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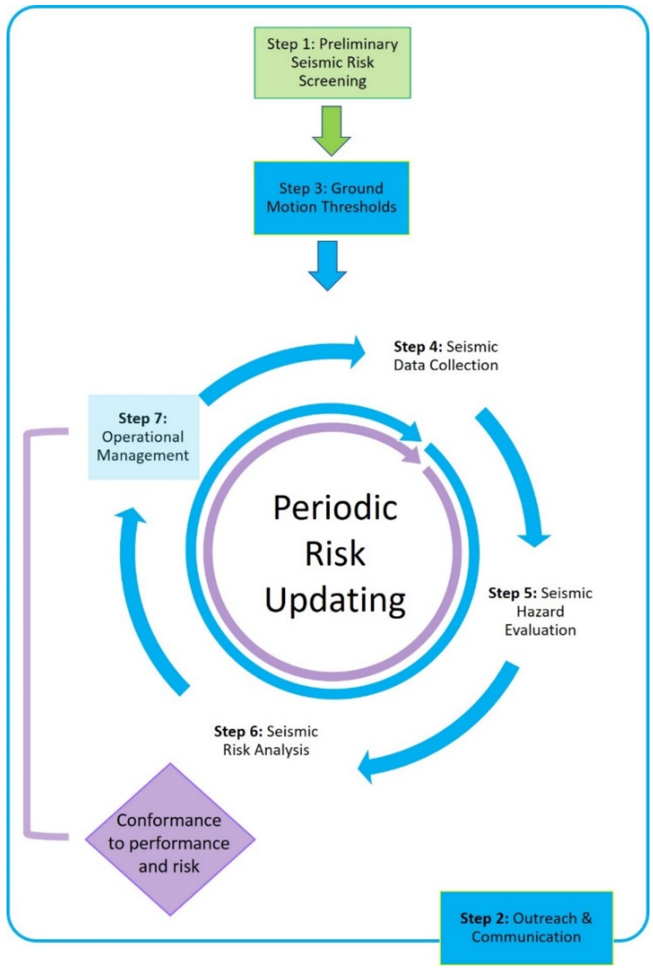

Recommended Practices for Managing Induced Seismicity Risk Associated with Geologic Carbon Storage

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Recommended Practices for Managing Induced Seismicity Risk Associated with Geologic Carbon Storage

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Acronyms, Abbreviations, and Symbols

Term	Description
2D	Two-dimensional
3D	Three-dimensional
ANSI	American National Standard Institute
ATLS	Adaptive traffic light system
CO_2	Carbon dioxide
CEUS	Central and Eastern United States
CEUS-SSC	Central and Eastern United States – Seismic Source Characterization
DOE	Department of Energy
DSHA	Deterministic seismic hazard analysis
EGS	Enhanced geothermal system
EPA	U.S. Environmental Protection Agency
FTA	Federal Transit Administration
GCS	Geologic carbon storage
GEM	Global Earthquake Model
GMM	Ground motion model
GPS	Global positioning system
GRID	Geothermal risk of induced seismicity diagnosis
IRIS-DMC	Incorporated Research Institutions for Seismology Data Management Center
ISO	International Organization for Standardization
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkley National Laboratory
LLNL	Lawrence Livermore National Laboratory
M_C	Minimum magnitude of completeness
MMI	Modified Mercalli intensity
MRI	Magnetic resonance imaging
M_w	Earthquake moment magnitude
NEIC	National Earthquake Information Center
NETL	National Energy Technology Laboratory
NRAP	National Risk Assessment Partnership
O&C	Outreach and communication

Acronyms, Abbreviations, Symbols (cont.)

Term	Description
PAGER	Prompt Assessment of Global Earthquakes for Response
PGA	Peak ground accelerations
PGV	Peak ground velocity
PISC	Post-injection site care
PNNL	Pacific Northwest National Laboratory
PSHA	Probabilistic seismic hazard analysis
PSHF	Probabilistic seismic hazard forecast
PSZ	Perturbed stress zone
RMS	Root-mean-square
ROC	Region of concern
SA	Spectral acceleration
SNR	Signal-to-noise ratio
TLS	Traffic light system
UCERF	Unified California Earthquake Rupture Forecast
USDW	Underwater source of drinking water
USGS	United States Geological Survey

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EXECUTIVE SUMMARY

The geologic storage of carbon dioxide (CO_2) is one method to help reduce or eliminate atmospheric CO_2 emissions. The sequestered CO_2 is originally captured from the atmosphere or from a stationary industrial source and subsequently injected into a deep subsurface porous rock formation. To facilitate the successful deployment of field scale carbon storage projects, the U.S. Department of Energy (DOE) is developing tools and protocols for defensible, science-based frameworks to quantify and mitigate risks associated with the long-term storage of CO_2.

This protocol specifically addresses the risk of induced seismicity due to injection in a geologic carbon storage (GCS) site. This integrated and risk-based protocol is a product of the U.S. DOE Fossil Energy's National Risk Assessment Partnership (NRAP), a multi-year collaborative research effort of Los Alamos National Laboratory (LANL), Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), National Energy Technology Laboratory (NETL), and Pacific Northwest National Laboratory (PNNL).

These recommended practices describe a set of 7 steps to evaluate, manage, communicate, and mitigate the risk of induced seismicity at GCS sites. The base methodology of the recommended practices follows a framework similar to the *Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems* (Majer et al., 2012), developed for the Geothermal Technology Office of the U.S. DOE.

These recommended practices present a framework to systematically assess the induced seismicity risk and quantify the associated uncertainties. These recommendations are based on current research and are sufficiently general to allow for modification and application to a variety of different types of sites. The substance of the recommended practices contained herein includes both technical and non-technical issues, and covers all operational stages of the GCS project lifecycle. They start at the preliminary risk assessment phase, continue through site assessment and characterization, include best practice communication and seismic monitoring plan methodologies, discuss the evaluation and mitigation of seismic hazard and risk, and closes with an exploration of operational management plans, which conclude when the induced seismicity risk abates back to background level.

The focus of these recommendations is on actively managing the risks associated with induced seismicity by developing an actionable risk management plan that starts at the project proposal stage and continues through site closure through an iterative assessment and improvement process. The audience of this document is expected to include all interested stakeholders (e.g., operators, project developers, regulators, and the general public) and is expressly written to be accessible to this broad range of partners.

This document is intended to disseminate knowledge gained through recent advances in the science of induced seismicity hazard and risk assessments, to provide updates based on recent experience gained by similar corollary injection-induced seismicity cases, and most importantly to establish a uniform framework to carry out a successful induced seismicity risk management plan for carbon storage projects in the future. These recommendations do not directly address any domestic or international regulations or standards. A complementary NRAP report makes recommendations for the assessment and management of environmental subsurface risks associated with unwanted fluid migration at GCS sites (Thomas et al., 2021) and should be referred to in order to address those additional GCS site risks.

INTRODUCTION

Geologic carbon storage (GCS) is a technology promising negative greenhouse gas emissions by injecting captured carbon dioxide (CO_2) into deep subsurface rock formations for long-term storage, thereby removing CO_2 from the atmosphere and sequestering it in underground reservoirs of porous rock. GCS is one cutting edge climate solution that can help address the global climate crisis. An inherent risk associated with this technology, however, is induced seismicity. Injection operations can modify the existing subsurface conditions thereby creating the potential for induced seismic events. Risks associated with that potential induced seismicity must be appropriately assessed and managed for GCS to be successful (White and Foxall, 2016). The goal of this document is to provide a suite of recommended practices to effectively evaluate, manage, communicate, and mitigate the induced seismicity hazard and risks associated with GCS projects. These recommended practices will serve as general guidelines to proactively deal with induced seismicity issues, setting expectations for operators, regulators, and the general public. While 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.

These recommended practices follow general risk management approaches and apply them to the induced seismicity problem (Fischhoff, 2015). The general risk management process involves:

- Preliminary risk analysis to identify and assess potential hazards
- Complete risk analysis for a more formal estimation of the magnitude of the risks
- Complete risk assessment to evaluate the acceptability of the risks
- Consideration of control mechanisms to mitigate risks
- Monitoring to assess if actual observations follow expected behavior
- Effective risk communication with potentially affected stakeholders across all project stages

A similar base methodology is followed in the *Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems* (Majer et al., 2012; 2016), developed for the Geothermal Technology Office of the U.S. Department of Energy (DOE) to address each of these areas. Here, the geothermal protocol is adapted to include insights from recent scientific developments in state-of-the-art evaluation, mitigation strategies, and modify the focus to highlight issues specific to GCS. The recommended practices for addressing induced seismicity associated with subsurface injection can be subdivided into the following 7 steps:

Step 1: Preliminary Seismic Risk Screening Evaluation

Step 2: Outreach and Communication

Step 3: Ground Motion Thresholds

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

This document is structured such that each of the seven steps includes: a) a Purpose section, b) a Recommended Practices section, and c) a Supporting Information section. While the Purpose section briefly describes the role of each step in the overall induced seismicity management plan, the Recommended Practices section serves as a list of actionable items to fulfill in order to successfully address the induced seismicity risk. Finally, the Supporting Information section describes the reasoning behind the recommendations in detail and includes references to the pertinent scientific literature.

While this document strives to be as quantitative as possible and outline actions, methods, and procedures that represent the application of current state-of-the-art best practices, it is recognized that additional approaches and methods will be developed in the future and that these recommended practices will inevitably evolve. Additionally, this document attempts to take a policy-neutral position such that the recommendations do not attempt to specifically address current policies or regulations. Specific tools and methods are not prescribed here and are, therefore, left to the discretion of the user of this recommended practice guide.

1. STEP 1: PRELIMINARY SEISMIC RISK SCREENING EVALUATION

1.1 PURPOSE

The purpose of this step is to determine an initial probability of success of candidate sites before investment of substantial resources, here initial success is defined as the ability to inject and sequester the supercritical CO_2 into a deep geologic formation without inducing significant seismic activity of concern for the operators and other stakeholders. The preliminary seismic risk screening evaluation is based on simple methods and acceptability criteria with the goal of determining a go/no-go decision for future planning. Investigations should focus on any issues that could impede a candidate site's licensing or acceptance by local stakeholders due to seismic risk factors. The preliminary evaluation should be conducted with sufficient rigor to allow the operator to make an informed decision as to whether a site is a good candidate for further study and potential development. Information resulting from this preliminary evaluation can also be used to support early technical communications with local stakeholders. This step assumes that an overall candidate site selection screening—based on geology, hydrology, and other physical considerations—has already been completed.

1.2 RECOMMENDED PRACTICES

1.2.1 Preliminary Classification of Site-Specific Seismic Risk

1.2.1.1 A preliminary site-specific seismic risk assessment should be completed to qualitatively classify potential seismic risk into one of four general categories: (I) Very Low, (II) Low, (III) Medium, or (IV) High (Table 1). This assessment should include, but is not limited to:

a) A review of local, state, and federal laws and regulations relevant to seismicity
b) A review of prior cases of injection-induced seismicity in comparable operational and geological settings
c) An initial estimate of the Region of Concern
d) A listing of the potential impacts to the local community within the Region of Concern
e) An estimation of the magnitude of the potential impacts
f) An assessment of local stakeholder risk tolerance
g) An integrated assessment of the overall preliminary seismic risk of the planned operation, based on a weighted combination of factors (a)–(f)

Table 1: Overall Preliminary Seismic Risk Categories with Recommended Go/No-Go Decisions (Modified from Majer et al., 2012)

I. Very Low:	II. Low	III. Medium	IV. 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.

1.3 SUPPORTING INFORMATION

1.3.1 Preliminary Classification of Site-Specific Seismic Risk

Seismic risk is formally evaluated based on a combination of the seismic hazard, the level of exposure of the population and built environment to the seismic hazard, and the vulnerability to shaking of the buildings and infrastructure within the risk area (McGuire, 2004). However, Step 1 is not intended to require extensive calculations, comprehensive research, or the development of extensive databases on seismicity and building vulnerabilities. It is instead a qualitative assessment of seismic risk, providing an informed but subjective evaluation based on simple bounding methods to determine if a project may have some obvious flaws that may prevent success in the short or long term.

The screening analysis for some projects may be quite clear. For example, a planned low-volume injection at a remote site with no active hazardous faults or local seismicity, and broad stakeholder approval, could be categorized as a clear Level I, while fluid injection at a heavily populated site with multiple mapped active faults and little public support could be a clear Level IV (Table 1). For those projects in all but category Level IV, which should be discarded after initial screening, this process will also highlight the aspects contributing to risk that will need to be addressed if the project were to move forward. If a candidate site is ultimately selected, a more detailed and complete seismic risk analysis will need to be subsequently performed. Each site is individual and will require customized treatment.

(a) Review of Local, State, and Federal Laws and Regulations

The relevant local, state, and federal laws and regulations should be assessed to determine if any effects of induced seismicity, however minor or unlikely, are barred. An assessment of damage liability requirements should also be made. At a minimum, documentation should include a list of the laws and regulations reviewed.

(b) Review of Prior Injection-Induced Seismicity Cases

To obtain a broad qualitative evaluation of the susceptibility of the site to induced seismicity, a review of prior cases of GCS injection-induced seismicity should be completed. This assessment should include a review of previous GCS sites with injection-induced seismicity, suspected induced seismicity, or no measured seismicity, ideally in a similar geologic province and reservoir size as that of the project. If no relevant GCS cases can be identified, the assessment should also include a review of studies investigating induced seismicity associated with other types of fluid injection operations in similar hydro-mechanical settings, such as at gas injection projects for example (Cesca et al., 2014; van Thienen-Visser and Breunese, 2015). In these cases, a description of how the operation and/or fluid mechanics are different from GCS should be included.

The purpose of this review is to attempt to incorporate regional-scale and operational trends associated with induced seismicity (Skoumal et al., 2018; Weingarten et al., 2015; Scanlon et al., 2019). Examples of observed trends can include the abundant induced seismicity in Oklahoma connected to wide-spread wastewater disposal in the Arbuckle group and the lack of injection-induced seismicity in the Williston Basin in north-central United States where large-scale fluid disposal is also occurring (Skoumal et al., 2018). Similarly, operational trends that influence the likelihood of injection-induced seismicity should be documented (Weingarten et al., 2015; Scanlon et al., 2019). This evaluation will allow the operators to incorporate general trends into the decision-making process since the causative mechanisms of induced seismicity and the geomechanical conditions at injection sites are diverse and involve many poorly constrained or unknown parameters. Significant uncertainties as to the likelihood of inducing seismicity can persist even after careful characterization as it may not be fully understood why some operations can cause significant induced seismicity while others do not. A matrix approach, where a variety of factors (e.g., injected volumes, depth, reservoir formations, level of natural tectonic seismicity, etc.) are identified and compared may be able to provide a structured mechanism by which to view and organize the information for this qualitative assessment (e.g., Trutnevyte and Wiemer, 2017).

Documentation should include an overview description of the sites used for comparison including a justification for why the selected sites are suitable for comparison to the project site (e.g., geologic setting, population density, building stock, etc.). Furthermore, operational parameters (e.g., injection duration, total injected fluid volume, maximum injection pressure, nature of injected fluid, etc.) and a description of previously observed induced seismicity should also be provided from those sites. Induced seismicity at comparative sites should also be quantified by the rate and cumulative number of earthquakes above a given minimum magnitude of completeness (M_c) as well as the maximum observed earthquake magnitude. The frequency magnitude distribution, which describes the occurrence rate of earthquakes across a range of magnitudes, of the observed seismicity should also be described to understand the productivity (i.e., the rate of seismic activity in a pre-defined spatio-temporal volume) and the potential of the seismicity. For reference, the M_c is the minimum magnitude above which all earthquakes in a certain area are expected to be reliably detected and located. M_c can depend on many factors including subsurface attenuation, site noise, and the distribution of the seismic monitoring network. M_c can also have a time-varying component, since M_c is progressively reduced as the density of a seismic monitoring network is increased over time. The spatial and temporal evolution of M_c, and the uncertainties associated with the M_c estimate, should be noted to add context to the evaluation of historical observations and to describe the propagation of these uncertainties when calculating seismicity parameters, such as the b-value in Gutenberg-Richter distributions (Woessner and Wiemer, 2005; Hutton et al., 2010).

(c) Region of Concern of Potential Seismic Events

An estimate of the Region of Concern (ROC) should be prepared. The ROC defines the ground surface area that could be negatively impacted by induced seismic events occurring at depth throughout the lifetime of the project. In practice, the ROC can be governed by many factors, such as the reservoir size, local geology/hydrology, distance to known faults, natural background seismicity, the in-situ state of stress, potential induced seismicity magnitudes and locations, and expected fluid injection rates, volumes, and injection pressure. In practice, the ground surface area that could be negatively impacted by these seismic events would be expected to expand as the fluid injection program progresses and the CO_2 migrates away from the wellbore. The ROC however describes the total area of concern over the lifetime of the project, but may still be updated over time as new data becomes available. In this Step however, the goal is to obtain only a first order approximation of the ROC. An estimate of the potential maximum magnitude induced seismic event, the location of such an event, the ground motions associated with such an event, and an estimate of the ground motion threshold above which negative impacts would occur are critical to estimating the ROC.

