DEEP

Innovation for:
De-Risking Enhanced
Geothermal Energy Projects

Deliverable

Deliverable 5.3 - Report containing the general guidelines for risk governance including protocols for seismic risk monitoring and imaging

Report information	
Work package	WP5: Advancing best practice and tools for seismic risk assessment, mitigation and communication
Lead	TUD
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Reviewers	DEEP community
Approval	[Management Board]
Status	Final
Dissemination level	internal
Will the data supporting this document be made open access?	Not Applicable
If No Open Access, provide reasons	This document has been submitted to the journal Review of Geophysics
Delivery deadline	31.05.2024
Submission date	31.05.2024
Intranet path	[DOCUMENTS/DELIVERABLES/Deliverable5.3.pdf]

Managing Induced Seismicity Risks from Enhanced Geothermal Systems: a Good Practice Guideline

A DEEP (De-risking Enhanced geothermal Energy Projects) consortium report

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Executive Summary

Geothermal energy is a source of clean, renewable, and sustainable source of power that could play an important role in climate-conscious energy portfolios. Enhanced Geothermal Systems (EGS) have the potential to scale up exploitation of thermal resources by allowing economical access to low permeability reservoirs. Permeability enhancement is accomplished through either chemical, thermal, or hydraulic stimulation. During hydraulic fracturing, fluids injected under high-pressure cause the rock mass to fail in tension, creating new fractures (or opening existing fractures) that improve fluid connectivity.

This increase of pore fluid pressure can also interact with pre-existing fault systems, potentially inducing earthquakes of significant size. Induced earthquakes can occur in association with drilling mud losses, hydraulic fracturing, fluid circulation, and reservoir temperature changes - potentially triggered by any thermo-hydro-mechanical process that disturbs the balance of fault stresses.

Induced earthquakes are a significant concern for EGS operations: their negative socio-economic impacts can undermine public acceptance of geothermal projects. In some cases, ground shaking nuisance, building damages, or injuries have spurred the early termination of projects (e.g., Basel, Pohang). On the other hand, EGS operations at Soultz-sous-Forêts (France), Helsinki (Finland), Blue Mountain (Nevada, USA), Utah FORGE (USA) have adequately managed induced earthquake risks.

The success of an EGS operation depends on the enhancements of reservoirs to economic levels of productivity, while maintaining acceptable seismic risk levels during every stage of the project. This requires state-of-the-art seismic risk management. This document reviews domains of seismology, earthquake engineering, risk management, and communication. We then synthesize 'good practice' recommendations for evaluating, mitigating, and communicating the risk of induced seismicity. These recommendations are based on existing guidelines and recent scientific developments. Representation from operators ensures the practical usability of our guidelines.

We advocate for a modular approach. Recommendations are provided for key technical aspects including (1) a seismic risk management framework, (2) pre-screening assessments, (3) comprehensive seismic hazard and risk evaluation, (4) traffic light protocol designs, (5) seismic monitoring implementation, and (6) step-by-step communication plans. Recommendations adhere to regulatory best practices, to ensure their general applicability in a wide variety of settings. Overall, our guidelines provide a template for effective earthquake risk management, aiding the successful development of EGS projects.

Abbreviations

a-value	Gutenberg-Richter a-value
ATLP	Adaptive Traffic Light Protocol (synonymously Adaptive Traffic Light System)
b-value	Gutenberg-Richter b-value
DAS	Distributed Acoustic Sensing
DSHA	Deterministic Seismic Hazard Analysis
EGS	Enhanced Geothermal Systems
FAIR	Findability, Accessibility, Interoperability, and Reusability
FoP	Factor of Proportionality
FORGE	Frontier Observatory for Research in Geothermal Energy
G-R	Gutenberg-Richter
GMPM	Ground Motion Prediction Model
GSIM	Ground Shaking Intensity Model
GRID	Geothermal Risk of Induced seismicity Diagnosis (Trutnevyte & Wiemer 2017)
IM	Intensity Measure
IPM	Intensity Prediction Model
ISRMF	Induced Seismicity Risk Management Framework
LoC	Level of Concern
Mc	Magnitude of Completeness
M_{felt}	Magnitude expected to cause nuisance to stakeholders
M_L	Local Magnitude
M_W	Moment Magnitude
MMI	Modified Mercalli Intensity
M_{min}	Minimum magnitude for engineering purposes
M_{max}	Maximum possible magnitude
MCE	Maximum Credible Earthquake
PSRA	Probabilistic Seismic Risk Analysis
PSHRA	Probabilistic Seismic Hazard and Risk Analysis
PSHA	Probabilistic Seismic Hazard Analysis
SHA	Seismic Hazard Analysis
SHRA	Seismic Hazard and Risk Analysis
SNR	Signal to Noise Ratio

SRA	Seismic Risk Analysis
SVA	Seismic Vulnerability Analysis
TLP	Traffic Light Protocol (synonymously Traffic Light System)
Σ	Seismogenic Index

1. Introduction

1.1. Enhanced geothermal systems (EGS)

Geothermal energy is considered a source of clean, renewable, and sustainable energy and could play an important role in the energy transition, to combat climate change. However, conventionally exploited hydro-geothermal energy resources are limited and only accessible in geologically favorable locations. Deep beneath the surface, temperatures increase significantly, normally with a gradient around 25 °C/km. Thus, even for areas that aren't in geologically favorable conditions, at 3-5 km depth, temperatures reach around 100°C, making it possible to harness heat by injecting cold water, and extracting hot water (steam) that can be used for electricity generation or direct heating. However, low rock porosity and permeability restrict fluid flow. Therefore, methods such as hydraulic stimulation or chemical stimulation are required to enhance rock permeability and fluid conductivity, leading to the creation of an EGS.

Conventionally, the hydraulic stimulation for EGS often intentionally targets formations with estimated natural small-scale fractures. The increase of fluid pressure in the reservoir induces slip along those fractures. Due to the heterogeneity and roughness of fractures, slip often creates dilatation, thus effectively creating pathways in the fracture network. In other cases, with enough fluid pressure, new fractures might be created and propants might be used to keep the fractures open. In either case, the induced slips can behave seismically, producing earthquakes that might be recorded or felt. Induced seismicity is thus an inevitable factor in EGS.

Additionally, geothermal production (circulation of hot and cold fluids) could also induce earthquakes due to e.g., pressure leaking to active faults (Schmittbuhl et al., 2021) or stress variations caused by heterogeneous temperature decreases (Parisio et al., 2019; Vörös & Baisch, 2022). Occasionally, mud loss during the drilling phase has also coincided with low-magnitude seismicity, often serving as a warning sign for future fault reactivation (Kim et al., 2018; Dost et al., 2012). Thus, the inevitable factor of induced seismicity requires thorough seismic risk management on each stage of an EGS project.

1.2. Induced seismicity risk management

Ideally, we want an EGS operation to generate only microearthquakes without any felt impact or risk to the nearby residents or personnel on site. Those microearthquakes can help to estimate the dimension of the reservoir and the efficiency of the stimulation, which are important factors for evaluating commercial production. However, larger events could potentially occur, posing risks (e.g., noise nuisance, property damages, financial losses, or personal injuries) on the residents and trigger financial/social consequences (e.g., project termination, social unrest, and obstacles for future development). Readers can refer to Table 27 in Maury et al. (2023) and Foulger et al. (2018) for a list of seismic incidents during geothermal operations.

The EGS project in Basel (Deichmann & Giardini, 2009) and the deep geothermal project in Strasbourg (Schmittbuhl et al., 2021) were terminated due to induced earthquakes of M_L 3.4, and M_L 3.6, respectively. The EGS project in Pohang, South Korea, caused the largest EGS-related earthquake, registering a magnitude of M_W 5.5 (U.S. Geological Survey; Woo et al., 2019). The Pohang earthquake resulted in dozens of hospitalizations, over 2000 property damages and around 300 million USD in economic damages, and the termination of the project (Kim et al., 2018). These highlight both the potential risk of

induced seismicity and the need for improved assessment and management, before and during deep geothermal and EGS projects.

On the other hand, we have observed EGS operations in Soultz-sous-Forêts (France; Dorbath et al., 2009), Newberry (USA; Cladouhos et al., 2016), Cooper Basin (Australia; Holl 2015) and Blue Mountain (USA; Norbeck & Latimer, 2023), Helsinki (Finland; Kwiatek et al., 2019) and Utah FORGE (USA; Moore et al., 2019), where induced seismicity did not pose unacceptable risk. Although not all of these cases achieved the expected conductivity for production. Examining the seismic risk management plans from those projects could potentially benefit future EGS initiatives.

This document aims to provide uniform and applicable good practice guidelines for managing induced seismic risk in EGS projects. It can serve as a reference for the EGS stakeholders including operators, regulators, independent experts, vendors, and residents, and it is based on existing documents and guidelines on induced seismicity. In particular, we draw insights from the existing guidelines in Europe (Baisch et al., 2016; Wiemer et al., 2017; Trutnevyte & Wiemer, 2017; Kraft et al., 2020; Maury et al., 2023; Braun et al., 2020; Bohnhoff et al., 2018; Dialuce et al., 2014; FKPE, 2013; Dutch Mining Act, 2003) and in the United States (Majer et al., 2012; 2016; Walters et al., 2015; Templeton et al., 2021). We also incorporate findings from the Geothermica project DEEP, which focused on the Utah FORGE EGS project (Moore et al., 2019; Wannamaker et al., 2020; Pankow et al., 2023) and consider information from analogous types of induced seismicity like hydraulic fracturing in the oil/gas industry (CAPP, 2019; Schultz et al., 2020a).

