakes and laid the responsibility on the project operator. In the UK, hydraulic fracturing was regulated by one agency following unworkably severe restrictions set by another government department. In Groningen, despite unprecedented efforts and investment in the characterisation of the induced seismic risk and clear plans to reduce this risk through a targeted programme of building strengthening, the regulatory body seems to have set itself a mission to have gas production terminated, notwithstanding the far-reaching consequences of this action.

The inconsistent and, in some cases, erratic regulatory responses to induced seismicity reflect, to a large extent, the challenges that have been faced by regulatory authorities having to adapt to the emergence of the phenomenon of anthropogenically induced earthquakes. For agencies that exist to regulate the production of hydrocarbons or mining operations,

the emergence of induced seismicity has come as an unforeseen and unprecedented new responsibility, and one for which the required expertise is very often lacking (especially in those regions where natural seismicity is very sparse). In some cases, it has not even been clear which agency should have responsibility for regulating induced seismicity. In the US, for example, Finley (2015) and Richards (2015) discussed the possibility of the Environmental Protection Agency (EPA) regulating induced seismicity associated with injection wells. While federal guidelines for induced seismicity management would be beneficial, the environmental impact of induced earthquakes is very limited (damage to operations and associated leakages caused by earthquakes have not been documented).

The emergence and expansion of technologies that can cause induced seismicity, including horizontal drilling for hydraulic fracturing, EGS and CCS, have often resulted in fragmented approaches to regulation. For example, in the UK, different aspects of hydraulic fracturing were regulated by the OGA (including induced seismicity), the Environment Agency and the Health and Safety Executive. Such situations have led to proposals for "one-stop-shop" to regulation of EGS (Goldstein et al. 2010), which would be helpful in terms of placing induced seismicity management within the overall project management framework. Another serious element of the fragmentation is inconsistency across industries in terms of how induced seismicity is managed and the tolerable thresholds that are set. In the UK, for example, induced seismicity associated with coal mining was commonplace during several decades, with the largest earthquake reaching M_L 3.1 (Westbrook et al. 1980). Coal mining was a nationalised industry in the UK, operated by the National Coal Board, and there appears to be no specific reference to regulation of the associated earthquakes. EGS projects in the UK have generally been regulated by local (municipal) authorities, including setting limits (if any) for induced earthquakes. As was noted in Sect. 2, regulation of induced seismicity due to hydraulic fracturing for shale gas established a red-light threshold on the TLS of M_L 0.5, a threshold that has been matched and exceeded by rock concerts (Denton 2014; UCL 2024). In the Netherlands, the assessment of potential damage due to earthquakes induced by gas production assumes such damage could occur within an area defined by the distance at which the median PGV could reach 0.5 mm/s (TCMG 2019), whereas for geothermal projects, it is assumed that the damage area is defined by a median PGV of 3 mm/s (Mijnlieff et al. 2023). Such disparities undermine the concept of tolerable risk levels associated with induced seismicity and cloud the communication of risk, an issue discussed further in Sect. 5.3.

Discussions of possible frameworks for the management and regulation of activities that can induce seismicity often allude to environmental regulatory experience and legislation as possible reference frameworks. A framework that might be more useful and more relevant when it comes to the management of induced seismicity is the wealth of experience accumulated in the regulation for the safe operation of nuclear power plants in the face of external hazards, including earthquakes.