To produce a first order estimate of the maximum magnitude injection-induced seismic event, it is necessary to make simplifying assumptions. One assumption that can be made is that the induced event would be spatially limited by the extent of the pore pressure perturbation zone, thus scaling with the total volume of fluid injected (McGarr, 2014; Shapiro et al., 2011; Yeck et al., 2015). This assumption would produce a lower bound on the actual potential maximum magnitude induced seismic event, since it ignores site-specific stress conditions and tectonic factors that have been shown to be important at other locations (Bhattacharya and Viesca, 2019). Other maximum magnitude models attempt to incorporate tectonic constraints on maximum earthquake size (van der Elst et al., 2016; Galis et al., 2017; Norbeck and Horne, 2018). These tectonic constraints attempt to incorporate the observation that subsurface stress changes propagate much further out than subsurface pore-pressure changes and that these stress changes would then be interacting with the pre-stressed crust around the reservoir. Observations from hydraulic fracturing projects, for example, using relatively small fluid volumes have been linked to a M_w4.6 earthquake in Canada (Atkinson et al., 2016). Similarly, injection of a rather modest fluid volume associated with an enhanced geothermal system (EGS) has been connected to a M_w5.4 earthquake in Pohang, South Korea (Kim et al., 2018; Lee et al., 2019; Yeo et al., 2020). The largest induced earthquake to date attributed to fluid injection activities documented in the scientific literature is a M_w5.8 event in central Oklahoma (Barbour et al., 2017).

An alternative method to estimate the size of potential injection-induced events at the sites under consideration at this early stage would be to use comparable fluid injection scenarios from similar geological conditions. An operator may also consider a series of scenario earthquakes (e.g., an M_w3.5, M_w4.5, and M_w5.5 at reservoir or basement depth) to assess how the ROC may vary with the often significant uncertainty associated with the maximum event size.

The hypothetical location of the maximum magnitude event, or scenario events, should be assumed for this estimate. For example, it may be appropriate to assume that early in the injection program, induced events would only occur near the injection zone. A discussion of where induced events may occur later in the injection program should be included. For example, some induced earthquakes due to fluid injection in the central U.S. appear to be connected to injection areas located tens of kilometers away, but along trends consistent with regional basement structures (Peterie et al., 2018).

Ground motion estimation for the assumed maximum magnitude event sizes at the assumed locations using general empirical relationships or comparable events is also acceptable at this stage. Broadly applicable empirical ground motion relationships between key parameters (magnitude, distance, surface shear wave velocity, etc.) and earthquake ground motions (peak or spectral acceleration, velocity, displacement, Mercalli intensity, etc.) are available for both tectonic events and more recently for induced events (for example, see Petersen et al. (2018) for a list of commonly used ground motion models (GMM) included in the creation of the U.S. national seismic hazard maps or McNamara et al. (2018) for an evaluation of GMMs for induced and tectonic events in the Central and Eastern U.S.). GMMs specifically developed for induced events should be preferentially chosen or developed when possible (Bommer et al., 2016). Also, whenever possible, site-specific parameters that consider local characteristics and geology should be included within the simplified scope of this step. Applying several potentially appropriate GMMs to this calculation would also be advisable to attempt to account for uncertainties within the models. Augmenting an existing seismic network could also be considered in order to help inform these preliminary analyses.

After the expected ground motions are calculated for an area, an estimate of the ground motion threshold above which negative impacts would occur in the region, such as where ground motions are expected to be recorded above the background noise level, would define the preliminary ROC. The ROC would subsequently be modified as new information is collected in this and later steps.

At a minimum, documentation for this Step should include: 1) an estimate of one or more potential maximum magnitude seismic events that could be induced by fluid injection in the reservoir; 2) an estimate of the locations where these events could occur; 3) an estimate of the ground shaking that could be associated with such events along with a description of how the shaking was calculated; 4) an estimate of the ground motion threshold above which negative impacts would be expected to occur; and 5) a description and estimate of the key uncertainties in the above preliminary analyses (e.g., GMMs, M_c, maximum magnitude event size, etc.).

(d) Potential Impacts to the Local Community Within the Region of Concern

Potential impacts to the local communities located within the ROC should be identified. These should include physical damages, social disturbances, nuisance, economic disruption, and the effects of secondary environmental hazards (landslides, liquefaction, seiches, etc.). This assessment should be carried out with early input from local stakeholders to ensure it includes all impacts that are of concern, thus building consensus and trust between all parties. Impacts of concern may vary depending on if the region's population has previously been exposed to some level of natural seismicity and if the buildings and infrastructure have been built using earthquake resistant designs.

Preliminary estimates of the population distribution and building/infrastructure inventories within the ROC should be determined. A crude order of magnitude estimate of the building inventory within the ROC is acceptable at this stage. Inventory data can include the number of residential buildings, commercial buildings, government facilities, schools, historical buildings, religious facilities, essential facilities (fire stations, police stations, hospitals, emergency operation centers, etc.), transportation lifelines (highways, airports, rail, ports, bridges, etc.), utilities (water, electricity, sewage, etc.), and potentially hazardous facilities (tank farms, refineries, dams, levees, liquefied natural gas plants or storage areas, chemical plants, nuclear plants, pipelines containing hazardous materials, unreinforced masonry buildings, etc.) (NRC, 1989).

At a minimum, documentation should include: 1) a description of potential impacts; and 2) an estimate of the number of people, structures, and industries that might be exposed to impacts of concern within the ROC. Particularly fragile or high-consequence infrastructure should be highlighted.

(e) Estimation of Potential Impact Magnitudes

A description of the potential impacts due to at least two induced events of different magnitudes, including a representative average induced seismicity magnitude event and the estimated worst-case scenario maximum magnitude event, should be included. Potential impacts can include a description of the number of people and structures that would reasonably be expected to be affected by each of the scenario events and the type of impact that would be reasonably expected. This can be based on the estimated ground motions that would be produced by the events, the population and preliminary building inventory estimates, and potential event locations. For the estimated worse-case scenario event, a general scenario loss model, providing estimates of economic losses and fatalities using general global models and databases, should also be performed (e.g., Jaiswal and Wald, 2011). There are various methodologies available for the estimation of losses due to larger earthquakes, including those focused on rapid estimations for large global earthquakes, based on differing factors of increasing complexity. All methods require some engineering and seismological expertise in order to interpret the results. 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.

Additionally, a preliminary comparison between potential impacts due to natural tectonic events and potential induced events should be conducted. An assessment or literature search should identify any tectonic events that may have occurred in the region and a map and catalog should be created for seismic events which have occurred within at least 200 km from the reservoir. This should include a description of their locations, mechanisms, and a description of the network and catalog quality. Baseline expected ground motions from one or more representative natural (tectonic) seismicity can be estimated using available data and simplified methods reliable enough to give an order of magnitude estimate. These potential ground motions and potential impacts can be estimated similar to the induced events and subsequently compared. The definition of what level of ground shaking could potentially cause a negative impact should be clearly stated (e.g., peak ground acceleration ≥ 0.01 g, Modified Mercalli Intensity ≥ III, etc.). This preliminary analysis could also start to illuminate if natural tectonic seismicity may be of concern for the site's infrastructure or reservoir as well.

Alternatively, the long-term probabilistic seismic hazard across the U.S. can be obtained from the regularly updated national hazard maps (USGS, 2019; Petersen et al., 2018; Petersen et al., 2014). In the past United States Geological Survey (USGS) hazard maps also included short-term probabilistic seismic hazard forecasts for the central and eastern U.S., but no new maps have been published since 2018. These baseline estimates could then be qualitatively compared with the induced seismicity ground motion estimates, recognizing that this is not a like-for-like comparison, but rather a general comparison of the two.

Documentation should include, at a minimum: 1) a description (map, tables, etc.) of the number of people and the number and type of structures that might be affected by each of the events; 2) the type of impact (nuisance, possible cosmetic building damage, possible minor or significant structural damage, etc.) to be expected based on ground motion estimates; 3) a qualitative comparison between the baseline hazard/ground motions from natural seismicity and the expected ground motions from the induced seismic events and, if applicable, expected ground motions from scenario natural tectonic events; 4) a description (time, location, and magnitude) of any nearby seismic events up to at least 200 km from the reservoir along with a description of the network and catalog quality; and 5) a description and estimate of the key uncertainties in the above preliminary analyses.

(f) 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 risk acceptance levels. Incorporation of stakeholder input allows for a more robust socio-technical approach to risk governance, even at this early stage. It should be noted that the process of soliciting input regarding risk can itself change how people perceive risk (e.g., by raising concerns about a risk they were not previously aware of or alleviating concerns by knowing that competent personnel are looking into the issue). Therefore, the solicitation process should be planned and carried out with care, ideally by an individual or team with experience in this specialist area (e.g., social scientists). The solicitation process should also highlight the positive impacts of the project, such as the benefits of releasing less greenhouse gases into the atmosphere and any local benefits.

Documentation should include a determination of the level of impact perceived to be acceptable by all stakeholders (regulators, community, operator, etc.) for each of the risk factors.

(g) Overall Seismic Risk of the Planned Operation

An integrated assessment of the seismic risk of the planned operation is developed by combining the information from the technical and social factors. Outreach and transparency play an important role in the determination of overall seismic risk. The threshold for unacceptable risk is project- and operator-specific and is dependent upon a host of factors.

There are many methods by which the overall seismic risk related to an individual site may be assigned to the broad seismic risk categories specified in Table 1: (I) Very Low, (II) Low, (III) Medium, or (IV) High. Individual risks can be categorized and ranked in terms of the likelihood of occurrence and the severity of the consequence. Acceptability criteria needs to be clearly defined for the various risk factors in each of the categories. The more specific the criteria, the easier it will be to communicate the risks to all stakeholders. 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).

Documentation should include a summary of the project and of the dominant risk issues, the preliminary seismic risk category for the project and a description of the factors that went into determining the risk category, the final decision regarding whether or not to pursue the project, and a brief discussion of the factors which influenced the decision-making process. Key uncertainties that would substantially alter the current assessment should be noted.

2. STEP 2: OUTREACH AND COMMUNICATION

2.1 PURPOSE

The purpose of this step is to develop an induced seismicity component to a project's general Outreach and Communication (O&C) program to facilitate communication and maintain positive relationships with stakeholders (e.g., community leaders, governmental agencies, tribal governments, regulators, public safety officials, non-governmental organizations, the general local community, etc.). 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. Stakeholder acceptance is a necessary component of any project. A successful O&C program will help facilitate that goal. Each O&C program will be site-specific and will require a custom approach. This section describes a general set of principles and engagement options founded on both the theory of stakeholder engagement as well as informed by previous experience with siting major energy and non-energy projects.

2.2 RECOMMENDED PRACTICES

2.2.1 Site-Specific Outreach and Communication Program

2.2.1.1 A site-specific O&C program should be implemented and reviewed annually. The program should include an induced seismicity component based on the following principles:

a) Institution of a broad-based participatory process
b) Broad agreement that the project is an improvement over the status quo
c) Broad stakeholder consensus regarding the project plan
d) Communication with stakeholders that stringent safety standards are being met
e) Commitment to fully address negative aspects of the project with stakeholders
f) Commitment to develop and maintain stakeholder trust

2.3 SUPPORTING INFORMATION

2.3.1 Site-Specific Outreach and Communication Program

There is no one size fits all approach to O&C. It is expected that each project dealing with the potential for induced seismicity will need to prepare an individualized O&C plan that addresses the specific local issues associated with the project site (GWPC and IOGCC, 2017) and the requirements within the Risk-Based Mitigation Plan (Step 7). It is expected that the effort expended on this step may vary significantly from site to site. 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 non-energy projects to achieve fair and efficient consensus building amongst all stakeholders (Kunreuther and Suskind, 1991). The O&C program should also integrate concepts of relationship management theory between organizations and the public so as to establish and maintain a positive and mutually beneficial relationship with the local community and other stakeholders (Ledingham and Bruning, 1998; Ledingham, 2003). The induced seismicity component described herein is expected to be part of the general outreach, communication, and education plan for GCS projects (NETL, 2017). The O&C plan should be reviewed in its entirely at least annually to ensure that it is meeting stakeholder needs. The O&C plan should also be periodically evaluated. This evaluation could include developing surveys, semi-structured ethnographic interviews, and/or media and social media analyses to help determine the success of the plan amongst the local community and other stakeholders.

(a) Institution of a Broad-Based Participatory Process

Stakeholder groups (e.g., local communities, governmental agencies, tribal governments, regulators, public safety officials, non-governmental organizations, etc.) who may be impacted by injection-induced seismicity associated with the project should be identified early in the process and preliminary discussions should be held to explain the project and determine stakeholder concerns. In particular, people and organizations who have the trust of the community at large should be engaged in these early discussions. These early-stage discussions could focus on communicating with elected and other local officials, and with various local civic organizations. At later stages, representatives from all stakeholder groups, including the community at large, should be invited to participate in the project at the appropriate level. Evaluating opinions and concerns in the early stages of the project will ensure that the outreach is responsive to the stakeholder community.

(b) Broad Agreement that the Project is an Improvement Over the Status Quo

General stakeholder acceptance of a project typically starts with an agreement that the project is needed (Meller et al., 2018). Public education and outreach efforts can include information regarding the consequences of not moving forward with the project (i.e., maintaining the status quo), in particular emphasizing the impact to the community's citizens. Discussions should include the relevant policies and context, including how the project could meet broader societal goals in addition to meeting local stakeholder needs as well.

(c) Stakeholder Consensus Regarding the Project Plan

All stakeholders should have the opportunity to communicate their comments and concerns to ensure that the project plan is ultimately beneficial to the local community. Technical expertise should be augmented with local knowledge. Alternative approaches, along with their short-term and long-term implications should be included in public discussions and framed in both technical and non-technical language, depending on the audience involved. Vigorous public debate about the pros and cons of the project also should be supported. Gaining an in-depth understanding of the diverse concerns of the community will allow the project proponents to gain better insights into how the project can support the community. This information exchange will also help provide context into the reasons behind the underlying views of the community about the project risks and benefits.

Information that should be disseminated to stakeholders over the course of the project includes: a general overview of the project, the motivation for conducting the project, what potential surface structures might look like, how the project was funded, and who is on the team. It might be desirable to include public institutions (e.g., USGS, public universities) and private organizations (e.g., consulting companies) selected to provide third-party assessments or peer-reviews in the discussions. This information should be disseminated during all phases of the project.

Specific seismic related information to include in stakeholder interactions should include explanations about:

a) Why induced seismicity may occur

b) The history of induced seismicity in other applications
c) The similarities and differences between induced seismicity and natural earthquakes (e.g., frequency, location, etc.)
d) The potential risks to the community
e) The risk mitigation strategies, including a description of the thresholds that will be used for triggering mitigation strategies
f) The monitoring systems (e.g., seismic monitoring and fluid injection monitoring) and associated analyses to be performed
g) Where to obtain more information about seismicity data gathered by the operator (e.g., frequently updated website with earthquake catalog information)

Even early communications should clearly distinguish the differences between potential induced seismicity associated with GCS and other types of subsurface fluid injection projects, such as wastewater injection and hydraulic fracturing. From the beginning, local communities and other stakeholders should be kept informed about induced seismicity in general and about what they could expect in particular.

(d) Communication with Stakeholders that Stringent Safety Standards are Being Met

Stakeholders should be informed of all best practice safety standards with respect to induced seismicity mitigation that will be implemented at the project site. This should include all mandated actions and best practice recommendations, as detailed in the Risk-Based Mitigation Plan (Step 7), and responsibilities of the local safety officials. Moreover, the communication team should ensure that robust communication mechanisms exist between the project and local safety officials both prior to and during any potential seismic event of concern to help the local communities mitigate, prepare, and respond to any potential felt seismic events. Stakeholders should also have an opportunity to recommend additional safety standards that would be of importance to the local host community.

(e) Commitment to Fully Address Negative Aspects of the Project with Stakeholders

To prepare for potential future negative impacts (e.g., nuisance vibrations, property damage, etc.), stakeholders should be fully informed of all potential negative impacts and come to an agreement as to how to report potential negative impacts (e.g., a call-in phone line, webpage, etc.) and the forms of compensation and mitigation measures that would be acceptable if such an event were to occur. This will ultimately be documented in the Risk-Based Mitigation Plan (Step 7). Any discussion of induced seismicity risks should be framed in the proper context, potentially through a comparison with the local natural seismicity or other common risks.

(f) Commitment to Develop and Maintain Stakeholder Trust

Lack of trust between groups can become a barrier to reaching consensus and acceptance of a project. Project proponents should address potential sources of mistrust (e.g., lack of local support, previous negative experiences, general suspicions toward government, industry and other institutions, etc.) through a vigorous and open O&C plan that is started early in the process. This process should be ongoing throughout the lifetime of the project.