From a legal-requirement point of view, there is in general a lack of legislation regarding the permitting process and risk management for EGS projects. We hope this document could inspire more national legislation on EGS regulation to prevent nuisance, protect residents' properties, and safety, while developing EGS to achieve decarbonization and energy security needs.

BOX 1.1 "Induced" versus "triggered"

Following McGarr et al. (2002), the adjective "induced" normally describes seismicity resulting from an activity that causes a stress change that is comparable in magnitude to the ambient shear stress acting on a fault, whereas "triggered" is used if the stress change is only a small fraction of the ambient stress level. Note that, in this document, we collectively refer to 'induced' and 'triggered' earthquakes as "induced seismicity". This is because it is difficult to distinguish them in practice, especially in near real-time, due to the very complex geomechanics involved (Ellsworth et al., 2019).

1.3. Outline of the guideline

The document comprises the following topics: (1) risk management framework, (2) preliminary risk screening, (3) probabilistic seismic risk analysis (for projects with pre-screened high level of concern), (4) traffic light protocols, (5) seismic monitoring, and (6) communication and outreach guidelines.

Throughout the document, we aim to clearly distinguish between good practice goals, recommendations, justifications, and examples. Herein, we define goals as the intended targets or purposes of a chapter, recommendations as the essential standards required to meet that goal, justifications as the scientific rationale for meeting the goals, and examples as concrete cases that implement this goal-recommendation-justification process. Because of these definitions, the words 'goals' and 'recommendations' will carry a special meaning in this document.

Specifically, we define recommendations based on (our informed opinion of) scientific consensus, which we anchor only to the most rigorously established and well demonstrated concepts. This is done so that

only clear and justifiable links are drawn between best science and best practices. This helps ensure that our recommendations are as universal and timeless as possible. In chapters where scientific consensus has not been established, we will be clear as to these deficiencies and the current scope of open-ended research directions. Examples will cover state-of-the-art demonstrations - in some cases outlining multiple competing methods; because of this scope difference, relevant examples will likely evolve following the publication of this document.

This document structure was intentionally chosen to ensure that our good practices adhere to state-of-the-art science and regulatory best practices (Coglianese, 2018). We aimed to create guidelines that blend elements of both prescriptive and performance-based approaches (Box 1.2); in order to ensure effective risk reduction, while still fostering innovation. Our guidelines list specific frameworks when scientific consensus on certain topics has been reached, while remaining more open-ended when such consensus is lacking; to encourage further scientific research.

BOX 1.2 Definition of prescriptive and performance-based guidelines

Rules, guidelines, or regulations can either be defined using prescriptive or performance-based approaches. Prescriptive standards tend to rigidly outline explicit details on what processes or methods are to be followed. Performance-based standards tend to define safety/quality metrics to be met, leaving the specifics on how to meet these targets flexible and open-ended. Performance-based approaches are also sometimes called outcome-based regulation regulation or non-prescriptive regulation.

We note that the philosophical difference between these two approaches does not necessarily imply that performance-based guidelines will be lax or unsafe in comparison to their more prescriptive counterparts. It simply means that given two equivalent ways to describe a rule, the performance-based approach prefers the more generic one.

The flexibility of performance-based approaches can be advantageous. This is because it will be better able to accommodate unknown examples, variation in location specifics, or future technological developments. This also allows room for development of new technologies to meet (or exceed) safety/quality standards, by providing targets for innovation; these innovations then impart improved safety/quality, performance, or cost savings onto future projects.

However, for performance-based guidelines to be effective, clear and measurable target metrics are required. Thus, adequate monitoring systems need to be emplaced for compliance assurance. In cases where clear and measurable performance targets are unavailable, more prescriptive approaches generally tend to be favorable.

For a simplified example, a prescriptive guideline might recommend exactly how many seismic stations are needed to monitor for induced seismicity. This implicitly comes with assumptions about the type/scale of operation, geological setting, sources of noise, type/quality of sensors, and signal processing techniques being used. On the other hand, a performance-based guideline could outline the required target threshold for detection instead. This leaves room for future approaches (e.g., distributed acoustic sensing or machine learning) to reach these targets, without imposing the prior assumptions of the more prescriptive approach. However, this comes at the cost of additional complexity in the verification of monitoring performance.

In many regulatory applications, guidelines will blend both prescriptive and performance-based aspects together. In an effort to gain the advantages of one type, while simultaneously covering for deficiencies of the other type.

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2. Induced Seismicity Risk Management Framework

Managing the risks associated with induced seismic activity is essential throughout the entire lifecycle of an EGS project, from exploration (e.g., site selection, license acquisition, data acquisition) and planning (e.g., detailed operation planning, site preparation, drilling of monitoring wells, if applicable) to operation (e.g., drilling of injection and production wells, stimulation and circulation) and post-operation (i.e., after well shut-in or well abandonment). We thus propose the development of an Induced Seismicity Risk Management Framework (ISRMF) for each EGS project.

The ISRMF is designed to involve multiple stakeholders:

1. Regulator(s): the licensing and/or governing authority, normally linked to the local or national government.

2. Operator(s): a company/organization that executes the EGS project, and is responsible for the safety of the operations.

3. Independent experts: an independent group of experts who are not involved in the operational aspects of the EGS project.

4. Vendors: a group of professionals, contracted to design or execute a specific task.

5. Affected communities and the general public: the target of protection of this guideline, they might refer to this guideline as an information resource.

Other existing guidelines include the EGS protocol by Majer et al. (2012; 2016), who proposed a seven-step risk management approach from an operators' perspective, in the USA. Their step-by-step approach is easy for operators to follow when executing an EGS project. In the Netherlands, Baisch et al. (2016) developed a multi-level framework for seismic hazard assessment of deep geothermal projects including EGS. In Switzerland, Trutnevyte & Wiemer (2017) built a framework of seismic risk governance for deep geothermal projects including EGS, which has mitigation measures recommended according to output from a preliminary seismic risk screening (including stimulation and circulation). In France, Maury et al. (2023) provide an overview of induced seismicity incidents from geothermal operations and recommend good practices for assessing and mitigating induced seismic hazard. Other guidelines have covered the topic of induced seismicity risks in the past (e.g., IMEPLS, 2016; GEORISK, 2018; Chen et al., 2020; Braun et al., 2020; Bohnhoff et al., 2018; Dialuce et al., 2014; FKPE, 2013; Dutch Mining Act, 2003; Walters et al., 2015; Templeton et al., 2021). Our ISRMF is informed by these prior guidelines. Specifically, it can be used to produce a document similar to the Induced Seismicity Mitigation Plan as in Majer et al. (2012) and Pankow et al. (2023), which is delivered by the operator in the permitting process.

2.1 ISRMF modules

In the current document, we redesign the step-by-step advice approach of Majer et al. (2012; 2016), while allowing tailoring based on various risk levels as in Trutnevyte & Wiemer (2017). Thus, recommendations are given as basic risk management components (Modules), which can be integrated to build an ISRMF. Here, we define as seismic risk the potential adverse impacts that a seismic sequence can have on the exposed individuals and structures as a collective, instead of focusing on the average probability that a single person will incur losses or physical harm. Hereafter, we provide a description of the six modules forming the risk management framework for EGS-induced seismicity. These modules are not defined in chronological order; instead, they can be flexibly integrated into the ISRMF (Figure 2.1).

Module 1 - Seismic risk pre-screening

Once an EGS project has been proposed by an operator, a preliminary seismic risk screening (referred to as pre-screening hereafter) must be completed, as proposed by various studies (e.g., Kraft et al., 2020, Majer et al., 2012, Baisch et al., 2016, Trutnevyte & Wiemer, 2017), to classify the seismic concern level of the project as either low or high. Besides evaluating the level of concern, the pre-screening should indicate where the knowledge gaps are, in order to improve the assessment accuracy. If knowledge gaps are too large to draw a meaningful risk screening, the operator initiates the data collection and research module. Once knowledge gaps are fulfilled, they re-run the pre-screening. Detailed description of Module 1 is given in Chapter 3.

Module 2 - Data acquisition and research (D&R)

In cases where available data are limited to drive a meaningful risk screening or comprehensive risk assessment (e.g., SHRA), data collection and research (D&R) should be conducted. As an example, the following procedures could be helpful to constrain fault activity and hazards:

As part of the pre-screening:

- Fault distribution mapping using field data acquisition (e.g., 2D/3D seismic, geological mapping).

As part of the comprehensive risk assessment:

- Collection of detailed fault geometry (e.g., 3D seismic, VSP surveys) and stress field (e.g., minifrac test).

- Derivation of ground motion characteristics (e.g., building 3D P and S velocity models) and site specific soil conditions (e.g., near surface surveys).

Given the strong variability on knowledge gaps and quick development on data acquisition and research, it is difficult to draw a guideline on how the D&R should be done. We thus don't provide a detailed description in this module. However, general principles such as open access policy and multiple stakeholders' involvement should be followed. Thus, we introduce the concept of learning targets (§2.3.2) to guide the process.

