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A Project Lifetime Approach to the Management of Induced Seismicity Risk at Geologic Carbon Storage Sites

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Abstract

The geologic storage of carbon dioxide (CO_2) is one method that can help reduce atmospheric CO_2 by sequestering it into the subsurface. Large-scale deployment of geologic carbon storage, however, may be accompanied by induced seismicity. We present a project lifetime approach to address the induced seismicity risk at these geologic storage sites. This approach encompasses both technical and nontechnical stakeholder issues related to induced seismicity and spans the time period from the initial consideration phase to postclosure. These recommendations are envisioned to serve as general guidelines, setting expectations for operators, regulators, and the public. They contain a set of seven actionable focus areas, the purpose of which are to deal proactively with induced seismicity issues. Although each geologic carbon storage site will be unique and will require a custom approach, these general best practice recommendations can be used as a starting point to any site-specific plan for how to systematically evaluate, communicate about, and mitigate induced seismicity at a particular reservoir.

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Introduction

Geologic carbon storage (GCS) is one technology that can reduce CO_2greenhouse gas emissions to the atmosphere by utilizing favorable hydrogeologic conditions to sequester CO_2 into the subsurface. However, increased subsurface fluid injection activity has led to an uptick of seismicity at some fluid injection sites, including near wastewater disposal sites, hydraulic fracturing sites, and engineered geothermal systems (EGS; Ellsworth, 2013; Keranen and Weingarten, 2018; Templeton *et al.*, 2020). This induced seismicity has raised concerns about the scalability of GCS considering the seismic hazard and risk associated with far-reaching subsurface pressurization and adjacent basement rocks (Zoback and Gorelick, 2012; White and Foxall, 2016).

Few commercial scale GCS sites exist that can be used as prototypes to study the induced seismic response. Two well-studied examples are the Illinois basin–Decatur (IDBP) project and the associated Illinois Industrial Carbon Capture and Sequestration Sources (IL-ICCS) project. To date, combined they have injected 2.8 million tons of CO_2 into the Mt. Simon saline sandstone reservoir and have detected nearly 20,000 seismic events with magnitudes between −2.1 and 1.2, although none have been felt at the surface (Williams-Stroud *et al.*, 2020). The IL-ICCS project moved the injection to a shallower zone in which a higher injection rate could be sustained with substantially lower seismic activity.

Although those two projects have been a success story in terms of induced seismicity management, a systematic strategy for dealing with induced seismicity is needed to be able to scale up, both in number and in injection volumes. This strategy should additionally be able to incorporate the fact that several GCS sites may be operating simultaneously within the same basin for extended periods of time, thus potentially posing a hazard to a much larger region. Zhou *et al.* (2010) modeled a scenario for 20 injection sites in the Illinois basin spaced approximately 30 km apart, each injecting about 5 Mt/yr over 50 yr. The modeled pressure behavior is observed to have an early stage in which individual injection well pressurizations do not interfere. This is followed by an intermediate phase in which transient pressure interference is observed between the injection sites and is followed by a final phase in which a continuous pressure buildup is driven by the combined behavior of all injection sites within the basin.

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Therefore, having a common systematic framework in which to evaluate, manage, communicate about, and mitigate the risk of induced seismicity will be necessary to help facilitate the expansion of GCS. The EGS community has previously taken this approach by adopting a proactive set of protocols and recommended practices for induced seismicity management (Majer *et al.*, 2012, 2016; Wiemer *et al.*, 2017). We have created a set of GCS focused recommended practices based on the EGS approach of Majer *et al.* (2012, 2016), as many of the induced seismicity issues are similar and a project lifetime approach is also used, which is essential for GCS sites. We add to their base recommendations by incorporating important lessons learned over the last decade and including details specific to GCS. The substance of the recommended practices contained herein includes both technical and nontechnical issues. Subsequently, we summarize recent key learnings that helped to inform our method and present the seven steps included in our approach. The recommendations described herein are also discussed more thoroughly and with greater detail in an expanded technical report available online (Templeton *et al.*, 2021).