5.2 The nuclear model

The ideal situation is that the regulation of induced seismicity falls within the purview of an authoritative regulatory body charged with control and management of the industrial process that potentially could cause earthquakes, and also possessing the relevant technical expertise. If this is the case, then the practice of regulation of safety in the nuclear industry may offer a model that can be emulated in the regulation of induced seismicity in energy technologies. Nuclear regulators have extensive experience in managing the threat to the public and to the environment from radiation leakage due to internal accidents or external hazards, which may be natural or anthropogenic. In many cases, even in regions of relatively low seismicity, earthquakes are one of the main contributors to estimates of core damage frequencies because operational and physical barriers can reduce the impact of most other threats. The management of induced seismicity associated with energy technologies is distinct in two key regards, the first being that the threat to people and to infrastructure will generally be posed directly by earthquake shaking rather than the consequences of failures within the energy operation caused by earthquakes (i.e., NaTech). Another distinction is that the risk thresholds established for nuclear safety are generally independent of location since radiation leakage is to be avoided regardless of the number of people immediately exposed, whereas regulation of induced seismicity may – and, indeed,

should – take account of the exposure in the vicinity of the operations. Notwithstanding these subtle differences, the experience of the nuclear industry could still be very valuable for other regulatory bodies, not least because of the support and guidance that nuclear regulators receive from international bodies such as the International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency (NEA). These global organisations promote good practice in regulation (e.g., OECD 2024b), including specific actions to enhance public trust (OECD 2024a), which is fundamental to public acceptance of nuclear energy (e.g., Ryu et al. 2018).

There are five key characteristics of nuclear regulation that could be of enormous benefit if reflected in the regulation of induced seismicity in energy technologies:

1. ***Common objective***. Nuclear regulators share a common goal with nuclear operators, namely the operation of safe nuclear power plants. This leads to nuclear regulators generally adopting a facilitating role, in so much that they offer guidance to how operators can achieve this goal. As a governmental agency, the regulator's position should include consideration of the broader societal impacts related to the opportunity costs of not continuing with an energy project (e.g., revenue loss, national security, diplomatic leverage, energy independence, inflation). For the operator, the primary concerns will mainly be loss of the initial investment and loss of potential income (Bommer et al. 2015).
2. ***Setting risk targets***. At the heart of the regulatory criteria established for nuclear power plant operators is the specification of targets to be met in terms of risk, specifically in terms of initiating events that could lead to uncontrolled release of radiation.
3. ***Evaluation of operator's risk assessment***. The key to granting nuclear operating licences is the review and interrogation of the risk assessment leading to the conclusion that the safety targets are very unlikely to be exceeded. This will entail technical challenge and interrogation of the operator's models, for which the regulator will require appropriate specialists.
4. ***Acceptance of the risk***. Once a risk assessment is accepted, the regulator then assumes responsibility to provide assurance regarding the risk. While this does not preclude the option for the regulator to impose additional limitations (including forced shutdowns) on the operation in the event of unforeseen conditions, it does mean that under normal operating conditions, the regulator becomes jointly responsible for the safety of the operation, even though the ultimate responsibility for the risk remains with the operator. Given the uncertainties associated with induced seismicity, there is a potential pitfall in that in order to be willing to take partial responsibility for the risk, the regulator may feel obliged to adopt very cautious criteria for the risk limits. In the nuclear industry, substantial safety margins allow the regulator to perform this function of assuming the risk.
5. ***Public communication***. A very important consequence of the previous point is that the regulator becomes the spokesperson to the public regarding the operations and the associated risk.

Key to these principles is that a regulator must convey to the public that it only takes partial responsibility for the risk after thorough vetting—it is important for the public to be able to view the regulator as a watchdog rather than a collaborator. In the next section, the adaptation of and implications for the regulation of induced seismicity are briefly discussed.

5.3 Risk targets, risk acceptance and risk communication

As indicated above, the regulation of induced seismicity should ideally fall within the purview of an agency with overall responsibility for regulating the energy technology that could potentially cause earthquakes. Such an agency would have the objective of ensuring and facilitating the safe operation of such technologies, recognising and promoting the benefits of the processes in question. If induced seismicity becomes the responsibility of an environmental protection agency, then there is likely to be risk-averse approach that will increase the probability of curtailing the operations rather than seek balanced measures to mitigate the risk due to induced earthquakes.