Module 3 - Communication and outreach

The operator involves all relevant stakeholders in the project in order to understand the context, stakeholders' perceptions, and build a communication team and strategy.
In this document, we suggest a 9-step approach (see Chapter 7 for details):

- Step 1: Identifying stakeholders and their networks relevant to the project

- Step 2: Understanding the context of the region

- Step 3: Setting up a multidisciplinary outreach team

- Step 4: Deciding the scale of community participation

- Step 5: Setting up upstream discussions and partnerships between all stakeholders

- Step 6: Tailoring information to the context and particular audience (i.e., target group)

- Step 7: Monitoring public perceptions in order to adapt the communication strategy

- Step 8: Developing a crisis plan

- Step 9: Giving regular updates about the project

Module 4 - Comprehensive seismic risk analysis

For projects falling into the high-risk concern category, the operator will need to commision a comprehensive site-specific analysis to better assess the seismic risk related to hydraulic stimulation and fluid circulation activities at the EGS site. When compared to the pre-screening tool, this analysis is expected to require similar but more quantitative data to be collected, and a much more demanding analytical process that includes the construction of a seismic hazard and risk model, as well as complex calculations that will likely require the establishment of a dedicated working group. Details are given in Chapter 4.

Module 5 - Technical seismic risk mitigation measures

Technical seismic risk mitigation measures should be in place before the start of the drilling of the operation well and maintained through the project life cycle. The technical measures include: (a) building a seismic monitoring network (see Chapter 6), (b) establishing a traffic light protocol (TLP), and (c) outline operational mitigation strategies in the case of a yellow-light and red-light occurrence (see Chapter 5).

Module 6 - Financial seismic risk mitigation measures

Financial risk mitigation measures should be conducted according to the risk analysis (Chapter 4), and be in place before operation well drilling starts, and include (a) evaluating the seismic risk to the overall project financial risk estimation and management; (b) preparing for the worst scenarios:

- Clarify liability in the case of nuisance or damages from induced seismicity (Cypser & Davis, 1998).

- Developing a damage compensation scheme, seeking earthquake insurance for covering damages caused by induced seismicity, or contributing to a public guarantee fund (if available).

- Screening infrastructure to evaluate their resilience to shaking for high-risk projects. Optionally, building retrofitting could be used to reinforce fragile infrastructure.

Various financial mitigation measures, including but not limited to the example given above, are expected to be taken into account by the operator in their business plan. Given the variability of these measures, we don't give a detailed description in the document. But the overall goal is to keep seismic risks in a financially tolerable range (e.g., Langenbruch et al., 2020). Including financial measures in the ISRMF is beneficial for protecting both the affected community and the operator from potential risks, and for maintaining project transparency.

2.2 Stakeholders' roles in the ISRMF

Regulator

The regulator reviews the permit application, including the risk management plan, of the operator. The regulator must protect the interests of the public, while fostering innovation and competition within industry. Given that the seismic hazard on site might fluctuate as new data is collected, continuous supervision from the regulator is required. To aid the supervision process, we suggest that the regulatory and legislative authorities:

- Clearly define the suite of critical risk metrics (e.g. population nuisance, structural damages, local personal risk) and their corresponding thresholds, which will inform the preliminary seismic risk screening, the comprehensive seismic risk analysis, and the design of the TLP.

- Work with the authoritative earthquake agency to densify the national/regional seismic network as soon as possible, to enhance the network for smaller events, establish an a priori baseline, and to provide independent measurements of possible induced events.

Operator

The operator is responsible for constraining the seismic risk within the regulator's acceptable thresholds across all phases of the project. We thus suggest that the operator:

- Deploy professional and experienced personnel to oversee the risk management of a project, which includes:

  ○ conducting or commissioning the continuous seismic risk assessment of the project (including the pre-screening), under the supervision of the regulator,

  ○ facilitating reasonable data requests from the regulator,

  ○ facilitating potential additional seismic monitoring needs,

  ○ following the agreed upon TLP,

  ○ facilitating potential operational changes to mitigate the seismic hazard.

- Implement a 'learning from operation' strategy. Learning targets are defined for each project phase and should be reported to the regulator and the public by the end of each phase.

Independent experts

The regulator may choose to appoint groups of experts to review the operator's risk management framework, the preliminary risk screening and the comprehensive seismic risk analysis, the seismic monitoring and the TLP. They can also produce alternative independent analyses for validation purposes. These expert groups should not be associated in any way with the operator.

Vendors

The operator (or the public) may choose to hire groups of professionals to fill needed expertise gaps. This may include designing/conducting the operator's risk management framework, the preliminary risk screening, the comprehensive seismic risk analysis, the seismic monitoring, and the implementation of their TLP.

Local population

The local residents and businesses have the right to be informed of the potential risks posed by the project, including the process and the results of the preliminary risk screening and of the comprehensive seismic risk analysis, and mitigation measures. Reports related to the ISRMF should include a summary in plain language for the general public. Their concerns need to be addressed in accordance with the law.

2.3 ISRMF workflow

Throughout the project lifecycle, we provide a template for the ISRMF (Figure 2.1) using the six modules for EGS seismic risk management. Additionally, we introduce the concept of 'learning targets' to guide the data acquisition in each phase of the ISRMF.

2.3.1 ISRMF template

In this template, we divide the ISRMF workflow/modules into phases, based on the lifecycle of an EGS project. Note that we assume Module 4 is required. In Chapter 3, we will discuss if the preliminary screening (Module 1) indicates a low level of concern, then Module 1 could replace Module 4 in each phase of the project.
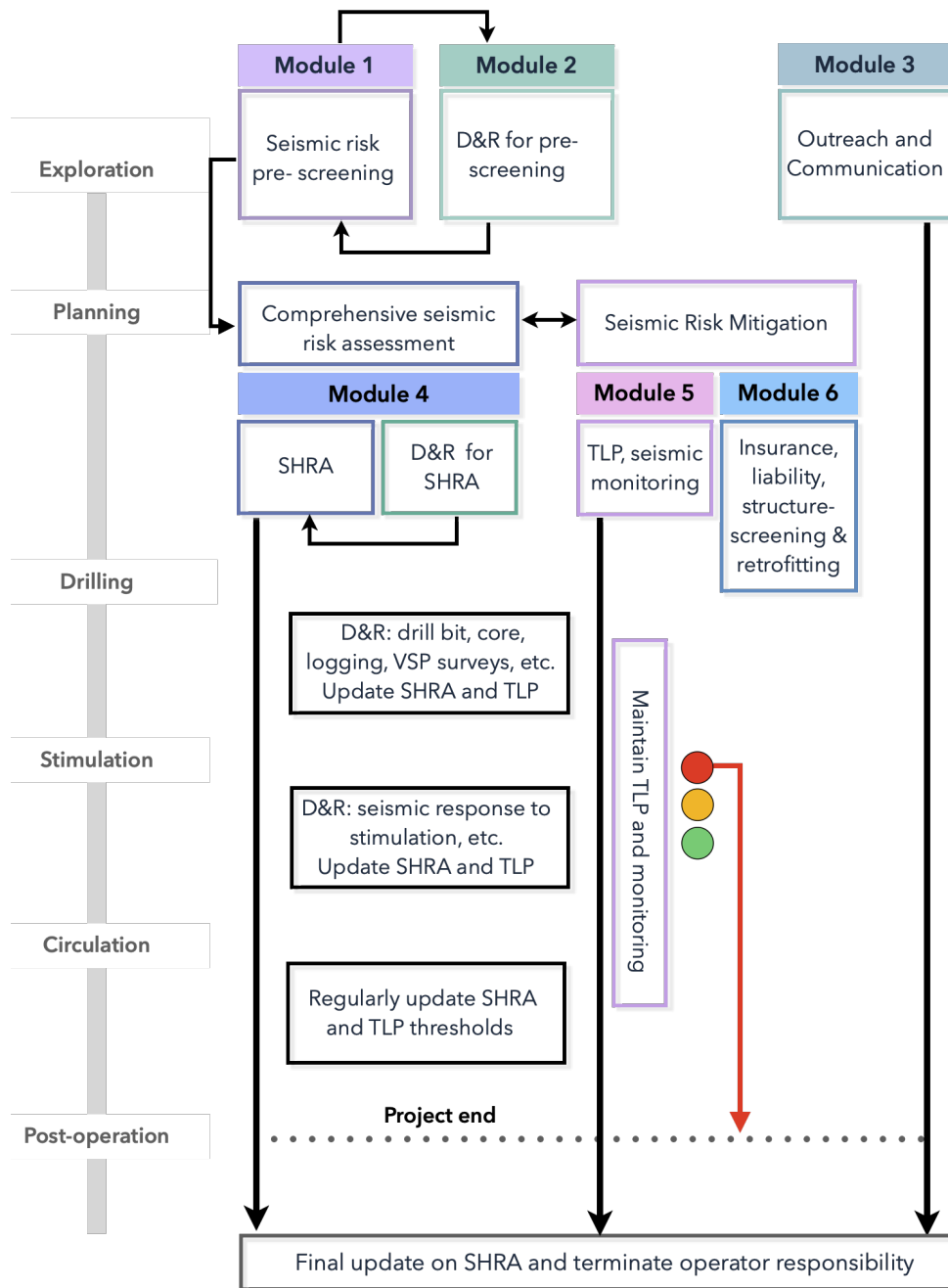
Figure 2.1. Schematic diagram of the ISRMF. Interrelationships between component modules are shown alongside the timeline of drilling phases.

Exploration phase

During the exploration phase, Modules 1, 2 and 3 are initiated. Preliminary screening (Module 1) and initial data acquisition (Module 2) will be used to inform if and how an EGS operation will move forwards. A series of exploratory wells might also be drilled and tested to facilitate the data acquisition process.

Planning phase

During the planning phase (site preparation), a comprehensive seismic risk assessment (Module 4) may be required. Risk mitigation Modules 5 and 6 are designed, while communication (Module 3) is continued. If the operator decides to move forward, they should provide a detailed plan on how to implement the relevant modules.