Key Lessons Learned in the Last Decade

Regions with low to moderate natural seismic activity may produce induced earthquakes in excess of M 4

Prior to 2009, Oklahoma and Kansas had shown very little seismic activity. Although the national seismic hazard map (Petersen *et al.*, 2008) identified a slightly elevated hazard, the area would not have been classified as high hazard. However, the start of large-scale wastewater disposal into the Arbuckle group initiated significant earthquake activity across an area about 200 km in width, including an **M** 5.8 event in Pawnee, Oklahoma, in September 2016 (Chen *et al.*, 2017; Schoenball *et al.*, 2018). Other examples of industrial activities inducing larger magnitude events include an **M** 5.3 event in the Raton basin (Rubinstein *et al.*, 2014), an **M** 4.1 event offshore the coast of Spain (Cesca *et al.*, 2014; Cesca *et al.*, 2021), an **M** 4.1 event in Alberta, Canada (Schultz *et al.*, 2017), and an **M** 5.4 earthquake connected to an EGS development in Pohang, South Korea (Lee *et al.*, 2019). Though GCS sites have not seen comparable seismicity, the hazard exists and should be considered.

Seismogenic response to fluid injection may vary strongly from site to site and between different injection intervals

In the case of Oklahoma, Langenbruch *et al.* (2018) have shown that the probability of fluid injection to induce earthquakes may vary significantly across spatial distances on the order of tens of kilometers. In addition, at the Pohang EGS site, the seismic response to injection in two boreholes, for which injection interval was less than 1 km apart, was markedly different although injected fluid volumes were comparable (Lee *et al.*, 2019). At the Decatur GCS site, a large number of small events were induced by injection into the lower Mt. Simon Sandstone, whereas fewer events were induced by injection at a higher injection rate in the shallower middle Mt. Simon Sandstone in the same borehole (Williams-Stroud *et al.*, 2020).

Regional trends of the seismogenic response to fluid injection do exist

Although it is difficult to forecast the induced seismic response to fluid injection at a new site, operating experience collected at neighboring field sites can often be applied to other local projects. For example, there have been several examples of regional trends, both for large seismic responses (e.g., the Arbuckle formation in Oklahoma and Kansas) and for almost no seismic response (e.g., the Williston basin in parts of Montana, North Dakota, South Dakota, and Canada) associated with nearby fluid injections (Skoumal *et al.*, 2018).

Seismicity may be induced tens of kilometers away from large-scale injection

Long-distance seismicity has been observed, for example, in Oklahoma (Keranen *et al.*, 2014; Goebel *et al.*, 2017; Schoenball *et al.*, 2018) and Kansas (Peterie *et al.*, 2018). The occurrence of seismicity farther away from injection implies that stress changes much smaller than 1 MPa may be sufficient to trigger seismicity even in naturally quiescent areas. Recent studies, involving hydromechanical modeling, indicate that effective stress changes on the order of 100 kPa or less can found near earthquake hypocenters, which supports the observation of long-distance seismicity (Keranen *et al.*, 2014; Barbour *et al.*, 2017; Norbeck and Rubinstein, 2018; Zhai *et al.*, 2020).

Even faults capable of magnitude 5 earthquakes may be previously unknown

In many of the induced seismicity cases, faults that hosted even the largest events >**M** 5 were not known beforehand. This is not exclusive to induced seismicity cases. Even natural events, such as the 2014 Napa earthquake, often occur on blind faults (Brocher *et al.*, 2015). This can be related to the difficulty of imaging faults in basement rocks or the lack of vertical offset in the sedimentary overburden from subvertical strike-slip faults. Even focused efforts on imaging the fault that produced the **M** 5.8 Pawnee earthquake on 3D seismic data produced ambiguous results (Kolawole *et al.*, 2019).