Communication with stakeholders should occur on a regular basis at a frequency that is acceptable to the stakeholders. Special meetings may need to be arranged to specifically address time-sensitive community concerns outside of regularly scheduled meetings. Meetings should be accessible to all stakeholders, with some held outside of regular working hours to accommodate members of the general public. Additionally, communication between technical and non-technical parties should be inclusionary and open to the greatest extent possible, avoiding the creation of opaque communication environments ladened with detailed technical language. The communication language and style should be periodically evaluated with key stakeholders providing feedback. Lastly, third-party monitoring of seismicity (e.g., by the USGS or other institutions) or a commitment to ensure that all data will be publicly available could assure stakeholders of unbiased and reliable results. This information can be documented in the Collection of Seismicity Data (Step 4).

The communications delivered to the public, particularly concerning real or perceived risks, should be coordinated by a central team to maintain consistent messaging, especially if the project developer is made up of several operators, agencies, and sub-contractors. The communication team should have clearly defined roles and responsibilities. Communication strategies that address specific potential scenarios should be created prior to operations to decrease response time following an event or activity of concern. The effectiveness of communication campaigns that support the Risk-Based Mitigation Plan (Step 7) and their impact on different target groups should be carefully reviewed and evaluated (Marti et al., 2020). The communication team should be able to call upon a multi-disciplinary group of people who are involved in key decision-making aspects of the project. These individuals could include project managers, scientists, government officials, company spokespersons, safety personnel, and technical service providers. The communications team should ensure that requests for information are fulfilled in a timely manner, including drafting and maintaining responses to frequently asked questions.

Local stakeholders should feel that there are easy methods in which to communicate their concerns and that their concerns are being addressed. This can include having a local project office or visitor center open to the community, engaging in various social media campaigns to inform the local populations about the project, holding public meetings and site visits to discuss both technical and non-technical issues, and having regularly updated open communication pathways (e.g., website, newsletters, articles in local newspapers with updates, email list, phone hotline, etc.) to advise stakeholders as to the state of current operations at the site and to solicit feedback.

Outreach activities should focus on educating the public about the facts of the project and technology involved. Outreach activities should also include aspects of earthquake awareness, education, and preparedness, especially in areas that may not typically experience natural seismicity. In areas where large historic earthquakes may have produced felt ground motions, outreach should particularly include those aspects in the earthquake education and risk discussions. In areas where natural earthquakes are not part of the region's background knowledge, earthquake education would be particularly important (e.g., discussing the importance of securing water heaters and heavy furniture to the walls, discussing actions to take if shaking were to start, highlighting the fact that people in different buildings or doing different types of activities may experience different levels of ground shaking even for the same event, etc.) Ideally, public meetings and site visits should be held before operations start at the site, before injection begins, and periodically during the injection program.

Documentation associated with the O&C program should be annually reviewed and should include: 1) a list of relevant stakeholders; 2) an archive of official documentation associated with the program, including letters of endorsement from different stakeholder groups; and 3) a description of the O&C plan, including a list of individual team members.

3. STEP 3: GROUND MOTION THRESHOLDS

3.1 PURPOSE

The purpose of this step is to determine site-specific ground motion thresholds to minimize nuisance and damage risks. These threshold levels should be determined after careful assessment of the local conditions and stakeholder risk tolerance. Existing standards specifying ground motion criteria for nuisance and damage risks should be evaluated so as to comply with any pertinent regulations instituted by other industries, such as mining and construction. 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. Additionally, 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).

3.2 RECOMMENDED PRACTICES

3.2.1 Review of Existing Standards and Criteria

3.2.1.1 A review of international, federal, state, and local ground motion standards and criteria relating to nuisance and damage due to ground shaking should be conducted. This review should include, but should not be limited to:

a) Reviewing local, state, and federal ordinances applicable within the ROC relating to ground motions.
b) Reviewing existing standards and criteria for ground motions developed for other industrial activities so as to ensure conformance with any pertinent standards and regulations.
c) Reviewing ground motion thresholds typically associated with both cosmetic damage and structural damage for buildings and infrastructure, typically stated in terms of peak ground accelerations (PGA), peak ground velocity (PGV), or spectral acceleration (SA).

3.2.1.2 A review of the standards and criteria relating to the limits of human perception of ground motions should be conducted.

3.2.2 Assessment of Site-Specific Conditions

3.2.2.1 A site-specific assessment of the existing environmental conditions within the ROC should be conducted to determine a baseline level of ground vibrations due to existing local activities and industries.

3.2.2.2 A site-specific assessment of the building stock within the ROC should be conducted. This assessment should include, but should not be limited to, the number and type of residential buildings, commercial buildings, fragile or historical buildings, and general infrastructure within the ROC.

3.2.2.3 An assessment of the level of ground shaking that could potentially interfere with industrial and institutional land uses within the ROC should be conducted. This assessment should include, but should not be limited to, sensitive industrial and commercial activities, research activities, medical activities, and wildlife habitats.

3.2.3 Designation of Site-Specific Ground Motion Thresholds

3.2.3.1 At a minimum, four types of ground motion threshold levels should be designated. They should include

a) The ground motion threshold for reaching an unacceptable nuisance risk level, based on the human perception of ground shaking within the ROC
b) The ground motion thresholds associated with both cosmetic and structural damage of infrastructure and building stock within the ROC
c) The ground motion thresholds for sensitive equipment (e.g., industrial, commercial, medical, etc.) and institutional land uses
d) The ground motion thresholds stipulated in federal, state, or local regulations applicable within the ROC

3.3 SUPPORTING INFORMATION

3.3.1 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. Ground motions from injection-induced seismicity at shallow depths could be of similar frequency and vibration content as those associated with construction, mining, mass transit, and other similar industries. To a first order, the experience and criteria developed for these industries could also be applied to the induced seismicity case and should be investigated.

A review of the human limits to the perception of ground vibrations should also be conducted. To describe events that do not cause damage but disrupt the local public, the nuisance risk concept has been introduced for induced seismicity (i.e., Foulger et al., 2018). Even small events might cause felt ground shaking that may pose a nuisance and cause anxiety to the local population, and potentially generate resistance to the project. This may be particularly true in areas that do not experience relatively frequent natural seismicity. Human perception of ground motion can vary with the individual, the physical setting, and the type of ground motion. The nuisance risk due to small events should be evaluated based on site-specific information and stakeholder input. Guidelines for assessing the human response to vibration have to a certain extent been explored in the induced seismicity context (Bommer et al., 2006; Douglas and Aochi, 2014; Schultz et al., 2021b). They have also been more rigorously, although more generally explored by American National Standard Institute (ANSI) S2.71-1983 (ANSI, 2020) Guide to the Evaluation of Human Exposure to Vibration in Buildings. This standard corresponds to International Organization for Standardization (ISO) 2631, parts 1 and 2 (ISO 2003). Similarly, the Federal Transit Administration (FTA, 2006) and the California Department of Transportation (Caltrans, 2020) have also established relevant standards and recommendations for both transient sources (e.g., single isolated vibration events) and frequent intermittent sources (e.g., events with frequent interrupted periods of continuous vibration) (Table 2).

Lastly, a review of threshold ground motion levels which may cause cosmetic damage or structural damage to different types of buildings and infrastructure should be reviewed. For example, although it has been observed that vibrations between 125 mm/sec to 250 mm/sec PGV will not cause damage to reinforced concrete structures, vibrations between 150 mm/sec and 275 mm/sec can cause cracking of free-standing masonry walls and could therefore be included as a potential ground motion threshold level (Dowding, 1996; Siskind et al., 1980; Siskind, 2000). Threshold ground motion levels can also be inferred from field observations; however, care should be taken to exclude field observations of damage due to medium-to-large magnitude earthquakes since these may not be reliable indicators of damage due to smaller magnitude events as the durations, number of cycles of motion, and energy content would all be lower. Ground motion thresholds associated with potential soil settlement which may disrupt structure foundations should also be reviewed. It is to be expected that the levels of ground shaking associated with cosmetic or structural damage would be significantly higher than the levels of ground shaking that would constitute only a nuisance to the local population. Additionally, it should be noted that these damage threshold values by themselves would not automatically mean that damage will ensue, just that the necessary conditions have been met.

Table 2: Potential Guideline Vibration Annoyance Criteria for Transient and Frequent Intermittent Sources (Caltrans, 2020)

Human Response	Maximum PGV Transient Source	Maximum PGV Frequent Intermittent Source
Barely perceptible	0.04 in./sec [1.02 mm/sec]	0.01 in./sec [0.25 mm/sec]
Distinctly perceptible	0.25 in./sec [6.35 mm/sec]	0.04 in./sec [1.02 mm/sec]
Strongly perceptible	0.90 in./sec [22.86 mm/sec]	0.10 in./sec [2.54 mm/sec]
Severe	2.00 in./sec [50.80 mm/sec]	0.40 in./sec [10.16 mm/sec]

Documentation should include: 1) a list of any relevant federal, state, or local standards regarding ground motions that are applicable within the ROC; 2) a list of any standards or criteria relating to ground motions in similar industries; 3) a list of the ground motion thresholds relating to human perception; and 4) a catalog of ground motion threshold levels for which cosmetic and structural damage could potentially occur for a range of building and infrastructure types.

3.3.2 Assessment of Site-Specific Conditions

An assessment of the existing environmental conditions within the ROC should be conducted to determine the existing baseline level of ground motions associated with existing local activities and industries, such as vibrations associated with mass transit.

An assessment of the building and structure types within the ROC should also be conducted, with particular attention 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. These structures should be identified and grouped by their construction attributes, physical condition, age, and any other factors which may affect their behavior during a seismic event. Several general building classification frameworks have been developed, for example by Hazus, Prompt Assessment of Global

Earthquakes for Response (PAGER), and Global Earthquake Model (GEM) (NIBS, 2003; Porter, 2005; Gallagher et al., 2013); however, site-specific classifications are strongly encouraged.

Lastly, an assessment of sensitive local industrial equipment, activities, and institutional land use areas which may be impacted by elevated levels of ground shaking should be conducted within the ROC. For example, medical equipment such as magnetic resonance imaging (MRI) machines or other hospital equipment have stringent requirements on the levels of acceptable vibrations, which can be below the level of felt ground shaking.

Documentation should include: 1) a report on the existing baseline level of ground motions associated with existing local activities and industries; 2) a listing of the building and structure types within the ROC categorized in the same manner as the building and infrastructure ground motion threshold catalog; and 3) a listing of the sensitive local industrial equipment, activities, and institutional land use areas that may be impacted by elevated levels of ground shaking, along with the maximum acceptable ground shaking threshold levels of each.

3.3.3 Designation of Site-Specific Ground Motion Thresholds

At a minimum, four ground motion threshold levels should be quantified in this step. They are (in no particular order): 1) the threshold for humans to perceive ground shaking; 2) cosmetic and structural damage to each type of building and infrastructure within the ROC; 3) ground motions that may affect local industrial and institutional land uses within the ROC; and 4) ground motions that are stipulated in federal, state, or local regulations that are applicable within the ROC. These ground motion levels should be determined after careful assessment of the regulations, local conditions, and careful evaluation of stakeholder risk tolerance. Additionally, when designating nuisance levels of ground shaking, these can depend on the amplitude of the shaking, the duration of shaking, and the number of shaking episodes.

Documentation for this step should include: 1) a description of the type of threshold levels, 2) the maximum ground shaking value or range of values for each threshold level, and 3) the supporting documentation used to determine the threshold.

4. STEP 4: COLLECTION OF SEISMICITY DATA

4.1 PURPOSE

The purpose of this step is to gather seismicity data that will be used for three related but different needs. The first need is to accurately assess and periodically re-assess the natural and induced seismic hazard and risk associated with the project. The second is to aid in the effective and rapid detection and characterization of induced seismicity occurring in the Perturbed Stress Zone (PSZ). The final need is to provide accurate data for input into induced seismicity mitigation plans (e.g., conventional or adaptive traffic light systems). In short, observed seismicity will be used not only to estimate and mitigate the hazard and risk at the site, but also to aid in reservoir characterization and management. Not included in this step is the collection or analysis of active seismic and other data required to characterize the subsurface reservoir system and its surroundings. However, the results of those efforts would certainly be necessary when estimating the seismic hazards (as described in Step 5).

4.2 RECOMMENDED PRACTICES

4.2.1 Seismic Activity Before Operations

4.2.1.1 Previous seismic activity should be characterized within a region of at least 200 km radius around planned injection operations. Elements of the seismicity characterization should include, but are not limited to, collecting existing information from:

a) Catalogs of instrumentally recorded earthquakes from national, state, or regional agencies
b) Historical records of earthquakes and observed fault ruptures, including but not limited to, historical earthquake catalogs, and newspaper and other contemporary records, and published reports of field geological investigations
c) Fault maps and fault characterizations, including but not limited to, scientific maps and publications
d) Paleoseismic fault displacement data, including but not limited to, published trenching studies
e) Previous induced earthquake activity, including but not limited to, earthquake catalogs and scientific publications investigating possible induced activity

4.2.1.2 Prior to commencing injection operations, a seismic monitoring network (as described in Section 4.2.2) should be operated for preferably 1 year or longer, but at least for 6 months.

4.2.2 Seismic Monitoring Network Design

4.2.2.1 A local seismic monitoring network should be installed and should have the following minimum requirements:

a) The seismic network should include a combination of weak-motion seismometers and strong-motion accelerometers
b) Each seismic station should consist of 3 orthogonal sensor components and record with a timing accuracy of 1 ms or better

c) The network should be able to record and locate seismicity in the PSZ with at least a 2-sigma location accuracy of 0.5 km in the horizontal direction and 1.0 km in the vertical direction
d) Seismic monitoring networks should be designed, and stations located such that ground velocities of 600 nm/s can be recorded with a signal-to-noise ratio of at least 6 in the frequency range 5–40 Hz within the ROC
e) The velocity model used to locate earthquakes should be calibrated using calibration shots or similar methods

4.2.3 Seismic Monitoring Network Operation and Reporting

4.2.3.1 The seismic monitoring network operation should be set up so that:

a) Seismic waveform data should be analyzed in near-real time to detect, associate, locate, and determine magnitudes of seismic events
b) The seismic monitoring network should continuously operate during the operational phase of the project and throughout the seismic post-injection site care (PISC) period
c) The operator should ensure that raw seismic data waveform, associated metadata, and event catalogs are archived throughout the lifetime of the project

4.2.4 Public Reporting and Engagement

4.2.4.1 The operator should provide a summary report on observed induced seismicity at least annually. This report should be made publicly available.

4.2.4.2 Earthquake catalogs should be made available in near-real time to the public through a web interface. The web interface should:

a) Provide information on each event including, but not limited to, the event origin date and time, 3D location, magnitude, number of stations used to compute the location, maximum azimuthal gap, distance of closest station to the event, root-mean-square (RMS) travel time residual, location uncertainty, and whether the event has been reviewed by a seismologist
b) Allow automatic queries to retrieve event information by computer systems of third parties
c) Include implementation of standard seismological data formats such as miniSEED, and data request and transfer schemas, such as FDSN StationXML and ArcLink

4.2.4.3 Continuous raw seismic data waveforms should be transmitted to a public data repository, such as the Incorporated Research Institutions for Seismology Data Management Center (IRIS-DMC), in near-real time.

4.2.4.4 The waveform data should be accessible to the public from an online data repository without limitations, excepting for a reasonable embargo period to ensure quality control.

4.2.4.5 The operator should supply additional seismic network metadata including, but not limited to, instrument locations, instrument data sheets, and instrument response functions.

4.2.4.6 The operator should supply additional related information including, but not limited to, the seismic velocity model and the seismic phase picks used for computation of the event locations.

4.3 SUPPORTING INFORMATION

4.3.1 Seismic Activity Before Operations

The first step in understanding the potential for induced seismicity from a new project is to identify any nearby past and present seismicity and the faults on which it originates. These data will be needed to: 1) perform the induced seismic hazard and risk analyses (Steps 5 and 6) initiated during the planning stage of the project; and 2) compare to any potential induced seismicity observed during the operation stage. A region much larger than the ROC (minimum of 200 km radius) is chosen 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 still impact the local hazard.

Seismic monitoring networks operated by national, state, or regional entities can provide information on larger events occurring in a region. The National Earthquake Information Center (NEIC) for example, has a goal of detecting and locating events in the U.S. that are greater than $M_W2.5$–$M_W3.0$, depending on the geographic region. However, processing of smaller events may take up to several weeks, or information on them may not be reported due to poor data quality or their signal can be masked by larger events. In general, this level of monitoring is not sufficient for monitoring induced seismicity. Routine detection of small events in the immediate vicinity of the injection site is necessary to detect problematic developments as early as possible.