Drilling phase

During the drilling phase, the operator completes the wells needed for operations, while following their risk management plan (Module 3, 4 & 5). We note that there is the potential for induced earthquakes starting at the drilling phase. Besides monitoring potential induced seismicity, the operator should also monitor drilling data such as mud losses, cuttings, well logs, and core recoveries, which might indicate the presence of faults (IMEPLS, 2016). After the drilling operation, the operator should start D&R (Module 2) to analyze the data from drill bits, well logs, vertical seismic profile (VSP) etc. and update the models of the SHRA.

Stimulation phase

During the stimulation phase, the operator continues following their risk management plan (Modules 3, 4 & 5); focusing on communication, real-time seismic monitoring and the TLP. After each stimulation, Modules 3, 4, 5 and 6 may need to be updated/verified based on the newly available data.

Circulation phase

During the circulation phase (i.e., geothermal production), the seismic risks still exist but will likely be driven by different mechanisms compared to the stimulation phase. the operator continues following their risk management plan (Modules 3, 4 & 5). After each circulation phase, Modules 3, 4, 5 and 6 may need to be updated/verified based on the newly available data.

Post-operation phase

At the end of the project, the wells are shut-in, plugged, and reclamation efforts commence. A project can end either from the natural completion of the wells' life cycle or prematurely due to a red-light event. The operator continues implementing Module 3, and the real-time seismic monitoring according to Module 5. Additionally, the operator should monitor for potential seismicity rate changes due to well shut-in, which might require updating Module 4 and 6. The same happens if after a sufficiently long period of monitoring, the seismicity rate and event magnitudes have decayed significantly. If the SHRA suggests that induced seismic risk has approached sufficiently low levels, the operator, regulator and the independent expert group discuss terminating the responsibility of the operator. In this case, the operator hands over the monitoring system to the national earthquake agency for continued monitoring and maintenance, until the seismicity level approaches pre-project background levels.

2.3.2 ISRMF learning targets

Throughout this workflow, we suggest that the operator adopts the concept of 'learning targets' (see Box 2.1) to guide D&R and assist in the efficiency and transparency of seismic risk management.

BOX 2.1. Learning from operations

The operator should define learning targets (in terms of gained knowledge) before each project phase that they need to reach. For example:

Before the exploration phase:
1) Are the population and infrastructure vulnerable to induced earthquakes?
2) Is the site geologically susceptible to induced earthquakes?
3) Will we get reliable geological data from geological and seismological agencies?
4) Will site amplification be an important element?
(…)
Before the drilling phase:
1) What data needs to be collected during drilling?
2) At what depth is it likely to encounter faults and fractures?
3) What is the mineral composition of the reservoir rock and how is the heterogeneity?

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4)   What is the in-situ stress state from a micro-frac test? Do the principal stress directions agree with existing data?
5)   Will there be mud losses and does that mean intersecting faults?
(…)

After each phase, the operator should review the results and determine how they should proceed with the project based on the new knowledge they have gained or not gained (Terrier et al., 2022). The learning targets and outcomes should be reported to the regulator and made open to the public to maintain transparency.

3. EGS Preliminary Seismic Risk Screening (Module 1 & 2)

In the proposed EGS seismic risk management framework, we suggest conducting a preliminary seismic risk screening (referred as pre-screening hereafter) during the exploration phase of a project. This includes using existing data to initially assess the level of concern (LoC) regarding the potential risks of induced earthquakes. The pre-screening should be conducted or commissioned by the operator and reviewed by the regulator (ideally after being reviewed/validated by independent experts). The process should be transparent and the results should be made available to the public, if a comprehensive SHRA is not commissioned. The pre-screening is used to inform the suitability of subsequent analyses. For this purpose, we refer here to seismic risk as the potential adverse impacts that a seismic sequence can have on the exposed individuals and structures as a collective. More detailed risk analysis focusing on the average probability that a single person will incur losses or physical harm will be part of a more comprehensive SHRA (Module 4).

Goals of the preliminary seismic risk screening

1. To utilize existing knowledge and project plans to provide an initial categorization of the project's LoC.

2. To identify knowledge gaps that will inform subsequent analyses and monitoring needs.

Note that the LoC is only a preliminary and qualitative estimation of seismic risk that uses incomplete information, thus it contains large uncertainty, and it does not replace the comprehensive seismic hazard and risk analysis. A pre-screening for LoC should include important geological, operational and exposural factors and consider data quality. Public attitude towards the project should also be measured, given the strong benefit-risk relevance to the local population from EGS projects.

The LoC categories serve as a reference for deploying further seismic risk mitigation measures (Modules 5 and 6). The LoC concept enables the operator to decide if the project is worth investing in, provides preliminary evidence for the regulator to evaluate the safety of the project, and communicates seismic risks transparently to the public. Knowledge gaps and quality of existing data are contributing to the uncertainty of the risk screening. Based on the identified gaps or data quality issues, the operator may conduct research and data acquisition (Module 2) to improve the quality of screening.

Table 3.1. Level of Concern categories resulting from the pre-screening and corresponding mitigation measures

LoC category	Comprehensive SHRA	Traffic Light Protocol	Seismic monitoring
Low	Optional	Standard magnitude thresholds or informed by loss risk analysis	Coarse resolution meeting TLP requirement (e.g., regional backbone network)
High	Mandatory and consequential	Thresholds informed by site specific risk analysis; Adaptive Traffic Light Protocol could be considered	High spatial and magnitude resolution

If a 'high' LoC is screened, both a more comprehensive study on the seismic risk potential of the area (SHRA) and high resolution seismic monitoring network are needed. The results of the detailed SHRA analysis supersede any pre-screening values and should inform the regulator's decisions on whether the project should be permitted, under which conditions and with which mitigation measures in place. A risk-based Traffic Light Protocol (TLP) to manage induced seismicity should be designed using site specific models. According to the requirements of TLP, a high resolution seismic monitoring network should be built to reach both magnitude of completeness (Mc) and event localization resolution thresholds (Chapter 6).

If a 'low' LoC is screened, the SHRA would still be informative but could be deemed optional by the regulator. Standard TLP thresholds required by the regulator might be used, and the regional backbone seismic monitoring network used if the backbone network meets the standard TLP Mc requirements.

Recommendations for the preliminary seismic risk screening

1. The LoC estimates should account for at least two main components of seismic risk: the seismic source characteristics (a combination of geological and operational factors), and the characteristics of the exposed assets (including their fragility and potential consequences from nuisance or damages).

2. The pre-screening should be conducted or commissioned by the operator and should be accepted by the regulator (ideally after a review/validation from independent experts). The results and evaluation process of the pre-screening should be made public, if a comprehensive SHRA is not commissioned.

3. In the current absence of scientific consensus, various approaches could be used for pre-screening. The operator's decision on which screening tool is to be adopted should be justified and agreed upon by the regulator (ideally with advice from independent experts).

4. The LoC should be updated if project plans change, or new knowledge is available. For example, from the comprehensive SHRA (Chapter 4) or from the seismic monitoring (Chapter 6).

It is important to stress that the existing screening tools do not address the potential impact of long-term geothermal production on induced seismicity, due to the lack of comprehensive data from operational EGS projects. Data from conventional hydrothermal projects show that the thermal production has not resulted in large magnitude earthquakes as long as the project is not located in an active fault region (see review by Buijze et al., 2019). However, in the case of EGS, available data is still too limited to draw definitive conclusions. Therefore, caution should be exercised, and mitigation measures must be sustained throughout the entire lifecycle of an EGS project to monitor any anomalies during the heat production phase.

3.1 Key factors for pre-screening

In general, the LoC is influenced by four main factors:

1. Geological and tectonic factors that influence the severity/frequency of earthquake hazards.

2. Operational factors that influence the occurrence and productivity of earthquakes.

3. Proximity, characteristics, and vulnerability of exposed assets (i.e., people and buildings).

4. Quality of data used to infer points 1-3.

Note that the attitude and perception of the local population could also significantly influence decision making. However, we suggest considering attitudes and perceptions separately as a legitimate concern (see §3.1.5).

3.1.1. Geological factors

The geological factors help evaluate the chance of having critically loaded faults in the vicinity of the project site. The basic principles involve keeping distance from active faults and seeking a less fractured (faulted) environment. This evaluation can be conducted through considering the following factors:

- Smallest distance to geologically known active or potentially-active faults;

- Regional historical earthquake activity;

- Modeled tectonic seismic hazard levels around the site;

- Length of the proximal faults and those faults' triggering potential, i.e., orientation with stress field;

- Potential for hydraulic pathways capable of transmitting pressure or stress changes to faults over a distance, whether horizontally or vertically.

- Lithology of formations near the operational target.

Note that near surface conditions amplifying surface ground motion are considered in §3.1.3.

3.1.2. Operational factors

The correlation between operations (stimulation and circulation) and seismicity remains a critical topic of induced seismicity. The direct response of seismicity to operations is still to be explored, while a few factors are known to be prone to induce or trigger fault slip events, including:

- Depth of the stimulation volume, which can serve as a proxy for the stress state and the proximity to basement faults.

- Net fluid injection volume, which has shown, in several cases, to have a linear relationship with the maximum observed magnitude (McGarr, 2014). However, it's important to recognize that these relationships can vary significantly from site-to-site.

- Fluid injection rate and pressure increase in the reservoir (Shapiro et al., 2010). The higher the flow rate and the pressure, the higher is generally the seismic hazard potential. Note that the stimulation strategy (e.g., single-/multi-stage, cyclical/monotonic injection rates, open-hole/perforated-casing) and the fluid composition might also influence the potential of induced seismicity.