Induced seismicity is driven by high fluid volume injection

Weingarten *et al.* (2015) and Schultz *et al.* (2018) show that the potential for inducing earthquakes in wastewater disposal and hydraulic fracturing, respectively, correlates positively with the total injected fluid volume and the rate of injection. Although large-scale wastewater disposal has occurred in Oklahoma since at least 1995, seismicity has only been observed when the volume has been increased significantly. This is the case since the beginning of 2006 in central Oklahoma and 2012 in northern Oklahoma. Based on this observation of long-term, low-rate fluid injection in Oklahoma with no observed seismic response before 2009, Langenbruch and Zoback (2016) postulate the existence of a threshold injection rate below which no triggering of earthquakes would be observed.

The Approach

We integrate these key lessons learned into a set of recommended actions that make up a project-wide and project-lifetime approach to induced seismicity risk management, specifically at GCS sites. We follow general risk management approaches (Fischhoff, 2015) and apply them to the induced seismicity case. The recommended practices can be subdivided into seven steps:

Step 1: Preliminary seismic risk screening evaluation.
Step 2: Outreach and communication.
Step 3: Thresholds of ground motion for damage and vibration.
Step 4: Collection of seismicity data.
Step 5: Hazard evaluation of natural and induced seismic events.
Step 6: Risk-informed decision analysis.
Step 7: Operational management of induced seismicity risks.

Step 1—Preliminary seismic risk screening evaluation

The preliminary seismic risk screening evaluation step aims to determine a preliminary seismic risk category for one or more GCS sites that are being considered for future significant investment. If one of the candidate sites is ultimately selected, it will be necessary to subsequently complete a more detailed seismic risk analysis. The preliminary screening can be subdivided into seven focus areas highlighted subsequently.

Review of local, state, and federal laws and regulations. The relevant local, state, and federal laws and regulations should be assessed to determine if the effects of induced seismicity, however minor or unlikely, are barred. An assessment of damage liability requirements should also be conducted at this time.

Review of prior injection-induced seismicity cases. To obtain a qualitative evaluation of the susceptibility of the candidate site to induced seismicity, a seismicity review of nearby or similar GCS projects across a wider regional trend should be completed. If no similar GCS cases can be identified, the assessment should instead focus on a review of other fluid injection projects, such as gas injection projects, in similar hydromechanical settings (Cesca *et al.*, 2014; van Thienen-Visser and Breunese, 2015).

Region of concern of potential seismic events. A preliminary estimate of a region of concern (ROC; i.e., the ground surface area that could be negatively impacted by induced seismic events) should be determined. This will require an estimate of the potential maximum magnitude-induced seismic event ($M_{\max}$), the potential locations of such an event, and any surface ground motions associated with it. At this early stage, simplifying assumptions in the input parameters will be necessary. For example, it could be assumed that $M_{\max}$ would be spatially limited by the extent of the pore pressure perturbation zone (Shapiro *et al.*, 2011; McGarr, 2014; Yeck *et al.*, 2015), by local tectonics and stress (van der Elst *et al.*, 2016; Galis *et al.*, 2017; Norbeck and Horne, 2018; Li *et al.*, 2021), or simply by similarity to observed events in similar settings. The hypothetical location of the maximum magnitude event will also need to be assumed, taking into consideration any local tectonic trends and the observation that induced seismicity events can occur even tens of kilometers away from injection sites. For the ground-motion estimates, ground-motion models (GMM) specifically developed for induced events should be preferentially chosen or developed when possible (Bommer *et al.*, 2016). The ROC could then initially be defined as the area over which felt ground motions could occur.