Historic reports of significant earthquakes can provide important information on time periods that predate instrumental recording. For rare events that occur once every few hundred to thousands of years, this may be the only evidence of seismic activity. Of course, the absence of historic reports of significant earthquakes does not necessarily indicate that no faults exist, that no earthquakes occurred in the past in the region, or that induced seismicity would not occur in the future. Geologic characterization of faults active in the Quaternary and paleoseismic studies of known faults enables inclusion of prehistoric earthquakes and complements the characterization of historical seismicity.

Evidence of anthropogenic earthquake activity should also be investigated. If the targeted region has a history of induced seismicity, this would be a strong indication of a critically stressed crust, i.e., relatively small perturbations to the subsurface stress field may be sufficient to induce seismicity. Such cases would need to be carefully scrutinized.

As indicated above, 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. Therefore, installing or augmenting an existing local monitoring network may be required in order to understand the response of the project site to injection operations. It is important to quantify the level of seismic activity before operations commence at the same detection level as will be used during injection operations. Recognizing that natural seismicity rates can vary over time, the local seismic network should begin operating as early as possible. One year or longer is recommended, but a minimum of 6 months of pre-injection monitoring is suggested.

4.3.2 Seismic Monitoring Network Design

The seismic monitoring network should be designed to detect and characterize seismicity occurring in the PSZ volume, down to at least M1, and should be able to record all expected felt ground motions due to those events effectively and rapidly. The PSZ is the three-dimensional (3D) subsurface region originating at the injection wells with perturbed pressure and stress in which seismicity could occur in a critically stressed crust. The PSZ could be estimated, for example, by creating a hydro-mechanical model of the reservoir injection scenarios and determining where the Mohr-Coulomb stress changes would exceed a pre-determined critical stress threshold (Figueiredo et al., 2015). The PSZ will also be expected to expand over time as the fluid migrates. As such, it would be expected that stations could be added to the seismic network over time to expand the network to adequately cover the evolving PSZ. Collecting and analyzing the necessary seismic data requires the appropriate sensors, electronics, network design, and computational capability. With regard to the sensors, 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. Two common types of high-gain sensors include broadband seismometers and geophones (Trnkoczy et al., 2002). Broadband seismometers typically have a wider frequency passband than geophones, can record lower frequency ground motion, and can therefore more accurately measure event magnitudes and peak ground velocities of induced seismic events (Yenier et al., 2016). Broadband seismometers are, therefore, the preferred high-gain instrument for monitoring induced seismicity. Strong ground motion instruments (i.e., accelerometers) more accurately measure the forces associated with larger earthquakes. Accelerometers can be located near sensitive structures to monitor for potential large ground motions at critical locations and should be able to measure strong ground motions up to at least 1 g.

Each seismic station should measure ground motion in three orthogonal directions (e.g., up-down, north-south, and east-west) to fully capture the movement of the seismic waves as they travel through the earth. The data should be recorded using at least a 24-bit digital data acquisition system and a global positioning system (GPS)-based field timing system to achieve the required timing accuracy of at least 1 ms. The instruments should be able to record the dominant frequencies of the earthquakes.

When designing the seismic network, it is best to strive for as much sensitivity and accuracy as is economically possible for optimal earthquake detection, association, location, and magnitude determination of both small microseismic events and the largest potential events that may occur due to injection activities. Azimuthal gaps between the seismic stations greater than or equal to 120 degrees should be avoided. To record seismicity within the PSZ, it is expected that the footprint of the seismic network would need to extend beyond the PSZ. The network should be designed to record and locate seismicity in the PSZ with at least a 2-sigma (i.e., 2 standard deviation) location accuracy of 0.5 km in the horizontal direction and 1.0 km in the vertical direction. These uncertainty values include the formal location uncertainty given by the location software and also any unmodeled uncertainties of the velocity model. The precision of locations in any subsequently relocated earthquake catalog, assuming that the original catalog was not systematically biased, may be significantly smaller, allowing for identification of fault structures.

The seismic network should be designed to clearly record events that originate in the PSZ subsurface volume. Wiemer et al. (2017) suggest that for sedimentary basins this would require measurement of ground velocity amplitudes as small as 600 nm/s with a signal-to-noise ratio (SNR) of at least 6 within the frequency range of 5–40 Hz; i.e., the noise level at each recording site should not exceed 100 nm/s. This criterion should enable a magnitude of completeness on the order of M1 to be achieved. To ensure the desired maximum noise level, Groos and Ritter (2010) recommend that background noise should be measured at each candidate recording site for least 7 days and a noise analysis be carried out prior to the installation of permanent instrumentation. The noise level should also be continuously assessed during the operational phase of the project and throughout the PISC period.

Seismic stations should be sited using commonly accepted procedures (e.g., Trnkoczy et al., 2002; Plenkers et al., 2015) to assure good mechanical contact with the ground and adequate protection of the equipment. If possible, the sensor should be installed below the weathered and alluvial layers in bedrock geology. If high-quality surface sites are not available, the use of shallow borehole installations (80–150 m depth) would be necessary to minimize background noise.

Velocity model uncertainties can lead to major uncertainties in earthquake locations, particularly in depth. These uncertainties can be reduced by calibrating the velocity model using one or more calibration shots (e.g., small explosions in a wellbore at target depth) (Akram and Eaton, 2013), or similar methods. Additionally, if available, subsurface velocity information from active seismic surveys or borehole sonic logs should be integrated into the seismic velocity model used for event location.

4.3.3 Seismic Monitoring Network Operation and Reporting

Making the monitoring effort transparent to regulators and the public by providing seismic waveform and earthquake catalog data to the public in near-real time is an important step to maintain the support of the local community, facilitate project oversight, and allow scientists to further analyze the data. While 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 be taken when engaging with the public. This will improve community trust and also improve the overall state-of-knowledge in the induced seismicity research community. The seismic monitoring network should be operating continuously during the pre-operational background assessment phase, during the operational phase of the project and throughout the seismic PISC period. Additionally, the operator should ensure that the continuous raw seismic data and event catalogs are archived throughout the life of the project and until the end of the seismic PISC. Magnitudes in event catalogs should preferably be calculated as moment magnitudes, although it is acknowledged that this is not always straightforward, particularly in areas that have not historically had earthquakes (Edwards and Douglas, 2014). In these cases, the reporting of local magnitudes may be necessary.

4.3.4 Public Reporting and Engagement

The operator should provide a summary report on observed induced seismicity at least annually. This report should be made publicly available. Additionally, earthquake catalogs should be made available in near-real time to the public through a web interface. This waveform data should be accessible to the public without limitations, excepting for a reasonable embargo period to ensure quality control (e.g., Salvage et al., 2021).

Archiving raw waveform data in near-real time at data centers, such as IRIS-DMC, can help with long-term storage and facilitate easy access by third parties. In particular, the IRIS-DMC has been certified as a trusted repository by the International Council for Science World Data System and is a common repository for seismic waveform data and station metadata information in the U.S. Additionally, seismic data protocols such as SEEDLink for real time seismic waveform data transfer or ArcLink for waveform data and station metadata transfer are highly recommended. Standard seismic data formats, such as miniSEED, are also recommended. The use of standard data schemas, such as FDSN StationXML for station metadata and QuakeML for event and phase data, and standard coordinate reference systems is strongly recommended. Sensor and station metadata documentation should include, but may not be limited to, instrument coordinates, instrument response functions, compression type, sampling rate, gain factors, etc. The operator should also supply any related information (such as the seismic velocity model, magnitude calculation method and if applicable the relationship to M_w, instrument data sheets, changes to the processing routine, replacement of any equipment, equipment failures, etc.) in the seismic summary report that is produced at least annually. Pertinent changes to the seismic network and processing routine should also be updated on the online web interface as changes occur, including reporting when, or if, the catalog is recalculated due to new information. If significant new information were to be obtained, such as a new velocity model, it would be recommended to retroactively correct the earthquake catalog.

Beyond standard seismic processing techniques, advanced data processing can often prove useful. This may include earthquake relocations using more advanced techniques, such as the double-difference relocation method, which reduces the uncertainty introduced by the velocity model between sources and receivers and utilizes only the relative travel times between neighboring events (Waldhauser and Ellsworth, 2000; Trugman and Shearer, 2017). Earthquake relocation can provide improved understanding of what drives the local seismicity and its relation, if any, to fluid injection. Examples of other advanced analyses include the determination of focal mechanisms or moment tensors, which describe the orientation and sense of slip on the earthquake source plane that provide additional constraints on the sources of the seismicity.

5. STEP 5: HAZARD EVALUATION OF NATURAL AND INDUCED SEISMIC EVENTS

5.1 PURPOSE

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. Once the surface ground shaking hazard is quantified, associated secondary hazards such as liquefaction, slope failure, caprock integrity, or the potential opening of fault leakage pathways, can be subsequently evaluated in separate procedures. This step should be performed before any operations are initiated at the site. Results from this seismic hazard evaluation will be input into the subsequent Risk-Informed Decision Analysis (Step 6). Additionally, these seismic hazard analyses will need to be updated as new information and model enhancements become available, especially during the early evaluation period of the project, as described in the Risk-Based Mitigation Plan (Step 7).

5.2 RECOMMENDED PRACTICES

5.2.1 Baseline Hazard from Natural Seismicity

5.2.1.1 A site-specific PSHA should be conducted in accordance with current practice of earthquake hazard estimation to evaluate the baseline hazard from natural tectonic seismicity. Input into the PSHA should include, but should not be limited to, the following:

a) A database of potentially damaging earthquake sources that may impact the ROC, that experienced activity during the Quaternary Period, including fault-specific sources and areal sources where appropriate
b) Spatial, temporal, and frequency-magnitude distribution models for each seismic source
c) Region appropriate GMMs for tectonic earthquakes as a function of at least earthquake magnitude and travel path
d) Information from geological, geophysical, and topographical studies within the PSZ should be included to incorporate local site responses

5.2.1.2 Results from the PSHA should include multiple hazard curves and hazard maps to report the results from the baseline seismic hazard analysis due to natural seismicity before injection operations commence.

5.2.1.3 A seismic hazard report should be prepared, if required by the regulatory agency, by a licensed professional having demonstrated competence in the field of seismic hazard assessment. The seismic hazard report should contain site-specific assessments of the seismic hazard affecting the project and relevant sites within the ROC. The report should identify any known seismic hazards that could adversely affect relevant sites within the ROC in the event of an earthquake. The contents of the seismic hazard report should include, but should not be limited to, the following:

a) A project description

b) A description of the geologic, geotechnical, and geophysical conditions within the ROC, including an appropriate site location map
c) An evaluation of site-specific seismic hazards based on geological and geotechnical conditions in accordance with current standards of practice
d) The name(s) and qualifications of the report preparer(s)

5.2.1.4 Prior to approving the project, the appropriate regulatory agency should independently review the seismic hazard report to determine the adequacy of the hazard evaluation. The reviews should be conducted by a licensed professional having demonstrated competence in the field of seismic hazard assessment.

5.2.1.5 The site-specific PSHA should be updated and re-submitted for approval to the appropriate regulatory agency as needed if significant new information pertinent to the hazard evaluation becomes available.

5.2.2 Additional Hazard from Induced Seismicity

5.2.2.1 Site-specific short-term 1-year probabilistic seismic hazard forecasts (PSHF) should be conducted in accordance with current practice to evaluate the hazard from induced and natural seismicity. Information gathered for the PSHF should include, but should not be limited to:

a) Input originally obtained for the PSHA (5.1.1)
b) Site-specific reservoir and caprock properties and operation parameters such as: the initial geometrical features of the subsurface reservoir; thermal and chemical properties of the reservoir and fluids; hydraulic and mechanical properties of the reservoir and caprock; stress and pressure state of the reservoir and caprock; and planned injection and pressure build rates

5.2.2.2 Results from the short-term PSHF should include multiple hazard curves and hazard maps to report the results from the additional seismic hazard due to potential induced seismicity.

5.2.2.3 The site-specific short-term 1-year seismic hazard forecast report should be prepared by a licensed professional having demonstrated competence in the field of seismic hazard evaluation (if required by the regulatory agency). The short-term seismic hazard forecast report should contain site-specific evaluations of the short-term seismic hazards affecting the site from both induced and natural earthquakes. This is in contrast to the report called for in Section 5.2.1.3, which includes only natural events. The short-term seismic hazard forecast report should also identify any known seismic hazards sources that could adversely affect relevant sites within the ROC in the event of an earthquake. The contents of the short-term seismic hazard forecast report should include the same items as those listed under 5.1.3.

5.2.2.4 Prior to approving the project, the appropriate regulatory agency should independently review the short-term seismic hazard forecast report to determine the adequacy of the hazard evaluation. The review should be conducted by a licensed professional having demonstrated competence in the field of seismic hazard assessment.

5.2.2.5 The short-term PSHF should be updated and re-submitted for approval to the appropriate regulatory agency annually, or more frequently as needed.

5.3 SUPPORTING INFORMATION

5.3.1 Baseline Hazard from Natural Seismicity

5.3.1.1 Overview

Although there could be many sources of potential seismic hazards at a particular site (e.g., ground shaking, fault offsets, soil liquefaction, landslides, etc.), for this purpose 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 hazard and risk associated with existing natural seismicity and any induced seismicity). Additional hazards can be incorporated at a later time, if needed (NRC, 1988).

Two general approaches have been developed for analyzing the seismic ground shaking hazard at a particular site: deterministic, which focuses on specific earthquake scenarios without considering their likelihood to reoccur; and probabilistic, which incorporates all seismic events that may impact a site and includes information on their recurrence times and uncertainties in source characterization and recurrence. A deterministic seismic hazard analysis (DSHA) may be useful when describing potential effects to stakeholders due to its more straightforward formulation. A PSHA allows for a broader understanding of the overall seismic hazard and can be input into subsequent seismic risk analyses (Cornell, 1968; McGuire, 2004). As such, PSHA is recommended when calculating the baseline seismic hazard at a particular GCS site due to natural tectonic seismicity.

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 years, 5,000 years, etc.) at a particular location due to future earthquakes. In practice, several different ground motion parameters over a range of different probabilities and time intervals can be calculated for a particular site. Hazard curves visualize those exceedance probabilities and allow for different sites to be easily compared.

A variety of computer programs are publicly available which 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 (an open-source program originally conceived by Ned Field of the USGS), the HAZ program (a free program originally developed by Norman Abrahamson at UC Berkeley), and EZ-FRISK (a licensed program available through Risk Engineering Inc.) (Hale et al., 2018). Some available codes do not convert the rate of exceeding a given ground motion intensity to the probability of exceeding a given ground motion intensity within the code itself, so this step must be conducted in post-processing (Hale et al., 2018). This last step requires estimating the probability distribution of time between earthquake occurrences and, to date, is almost always assumed to be Poissonian.

The hazard and risk analyses in Steps 5 and 6 will help better define the ROC. The ROC was preliminarily estimated in Step 1. The ROC defines the ground surface area that could be negatively impacted by seismic events occurring at depth throughout the lifetime of the project. Throughout the lifetime of the project, it is also 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. The ROC may also expand or contract due to new information. Additionally, since some parameters of the natural and induced seismic hazard analyses should be similarly aligned to ensure consistency, those performing the two analyses should either be the same entity or they should be in frequent communication.

5.3.1.2 PSHA Inputs

Information from three general input categories are required for PSHA. They are a) earthquake source locations and geometry, b) spatial, temporal, and frequency-magnitude (recurrence) models for each of the earthquake sources, and c) source-site-appropriate earthquake GMMs, with adjustments for local site response conditions.

(a) Earthquake seismic sources that could constitute a ground motion hazard to the local communities, operational infrastructure, or to the subsurface reservoir itself should be identified and incorporated in the PSHA. PSHA seismic sources fall into two general categories: fault-specific sources and areal sources (SSHAC, 1997).

For fault-specific sources, the current criteria for defining an "active", "potentially active", or "capable" fault varies between different U.S. government regulatory agencies (Jennings and Bryant, 2010). For this purpose, at a minimum, faults that have exhibited coseismic surface deformation within the past 1.6 million years, (i.e., the Quaternary time period as defined by the 1983 Geologic Time Scale) should be included as a fault-specific source. The USGS maintains a U.S. Quaternary Fault and Fold Database, which is a source for faults used in the National Seismic Hazard Maps, and which could serve as a starting point for the PSHA analysis (USGS, 2006). Surface fault location, fault length, strike, dip direction and dip angle, slip rate, and slip sense (strike-slip, normal, or reverse/thrust) are included in this database, although the quality and level of completeness of information available for each source varies. Information should be closely scrutinized and augmented with additional geological, geomorphological, geodetic, geophysical, and seismological data, including review of recent literature when available. Supplementary information from regional investigations, such as the Unified California Earthquake Rupture Forecast (UCERF) project for California or the Central and Eastern United States – Seismic Source Characterization (CEUS-SSC) project for the CEUS, have developed region-specific databases that can be important sources of more detailed information (CEUS-SSC, 2012; Field et al., 2013). Nevertheless, site specific studies will most likely be necessary. Additional information for fault-specific sources, particularly within the PSZ, that will be needed for a site-specific PSHA would be: 1) the down-dip length and subsurface geometry of the fault; 2) the identification of any blind faults (i.e., faults that do not have a surface expression); and 3) an indication of any of fault segmentation, which may pose a limit on the rupture length (e.g., Field et al., 2013; SSHAC, 1997).