- Temperature decrease during fluid-circulation (thermal production) causes stress changes in the subsurface due to thermal-elastic effect, which could trigger seismicity (Vörös & Baisch, 2022; Cao et al., 2022).

- Well orientation, which might influence the fluid-fracture/fault interconnection. To determine this, a detailed localized study is required.

3.1.3. Exposed assets

The evaluation of seismic exposure should consider population density, building taxonomy, importance/fragility of assets, and local soil conditions. Induced earthquakes can cause damage over an extended area; thus exposure data collection should cover a comparable region. The presence of highly critical infrastructure (e.g. nuclear power plants, dams, oil refineries, cultural heritage sites, long bridges),

noise sensitive infrastructure (e.g. hospitals, sensitive laboratories), or buildings which are not designed for earthquake resistance, should be accounted for.

When considering the risks posed on structures and population, it is also important to consider the amplification of ground motion at each asset's location, due to near surface soil/rock conditions (e.g., Van Ginkel et al., 2022) or topographic effects (e.g., Massa et al., 2014). In general, hard rock has lower amplification than soft rock (Eurocode 8).

3.1.4. Data quality factor

Data quality significantly influences the reliability of the pre-screened LoC. If data quality is limited, the pre-screening must be conservative, which might lead to higher apparent LoC. By assigning a penalty on data quality, one ensures that LoC is not underestimated because of poor data quality.

Here, we emphasize data quality considerations for a few examples of the geological factors, which could be considered in the pre-screening:

- Seismic images (2D, 3D seismic reflection profiles, seismic velocity models); This dataset is crucial for estimating hidden fault existence at a local scale. Sometimes this information may be supplemented with offsets from well logs. The best quality seismic data would be 3D seismic or multiple 2D seismic-line with dense covering and deep penetration.

- Geological and tectonic maps (2D, 3D fault maps); these maps are often available from geological institutes and national topographic agencies. This data provides important information on regional scale faults. The resolution of these maps might be used as an indicator of data quality.

- Site characterization (e.g., soil profiles, surface geology maps, Vs30 maps, or site amplification maps); Since site characterization is also a crucial parameter for earthquake hazard, it is often available from national/regional geological institutes. The resolution of these maps might be used as an indicator of data quality.

- Stress field (e.g., maximal horizontal stress direction and magnitude, faulting mechanism, regional borehole stress measurements, seismic anisotropy measurements); Stress data is important for estimating fault activity, especially for seismically inactive regions. Indicators of stress field data quality could be the type of measurements and the proximity/relevance of the measurement site to the project site.

- Past earthquake activity (instrumental, historical, or paleoseismic); These data are often available through the national or regional earthquake agencies or from published studies. An important data quality factor is the completeness of the instrumental data through time, and the consensus behind historical or paleoseismic findings.

An important aspect of data quality is to identify knowledge gaps that need to be improved for site-specific risk assessment.

3.1.5. Public attitudes and concern

While public attitudes have sometimes been defined as a risk to an EGS project (Wiemer et al. 2017), it is crucial to think of public attitudes as a legitimate set of concerns to engage with, since the attitudes can both help and hinder the project. Contrary to the data quality score, determining a score for residents' attitudes is difficult as the attitudes towards the project will likely evolve with time. A region could initially be enthusiastic about an EGS project but whether this stays will be determined by the dynamics and quality of communications among all stakeholders. In parallel to the risk screening, initial assessment of attitudes and concerns is therefore important (Trutnevyte & Wiemer, 2017). To get an overall sense of

attitudes towards the project in the initial stage of the project, steps 1 and 2, found in §7.1, may be followed. To get quantitative data on public attitudes, surveys to measure the attitudes and concerns of the general public could be used. To have deeper insights on how the local population perceives the project, face-to-face meetings, focus groups or interviews are preferred. These surveys and meetings should be repeated as the project progresses to monitor the evolution of the public opinion.

3.2 Existing pre-screening tools

In the early stages of Enhanced Geothermal Systems (EGS) projects, especially when available data are limited, diagnostic methods are often used for pre-screening seismic risks.
Notably, five screening tools were developed for EGS or geothermal projects in general:

1. Majer et al. (2012) proposed the first pre-screening process for EGS projects. This process focuses on analyzing ground shaking and exposure from the average expected induced seismicity and the 'worst case' scenario (e.g., Wong et al., 2023). In Majer et al. (2012), the worst case and the risk boundaries are not defined and are expected to be judged by experts.

2. Quick-Scan is the first diagnostic tool developed by Baisch et al. (2016) for deep geothermal in the Netherlands. It has scores defined over geological and operational parameters for induced seismicity potential. Thus, it only focuses on the seismic source and leaves the seismic risks to be estimated in a quantitative SHRA. This tool was particularly designed within a risk assessment framework for the geological conditions in the Netherlands (Baisch et al., 2016).

3. Geothermal Risk of Induced Seismicity Diagnosis (GRID), a diagnostic tool developed by Trutnevyte & Wiemer (2017) for geothermal activities specifically in Switzerland. Instead of focusing on a specific component of the seismic risks, GRID takes all components of seismic risk analysis and adds social attitudes to define a level of concern. A risk-matrix approach is then applied to these concerns to determine the concern categories.

4. Maury et al. (2023) developed a decision tree tool to screen the potential hazard level at geothermal projects. Similar to Quick-Scan, this tool focuses on induced seismicity potential from geological and operational parameters. Specifically, it is designed to perform a first order hazard evaluation alongside the timeline of the project phases.

Table 3.2. Summary of screening parameter matrices for 4 existing screening tools.

Screening tools	Geology	Operations	Exposure	Public concern	Data quality	Low LoC	High LoC
Majer et al. 2012	briefly	briefly	detailed	-	-	not defined	not defined
Quick-Scan	detailed	detailed	-	-	-	< 0.32	≥ 0.32
GRID	detailed	detailed	detailed	detailed	-	Cat. 0 & I	Cat. II & III
Maury et al. 2023	detailed	detailed	-	-	-	Level 0 & 1	Level 2 & 3

Other approaches, using statistical learning (van Eijs et al., 2006) or machine learning (Pawley et al., 2018) methods to assess the likelihood of encountering induced seismicity might also be used for the purpose

of screening the seismicity potential. Alternatively, geomechanical simulations to assess critical slip (Walsh & Zoback, 2016), when fault geometry and in situ stresses are known, have also been used for pre-screening purposes. These tools approach subsets of the pre-screening problem. With the development of EGSs, more data will become available, and as research into induced seismicity advances, more sophisticated tools will be likely developed.

3.3. How to conduct the preliminary screening

The implementation of the preliminary risk screening does not have an established scientific consensus. With time, new pre-screening tools will likely develop, and more sophisticated tools will be available. In the current stage, we recommend the risk pre-screening to be conducted with good confidence over the main factors: geological and operation factors, exposure, and data quality, while taking public attitude and concern as a supplementary measure.

3.3.1. Referring to previous projects

Existing projects play a significant role in planning future projects, both societally and scientifically. Social reactions built from previous projects strongly influence the residents' attitudes. Knowledge of geology and of the relationship between operations and seismicity learned from previous projects are beneficial to guide the site-selection and operations design and also seismic risk assessments. Thus, it is important to refer to previous successful/unsuccessful projects during the preliminary screening. When available, a project's pre-screening results should be compared against past projects' LoC and seismic response.

3.3.2. Iteratively updating the pre-screening

Given the empirical nature of risk pre-screenings, they should be updated as soon as new knowledge has been gained. If the operational parameters have changed substantially during the project (e.g., deviated well crosses a fault, while a vertical well not crossing a known fault was the initial plan), or new geological data (new faults are found during drilling) are available, the LoC should be re-evaluated.

As discussed in §3.1, geological, operational, and exposure data are all crucial for performing reliable screening. If data quality is poor enough to identify knowledge gaps (§3.1.4), it may be required to collect additional data. In case of data limitations, D&R (Module 2) could be implemented.

4. Seismic Hazard and Risk Analysis (Module 4)

For projects whose LoC falls into the "high" risk category, the operator is instructed to conduct or commission a comprehensive site-specific analysis to better assess the seismic risk related to the stimulation activities at the EGS site. The analysis should be reviewed by an independent expert group (on behalf of the regulator). In the end, the responsibility for the accuracy of the results should fall on the operator. The results of the seismic hazard and risk analysis (SHRA) supersede those acquired during the pre-screening (Chapter 3).

Seismic hazard analysis (SHA) forecasts earthquake-caused ground shaking for a target location or region (Baker et al., 2021). SHA is typically divided into so-called deterministic (DSHA) and probabilistic (PSHA) approaches (Box 4.1). The primary difference is related to the treatment of the uncertainty behind the seismic source. Both approaches can consider the uncertainties behind the ground motion propagation (including site-effects) and eventually produce a probability of exceeding a certain ground shaking level. Notably, DSHA results in a seemingly narrower range of uncertainty, by masking the epistemic and aleatory uncertainties related to the seismic source. The two approaches can be used on their own, or they may be used together to provide complementary information of varying complexity for decision making.

Next, the seismic vulnerability analysis (SVA; §4.5) deals with the undesirable consequences of ground shaking, which include nuisance, personal injury, physical structural and non-structural damage to buildings and infrastructure, interruption of business and social activities, and the direct and indirect costs associated with such outcomes (Bommer, 2022). Seismic risk analysis (SRA) combines SHA and SVA to quantify the probability of a certain level of loss being exceeded.

The SHRA may be performed prior to any reservoir stimulation taking place or after one or more stimulations have already occurred. As new local data are collected, the SHRA can undergo iterative updates on an ongoing basis. Obviously, the more local seismological and hydromechanical data are available, the more constrained the uncertainty behind the results will be.