Potential impacts within the ROC. Items and activities that may be impacted within the ROC can include physical damages to buildings and infrastructure, social disturbances, nuisance, economic disruption, and the effects of secondary environmental hazards (landslides, liquefaction, seiches, etc.) (National Research Council [NRC], 1989). This assessment should be carried out with early input from local stakeholders to ensure it includes all items and activities of concern, thus building consensus and trust between all parties. Preliminary estimates can include the population distribution in the region and simple building inventories taken from existing databases. Impacts of concern may vary depending on whether the region's population has previously been exposed to some level of natural seismicity and whether the buildings and infrastructure have been built according to appropriate seismic building codes.

Estimation of potential impact magnitude. A qualitative estimation of the magnitude of potential impacts should be calculated and can, for example, encompass the number of people who would feel an $M_{\max}$ event and the number of structures that could potentially be damaged by it. A general scenario loss model, providing estimates of economic losses and fatalities using global models and databases, should also be performed (Jaiswal and Wald, 2011). In addition, framing the comparison in terms of the impact due to a series of scenario events of increasing magnitude can provide a structured way to present the information.

TABLE 1
Overall Preliminary Seismic Risk Categories with Recommended Decision Pathways

Very Low	Low	Medium	High
Proceed with planning	Can proceed with planning but may require additional analysis to confirm	Probably should not proceed at this site, but additional analysis might support proceeding	Do not proceed

Adapted from Majer *et al.* (2012).

Assessment of local stakeholder risk tolerance. The level of stakeholder concern regarding the project, used to calibrate the risk scale to an individual location, should be assessed with the understanding that different communities may have different seismic risk acceptance levels and that these risk acceptance levels may differ based on real or perceived risk associated with the GCS technology. Incorporation of stakeholder input allows for a more robust sociotechnical approach to risk governance, even at this early stage. Stakeholders can include community leaders, governmental agencies, tribal governments, regulators, public safety officials, nongovernmental organizations, the general local community, and so on.

Overall seismic risk of the planned operation. An integrated assessment of the seismic risk of the planned operation can be developed by combining the information from the technical and social factors. There are many methods by which the overall seismic risk related to an individual site may be assigned to broad seismic risk categories, such as those specified in Table 1. One such method is to create a grid and define what each category of risk would entail for each of the potential impacts, similar to the Geothermal Risk of Induced seismicity Diagnosis (GRID) method proposed for Switzerland (Trutnevyte and Wiemer, 2017). Ultimately, the threshold for an unacceptable risk would be project specific and dependent upon a host of factors.

Step 2—Outreach and communication

A GCS-induced seismicity component to a project's general Outreach and Communication (O&C) program to facilitate communication and maintain positive relationships with stakeholders will need to be developed. Across all stages of project planning, operation, and decommission, it is critical that stakeholders are kept informed and that their input is considered and acted upon in a timely and meaningful way. There is no one size fits all approach to O&C. It is expected that each project will need to prepare an individualized O&C plan that addresses the specific local issues associated with the project site (Ground Water Protection Council and Interstate Oil and Gas Compact Commission [GWPC and IOGCC], 2017) and that it will also include any requirements made within the risk-based mitigation plan (step 7). Nonetheless, any O&C program should strive to adhere to the general working principles associated with the theory of stakeholder engagement and to build on previous experience associated with siting major energy and nonenergy projects to achieve fair and efficient consensus building amongst all stakeholders (Suskind, 1990). This should include the institution of a broad-based participatory process, obtaining broad agreement that the project is an improvement over the status quo, obtaining stakeholder consensus regarding the project plan, providing adequate communication with stakeholders that stringent safety standards are being met, making a commitment to both fully address negative aspects of the project with stakeholders, and committing to develop and maintain stakeholder trust. All O&C programs should also incorporate an induced seismicity and GCS education component.

Step 3—Ground-motion thresholds

Site-specific ground-motion thresholds, which would minimize nuisance and damage risks, will need to be determined. These nuisance and damage thresholds should be determined after assessment of the local population distribution, building conditions, and stakeholder risk tolerance. Information from this step will be used for the design of a seismic monitoring program (step 4) and as a site-specific baseline against which subsequent induced seismicity hazard and risk analyses results (steps 5 and 6) can be juxtaposed. In addition, a subset of the threshold levels identified in this step may be used to inform the traffic light threshold levels within the risk-based induced seismicity mitigation plan (step 7).