Areal seismic sources are distinct volumes within the Earth's crust that encompass concentrated zones of seismicity, seismic sources defined by regional seismotectonic characteristics, or areas with potential for general background earthquakes. Areal sources can account for the possibility of earthquakes occurring on faults that are not currently mapped or to account for known large earthquakes that have yet to be associated with a particular mapped fault. Areal sources are defined by their lateral and subsurface extents and slip sense (strike-slip, normal, or reverse/thrust). Geologic, geophysical, and seismological data can be used to identify local and regional areal sources (SSHAC, 1997).

A 3D structural and stratigraphic model of the PSZ should be developed. It should include faults and fractures that could be sources of future seismicity. Inputs into the 3D model could include information from drilling logs, wellbore image logs, seismic reflection data, seismic tomography, potential field data, etc.

Each seismic source can be characterized by multiple plausible configurations, each with an associated weight or credibility (SSHAC, 1997). Lastly, regional and site investigations used to identify seismic sources for input into the PSHA should have a resolution at least consistent with a 1:5,000 scale map above the subsurface reservoir and a scale of 1:50,000 above the PSZ for best fidelity (U.S. Nuclear Regulatory Commission, 2007).

(b) For each seismic source, models of the spatial, temporal, and earthquake frequency-magnitude distributions should be determined in order to appropriately characterize each source (SSHAC, 1997).

The spatial distribution models for earthquake sources are used to calculate the distance distribution between potential future events and sites within the ROC. For fault-specific sources, the spatial distribution model describes the potential event locations across the fault. Potential locations can be represented as either point sources on a two-dimensional (2D) or 3D fault plane or as a rupture area with finite dimensions. Spatial distribution models for areal sources can either be uniformly distributed over the entire zone, which would allow for the possibility of incorporating future earthquakes within regions of little observed historical seismicity, or they can attempt to match the historical earthquake catalog, usually with some degree of spatial smoothing (Abrahamson, 2006). Estimating distances for area-type finite fault seismic sources requires subjective assumptions of fault rupture details (strike, dip, and rupture area) and should be well documented.

The selection of a model for the temporal distribution of earthquakes for each seismic source is usually Poissonian, which assumes that each earthquake occurs independently in time from each other (e.g., Cornell, 1968; NRC, 1988).

Earthquake recurrence (frequency-magnitude) models provide information on the relative frequencies of occurrence of seismic events of different magnitudes, between a pre-selected minimum earthquake magnitude of concern up to a pre-determined maximum magnitude that the source is considered capable of producing. The minimum magnitude threshold is typically considered the smallest magnitude event that can generate potentially damaging ground motions (Bommer and Crowley, 2017). When conducting the natural and induced seismic hazard analyses, the same, or very similar, lower threshold magnitudes should be used. The maximum magnitude is a key parameter in earthquake recurrence models but is often poorly constrained. For fault-specific sources, the maximum earthquake magnitude can either be derived using empirical relationships between magnitude and one or more key fault parameters (e.g., surface displacement, fault rupture length, rupture area, etc.) (Slemmons, 1977; Bonilla et al., 1984; Wells and Coppersmith, 1994; Stafford, 2014; Allen and Hayes, 2017; Thingbaijam et al., 2017) or observationally through the use of the historical seismic catalog. Maximum earthquake magnitude estimates for areal sources are particularly challenging since potential fault dimensions are extremely difficult to determine. In practice, the maximum earthquake magnitude is often presented as a distribution of potential values, rather than as a single value, based on the available information (SSHAC, 1997). When conducting the natural and induced seismic hazard analyses, the maximum magnitude values could be the same or independent from each other.

Earthquake recurrence relationships for fault-specific sources can include information from both earthquake catalogs, which provide information on smaller magnitude, higher frequency events, and paleoseismic/geologic information, which provides information on larger magnitude, lower frequency events. Common earthquake recurrence models include the truncated exponential model—a form of the classical Gutenberg-Richter model (1944) that assumes spatial and temporal independence of events—and the characteristic earthquake model, which often combines the Gutenberg-Richter model for smaller magnitude events with a characteristic maximum event that displays a different recurrence behavior (Youngs and Coppersmith, 1985; Gutenberg and Richter, 1944).

Earthquake recurrence relationships for areal source zones typically use de-clustered historical catalogs as the primary source of information. Truncated exponential models are often used to combine the observed data with the estimate of maximum magnitude to determine the recurrence parameters (SSHAC, 1997).

(c) Site-appropriate earthquake GMMs specify the estimated ground shaking at a particular site as a function of, at least, the magnitude, distance of potential seismic events, and, indirectly, the local tectonic regime (e.g., Boore and Atkinson, 2008). Other factors that should be incorporated include focal mechanism, hanging wall effects, and event depth. Additionally, local site effects can dramatically influence the amplitude, duration, and frequency content of ground shaking at a particular site and should be incorporated into the model. These site factors can include local geologic and soil characteristics, topographic influences, and soil non-linearity (SSHAC, 1997). One way that earthquake GMMs can incorporate local site response is through the use of V_s30, the average shear-wave velocity (V_s) in the top 30 m of the subsurface. The V_s profile at a site can be obtained through a range of common geophysical methods (Idriss et al., 2018).

A wide variety of peer reviewed GMMs exist (e.g., Bozorgnia et al., 2014; PEER, 2015). A careful selection of the most appropriate site-specific models should be conducted, which should include a comparison between any available relevant observed data and the calculated model results, recognizing that caution must be exercised in interpreting results if extrapolating GMMs outside of their magnitude validity ranges due to a lack of more appropriate GMMs (Beauval et al., 2012; Idriss et al., 2018). Additionally, to ensure consistency between the natural and induced seismic hazard analyses, the GMMs should be the same between the two. Recognizing that this could be quite difficult, it may therefore be necessary to use different GMMs in the two cases, but to verify that for common magnitudes and depths, they yield comparable predictions.

5.3.1.3 PSHA Results

The primary products of the PSHA are seismic ground motion hazard curves that show the estimated probability of exceedance per unit time (typically annually) on the vertical axis and different levels of the selected ground motion parameter on the horizontal axis (Figure 1). Low levels of ground motion are exceeded relatively often (higher probability), while high levels of ground motion are exceeded rarely (lower probability).

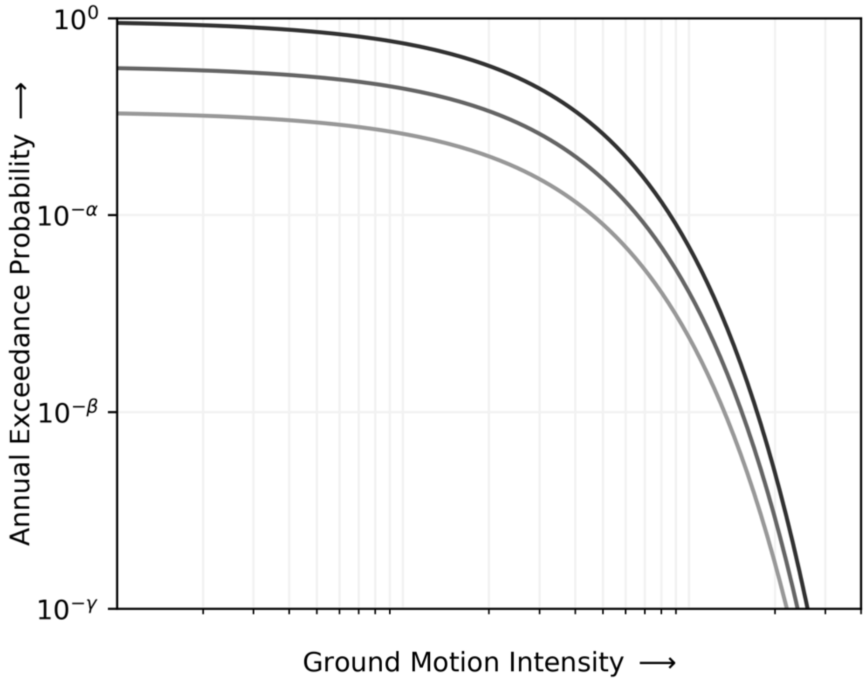

Figure 1: Example seismic hazard curve specifying the probability of exceedance (theoretically between 0–1) as a function of increasing ground motion intensity (e.g., PGA, spectral acceleration, etc.). An annual exceedance probability of 1 would indicate an expected 100% chance of exceeding the specified ground motion intensity.

The ground motion parameters most frequently selected for the presentation of PSHA results are PGA, PGV, or SA at selected periods. Results given in terms of PGA or response SA can be compared to seismic design regulations and building codes, while results given in terms of PGV can be compared to cosmetic and structural building damage criteria, criteria for vibration sensitive research and manufacturing facilities, and with human activity interference criteria (Petersen et al., 2014; Rutqvist et al., 2014).

Estimates of uncertainty can be captured on the hazard curves. For example, epistemic uncertainties (i.e., uncertainties arising from the potential of having a range of input sources, GMMs, and other input parameters that could be appropriate at a particular site) can be estimated using logic trees which allow for the incorporation of different combinations of models and parameter ranges into the hazard analysis (e.g., NRC, 2012b; NRC, 2018). The subsequently calculated hazard curves would then be based on different, but defensible, underlying assumptions which, when plotted together, can illustrate the effect of these uncertainties on the results. The mean hazard curves can be plotted along with two or more associated confidence band curves, such as the 5% and 95% percentile curves (SSHAC, 1997). When presenting uncertainty in this manner, a description of the center and range of technically defensible interpretations should be included in the discussion.

Furthermore, PSHA result maps should show earthquake ground-shaking levels for several annual exceedance frequencies or return periods. Hazard maps present a more complete overview of the hazard and may be easier to comprehend in a more general sense. PSHA maps may show the various earthquake ground-shaking levels with a fixed probability of exceedance over a specified time period. One important value to define a priori would be the lowest annual frequency of exceedance for which ground motions of interest should be evaluated, again recognizing that this minimum value should be common between the natural and induced seismic hazard analyses. For reference, for the design of critical facilities, the annual frequencies of exceedance of interest are generally in the range of 10^{-4} to 10^{-5} (NRC, 2018).

5.3.1.4 PSHA Report

The site-specific seismic hazard report should contain sufficient information to allow the regulatory agency's technical reviewer(s) to satisfactorily evaluate the potential for seismic ground shaking hazards (CGS, 2008).

(a) The project description should include at minimum the stated purpose of the project and a listing of the owners and operators.

(b) The geologic, geodetic, geotechnical, and geophysical descriptions of the site should include at minimum: a physical description and map of the carbon storage reservoir and PSZ; 3D cross-section(s) of the reservoir including locations of known drinking water aquifers; a description of the geologic and tectonic setting of the site; a description and map of the seismic monitoring network and an estimate of the minimum magnitude of completeness; a description and map of any wells located within the PSZ; a description of any published or unpublished site-specific or regional investigations pertinent to the evaluation; and a description of any site-specific investigations undertaken during the course of the evaluation.

(c) In addition to presenting the PSHA results, the PSHA report should document and justify all assumptions, data, methods, models, uncertainties, and input parameters. The report should include all sources of information, both published and unpublished, that were used in the analysis. Specific effort should be applied to effectively communicating the effect of the uncertainties (both epistemic and aleatory) on the results so as to develop a true understanding of the seismic hazard.

    The database of potential sources of damaging earthquakes should include potential locations, a description, parameter value ranges, and the stated basis for the identification of the seismic sources. The earthquake recurrence relationships should include the frequency of observed earthquakes with associated statistical error bars, the recurrence intervals from paleoseismic data, and (if applicable) the mean recurrence curves derived from the slip rate and magnitude-distribution model should be included (SSHAC, 1997). The PSHA report should also include a description of the spatial, temporal, and earthquake recurrence models and parameters for each source. A description of the GMMs, input parameters, and the reason for choosing particular models should also be documented. If a new site-specific GMM is derived, a full description of the development of the new model should be included. Predictions from the GMMs should be compared to relevant recorded data to determine the fidelity of the calculated results.

A logic tree capturing the epistemic uncertainties in the source and GMMs should also be included along with the assigned model and parameter weights representing the relative merit of each of the alternatives. Logic trees allow for the incorporation of the full range of viable alternative source models, recurrence parameters, maximum magnitudes, GMMs, etc. A Monte Carlo approach can be used with logic trees, for example, to sample the uncertainty space of model parameter values and of ground motion model aleatory uncertainties (natural random variability). Monte Carlo methods can be used to sample the distributions whether they are represented by discrete branches or continuous distributions. Logic trees are discrete representations of probability distributions where many branches could potentially be replaced by continuous distributions. The chosen procedure should be carefully documented since the assessment of epistemic uncertainties can be equivocal, given its dependence on expert judgement and data availability. These uncertainties can then be propagated into the subsequent risk assessment so that decision makers can make better informed decisions.

(d) The name(s) and qualifications of the report preparer(s), who should have competence in the field of seismic hazard evaluation, should be included in the report documentation.

5.3.1.5 PSHA Review

The technical review by the appropriate regulatory agency is a critical part of the evaluation process. The regulatory reviewer ensures compliance with existing laws and current standards of practice to protect both regulatory and stakeholder interests. The reviewer should be familiar with the investigative methods employed and the techniques available to perform the analysis; however, it would be appropriate for reviewers to ask for the opinion of others more qualified in specialty fields if necessary. Reviews should be based on logical and defensible criteria. Guidelines for the report and any supplementary material should be made available to applicants beforehand. This information should cover procedures, report formats, and levels of appropriate investigative detail that will expedite the review and approval of the project (CGS, 2008).

5.3.1.6 PSHA Update

Site-specific PSHA reports to the regulatory agency should be updated if future geological, seismological, or geophysical investigations reveal significant new and different information than that used in the original PSHA, such as new seismic sources or improved GMMs.

5.3.2 Additional Hazard From Induced Seismicity

5.3.2.1 Overview

The probabilistic short-term seismic ground shaking hazard forecast 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. For example, the range of mechanisms which can induce seismicity at a local fluid injection site (e.g., pore pressure changes due to fluid injection, temperature and chemical changes within the reservoir host rock caused by the fluids, and poro-elastic stress changes) can be, but are not necessarily, different than the mechanisms which typically create natural tectonic earthquakes.

These short-term site-specific seismic ground shaking hazard forecasts, incorporating both natural and induced seismicity, should be periodically computed during the lifetime of the project. These forecasts should ideally be for 1-year duration or shorter, depending on the planned injection schedule. These short-term forecasts are, however, difficult to calculate since induced or potentially induced earthquakes can vary rapidly in space and time based on anthropogenic activity. The seismic response to injection can also vary drastically among nearby sites or even between different injection depth intervals. These factors make it difficult to extrapolate values, although regional trends in the seismic response may exist. While 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.

Estimating the frequency-magnitude characteristics of induced seismicity, which are likely to be time- and space-dependent, before injection starts is a significant challenge since not all of the geological and geomechanical factors that govern the seismic response of a site can be accurately quantified at this stage. Because of this, in this time period before injection starts, either a full probabilistic hazard analysis or a pseudo-probabilistic hazard assessment could be appropriate (Cornell, 1968; Edwards et al., 2021). It would only be during this relatively brief time period, and only if an appropriate range of possible earthquake recurrence models could not be identified, where a pseudo-probabilistic hazard assessment using scenario events would be acceptable. After collection of sufficient post-injection data only a PSHF would be appropriate.

The PSHF will necessarily need to be systematically checked, updated, and predictions continuously calibrated against new observations. A new risk analysis (Step 6) will most likely be necessary as well if the PSHF significantly changes. This may change the ROC as well and new data and models become available. To ensure consistency between the PSHF and the PSHA, those performing the two analyses should either be the same entity, or they should be in frequent communication.

5.3.2.2 PSHF Inputs

Similar to the long-term approach, information from three general input categories are required for the PSHF. They are: a) earthquake source locations and geometry; b) spatial, temporal, and recurrence (frequency-magnitude) models for each of the earthquake sources; and c) site and scale-appropriate earthquake GMMs with adjustments for local site conditions.

(a) Earthquake sources, both natural and induced, that could constitute a ground motion hazard to the local communities or operation infrastructure should be identified and input into the PSHF. Both fault-specific sources and areal sources should be identified, similar to the procedure for the long-term approach.