When compared to the pre-screening (Chapter 3), the SHRA is expected to require additional data to be collected, and a much more rigorous analytical process that includes the construction of a seismic risk model (McGuire, 2004; Bommer, 2022), as well as complex calculations that will likely require dedicated software packages (Pagani et al., 2014). Input data might include regional historical earthquake catalogs and strong-motion data, fault geometry, local stress field, hydraulic input of planned stimulations, portfolio of regional structures, population distribution, and regional soil conditions.

Goals of the SHRA

1. To provide a comprehensive estimation of the expected seismic risk, using a more sophisticated approach compared to the pre-screening tools.

2. To demonstrate the range of uncertainty behind the modeled results, using tailored quantitative methods.

3. To inform cost-benefit analyses - allowing stakeholders to decide whether a project should start, continue, or acquire (additional) earthquake insurance.

4. To aid risk mitigation plans by informing the parametrization of the TLP.

Recommendations for the SHRA

1. The SHRA is the responsibility of the operator. It should be reviewed by an independent group of experts, which is chosen by the regulator and is not affiliated with the operator or with other key stakeholders. The operator should accommodate any data requests and remain liable for its conclusions.

2. The SHRA should be based on established state-of-the-art models, with justification for their selection.

3. The SHRA needs to be updated when important new local data is acquired.

4. The analysis should cover multiple risk metrics, including population nuisance, structural damages, and personal injuries.

5. If the project is to be permitted, the SHRA results, methods, and data should be released in advance for public review.

The SHRA will most likely require a dedicated software engine to perform the calculations. We suggest using the OpenQuake engine (Pagani et al., 2014; Silva et al., 2014) for the hazard and risk calculations, which is a well-established and continuously supported open-source product of the Global Earthquake Model (GEM). Alternatives include OOFIMS (Franchin, 2014), SELENA (Molina et al., 2010), CARPA (ERN-AI, 2020), RiskScape (Paulik et al., 2023) or EQRM (Robinson et al., 2005). For a review of the available seismic risk engines see Hosseinpour et al. (2021). Finally, for hazard-only calculations one could use OpenSHA (Field et al., 2003), R-CRISIS (Ordaz et al., 2021), or REASSESS (Chioccarelli et al., 2019).

BOX 4.1 Deterministic versus probabilistic SHA

DSHAs that assume the "maximum possible" magnitude as the earthquake scenario will always be more conservative than PSHAs, which also assign probabilities to smaller magnitudes. In that sense, if the seismic risk from such a DSHA is tolerable, then there is no need to conduct a more complex PSHA. However, DSHAs that adopt as "maximum credible" earthquake (MCE) a magnitude smaller than the "absolute maximum" adopted by the PSHA may or may not be more conservative. In modern times, the probabilistic approach has more or less prevailed, with very few exceptions (Bommer, 2022), and this is why we generally suggest it. PSHA has been used by the United States Geological Survey (USGS) to produce one-year hazard maps in areas with induced seismicity (e.g. Petersen et al., 2016), and by Convertito et al. (2012) and Bourne et al. (2015) to assess the time-dependent seismic hazard due to geothermal operations and fluid extraction, respectively. A number of studies have gone one step further performing seismic risk assessment of varying complexity for the Groningen gas field (Crowley et al., 2019), for an Enhanced Geothermal System in Basel (Mignan et al., 2015), for a HF sequence in the UK (Edwards et al., 2021) and for large-scale wastewater-disposal activities in Oklahoma (Gupta & Baker, 2019; Grigoratos et al., 2021).

4.1 General framework

Here, we outline the framework for performing a SHRA. A SHRA model for an EGS site should include the following components:

a) a seismic source model, namely a set of one or multiple possible ruptures of specified sizes and hypocenters. In the case of PSHA, the rupture set is paired with corresponding probabilities of occurrence.

b) a ground shaking intensity model, estimating the spatial distribution of ground shaking levels given a certain earthquake magnitude, focal mechanism, and depth.

c) a site-amplification model, capturing the effects of soil conditions on ground motions.

d) an exposure dataset, containing the relevant assets that may be affected (e.g. structures, contents, people, roads).

e) structure-specific fragility curves, capturing the structural or non-structural damages expected, given various levels of shaking.

f) structure-specific consequence curves, capturing the direct or indirect economic, human or social losses, given various levels of damage.

The model components should be deemed applicable to the EGS location in question. A logic tree structure (Bommer & Scherbaum, 2008) that includes various models for each component is needed, unless a specific model can be validated against regional data. Logic trees are considered as the state-of-the-art tool to quantify and incorporate epistemic uncertainty which is the uncertainty related to the lack of knowledge (McGuire, 2004). Creating a logic tree involves selecting alternative models or model parameters for various components and then assigning weights to the different branches at each node to reflect (in a probabilistic way) the degree-of-belief of the analyst in each option (Scherbaum & Kuehn 2011; Bommer, 2012). Crucially, the different models must be mutually exclusive and collectively exhaustive. Logic tree branching levels (Figure 4.1) are common for the Gutenberg-Richter (GR) parameters, the maximum magnitude, the Ground Shaking Intensity Models (GSIMs), and, in some cases, for the vulnerability curves. That said, the complexity of the structure of a logic tree can increase exponentially (Bommer, 2022). In the end, each branch of the logic tree is computed as a separate model-realization and taken into account based on its corresponding aggregate weight. More details about the computational mechanics are summarized in Box 4.2.
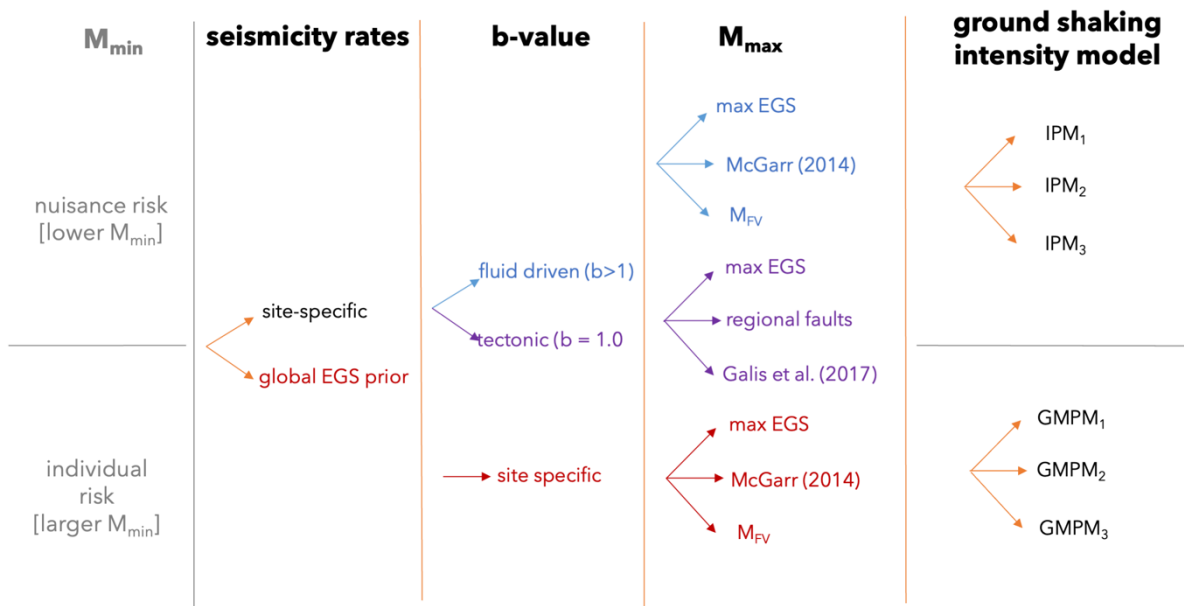
Figure 4.1. Illustrative example of a PSHA logic tree with four branching levels (weights not shown). The term "max EGS" represents the maximum recorded event at any EGS site (currently M_W 5.5), while the term M_{FV} refers to the "lower bound" (finite volume) formulation in Shapiro et al. (2013). "IPM" stands for Intensity Prediction Model and "GMPM" stands for Ground Motion Prediction Model. The term "global EGS prior" refers to an empirical model calibrated on past EGS datasets.

BOX 4.2 Computational framework of a SHRA

For each simulated rupture many random fields of ground motion intensity measures (IMs) are generated (Kohrangi et al., 2016). The random fields are then used as input to the fragility model to estimate the damage severity that any given structure may suffer when subject to the predicted level of IM (Crowley and Bommer, 2006). Next, for each rupture and IM random field, the loss for the entire affected portfolio of structures is estimated by simply summing the losses predicted for each structure (given its damage state and value) in the footprint of the random field. This procedure is repeated for all random fields of each simulated rupture. Finally, the rate of exceeding any portfolio loss is empirically found by keeping track of the number of exceedances occurring over all the simulated realizations. This general approach to estimate earthquake risk to portfolios of structures at a regional level still holds for the case of induced seismicity but given the peculiarities of the phenomenon, some modifications may be appropriate, especially in order to ensure that the traditional Poissonian recurrence models are valid (Gupta and Baker 2019; Grigoratos et al., 2021). This approach also allows for implementation of spatial correlation between ground shaking at multiple sites from the same earthquake (Jayaram and Baker, 2009), due to common source and wave traveling paths and to similar distance to fault asperities. Incorporating spatial correlations improves the reliability of the risk estimates when dealing with spatially distributed structural portfolios (Park et al., 2007). This computational framework has been described further in Grigoratos et al (2021).