Review of existing standards and criteria. Federal, state, and local standards regarding ground motions should be reviewed to determine if any regulatory criteria are applicable within the ROC. In addition, ground-motion thresholds relevant to the nuisance risk (i.e., Foulger *et al.*, 2018) should be reviewed. Finally, a review of threshold ground-motion levels that may cause cosmetic damage or structural damage to different types of buildings and infrastructure within the ROC will be necessary.

Assessment of site-specific conditions. An assessment of the building and structure types within the ROC should also be conducted, using the preliminary assessment conduced in step 1 as a starting point. Particular attention should be paid to identifying fragile structures, historical structures, and other structures of particular importance to the local community. Particularly in regions of low natural seismic hazard, the building stock may not be engineered to withstand ground shaking and so even moderate earthquakes may lead to significant damage. In addition, an assessment of sensitive local industrial equipment, activities, and institutional land use areas that may be impacted by elevated levels of ground shaking should be conducted within the ROC.

Designate site-specific ground-motion thresholds. At least four ground-motion threshold levels should be quantified. They are (in no particular order): (1) the threshold for humans to perceive ground shaking; (2) cosmetic and structural damage thresholds for each type of building and infrastructure within the ROC; (3) ground motions that may affect local equipment and activities within the ROC; and (4) ground-motion limits that are stipulated in federal, state, or local regulations.

Step 4—Collection of seismicity data

Seismic data needs to be gathered, analyzed, and archived during the lifetime of the GCS project. These data are needed for varying activities. One is to accurately assess and periodically reassess the natural and induced seismic hazard and risk associated with the project. A second is to aid in the rapid and effective detection and characterization of the seismicity at the site. This is especially needed as input into induced seismicity mitigation plan protocols (e.g., traffic light systems).

Seismic activity before operations. To understand the potential for induced seismicity at a new project location, it will be necessary to first identify any nearby past and present seismicity in the area and the faults on which they originate. A region much larger than the ROC should be chosen to explore to ensure that wider regional trends are considered in the seismic hazard assessment. This consideration reduces the possibility of overlooking infrequent but possibly large events that could impact the local hazard. National, state, or regional seismic networks are typically not sensitive enough to detect the level of seismic activity that should be recorded at local sites. Installing or augmenting an existing local monitoring network will be required to understand the response of the project site to injection operations. The local network should be active for at least 6 months–1 yr prior to operations commencing. GCS operators who are working in the same basin should cooperate to share data.

Seismic monitoring network design. The seismic monitoring network should be designed to detect and characterize seismicity down to at least **M** 1 and should be able to record all expected felt ground motions at the surface due to those events. Local monitoring networks should include a combination of high-gain sensors, which can optimally record weak ground motions from small local earthquakes, and low-gain accelerometers, which can optimally record strong ground motions from nearby larger earthquakes. The network should be designed to record and locate seismicity with at least a 2-sigma location accuracy of 0.5 km in the horizontal direction and 1.0 km in the vertical direction. The network should be equally sensitive across the ROC because it should be able to measure even strongly varying seismogenic responses between different GCS injection sites within the same basin. Various approaches are available to help design such seismic networks at local and regional scales (e.g., Kraft *et al.*, 2013).

Seismic monitoring network operation and reporting. The seismic monitoring network should be operating continuously from the preoperational background assessment phase until postclosure when the level of detected seismicity approaches the background rate. Although there may be legitimate operational reasons to briefly embargo data to ensure quality control and accuracy of interpretation, it is highly recommended that an open-access data approach for the waveforms and earthquake catalogs be taken when engaging with the public and any other GCS operators working in the same basin. This will improve community trust and the overall state-of-knowledge of the GCS reservoir and of GCS-induced seismicity in general. In addition, summary reports should be made publicly available at least annually, which could include information on recent observed induced seismicity, the seismic network metadata, any related seismic information, such as the applied seismic velocity model, and results from any advanced analysis conducted on the data, such as event relocation or moment tensor analysis.