    Differences from the PSHA analysis arise in that slip on faults and fractures may be induced by the injection program due to changes in the in-situ normal stress field from pore pressure changes, and changes in normal and shear stress from poroelastic stressing and mass loading. Characterization of the local and regional stress field is therefore necessary to identify which features are more likely to be triggered. The characterization of the stress field can be estimated from in situ stress measurements (e.g., hydraulic fracturing, borehole breakouts, and core-induced fractures), and is also needed for other aspects of the project development. Characterization of the strain rate near faults may also be useful (Hussain et al., 2018). Earthquake focal mechanisms can provide information on the principal stress directions and their relative, but not absolute, magnitudes. With knowledge of the in-situ stress field, a Mohr-Coulomb stress analysis can be performed to assess the critical stress required to trigger slip on favorably oriented faults and compare that to the expected stress changes due to the fluid injection program in order to identify potential induced earthquake sources (e.g., Walsh and Zoback, 2016). However, it must be noted that the distributions of stress and material properties at the reservoir scale can be highly heterogeneous and are generally poorly constrained. Therefore, uncertainties remain about the potential to reactivate an individual identified source.

(b) Spatial, temporal, and earthquake recurrence models for induced seismicity are conceptually similar to the those used in conventional PSHA but must consider differences between natural and induced seismicity in occurrence characteristics (Petersen et al., 2016). Temporal models, for example, must consider expanding beyond the conventional stationary Poissonian model to consider earthquake occurrence that varies in space and time, which means that the short-term hazard due to injection is inherently non-stationary. The construction of these models is an area of active research.

Developing an occurrence model for induced seismicity is the most challenging task in assessing the hazard. Induced seismicity results from the interaction between the fluid injection parameters and the in situ lithologic, structural, hydrologic, and thermal conditions. These are challenging characteristics to evaluate because of the difficulty in imaging the subsurface and its inherent heterogeneity. Earthquake occurrence models for induced seismicity can be based on statistical, physics-based, or hybrid approaches, all of which use different input and calibration data (e.g., Dieterich et al., 2015; van der Elst et al., 2016; Broccardo et al., 2017). Some approaches were reviewed by Gaucher et al. (2015). Recently, the approaches that include physical models have gained more attention since they can integrate more site-specific hydromechanical information into the seismic hazard analyses (Langenbruch et al., 2018; Norbeck and Rubinstein, 2018; Zhai and Shirzaei, 2018; Dempsey and Riffault, 2019; Grigoratos et al., 2020a, 2020b) and appear to more accurately forecast the hazard than observational models alone (Rubinstein et al., 2021).

Determining the range of anticipated minimum and maximum magnitude events that may be of concern is more difficult for sources of induced earthquake. The minimum magnitude considered in typical PSHAs for engineering design is often in the range of M_w 4.5–5.0, since empirical data indicate that smaller events seldom cause structural damage. However, since induced events are typically shallower, smaller magnitude events will most likely also be of concern (Bommer et al., 2006), not least because events as small as about $M_w 2$ can contribute to the nuisance risk and also to cosmetic damage. When conducting the natural and induced seismic hazard assessments, it is recommended to use the induced seismicity minimum magnitude threshold, or something very close to it, for both analyses, assuming it to be the lower threshold. For maximum magnitude estimates, an evaluation of the sizes, nature and spatial distribution of pre-existing fractures and faults, the local stress field in the volume of rock surrounding the injection wells, and the estimated characteristics of the pore pressure and poroelastic fields due to injection need to be considered. Alternatively, various simple empirical relationships have also been developed to estimate the maximum magnitude of an induced earthquake based on, for example, the inferred dimensions of the stimulated volume, total injected fluid volume, or on probabilistic approaches based on the seismic activity rates (McGarr, 2014; Shapiro et al., 2011; Yeck et al., 2015). However, these proposed relationships generally do not take into consideration tectonically influenced, yet anthropogenically induced, ruptures on critically stressed faults that extend beyond the perturbed pressure and stress volume (van der Elst et al., 2016; Galis et al., 2017; Norbeck and Horne, 2018). When conducting the natural and induced seismic hazard assessments, the maximum magnitude threshold value could be the same or independent from each other.

(c) Site-appropriate earthquake GMMs, similar to those used in conventional PSHA, should specify the estimated ground shaking at a particular site as a function of (at a minimum) the magnitude and distance (e.g., Novakovic et al., 2018). Additional considerations for induced seismicity sources include the fact that injection-induced earthquakes are often more shallow than typical natural tectonic events, which increases the level of ground shaking for comparable sized events. The majority of the existing GMMs however, were created assuming tectonic sources and as such may not be well suited for induced seismicity. Significant work has been done to incorporate induced seismic sources in GMMs and it is essential that this work is included in the PSHF (e.g., Douglas et al., 2013; Atkinson, 2015; Bommer et al., 2017; Cremen et al., 2020). Additionally, to ensure consistency between the natural and induced seismic hazard analyses, the GMMs should be the same between the two. Recognizing that this could be quite difficult, it may therefore be necessary to use different GMMs in the two cases, but to verify that for common magnitudes and depths, they yield comparable predictions.

5.3.2.3 PSHF Results

Primary results of the PSHF include seismic ground motion hazard curves that show the estimated probability of exceedance per unit time (typically annually) on the vertical axis and different levels of the selected ground motion parameter on the horizontal axis for a particular location. For the short-term approach, ground motion parameters suggested for the presentation of PSHF results are PGA, PGV, SA or pseudo-spectral velocity, and perhaps modified Mercalli intensity scale (derived from PGA or PGV) (Rutqvist et al., 2014; Petersen et al., 2016; Petersen et al., 2018).

As with PSHA, estimates of uncertainty can be captured on the hazard curves. One-year hazard models produced by the USGS of the CEUS report only the mean hazard curve due to the complexity of the methodology. Uncertainties can be captured however using, for example, a bootstrapping approach to quantify the variability in the short term estimated hazard curves, or a logic tree approach (Mousavi et al., 2018; Petersen et al., 2016). Regardless, when plotting the seismic hazard curves, the rationale behind the input choices and a description of the range of technically defensible interpretations should be included with the results.

PSHF result maps could show the various earthquake ground-shaking levels with a fixed probability of exceedance over a specified time period. Alternative measures of ground shaking intensity include Modified Mercalli Intensity (MMI), PGV, a time history of motion, or the duration of strong shaking. One important value to define a priori would be the lowest annual frequency of exceedance for which ground motions of interest should be evaluated, again recognizing that this minimum value should be common between the natural and induced seismic hazard analyses.

5.3.2.4 Short-Term Seismic Hazard Analysis Report

The site-specific short-term seismic hazard report should contain sufficient information to allow the regulatory agency's technical reviewer(s) to satisfactorily evaluate the potential for short-term seismic ground shaking hazards.

The PSHF report should follow the same guidelines as the PSHA report outlined above. The PSHF report should be similar in structure to the PSHA report, with the only significant difference being the inclusion of details associated with the anticipated injection program. If a pseudo-probabilistic hazard assessment was opted for prior to injection, the pre-injection report should follow a similar format to the PSHA report, where appropriate.

5.3.2.5 Short-Term Seismic Hazard Analysis Review

The technical review by the appropriate regulatory agency is a critical part of the evaluation process. The regulatory reviewer ensures compliance with existing laws and current standards of practice to protect both government and community interests. The reviewer should be familiar with the investigative methods employed and the techniques available to perform the analysis, however it would be appropriate for reviewers to ask for the opinion of others more qualified in specialty fields. Reviews should be based on logical and defensible criteria. Guidelines for the report and any supplementary material should be made available to applicants beforehand. This information should cover procedures, report formats, and levels of appropriate investigative detail that will expedite the review and approval of the project (CGS, 2008).

5.3.2.6 Short-Term Seismic Hazard Analysis Updates

Site-specific PSHF reports to the regulatory agency should be updated annually or more frequently if future geological, seismological, or geophysical investigations reveal significantly new and different information than that used in the original PSHF, or if the observed induced seismicity is significantly different from initial expectations of induced seismicity. If prior to injection a pseudo-probabilistic hazard assessment was conducted instead of a PSHF, a PSHF report should be delivered to the regulatory agency 1-year after injection start.

6. STEP 6: RISK-INFORMED DECISION ANALYSIS

6.1 PURPOSE

The purpose of this step is to add elements to the project plan that are based on rigorous and credible estimates of the seismic risk associated with the design, operation, and closure of a carbon storage project. This will include identification and quantification of the seismic risks, an evaluation of their acceptability by stakeholders, and a final determination as to the most favorable options. Ground shaking due to geologic carbon storage operations may impact the quality of people's lives, the built environment, and the economy in several ways, therefore, the risk needs to be evaluated. The risk analysis will need to be time-dependent to account for the expected time varying stress conditions in and around the reservoir due to the sequestered CO_2. 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. Once the seismic risks have been evaluated, associated risks, such as brine or CO_2 contamination of underground drinking water sources, can be subsequently determined. Results from the risk informed decision analysis described here will be tightly coupled with the risk management framework described in Step 7.

6.2 RECOMMENDED PRACTICES

6.2.1 Seismic Risk from Natural Seismicity

6.2.1.1 A site-specific seismic risk analysis should be conducted to determine the baseline risk from natural tectonic seismicity. This assessment should include, but should not be limited to, the following:

a) Incorporation of seismic hazard results from natural tectonic seismicity
b) Identification of assets and activities that could be adversely affected by natural tectonic seismic activity within the ROC
c) Characterization of the vulnerability of the assets and activities to the natural tectonic seismic hazard within the ROC
d) Quantification of the seismic risk due to natural tectonic seismicity. At a minimum this should include a mean or median estimate in addition to confidence intervals on expected annual losses due to seismic activity

6.2.2 Seismic Risk from Induced Seismicity

6.2.2.1 A site-specific seismic risk analysis should be conducted to determine the risk from induced seismic events. This assessment should include, but should not be limited to, the following:

a) Incorporation of seismic hazard results from induced seismicity (Step 5.2)
b) Identification of assets and activities that could be adversely affected by induced seismic activity within the ROC
c) Characterization of the vulnerability, including nuisance vulnerability of the assets, activities, and local communities, to the induced seismic hazard within the ROC

d) Quantification of the seismic risk due to induced seismicity. At a minimum this should include a mean or median estimate in addition to confidence intervals on expected annual losses due to seismic activity

6.2.3 Risk Informed Decision Analysis

6.2.3.1 Evaluate and compare site-specific seismic risks and make risk-informed decisions concerning the project plan based on the risk-tolerance of the affected stakeholders.

6.3 SUPPORTING INFORMATION

6.3.1 Seismic Risk from Natural Seismicity

Seismic risk is calculated from three main contributing factors: (1) the seismic hazard at locations within the ROC; (2) the collection of exposed assets, activities, and communities at those locations; and (3) their vulnerability to the hazard (McGuire, 2004). As an example of the interplay between these three factors, consider a location next to an active earthquake fault which has a high potential for damaging ground shaking (high seismic hazard), but which has only one untenanted building located within the ROC (low exposure) that has been seismically retrofitted to withstand the anticipated maximum magnitude event (low vulnerability). In this case, it could be determined that the overall seismic risk in that particular location would be low.

Seismic risks from natural tectonic earthquakes in particular describe the harm or loss that would be likely due to exposure to natural seismic hazards. These risks can be measured in a number of ways, including direct economic losses (dollar loss due to the repair and replacement costs of physical assets), indirect economic losses (losses due to interruptions to the supply chain), downtime, and the potential number of injuries and fatalities (FEMA, 1989, 2013).

Calculating the 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. The calculated risks also enable an a priori risk-cost-benefit analysis for the considered operation.

(a) Incorporation of Seismic Hazard Results from Natural Tectonic Seismicity

One of the three major inputs into the seismic risk analysis are the hazard curves for natural seismicity generated from the PSHA conducted in Step 5.1. For the seismic risk analysis, it should be noted that since the risk depends strongly on the anticipated ground shaking that can occur, just using the median hazard often leads to an underestimation of the risk and so the mean hazard curve should be used instead (McGuire et al., 2005; Muntendam-Bos et al., 2015). Additionally, hazard curves from a scenario-based approach using Monte Carlo analysis will be needed to create a stochastic catalogue of events

(b) Identify Assets and Activities that could be Adversely Affected by Tectonic Seismicity

Assets and activities within the ROC that could be adversely affected by exposure to natural tectonic seismicity should be identified. Some of these assets and activities may be relatively straightforward to include, such as the number of potentially affected people and structures (e.g., residential housing, community facilities, government facilities, schools, historical buildings, religious facilities, critical infrastructure, commercial facilities, industrial facilities, medical facilities, essential facilities, transportation lifelines, utilities, potentially hazardous facilities, the

GCS injection infrastructure, etc.) (NRC, 1989). There are publicly available general building stock databases and well-accepted direct and indirect methods to supplement general database information (Anagnos et al., 2012). General building information should include the geographic location, construction classification, the category of seismic resistance, the economic value of the building, the number of occupants, and the type of occupancy of the building (FEMA, 1989). Buildings and structures of the same type may be grouped together for analysis and reporting purposes in larger studies (FEMA, 1989). It may also be useful to assess the pre-existing conditions of certain highly vulnerable properties or to consider an incentive program whereby local residents can perform a self-assessment of their property before operations start so as to obtain a more accurate determination of any pre-existing conditions.

The socioeconomic impact from damaged infrastructure and business operation interference can also be included using standard tools (FEMA, 2018). Social, economic, and personal well-being rely heavily on the reliability of complex and often interconnected utility networks (e.g., telephone, internet, water, gas, electricity, public transportation systems, etc.) that are vital to both business and personal needs. Any damage leading to operational malfunctions (e.g., internet service becoming unavailable) can create interruptions that should be included in the risk analysis. These types of losses should include, but are not limited to, 1) the loss of the utilities themselves, 2) business interruptions caused by the loss of the basic utilities, and 3) business interruptions due to a lack of supplies.

The determination of the ROC when identifying these assets and activities should be based on a maximum acceptable level of expected surface ground motions. In projects where there are residents within the assessment area, the choice of a ground motion threshold could be based on the ground shaking level associated with human perception (Step 3) (Bommer et al., 2006; Caltrans, 2020; Schultz et al., 2021b). A site-specific computer simulation of expected levels of ground shaking due to hypothetical events could therefore help delineate the ROC.

(c) Vulnerability Potential of the Assets and Activities to the Seismic Hazard

The vulnerability of the identified assets and activities within a particular site to the seismic hazard should be quantified through a vulnerability assessment of the area. The most appropriate relationships correlating ground shaking intensity, resulting damage, and associated losses (e.g., economic losses, downtime, injuries, fatalities, etc.) at the site will need to be chosen for input into the seismic risk assessment. The evaluation of the anticipated losses as a function of ground motion intensity can be achieved either directly by using vulnerability functions or indirectly through the use of fragility functions (Rossetto et al., 2015; Silva et al., 2013, Porter, 2020). Vulnerability functions directly relate ground motion intensity to anticipated losses (Figure 2). Fragility functions, on the other hand, relate ground motion intensity to the probability of damage and are often expressed as either loss ratio curves, damage probability matrices, or fragility curves (Figure 3). Therefore, when using fragility functions, appropriate damage-to-loss functions are also needed to link the anticipated losses with ground shaking intensities (FEMA, 1989). Additionally, in the literature, these vulnerability and fragility functions are often also referred to as curves, and it is worth noting that more research has been conducted on fragility functions than on vulnerability functions.

The vulnerability of standard construction is a long-documented field and there are many tools publicly available. Standard vulnerability models applicable to natural tectonic earthquakes are included in publicly available software packages for seismic loss estimation, such as Hazus

(FEMA, 2013). Commercially available seismic risk analysis codes may provide more detailed vulnerability assessment information. Additionally, databases of vulnerability and fragility functions for economic losses, downtime, and casualties associated with natural tectonic earthquakes are publicly available (Rossetto et al., 2015; Yepes-Estrada et al., 2016; Martins and Silva, 2020). Lastly, when accounting for property losses, either replacement costs or market value can be used in the calculations, with the choice clearly stated.

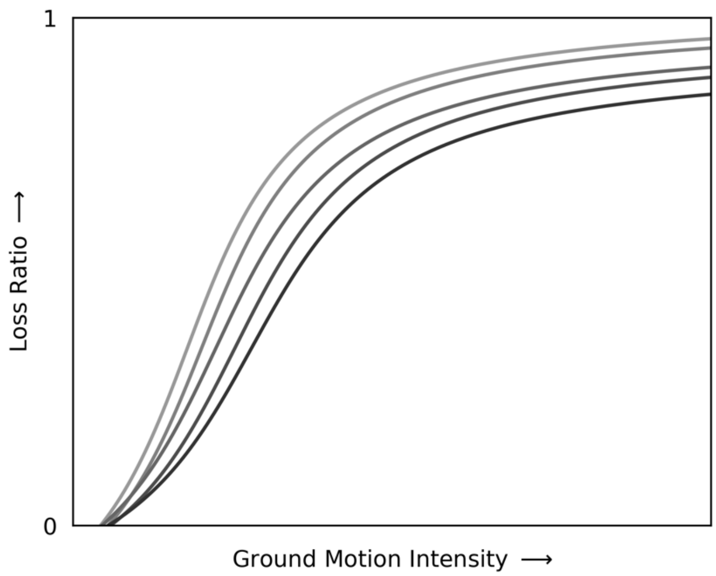

Figure 2: Example seismic vulnerability functions specifying the loss ratio (i.e., anticipated repair costs normalized by the replacement value) of various assets or asset classes, illustrated as individual grey lines, as a function of increasing ground motion intensity (e.g., PGA, spectral acceleration, etc.) A loss ratio of 1 would indicate that the repair of an asset would equal the replacement cost.