4.2 Seismic source

Defining the characteristics of the seismic source is a very challenging and highly uncertain task of seismic risk modeling. This remains true for EGS projects, especially in terms of activity rates and magnitude range. Here, we attempt to introduce the key modeling parameters that need to be constrained, listing possible methods for their estimation, with future research expected to provide further implementation details.

In DHSA, the seismic source for an EGS stimulation is usually defined as:

1) one hypocenter that can form a rupture zone of a given aspect ratio and focal mechanism;

2) a fixed magnitude scenario.

In PHSA, the seismic source for an EGS stimulation can be defined as:

1) one or more hypocenters that can form rupture zones of a given aspect ratio following certain focal mechanisms;

2) a probability distribution for the magnitudes of each hypocenter, bounded by a maximum magnitude.

For EGS sites, the hypocenter of the seismic source is more or less known, since it is assumed/expected to be very close to the stimulation zone (less than 2 km away; Zang et al., 2014; Grigoratos et al., 2022). During circulation, the nucleation zone might be slightly further away. Furthermore, the focal mechanism can be potentially inferred from the local stress regime. The rest of the seismic source parameters, e.g. the potential magnitudes and their frequency, are very difficult to meaningfully constrain before any local stimulation data are collected.

For EGS sites, the deterministic approach (DSHA) assumes a single (scenario) rupture with a predefined focal mechanism of the maximum credible earthquake (MCE), which is the largest magnitude reasonably expected during the human activities in question. This magnitude is selected based on historical seismicity, geological considerations, and expert judgment (Bommer, 2002); MCE is usually smaller than the largest possible magnitude (M_{max}; §4.2.2), because it conceptually represents a finite return period.

4.2.1 Seismicity rate parameters

The probabilistic approach (PSHA) takes into account numerous potential ruptures (of different sizes and potentially focal mechanisms) and their estimated probabilities of occurrence. This approach is expressed by a magnitude-frequency distribution, double-truncated by the minimum (§4.7) and maximum magnitude (§4.3). The most widely used magnitude-frequency distribution is the Gutenberg-Richter curve (Gutenberg & Richter, 1956), which has two parameters, the a-value (total rate of events above M 0 in log10 scale) and the b-value (log-linear slope of the seismicity rate with magnitude). The b-value depends mainly on the local stress conditions and on the interconnectivity of the fracture network. Although hydraulic stimulation can alter both of these variables, the b-value is usually considered static, as far as the SHA calculations are concerned. During fluid injection operations, the a-value is often linked to the pressurization rate via a factor of proportionality (FoP), which is a proxy for how susceptible fault-stability is to pore-pressure changes (Shapiro et al., 2010; Grigoratos et al., 2022). If a hydromechanical model is not available, the injection rate may be used as a proxy for the pressurization rate, as long as the latter is not decreasing (Shapiro, 2015).

Notably, the seismicity often continues even after the injection operations have ceased. The decaying seismicity rate after the injection rate has dropped significantly or is zero, can be modeled with a modified Omori law (Langenbruch & Shapiro, 2010; Schultz et al., 2023a; Kwiatek et al., 2024). Even though the vast majority of events usually occur during the stimulation (Langenbruch & Shapiro, 2010), the magnitudes of the trailing seismicity (after shut-in) can be relatively large or even the largest ones (Verdon & Bommer, 2020).

Even though the a-value fluctuates during a stimulation, for the purposes of the PSHA, it is taken as a static variable, expressed in cumulative terms. Its estimation is very difficult and requires local seismological and hydraulic data from past stimulations. The seismic response of the reservoir to future hydraulic input has to be calibrated using either statistical approaches (e.g., Shapiro, 2015) or physics-based hydromechanical numerical methods (e.g., Baisch et al., 2010; McClure & Horne, 2011). The former relies on crude assumptions for the underlying physics, while the latter requires several poorly constrained hydromechanical parameters and complex mathematical frameworks.

As far as the b-value is concerned, a local earthquake catalog is needed for calibration (Box 4.3). Even if that is feasible, b-values cannot be applied with confidence outside the magnitude range of their calibration. Furthermore, at moderate (above 4) or large magnitudes (above 6) the b-value will likely converge to the global (tectonic) average of 1.0 (Bell et al 2013; Michael, 2014; Navas-Portella et al 2019), given that the rupture is so extensive that it has propagated outside the (limited) pore-pressure perturbed zone, encountering faults that have accumulated stress via tectonic strain. For this reason, we suggest either adopting magnitude-dependent b-values or including a branching level for the b-value in the logic tree, with equal weighting assigned to the locally calibrated b-value and the global average of 1.0 (Petersen et al., 2016).

BOX 4.3 Methods for computing the b-value

The b-value should be computed following maximum likelihood methods such as Weichert (1980) or the ones outlined in Marzocchi & Sandri (2003). Least-squares fitting is usually not an appropriate regression method (Sandri & Marzocchi, 2005). Resampling to account for measurement/conversion uncertainties behind the cataloged magnitudes is strongly encouraged (Taroni 2022; Kwiatek et al., 2024). The default magnitude binning interval should be 0.1 units (Marzocchi et al., 2020). A crucial step for the estimation of the b-value is the determination of the magnitude of completeness (Mc). The latter is the magnitude above which the overwhelming majority of earthquakes are reported in the available catalog. Small changes in the Mc can lead to impactful variations in the b-value, and thus to the hazard and risk. Examples of misrepresentations of Mc due to spatiotemporal variations in the performance of

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the seismic network can be found in Mignan (2012). The Mc could be estimated using more than one of the methods outlined in Zhou et al. (2018). If the b-value derived from traditional methods (Marzocchi & Sandri, 2003) differs by more than 0.2 units from the b-value derived following van der Elst (2021), then perhaps further sensitivity analysis is required.

If the SHRA is required prior to the first stimulation at the site, when no local data are available, both the MCE and the magnitude frequency distribution are extremely uncertain variables, with very large influence on the final risk estimates. One way of tackling this problem is to assume that the site will respond in line with other global EGS stimulation for which the relevant parameters (MCE or FoP, b-value, and decay rate) are obtainable. All other EGS stimulations can be weighted based on how similar they are to the one in question. For example, the criteria could be: depth, temperature gradient, lithology, average hourly fluid volume, injection protocol (monotonic, cyclical), or the ratio between the local Seismogenic Index (Shapiro et al., 201   0) and the b-value.

4.2.2 Maximum possible magnitude

Any EGS-related SHA is bounded by the maximum possible magnitude (M_{max}) assigned to the stimulation under investigation. Note, that our definition of M_{max} is not (an estimate) of the largest observed earthquake, but rather the largest magnitude that this seismic source could accommodate. The M_{max} might be limited either due to tectonic constraints or due to the limited scope of the anthropogenic operations. Below we outline certain considerations that might inform the estimation of M_{max}. That said, this is a topic of ongoing research and debate. Thus, resorting, at least to a certain degree, to expert judgment might be an unavoidable outcome. In that case, a logic tree structure for the M_{max} might be an appropriate expression of the elevated uncertainty levels.

For stimulation-induced seismicity, assuming no runaway ruptures (i.e. self-sustaining outwards propagation via tectonic strain), M_{max} may be limited by the size of the rock volume perturbed by pore pressure (Shapiro et al., 2013) or the total injected fluid volume (McGarr, 2014; Galis et al., 2017). The method by Shapiro et al. (2013) requires data from at least one local stimulation, while Galis et al. (2017) require as input four geomechanical properties of the reservoir (bulk modulus of the reservoir rock, reservoir thickness, dynamic friction coefficient, background stress drop). The method of McGarr (2014) is the easiest to apply but is also the least site-specific. All three methods use as input the total injected fluid volume (Box 4.5).

For tectonic seismicity and runaway induced ruptures, M_{max} is usually dictated by the size and interconnectivity of the local fault network and the expected stress drop (Box 4.4). The calculation employs empirical fault-scaling relations (Leonard, 2014) that infer the magnitude of an earthquake given the geometry and focal mechanism of a given rupture. Notably, these empirical relations have been derived from moderate to large magnitude earthquakes, with deeper hypocenters than the ones expected at EGS sites. Therefore, it is likely that the relations overestimate the magnitude of small and/or shallow faults (Grigoratos et al., 2021). Alternatively, numerical simulations could be used to infer M_{max} combining physical understanding of dynamic fault slip and geological knowledge of the fault (e.g., Wentinck & Kortekaas, 2023). Notably, if the stimulation zone is within the shallow sedimentary cover, large-magnitude events (e.g. above magnitude 6) are arguably less likely (Bommer & Verdon, 2024). This is because these sedimentary layers tend to have lower stress drops (due to lower stiffness and frictional strength) and fewer and shorter faults (due to younger formation age). Furthermore, in general, shallow hypocenters (e.g. depth below 5 km) rarely produce large ruptures given that this would likely require rupture-propagation downwards into the crust, against increasing frictional strength and confining stress (Bommer & Verdon, 2024).

BOX 4.4 Largest observed magnitudes

To date, the largest magnitude earthquake linked to hydraulic fracturing stimulations for EGS projects is the M_W 5.5 Pohang, South Korea, event (Ellsworth et al., 2019). The largest magnitude decisively confirmed to be linked to hydraulic fracturing stimulations for oil and gas activities is smaller, around M 4.6 (Mahani et al., 2017). Larger magnitudes have been reported in China (Lei et al., 2019; Zhao et al., 2023), but the associations are less conclusive. Seismicity during the production (circulation) phase of a geothermal project has reached magnitudes up to M 4.6 in the Geysers (Majer & Peterson, 2007). Finally, a seismic swarm with magnitudes up to M 5.4 in the North Brawley might have been triggered by aseismic slip originating from shallow geothermal wells (Im & Avouac 2021).