Step 5—Hazard evaluation of natural and induced seismic events

The purpose of this step is to estimate the ground shaking hazard at the proposed site and within the ROC due to natural tectonic seismicity and the additional hazard due to induced seismicity using probabilistic seismic hazard analysis (PSHA). Assessing the ground shaking hazard from natural seismicity will provide a baseline from which to evaluate the additional hazard from induced seismicity. This step should be performed before any operations are initiated at the site, repeated as needed during the early evaluation period, and at least yearly thereafter. Results from this seismic hazard evaluation will be input into the subsequent risk-informed decision analysis (step 6).

Baseline hazard from natural seismicity. The baseline seismic hazard will focus exclusively on ground shaking hazards associated with natural tectonic seismic events that could impact the site infrastructure (to inform any hazard mitigation procedures) and the local population (to allow for ease of comparison of the natural and induced hazard and risk). PSHA is recommended when calculating the baseline seismic hazard at a particular GCS. PSHA involves obtaining, through a formal mathematical process, the level of a selected ground-motion parameter (e.g., PGA, PGV, etc.) that has a selected probability of being exceeded (e.g., 0.01% probability, 10% probability, etc.) during a specified time interval (e.g., 50, 5000 yr, etc.) at a particular location due to future earthquakes. A variety of computer programs are publicly available that can be used to perform site-specific PSHA, such as the free and open-source software OpenQuake Engine (Pagani *et al.*, 2014). Several others have also been validated by the Pacific Earthquake Engineering Research Center, including the OpenSHA program, the HAZ program, and EZ-FRISK (Hale *et al.*, 2018). These hazard and risk analyses will also help better define the ROC. Throughout the lifetime of the project, it is expected that the PSHA analysis will need to be updated if future geological, seismological, or geophysical investigations reveal significantly new and different information than that used in the original analysis.

Additional hazard from induced seismicity. The probabilistic short-term seismic ground shaking hazard forecast for GCS-induced seismicity is determined generally the same as for the long-term approach, with adjustments made for different source and GMMs to accommodate the differences between induced and natural seismicity. These short-term forecasts, incorporating both natural and induced seismicity, should be periodically computed during the lifetime of the project. These forecasts should ideally be for one-year duration or shorter, depending on the planned injection schedule. In addition, it is recognized that although it may be possible to make some estimates ahead of the initial injection program, real forecasting power requires actual observations of the seismic response to injection tests to calibrate and validate the forecasting models and assumptions made in the initial assessment. Because of this, and only in the time period before injection starts, either a full probabilistic hazard analysis or a pseudoprobabilistic hazard assessment could be appropriate (Cornell, 1968; Edwards *et al.*, 2021). The short-term probabilistic seismic hazard forecast will necessarily need to be systematically checked and updated. Predictions will need to be continuously calibrated against new observations. If different GCS operators are working in the same basin, it is recommended that they share input parameters and models (e.g., 3D geological models) that inform their short-term forecasts.

Step 6—Risk-informed decision analysis

Conceptually, this step is similar to the preliminary seismic risk assessment in step 1; however, instead of aiming for an order of magnitude assessment, a more precise estimate of risk is required. Results from the risk informed decision analysis described here will be tightly coupled with the risk management framework described in step 7.