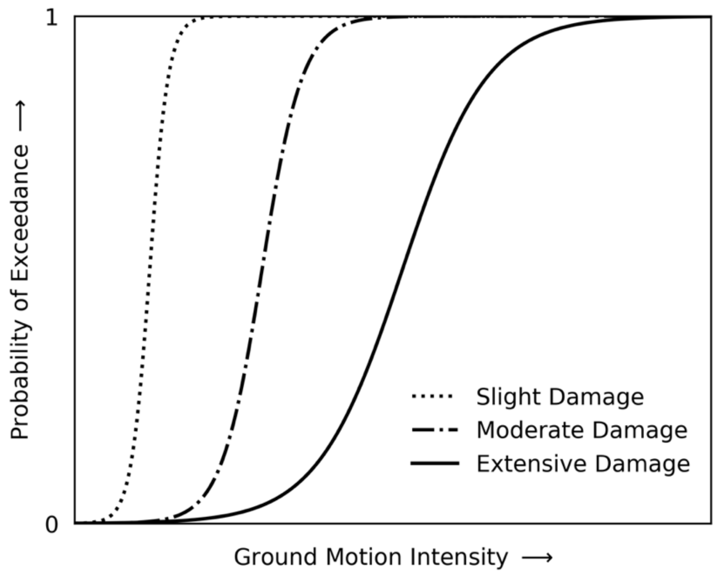

Figure 3: Example seismic fragility functions representing the probability of exceeding a given damage state (e.g., slight damage, moderate damage, extensive damage, etc.) as a function of increasing ground motion intensity (e.g., PGA, spectral acceleration, etc.) A probability of exceedance of 1 would indicate that the damage state is expected to happen at that ground motion intensity.

(d) Quantification of Seismic Risk Due to Natural Tectonic Seismicity

Regional or global seismic risk models, such as the GEM (Silva et al., 2020), can be used to gain a broad understanding about the risk of natural seismicity in the area; however, a site-specific seismic risk assessment due to natural seismicity should also be conducted. Seismic risk analysis can provide results in a variety of forms (Jonkman et al., 2003). These can include the mean annualized loss (the mean annual frequency with which the loss in question occurs), the mean annual number of damaged buildings, the probability that at least a certain level of loss will be exceeded during a specific period of time, the probable maximum loss, the local personal risk metric (e.g., the annual probability of fatality for a hypothetical person who is continuously present inside a building), and many others. Some of these results can only be obtained using a stochastic catalogue of events generated from the seismic hazard model (e.g., Van Elk et al., 2019). Results can be provided as individual risk curves or as maps that show results for each type of loss of concern for the region of concern.

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 (FEMA, 2013; Lang et al., 2007; Porter and Scawthorn, 2007; Trendafiloski et al., 2009; Pagani et al., 2014; Silva et al., 2014; Silva et al., 2018), while others are provided by commercial risk management companies that can also perform the analysis for a fee.

6.3.2 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 due to a particular proposed well location, injection plan, etc. Therefore, prior to operations, plans can be modified and the risk iteratively re-assessed so as to come to a risk level acceptable to stakeholders (Silva et al., 2021).

Previously, 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 is beginning 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. For example, physical damage to structures will have to account for the appearance of small cracks and other minor architectural damage in addition to more severe structural damages. Also, human perception of low amplitude ground shaking, and the associated nuisance need to be considered as elements of the risk. The nuisance produced by small vibrations will depend not only on the amplitude and dominant frequency of the ground shaking, but also on how often the events occur.

The induced seismicity risk assessment will also need to include a time-dependent component governed by the time dependent nature of the induced seismic hazard. The risk will often change due to operational changes at the site, changes in the exposure within the ROC (e.g., population changes, new building creation, or structural strengthening of existing buildings), changes in the tolerance of risk at the site, or with the addition of new information (van Elk et al., 2019). Additionally, 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. Additionally, since forecasting the vigor of a site's seismogenic response prior to the start of injection is difficult, there should be a dedicated effort at the beginning of injection to evaluate and model the seismogenic response based on the observations in near real-time, which will inform and help refine the initial hazard and risk analyses (Wiemer et al., 2017). After the early evaluation period, the probabilistic seismic risk assessment should also be periodically updated as new data arrives.

Specific plans should be made for the involvement of key stakeholders throughout the study. Additionally, experts unaffiliated with those conducting the risk analysis should provide periodic independent guidance and review over the course of the study that should address its goals, the seismic hazard analysis, the asset and activity inventory-defining process, the vulnerability functions, and the final results. This will increase confidence in the results of the study and conform to generally accepted validation procedures (FEMA, 1989).

(a) Incorporation of Induced Seismic Hazard Results

Induced seismicity hazard curves generated from the PSHF conducted in Step 5.2 will be the primary input into the induced seismicity risk analysis. Hazard curves for multiple seismic hazard forecasts based on varying injection operational scenarios should be included to create alternative estimates of seismic risk to inform project planning (e.g., different injection well locations, differing fluid flow path lithologies, modifications to injection pressure and volumes, etc.).

(b) Identification of Assets and Activities Adversely Affected by Seismicity within the ROC

Similar as for the tectonic seismicity, assets and activities within the ROC that could be adversely impacted by exposure to induced seismicity should be identified and a pre-assessment performed to the degree feasible. In addition to the negative impacts considered in relation to natural seismicity, impacts resulting from lower magnitude induced events, such as interference in human activity (e.g., sleep disturbance, creaking walls, enjoyment of recreation or entertainment, etc.), minor cosmetic damage, or psychological effects (e.g., anxiety due to the frequent occurrence of felt earthquakes), must also be included. The definition of the ROC could be based on a maximum acceptable level of expected surface ground motions associated with these lesser impacts.

(c) Characterization of the Vulnerability of the Assets and Activities to the Seismic Hazard

Development of fragility and vulnerability functions in general deal primarily with damage and losses (e.g., economic losses, downtime, injuries, fatalities, etc.) resulting from medium-to-large earthquakes. Vulnerability functions specific to the site and other nearby locations will need to be developed, and in particular need to include the impacts from relatively low levels of ground shaking outlined above.

The interference with human activities should also include nuisance, which refers to the annoyance that is created by low-level ground shaking that does not necessarily generate physical damage on the built and natural environment but can be felt by humans. Repeated vibration or noise, even of very small amplitude, can negatively impact people's way of life and well-being. This type of impact is difficult to quantify and there is as yet no well-established methodology to do so for induced seismicity. At present, following practices from other fields is recommended such as mining, geothermal energy production, or transportation. This would include using ground motion or noise criteria determined in Step 3 to be used in the formulation of vulnerability functions. An estimate of the annual probability of the number or percentage of people mildly, normally, or severely inconvenienced by the induced seismicity would be ideal.

(d) Quantification of Seismic Risk Due to Induced Seismicity

The seismic risk analysis can provide results in a variety of forms to address the different aspects of risk that are of importance to the various stakeholders. The choice of which risk metrics to focus on will also determine which aspects of the hazard and risk assessment should receive additional consideration (Bommer et al., 2015). The assessment of seismic risk due to induced seismicity should be site specific and adaptable in the case of new information. It will depend on the calculated seismic hazard, including the influence of operational factors (e.g., different injection programs, different injection formations, etc.), on the number and nature of exposed assets and activities that may be impacted, and on the determination of their level of vulnerability to the hazard. The risk analysis and resulting risk metrics should be similar in form to the tectonic seismicity for ease of comparison.

The seismic risk assessment will need to include hazards from both large and small seismic events. Seismic risk assessment methodologies and software have largely been developed assuming only larger tectonic events are the events of concern. Subsequently however, seismic risk assessments due to induced seismicity have started including the risks associated with smaller events as well. Additionally, a probabilistic seismic risk analysis, using time-dependent induced seismicity forecast models and a logic tree approach will permit epistemic uncertainties in the induced seismicity risk assessment to be incorporated in a more cohesive manner (Mignan et al., 2015).

6.3.3 Risk Informed Decision Analysis

The evaluation of the seismic risk due to induced seismicity is expected to depend significantly upon the project plan and would be expected to be updated as more information becomes available during the lifetime of the project. Therefore, determination of the project plan specifics should occur in conjunction with the risk assessment. This risk informed planning can help with decisions such as evaluating wellbore placement and operational injection plans. Using the site-specific seismic risk analysis, risk-informed decisions for the project plan based on the risk-tolerance of the affected stakeholders can be made. Effort should be made to appropriately communicate the uncertainty present in the risk assessment to stakeholders and decision makers. Risk-tolerance matrices are one method that can balance the level of risk tolerance of stakeholders with the expected benefits of the project (Walters et al., 2015). Risk-tolerance matrices allow for an estimation of the intersection between the anticipated risks and stakeholder tolerance for those risks.

Documentation should include the data used to inform the risk analysis, how the data were analyzed to determine risk, the results of the risk analysis (including uncertainties), and how management decisions will be determined based on the results of the risk analysis. This should include the types of losses considered, how the extent of the ROC was determined, the kinds of structures and facilities included in the analysis, a description of the vulnerability of sites within the ROC to the natural and induced seismic hazards in terms of impacts on the assets and activities, and a description of the sources of uncertainties in the analysis. The hazard and risk analyses should be presented in similar terms (e.g., PGA, PGV, etc.). Results can be presented as an estimate of the total loss expected annually (monetary, downtime, annoyance, injuries, casualties, etc.), losses expected as a function of time from the start of operation (with uncertainty ranges), and as a geographic map showing the spatial distribution of expected value losses in the region as a function of time and for several annual probabilities of exceedance. Variations of these results should be included when discussing different project plan options being considered.

7. STEP 7: OPERATIONAL MANAGEMENT OF INDUCED SEISMICITY RISKS

7.1 PURPOSE

The purpose of this step is to create and implement a site-specific, real-time plan to monitor, assess, control, and mitigate the risks associated with induced seismicity during and after fluid injection. 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 pre-determined criteria. The plan should be in place before injection operations commence and before any level of induced seismicity may be observed. This risk-based mitigation plan for induced seismicity is expected to be one component of a more comprehensive risk management plan covering the entire project.

7.2 RECOMMENDED PRACTICES

7.2.1 Induced Seismicity Mitigation Plan

7.2.1.1 The operator should create a site-specific induced seismicity mitigation plan based on a TLS framework. The TLS framework should include, but should not be limited to:

a) At least three response levels, indicating operation as usual (green), heightened awareness and reassessing and modifying as appropriate of injection operations (yellow), and stopping injection (red)
b) Clear threshold level criteria defining when an increase in response level is necessary
c) A clear description of mandatory and optional actions and procedures at each of the response levels
d) A description of the conditions, actions, and procedures necessary to reduce the response level to a lower level
e) Adequate near real-time data input from the seismic monitoring network

7.2.1.2 The induced seismicity mitigation plan should be operational throughout the active operation of the site and through the end of the seismic PISC period.

7.2.1.3 The induced seismicity mitigation plan should be endorsed by the Expert Panel and approved by the regulatory agency.

7.2.1.4 A reduction in the response level should occur when recommended by the Expert Panel and approved by the regulatory agency.

7.2.2 Expert Panel

7.2.2.1 An Expert Panel should be created whose purpose is to provide evidence-based information and recommendations pertaining to the induced seismicity risk posed by the project.

7.2.2.2 The Expert Panel should be comprised of representatives from the operator, local stakeholders, the regulatory agency, and appropriate independent subject matter experts. The chairperson should be selected from the independent subject matter experts.

7.2.2.3 Should there be other active or planned projects involving fluid injection that jointly contribute to a composite PSZ, representatives of the respective operators should be additional members on the Expert Panel. The regulatory agency should approve the members and the chairperson of the Expert Panel.

7.2.2.4 The Expert Panel should convene at least annually to independently review past seismic activity, the appropriateness of the seismic monitoring network and operation, updated hazard and risk assessments, and the current induced seismicity mitigation plan. The operator should supply the Expert Panel with all reports and information necessary to perform the review.

7.2.3 Early Evaluation Period

7.2.3.1 The first year of injection operations should be considered an Early Evaluation Period.

7.2.3.2 The Expert Panel should convene at least weekly during the first month of the Early Evaluation Period and at least monthly during the following 5 months of the Early Evaluation Period to review the seismogenic and hydraulic site response and to verify the continued appropriateness of the induced seismicity mitigation plan, including the hazard and risk assessments originally performed in Steps 5 and 6 prior to injection operations.

7.2.3.3 Reduction of the review schedule during the Early Evaluation Period after the first 6 months should be approved by the regulatory agency.

7.2.3.4 Injection operations should ramp up gradually during the Early Evaluation Period and the Expert Panel may recommend to the regulatory agency that injection activities be slowed or halted if warranted.

7.2.4 Seismic PISC

7.2.4.1 The default duration of the seismic PISC should be the duration of the regular PISC after the end of injection operations.

7.2.4.2 The Expert Panel should make a recommendation whether or not to modify the seismic PISC period, considering the seismic response of the site during and after active injection.

a) The regulatory agency may approve a reduced, or require an increase in, the duration of the seismic PISC.

b) The seismic PISC period should not end before pressure and stress perturbations in and surrounding the reservoir have stabilized and observed seismicity approaches tectonic baseline levels.

7.2.5 Liability and Insurance

7.2.5.1 The operator should be insured against potential damages associated with induced seismicity or demonstrate sufficient assets to self-insure for potential damage outlays consistent with the estimated seismic risk.

7.2.5.2 Levels of insurance coverage should be set based on the estimated induced seismicity risk and should be re-evaluated annually.

7.2.5.3 Liability for the consequences of induced seismic events should be shared among operators whose estimated PSZ extends to the epicenter of a damaging or felt event.

7.3 SUPPORTING INFORMATION

7.3.1 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. A TLS, as defined here, is a risk management tool which serves several purposes: it communicates the status of the project; it specifies predefined actions that should occur in order to attempt to prevent large magnitude induced events, and it prompts the operator to consider changes to the operations if a concerning trend of seismic activity has been observed. The TLS status should be made easily available to both the operators and the public. A TLS will typically have three or more response levels, corresponding at a minimum 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). In a TLS, the status of a project is continuously evaluated with the goal of avoiding induced seismicity that could endanger the local population or damage infrastructure (NRC, 2012a). For example, during the Basel EGS project, their yellow level was triggered due to a medium size seismic event, which caused them to reduce their injection rate. Ongoing seismic activity increased the level to red, which lead to a cessation of the injection program. However, unfortunately, a magnitude M_w3.4 could not be prevented with the TLS (Haering et al., 2008).

A traditional TLS, such as that used in the Basel EGS project, 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). A major shortcoming of traditional TLSs is that they are not forward-looking and do not provide a forecast of future seismic activity. Adaptive traffic light systems (ATLS) and physics-based forecasting methods, however, can help to inform operation decisions, such that elevated risk levels might not be reached in the first place (Figure 4).

An ATLS is fully probabilistic, incorporates new data on the fly (automatically as much as possible) to update geomechanical and seismicity forecasting models, and integrates hazard, exposure, and vulnerability into the automatic 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 become available. An ATLS incorporates not only the past observations of seismicity but produces projections of seismicity rates based on the actual or projected injection and production rates in a reservoir (e.g., Bachmann et al., 2011). Although the deployment of an ATLS is currently an active research topic, operators are encouraged to implement the most up-to-date system with a site-specific forecasting method that is adapted to the local conditions. This would allow for a more proactive management approach to induced seismicity compared to the reactive approach in traditional TLS. Additionally, an ATLS could potentially be used to optimize operations in addition to minimizing seismicity by providing forecasts based on different injection scenarios.

In both TLSs and ATLSs, the threshold criteria determining when an increase in response level is necessary should be defined such that they allow effective intervention to prevent the traffic light from reaching the highest response level requiring a full stop of the operation (Kao et al., 2018). Threshold criteria that could be added to a site-specific plan include: a basic magnitude threshold criteria; a peak ground velocity threshold (such as those determined in Step 3) (Bommer et al., 2006); the identification of a concerning seismic trend (such as observed seismicity delineating a potential fault capable of producing an event of concern) (Lee et al., 2019); a comparison with magnitude exceedance probabilities (van der Elst et al., 2016; Shapiro et al., 2010; Langenbruch et al., 2016); a comparison with calculated seismic risk criteria (Douglas and Aochi, 2014; Mignan et al., 2015); a comparison to economic loss criteria (Langenbruch et al., 2020); or public response (Wiemer et al., 2017).