The regulatory body should define risk targets for operators rather than imposing global limits of hazard that take no account of the local exposure. The risk

of disturbing the local population through episodes of felt shaking should not be the basis for these targets, since this will lead to excessively low thresholds (as discussed in Sect. 4.3). Such nuisance risk can be handled in many ways, as discussed below, and will also depend on the information provided to the local community and their attitudes towards the project: for green technologies or projects that generate local employment, there may be higher tolerance to felt shaking, although the concern that stronger (and damaging) levels of motion could ensue also needs to be addressed. In other situations, it might be that compensation schemes for nuisance could be devised, which could radically alter the response from local inhabitants. The approach adopted will be both location- and technology-specific, reflecting how the local population perceives the risks and benefits of the operations (e.g., Campbell et al. 2020; Tracy et al. 2021), noting that in surveys of local attitudes, responses may be influenced by how questions are framed (e.g., Evensen et al. 2022). While I have made the case for not basing TLS or regulatory limits on the basis of the nuisance caused by ground shaking, this should not be interpreted as meaning that such disturbance is unimportant, especially if people are subjected to repeated episodes of vibrations. From this perspective, it may be useful to define criteria for monitoring the nuisance levels, based on factors such as the frequency of felt shaking and/or the number of people affected.

The controlling risk targets for regulation, however, should be related to the possibility of low levels of damage in typical exposed buildings. This could be done in several ways, including invoking existing guidelines for tolerable levels of vibration related to the onset of damage – usually expressed in terms of peak ground velocity (PGV) – and then converting these to magnitudes on the basis of the relative locations of the operations and the buildings, local soil conditions and expected ground motion attenuation rates, for example.

A highly desirable feature of induced seismicity regulation would be for uniform risk targets across all technologies (and therefore across all regulatory bodies). While attitudes to nuisance risk may well vary with attitudes towards the operations in question, physical risk measures should be defined objectively and independently of the causative activities. This consistency would create a level playing field for all energy-related technologies. Such harmonisation would also be beneficial to promoting rational attitudes towards risk quantification and mitigation. For example, those wishing to 'weaponise' induced seismicity as part of opposition to fracking would need to understand that such actions would consequently militate against enhanced geothermal projects as well.

Once the risk targets have been defined by the regulator, it would then fall to the operator to make a quantitative assessment of the risk of potential induced seismicity. Such assessments should account for uncertainties but also map out how the risk estimates may be updated as data is gathered during operations. The assessment should also incorporate the expected benefits from mitigating measures such as the installation of monitoring systems and establishing a TLS; more traditional application of earthquake engineering, such as the seismic retrofit of the most at-risk buildings, should also be considered (Bommer et al. 2015), even though the practical challenges of implementing such measures for occupied buildings should not be underestimated. This risk assessment would then form the basis for the safety case to be submitted to the regulator.

The regulator would then review and evaluate the operator's safety case, likely asking for additional information and clarifications and possibly challenging some elements; the regulator would clearly need to engage appropriate expertise for such reviews. Through such an iterative process, it would be hoped that eventually concurrence would be reached in terms of the regulator agreeing that the operator's plans provided a high probability of compliance with the specified risk targets. The key development at this stage is that the regulator then accepts the risk due to induced seismicity, which it has determined to be sufficiently low. As noted previously, this does not in any way limit the regulator's ability to demand new actions – including reduction or cessation of operations – in the case of unforeseen levels of earthquake activity. The shared responsibility for the risk would also not mean that the regulator would become responsible for compensation for any damage caused by induced seismicity, although more coordinated and clearer approaches to that issue would be helpful (e.g., Konschnik 2016). What is does mean, however, is that the regulator becomes the interface with the public regarding the potential for induced earthquakes, the associated seismic risk and the mitigation

measures in place. The communication of these topics to the media and the public constitutes a major challenge (e.g., Trutnevyte and Ejderyan 2018). This has prompted extensive debate regarding not only how induced seismic risk should be communicated but also who should be charged with such communication and whether this should fall to politicians, operators, academics or others. When an effective and trusted regulatory body assumes responsibility for the risk and its management, this question becomes moot.