Seismic risk from natural seismicity. Seismic risk is calculated from three main contributing factors: the seismic hazard at locations within the ROC; the collection of exposed assets, activities, and communities at those locations; and their vulnerability to the hazard (McGuire, 2004). Calculating a site-specific risk due to natural seismicity will allow for a quantitative comparison between the accepted natural seismicity risks and the potential additional induced seismicity risks associated with the project. Seismic risk analysis can provide results in a variety of forms and should be tailored to the site (Jonkmann *et al.*, 2003). There are a variety of seismic risk assessment software packages available to assess seismic risk due to natural tectonic seismicity. Some are open and freely available (Lang *et al.*, 2007; Porter and Scawthorn, 2007; Trendafiloski *et al.*, 2009; Federal Emergency Management Agency [FEMA], 2013; Pagani *et al.*, 2014; Silva *et al.*, 2014, 2018), whereas others are provided by commercial risk management companies that can also perform the analysis for a fee.

Seismic risk from induced seismicity. The induced seismicity seismic risk analysis will facilitate sound and efficient decision making relating to induced seismicity. Seismic risk assessment methodologies applied to a site in the design phase, for example, can highlight unacceptable potential future damages prior to operations, when plans can be more easily modified and the risk iteratively reassessed so as to come to a risk level acceptable to stakeholders (Silva *et al.*, 2021). Early on, much of the research into, and applications of, induced seismic risk had focused on the impact of lower probability, higher impact moderate-to-large earthquakes (Grigoratos *et al.*, 2021). Moving forward, injection-induced seismicity risk began to more frequently incorporate smaller magnitude earthquakes, which may cause significant nuisance to the local population but only relatively minor physical damage to structures (van Elk *et al.*, 2019; Edwards *et al.*, 2021). Although the fundamentals of risk estimation do not change for small ground-motion events, the models used in the characterization of these risks will need to be calibrated for the lower amplitudes of ground shaking and shorter distances often associated with induced seismic events. In addition, the hazard and risk analysis should be revisited periodically during the operational period of the project and after site closure, especially if observed seismicity differs significantly from the expected location or rate.

Risk-informed decision analysis. Risk-informed decision analysis can facilitate decision making both prior to and during injection operations. Risks associated with different injection programs, especially those considered high-volume or high-rate flows, which have been shown to increase the potential for induced seismicity, can be independently evaluated and assessed. Incorporating the risk tolerance of the stakeholders with the risk analysis results will allow for informed decision making at all levels. Risk-tolerance matrices are one method that can estimate the intersection between the risk tolerance of stakeholders with the expected benefits of the project (Walters *et al.*, 2015). The risk tolerance of the local stakeholders may be able to be modified through outreach and education associated with the O&C program (step 2) by demystifying the GCS technology.

Step 7—Operational management of induced seismicity risks

A site-specific, real-time plan to monitor, assess, control, and mitigate the risks associated with induced seismicity during and after fluid injection is necessary. The framework of the risk-based mitigation plan should be based on a traffic light system (TLS), which can provide clear and direct actions to take in response to given situations according to predetermined criteria.

Induced seismicity mitigation plan. An induced seismicity mitigation plan should be in place before any injection operations begin. The framework of the plan should be based on a TLS protocol with at least three or more response levels corresponding to a continuation of operations as planned (green); heightened awareness and revisiting of injection operations due to concerning observed seismicity or trends (yellow); and stopping of injection due to an unacceptable level of induced seismicity (red) (NRC, 2012). Although a traditional TLS typically defines the actions to be taken solely in response to the occurrence of certain observed criteria (e.g., the occurrence of a seismic event above a certain magnitude or a level of surface ground shaking above a certain threshold), an adaptive traffic light systems (ATLS) with physics-based forecasting methods, can help to inform operation decisions, such that elevated risk levels might not be reached in the first place (Fig. 1). An ATLS is fully probabilistic, incorporates new data automatically as much as possible, and naturally integrates hazard, exposure, and vulnerability into the system (Wiemer *et al.*, 2014; Mignan *et al.*, 2017; Langenbruch *et al.*, 2020). In this way the hazard and risk calculations originally produced in steps 5 and 6 can be automatically updated as new data and models becomes available.