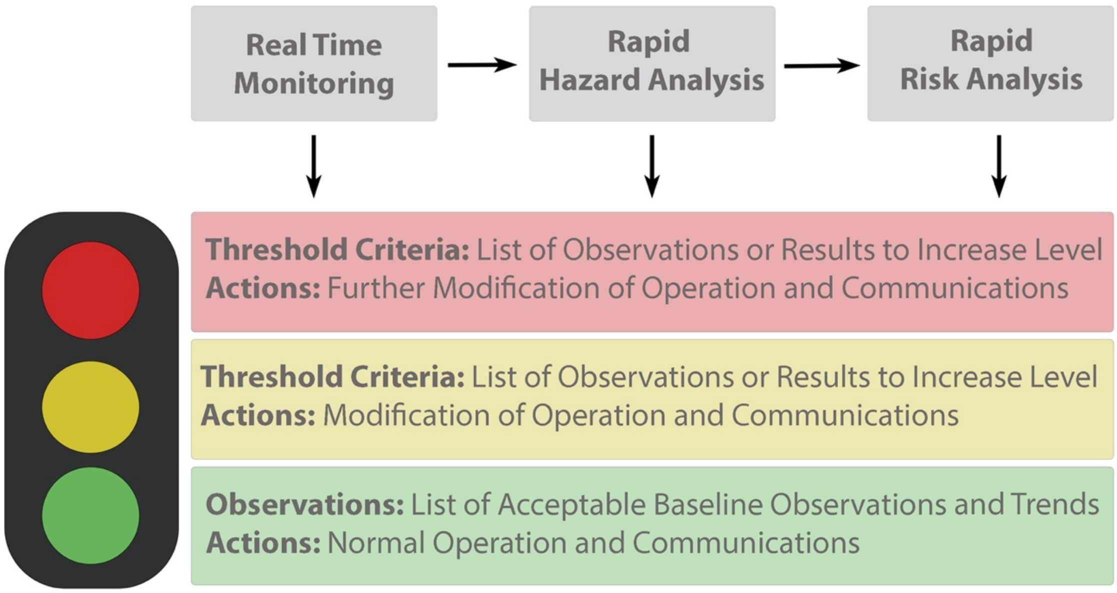

Figure 4: Example adaptive traffic light system. Real time seismic, hydraulic, and operational monitoring can either directly increase the response level or indirectly help inform rapid hazard and risk analyses which may prompt a change in response level due to updated results.

When selecting the threshold criteria, two points need to be considered: (1) the magnitude-frequency relationship of earthquakes (Gutenberg and Richter, 1944); and (2) the temporal delay between changes in injection operations and the response of seismic activity. Regarding the first point, it has been observed that for every tectonic earthquake of a given magnitude occurring in a volume of the Earth's crust about 10 times as many earthquakes one magnitude unit smaller are expected to be observed. For example, for every 100 M_w1 earthquakes, on average 10 M_w2 earthquakes and one M_w3 earthquake are expected to be observed. This behavior is embodied by the Gutenberg and Richter (1944) relationship with a b value approximately equal to 1. This empirical rule generally holds for induced seismicity as well, although the precise relationship may vary from site to site and can vary during the injection cycles (e.g., Bachmann et al., 2012; Martínez-Garzón et al., 2014,). If using magnitude thresholds, Schultz et al. (2020) argue that the yellow light threshold should be set 2 magnitude units below the red light. Using this criterion and assuming a Gutenberg-Richter b value of 1, 99% of the cases would be expected to present an opportunity to initiate mitigation measures to avoid the highest response state and in only 1% of the cases would the traffic light be expected to jump from green to red, skipping the yellow level. Additionally, b values greater than 1 at a site, as found in some EGS co-injection and post-injection settings (Bachmann et al., 2012), would be expected to lead to even fewer cases of jumping directly from green to red. Recent research has also focused on risk-based approaches for choosing appropriate red-light thresholds at certain types of fluid injection sites (Schultz et al., 2021a).

Regarding the second point and particularly for typical GCS long-term injections, the pressure plume potentially causing seismicity may reach many kilometers or tens of kilometers away from the injection point (Goebel et al., 2017; Peterie et al., 2018). While the pressure around the injection well may fall rapidly in response to reductions of the injection rate, it may continue to rise further away, where earthquakes may continue to be induced by small pressure perturbations. It may be months or longer for changes in the injection operations to take effect, especially if seismicity has already been observed far away from the injection point. It has been observed in several injection projects that the largest events occurred after injection ceased, which can be explained in part by the continuing propagation of pressure plumes and delayed aftershocks (Dieterich et al., 2015). Event triggering by poroelastic stress changes rather than directly by elevated pore pressure is subject to the same temporal behavior as described above. In addition, aftershock sequences may produce seismicity several years after their mainshock.

At the normal “green” TLS operating state, routine operation of the real-time monitoring system should also include more detailed analysis of potential pre-monitory seismicity. These detailed analyses should include enhanced event detection (e.g., through template matching) (Skoumal et al., 2014; Chamberlain et al., 2018; Templeton et al., 2020), precise relative relocation (Waldhauser and Ellsworth, 2000; Trugman and Shearer, 2017), and focal mechanism analyses to identify fault planes. Additionally, seismological signatures indicating the possibility of fault rupture may also be visible in the data, as it was for example in the Pohang EGS case (Ellsworth et al., 2019). At this early stage, potentially concerning trends such as an injection pressure increase (even if it is still within normal ranges), incremental increases in induced earthquake magnitudes that are still below the threshold level, and the observation of evolving patterns of seismicity (such as clusters or delineations of faults), can be evaluated so as to initiate potential mitigation measures before more concerning induced seismicity is induced. The information from these studies should be made available to the Expert Panel so that they can make appropriate recommendations.

Operation at elevated alert levels should include informing the regulatory agency and other project stakeholders. Observed seismicity should be further analyzed in order to understand the causative mechanisms and inform the choice of potential mitigation steps. Should the alert level continue to increase due to ongoing seismicity, injection should be reduced or stopped, and other steps taken to ensure the safety of the site and local populations.

Once seismic activity has been induced above a threshold level there is only a limited range of possible operational procedures that may be able to mitigate further seismicity. The operator can modify the injection operation by reducing injection rates or volume, stopping injection, producing from the injection well, or producing fluid elsewhere with the goal of reducing the pressure at a location distant from the original injection well to potentially steer the pressure plume. The efficacy of active pressure management is an area of active research (Kroll et al., 2020).

With any of these changes to operations it should to be acknowledged that they may take a significant amount of time until a geomechanical effect is achieved. Hence, it is important to implement low enough traffic light thresholds in order to react early enough to avoid damaging levels of seismicity.

It is important to document a clear procedure that would allow for the reduction of the response level of a traffic light framework. The conditions to be met for reducing the response level will vary from site to site. However, in every case the observed seismicity should be carefully analyzed along with the pertinent operational parameters and geomechanical models to understand what conditions led to the heightened alert level. This analysis should engage the appropriate specialists, including seismologist, geologists, and engineers to review available data and if necessary, design and conduct engineered trials to inform operating procedure adjustments. Subsequently, subsurface models should be modified to determine what has changed from the initial assumptions and determine how operations can be modified such that a higher response level will not be reached. The Expert Panel should recommend, and the regulatory agency should approve, any reduction in the response level at a site.

All traffic light frameworks are dependent on adequate near real-time seismic monitoring. While a traditional TLS may be operated successfully with a magnitude of completeness about 0.5 units below the lowest threshold criteria defined in the site-specific plan, a prospective ATLS greatly benefits from a much lower completeness. Seismic forecast models that are incorporated into ATLS perform best when their statistical features (e.g., b-values or seismicity rate variations) are based on the lowest completeness achievable. These lower magnitude events are also necessary for near-real-time evaluation of the effectiveness of enacted risk mitigation protocols and for a more rapid identification of potential signs of fault activation.

7.3.2 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, such as changes to the injection operations, 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).

The Expert Panel is tasked with: recommending for approval the induced seismicity mitigation plan prior to subsurface injection; recommending actions on an as-needed basis during injection and during the seismic PISC period; recommending actions after a change to the response level; and recommending the lowering of a response level. The Expert Panel is expected to review, at least annually, the induced seismicity mitigation plan, the appropriateness of the seismic monitoring network and operation, updated hazard and risk assessments, and the detailed seismological analyses that will be routinely conducted by the operator.

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 project's 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 whose ROCs may overlap.

7.3.3 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 analyzed to calibrate, verify, and/or update the pre-injection models and parameters. Forecasts of the level of induced seismicity derived from pre-injection assessment using estimated values are likely to be of limited value without this calibration and verification step. Therefore, the Expert Panel should convene, virtually or in person, at least weekly during the first month of the early evaluation period and monthly during the following 5 months to assess the appropriateness of the models, input parameters, the induced seismicity mitigation plan, and to recommend modifications if necessary. If no seismicity is observed meetings can be adapted to simple check ins.

During this critical time, the relative changes in pressure and stress may be at their greatest. Therefore, it is suggested that injection operations should be gradually increased and that any increases in the planned injection rate be recommended by the Expert Panel. The Expert Panel should be empowered to recommend a slowing or halting of injections to the regulator if hazardous conditions warrant it.

7.3.4 Seismic PISC

The PISC duration is defined as the time period following cessation of CO_2 injection in which appropriate monitoring and other actions are needed to ensure that any underwater source of drinking water (USDW) is not endangered. With regard to induced seismicity, the Expert Panel may recommend implementing a seismic PISC which may have a duration that is different from the PISC. It may be reduced or extended relative to the PISC in order to account for the different requirements of the induced seismicity mitigation plan. For example, if only very low levels of induced seismicity were detected during the active injection phase of the project, the Expert Panel may be justified in recommending an earlier end to the seismic PISC than for the PISC. If, however, significant seismicity was observed, it may be required to continue execution of the induced seismicity mitigation plan throughout and beyond the PISC period. Determinations should be based on two factors: (1) stabilization of pressure and stress perturbations to steady-state values; and (2) clear demonstration that the seismic frequency-magnitude behavior is approaching baseline tectonic conditions. For example, at the site of the Basel EGS there has been observed seismicity for over 10 years following shut-in after a fluid-injection program that lasted only 2 weeks (Herrmann et al., 2019).

During the seismic PISC, seismic monitoring, the outreach and communication program, and the implementation of the Induced Seismicity Mitigation Plan should continue, maintaining the number of monitoring stations and review procedures. Additionally, during the seismic PISC, the schedule of review meetings by the Expert Panel may be reduced if deemed appropriate by the Expert Panel. This should require approval by the regulatory agency.

7.3.5 Liability and Insurance

Liability and compensation coverage for damages cause by 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). Further, having insurance and a compensation scheme in place prior to operations may significantly increase public acceptance for a subsurface injection project. Operators should be sufficiently covered or demonstrate sufficient assets to self-insure against damages from induced seismicity. Insurance coverage for potential losses at the median annual exceedance probability of 10^{-4} or greater have been suggested for EGS (Wiemer et al., 2017). The amount of coverage should be re-evaluated annually. In the case of a damaging event there are often legal disputes about who is at fault. This may occur specifically in cases where several operators have overlapping ROCs. Assigning a single operator to be at fault would ignore the fact that pressure diffusion from several injection sources is additive (e.g., Dempsey and Riffault, 2019). An induced event could occur because of the sum of all injection operations in its vicinity. Therefore, it is recommended that operators pay contributions to an insurance fund that would compensate for any damages resulting from induced seismicity in a shared ROC. Operators who expect to have overlapping ROCs should negotiate these details in advance of injection.

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APPENDIX I - TERMINOLOGY

2-sigma: The two standard deviation uncertainty.

Region of Concern (ROC): The expected ground surface area around an injection well where there could be a negative impact due to potential seismic events occurring in the perturbed stress zone (PSZ) throughout the lifetime of the project.

Area of Review (AOR): The region around an injection well where USDWs may be endangered by the injection activity.

Geologic Carbon Storage (GCS): The long-term containment of a gaseous, liquid, or supercritical carbon dioxide stream in subsurface geologic formations.

Peak Ground Acceleration (PGA): Maximum ground acceleration that occurs at a particular location due to a seismic event and is typically expressed as a fraction of gravitational acceleration (g).

Peak Ground Velocity (PGV): Maximum ground velocity that occurs at a particular location due to a seismic event.

Perturbed Stress Zone (PSZ): The subsurface region around an injection well with perturbed pressure and stress in which seismicity could occur in a critically stressed crust. This zone is expected to expand over time as the subsurface fluid migrates away from the injection point.

Post-Injection Site Care (PISC): Appropriate monitoring and other actions (including corrective action) needed following cessation of injection to ensure that USDWs are not endangered. PISC monitoring must continue until it can be demonstrated that the site poses no further endangerment to USDWs. The default duration for PISC, as stated in the U.S. Environmental Protection Agency (EPA) guidelines, is 50 years.

Seismic PISC: The PISC that relates to the Induced Seismicity Mitigation Plan. The seismic PISC duration may be decoupled from the duration of the general PISC depending on the seismic response of the site during active injection.

Underground Source of Drinking Water (USDW): An aquifer or portion of an aquifer that supplies any public water system or that contains a sufficient quantity of ground water to supply a public water system, and currently supplies drinking water for human consumption, or that contains fewer than 100,000 mg/l total dissolved solids and is not an exempted aquifer.

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APPENDIX II –NRAP TOOLS AND PUBLISHED STUDIES RELEVANT TO RECOMMENDED PRACTICES

Recommended Practice	Relevant NRAP Tools	Published NRAP Applications
PRELIMINARY SEISMIC RISK SCREENING EVALUATION	GMPIS	• Coblentz, D.; Lee, R.; Wilson, J.; Bradley, C. *Kimberlina, California Site Characterization for Applications to Potential Induced Seismicity*; NRAP-TRS-III -007-2017; NRAP Technical Report Series; U.S. Department of Energy, National Energy Technology Laboratory: Morgantown, WV, 2017; pp 56.
OUTREACH AND COMMUNICATION		[No NRAP studies relevant to this topic have been published to date.]
GROUND MOTION THRESHOLDS		[No NRAP studies relevant to this topic have been published to date.]
COLLECTION OF SEISMICITY DATA	PSMT	• Chen, T.; Huang, L. Optimal design of microseismic monitoring network: Synthetic study for the Kimberlina CO_2 storage demonstration site. *International Journal of Greenhouse Gas Control* **2020,** *95*, 102981. https://doi.org/10.1016/j.ijggc.2020.102981 • Chen, Y.; Huang, L.; EGS Collab Team. Optimal design of 3D borehole seismic arrays for microearthquake monitoring in anisotropic media during stimulations in the EGS Collab project. *Geothermics* **2019,** *79*, 61–66.
HAZARD EVALUATION OF NATURAL AND INDUCED SEISMIC EVENTS	SoSAT	• Appriou, D. *Assessment of the geomechanical risks associated with CO_2 injection at the FutureGen 2.0 Site*; PNNL-28657; Pacific Northwest National Laboratory, Richland, WA; 2019. • Burghardt, J. Geomechanical Risk Assessment for Subsurface Fluid Disposal Operations. *Rock Mechanics and Rock Engineering* **2018,** *54*, 2265–2288. DOI: 10.1007/s00603-018-1409-1.
RISK-INFORMED DECISION ANALYSIS	RiskCat	• California Energy Commission. Investigation of Potential Induced Seismicity Related to Geologic Carbon Dioxide Sequestration in California; Report No. CEC-500-2017-028; August 2017. https://ww2.energy.ca.gov/2017publications/CEC-500-2017-028/CEC-500-2017-028.pdf (accessed Dec 24, 2019).
OPERATIONAL MANAGEMENT OF INDUCED SEISMICITY RISKS	STSF	• Bachmann, C. E.; Wiemer, S.; Woessner, J.; Hainzl, S. Statistical analysis of the induced Basel 2006 earthquake sequence: introducing a probability-based monitoring approach for Enhanced Geothermal Systems. *Geophysical Journal International* **2011,** *186*, 793–807. 10.1111/j.1365-246X.2011.05068.x. • Hainzl, S.; Ogata, Y. Detecting fluid signals in seismicity data through statistical earthquake modeling. *J. Geophys. Res.* **2005,** *110*, B05S07. DOI:10.1029/2004JB03247.

Where: GMPIS – Ground Motion Prediction applications to potential Induced Seismicity, PSMT – Passive Seismic Monitoring Tool, SOSaT – State of Stress Analysis Tool, and STSF – Short-Term Seismic Forecasting Tool

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NRAP is an initiative within DOE's Office of Fossil Energy and is led by the National Energy Technology Laboratory (NETL). It is a multi-national-lab effort that leverages broad technical capabilities across the DOE complex to develop an integrated science base that can be applied to risk assessment for long-term storage of carbon dioxide (CO_2). NRAP involves five DOE national laboratories: NETL, Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), and Pacific Northwest National Laboratory (PNNL).

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