6 Conclusions

The threat posed by induced seismicity to energy technologies is not theoretical – many projects have already been curtailed or cancelled due to induced earthquakes, with the consequent undermining of confidence in the technologies.

In some cases, the reduction or suspension of operations in response to induced earthquakes has been well justified. Sustained injections into seismically sensitive formations have led to earthquakes large enough to cause damage, the only feasible risk mitigation option being to stop the injections. However, in other cases, the drastic response to induced earthquakes of small magnitude does not seem to have been a rational and technically justified course of action. It is vital to learn from those cases in order to prevent recurrence of these failures to manage induced seismicity in energy technologies. In this paper, I have presented a counterpoint to publications and practices that may reflect excessively conservative approaches to handling induced seismicity, with the intention of both challenging these positions and, hopefully, initiating discussion of these issues.

A key contributing factor has been exaggeration of the impact of small earthquakes, which makes it very important to clarify the true impact of the earthquakes that resulted in these shutdowns and to not continue blindly citing them as examples of how much damage can be caused by a small earthquake. Another very important factor in some cases has been unrealistically high estimates of the largest earthquake magnitude that could be induced – and the perception of these estimates as predictions. While it would clearly be helpful to change the way M_{max} is misunderstood, it would be timely to re-visit the way that this parameter is evaluated, even for natural seismicity. An action that would already go some way to avoiding this pitfall would be to make M_{max} estimates depth-dependent (e.g., Grigoratos et al. 2025b), which could also be implemented by defining magnitude-dependent focal depth distributions. Otherwise, if the seismic source model in a PSHA for induced earthquakes is going to include magnitude 6 earthquakes initiating at 2 km depth, a clear physical justification should be provided.

There are clear benefits from adopting or adapting well-defined protocols for the management of induced seismicity. Ideally these will be implemented within a clear regulatory framework, in which the responsible agency or agencies are identified and the risk targets agreed. The estimation of the risk posed by any potential induced seismicity should be quantified, carefully balancing the need to account for uncertainty and the pitfalls that can grossly overestimate the risk due to induced earthquakes – especially with respect to that posed by natural earthquakes. It is very important to avoid excessively low M_{min} values and to adopt appropriate distributions for M_{max}, that acknowledge how small the largest event might be and only assign very large magnitudes if these are physically realisable. Seismicity models must be calibrated to appropriately account for the spatial distribution of induced events and the duration of the operations. Particular challenges include the development of ground-motion models and fragility functions. The focus should always be, in the first instance, on physical risk and any empirical data used to calibrate such functions should be substantiated. The risk assessment should take account of all mitigation measures, which may include TLS and building strengthening.

Once the risk is quantified and the risk management plan agreed (including courses of action in the case of significant exceedances of the foreseen outcomes), the regulator should then become responsible for providing assurance regarding the risk to the public and other government agencies. The key is to be prepared to manage and communicate the risk ahead of time, with clearly defined responsibilities and requirements.

There should be no illusion that the ideal situation outlined herein would be easy to achieve, but the effort of pursuing it is well worthwhile given the potential consequences for key energy technologies, particularly those favourable to decarbonisation, being shut down. In the meantime, there is great

benefit to open documentation of both successful and unsuccessful cases of managing induced seismicity.

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Data availability The Groningen ground-motion data used to generate Fig. 1 are freely available for download as described in the paper by Ntinalexis et al. (2023). The coefficients for the GMPEs used to represent natural seismicity in Fig. 8 were downloaded from https://www.seismotoolbox.ca/2012GMPEs.html. The data in the left-hand plot of Fig. 9, except for Huizinge, were extracted from The Munich Re NatCatService database (Munich Re 2019).

Declarations

Competing interests The authors declare no competing interests.

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