Expert panel. An expert panel should be formed to provide evidence-based information and recommendations pertaining to the induced seismicity risk posed by the project. The panel should serve as a forum in which the operator, the regulatory agency, other stakeholders, and independent subject matter experts will be able to monitor and assess the induced seismicity and develop recommendations for necessary operational responses, increased seismic monitoring, more detailed analyses, and other mitigation measures. Expert panels and expert elicitations have proven successful particularly in the presence of substantial epistemic uncertainties, such as at a greenfield site and investigating the potential for induced seismicity (Trutnevyte and Azevedo, 2018). Because the ROC may be extensive, it may overlap with other uses of the subsurface or with the ROC of another GCS project or other injection operations. If several ROCs overlap, the probability of inducing seismicity is determined by the sum of individual projects contributions (Dempsey and Riffault, 2019). Therefore, the task of managing induced seismicity should be addressed by a larger group of stakeholders including representatives from all subsurface projects for which ROCs may overlap.

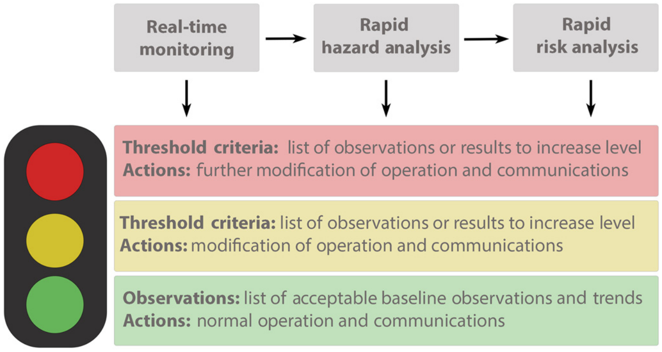

Figure 1. Example adaptive traffic light system. Real time seismic, hydraulic, and operational monitoring can either directly increase the response level or indirectly help inform rapid hazard and risk analyses that may prompt a change in response level due to updated results. The color version of this figure is available only in the electronic edition.

Early evaluation period. The first year of injection operations should be considered an early evaluation period. During the early evaluation period, the seismogenic and hydrologic behavior of the target reservoir and underlying basements units should be continually analyzed to calibrate, verify, and/or update the preinjection models and parameters. Forecasts of the level of induced seismicity derived from preinjection assessment using estimated values are likely to be of limited value without this calibration and verification step.

Late evaluation period. After operations cease at the site, seismic monitoring, the O&C plan, and the induced seismicity mitigation plan should continue until the pressure stabilizes, stress perturbations achieve steady-state values, and it is established that the seismic frequency–magnitude behavior is approaching baseline tectonic conditions, as measured in step 4.

Liability and insurance. Liability and compensation coverage for damages cause by GCS-induced earthquakes should be included in the induced seismicity mitigation plan as a last means of indirect mitigation. Such indirect mitigation has been used in EGS contexts in the past (Giardini, 2009). Operators should be sufficiently covered or demonstrate sufficient assets to self-insure against damages from induced seismicity. In areas where several GCS operators are active, an induced event may occur because of the sum of all activity in the vicinity (e.g., Dempsey and Riffault, 2019). Therefore, it may be sensible for operators to pay contributions to an insurance fund that would then compensate for any damages resulting from induced seismicity in a shared ROC.

Conclusions

GCS is a technology that promises to remove greenhouse gas emissions from the atmosphere by injecting captured CO_2 into deep subsurface rock formations for long-term storage. One inherent risk associated with this technology is induced seismicity. Here we present a suite of seven recommended focus areas, which when combined would be able to help evaluate, manage, communicate, and mitigate the induced seismicity hazard associated with GCS projects. These recommended practices can serve as general guidelines to proactively deal with induced seismicity issues, setting expectations for operators, regulators, and the public. Although each carbon storage project will be unique and will require a custom approach, these general science-based recommended practices can be used as a starting point for any site-specific induced seismicity risk management plan.

Data and Resources

No data were used in this article.

Declaration of Competing Interests

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