BOX 4.5 Available equations to calculate the M_{max} of induced earthquakes

McGarr (2014) proposed a simple formula to compute an upper bound for the cumulative seismic moment that can be released during a fluid-induced earthquake sequence.

$$\Sigma M_0 = 2 * G * \Delta V \qquad \text{(EQ:01)}$$

where G is the shear modulus, often assumed equal to 30 GPa, and ΔV is the net total injected fluid volume. The approach is based on volumetric changes inducing seismic slip in a linear fashion. It assumes that, on average, each fault patch is about half a seismic stress drop below the yield stress and so it only takes half as much stress change imposed by the volumetric change to induce seismic slip.

Assuming a G-R relation, one can employ the b-value to convert this cumulative seismic moment into a single maximum magnitude, which is given by:

$$M_0^{max} = \frac{1-B}{B} \frac{2\mu\,(3\lambda+2G)}{3} \Delta V \qquad \text{(EQ:02)}$$

where B = 2b/3 . Assuming λ = G and μ = 0.6 this leads to:

$$M_0^{max} = G * \Delta V \qquad \text{(EQ:03)}$$

Then, the corresponding moment magnitude can be derived as:

$$M_W^{max} = \frac{2}{3} log_{10}(M_0^{max}) - 6.033 \quad \text{(EQ:04)}$$

Galis et al. (2017) proposed an estimate for the maximum moment Momax that can be released during an arrested rupture based on the notion that such rupture is controlled by a competition between two sources of elastic energy: injection-induced fluid pressure and tectonic prestress. The contributions of these two sources are both positive. However, the energy contributed by injection-induced fluid pressure decays with increasing rupture size, whereas the energy contributed by tectonic prestress increases, thereby creating a trade-off between these two strain-energy sources. At the maximum arrest size, both contributions are comparable. The value of Momax is dependent on the total net injected volume ΔV with an exponent of 3/2 (instead of 1 for McGarr 2014). The rest of the formulation includes various geomechanical parameters related to the target-reservoir that can be combined in a single parameter γ:

$$M_0^{max} = \gamma * \Delta V^{3/2} \qquad \text{(EQ:05)}$$

Galis et al. (2017) demonstrated that assuming b=1, $\Sigma = 2/3 log_{10}\gamma - 6.07$, and at every time-iteration i, Σ is equal to:

$$\Sigma_\gamma(i) = log_{10}\left(\frac{N(i)}{10^{(-M_c)}\Delta V(i)}\right) \qquad \text{(EQ:06)}$$

where N is the total number of events above Mc.

The so-called "lower-bound" formulation of Shapiro et al. (2013) assumed that a rupture can nucleate only within the stimulated rock-volume and cannot propagate outside of it. This applies a geometrical constraint on the 3D size of any rupture. As a proxy for the stimulated rock-volume one can fit an ellipsoid around the evolving seismicity cloud, to represent the expanding triggering front during pore-pressure diffusion. If the stimulation has not yet started, the evolving perturbed volume could be simulated using hydromechanical models. The formulation results in a maximum magnitude equal to:

$$M^{max,L} = log_{10}L^2 + 2/3(log_{10}\Delta\sigma - log_{10}C) - 6.07 \quad \text{(EQ:07)}$$

where L denotes a characteristic scale of the stimulated volume, Δσ is a static stress drop, and C is a geometrical constant close to 1. If $L_{min} < L_{int} < L_{max}$, Shapiro et al. (2013) found that:

$$L = \left[\frac{1}{3}(1/L_{min}^3 + 1/L_{int}^3 + 1/L_{max}^3)\right]^{-1/3} \quad \text{(EQ:08)}$$

often provides a good estimate of the characteristic scale. The values for $L_{min}, L_{int}, L_{max}$ are the principal axes of the fitted ellipsoid, while Δσ, Σ and b are derived jointly using grid-search maximum likelihood regression (Poisson assumption; Kwiatek et al., 2024).

4.3 Ground shaking intensity

The primary predictor variables for the spatial distribution of ground motion are usually: magnitude, distance to the rupture, and soil conditions (Boore et al., 1997). Additional variables may be included, such as style of faulting, depth to top of the rupture, depth to a velocity of 1 km/s, or others (Gerstenberger et al., 2020). Some Ground Motion Prediction Models (GMPMs) may incorporate additional constraints from physics-based simulations of ground shaking data. Usually, the output variables of a GMPM are spectral accelerations (SA) at different periods (e.g., 0.01 to 10s), Peak Ground Velocity (PGV), Peak Ground Acceleration (PGA) or Arias intensity. These variables are expressed in mean plus standard deviation values. The uncertainty range is usually truncated at 3 standard deviations.

Applicable GMPM should have been calibrated with earthquake data compatible with the selected M_{min} (§4.6) and M_{max} values for the SHRA (Grigoratos et al., 2023; Box 4.6). They should also be compatible with the tectonic regime and focal depth of the site. Hybrid GMPM that combine recorded ground motion data with 3D representations of Earth's structure in conjunction with dynamic kinematic representations of the earthquake source are also a viable alternative (e.g. Edwards et al., 2018). Site-specific GMPM should be derived when rich seismic datasets (both in terms of sample size and magnitude range) are available.

It is important to point out that ground motion estimates are very sensitive to the stress drop value assigned to the source (Baltay et al., 2013; Edwards & Fah, 2013; Trugman & Shearer 2018). Thus, the selected GMPMs should be compatible with the range of stress drops expected at the site. Here, we should caveat that stress drop measurements can be highly uncertain due to factors such as data quality, source model assumptions, methodology, path/site effects, or instrumental response (Baltay et al., 2024). Overall, induced earthquakes do not appear to have significantly different stress drop than tectonic ones (Huang et al., 2017; Yu et al., 2020). That said, an inverse relationship between stress drop and proximity to the stimulation might exist at close (<2km) distances (Goertz-Allmann et al., 2011; Kwiatek et al., 2014; Yu et al., 2020). Stress drops also depend on the focal mechanism (Allmann & Shearer, 2009; Oth 2013; Hauksson, 2015), on the local lithology (Goebel et al., 2015), formation age (Bommer & Verdon, 2024), on the rate of tectonic deformation (Hauksson, 2015; Goebel et al., 2015), and likely increase with magnitude until magnitude values around 4 (Edwards & Fah, 2013; Trugman et al., 2017). There is no scientific consensus on whether stress drop increases with depth; some studies favor this observation (Oth, 2013; Trugman et al., 2017; Walter et al., 2017; Goebel et al., 2015), while others do not (Allmann & Shearer, 2009; Hauksson, 2015; Clerc et al., 2016; Wu et al., 2018; Jeong et al., 2021; Abercrombie et al., 2021). Notably, significantly lower stress drops tend to be observed in geothermal (Hauksson, 2015) and volcanic (Oth, 2013) areas, either due to high temperatures or due to the presence of fluids.

The variability in the near-surface geology is well known to have a strong influence on the level of amplification of seismic ground motion during an earthquake. The presence of low seismic velocity

sediments overlying stiffer bedrock, especially near the surface, modifies earthquake ground motions by affecting amplitudes and frequency content. This phenomenon is referred to as seismic site response or site effects and is critical when assessing seismic hazard levels in a given area. It is usually dealt with by GMPMs in a crude way, using scaling based on the Vs30 parameter. Site-specific site-amplification factors would be ideal (van Ginkel et al., 2022), if there is enough data to derive them.

BOX 4.6 Examples of GMPMs and treatment of uncertainty

GMPMs are inherently limited by the scarcity of data related to large shaking amplitudes, and/or near-source recordings. This is particularly challenging for stable continental regions, where low seismicity rates and typically sparse seismic networks exacerbate the lack of data (Gerstenberger et al., 2020). As far as induced events are concerned, due to their triggering process, they are likely to be of smaller magnitude and at shallower focal depth than typical tectonic earthquakes (Grigoratos et al., 2021). The focal depths of potentially induced events generally lie within the upper 6 km of the crust, making the seismic wave propagation more dependent on the heterogeneous properties of the uppermost crustal layers (Bommer et al., 2016).

To address these issues, several studies have developed region- or even sequence-specific GMPM for induced seismicity. Here, we exclude cases of mining-induced seismicity. Novakovic et al. (2018; 2020) and Zalachoris & Rathje (2019) developed GMPMs for Oklahoma (USA); Douglas et al. (2013) for low-magnitude earthquakes from geothermal areas in Europe; Sharma et al. (2013) for the Geysers Geothermal Area (USA), Edwards et al. (2018) for the Basel sequence (Switzerland), Sharma et al. (2022) for the St. Gallen sequence (Switzerland), and Cremen et al. (2020) for the Preston New Road HF sequence (UK). Finally, there are several GMPMs related to fluid-extraction based on the Groningen data (Bommer et al. 2016; 2017; Paolucci et al. 2020; Ruigrok et al. 2022; Bommer et al. 2022ab).

Notably, when Cremen et al. (2020) tested the model by Douglas et al. (2013) against the Preston New Road data, the fit was not satisfactory despite the broad similarities in magnitude range, focal depth and tectonic setting. Furthermore, Grigoratos et al. (2021) demonstrated that even relations developed from similar datasets can exhibit very different attenuation functions. Therefore, it is very difficult to confidently select a GMPM unless it can be re-calibrated or at least tested against local data.

To deal with uncertainties, it is common practice to combine multiple GMPMs via logic trees. As explained in Gerstenberger et al. (2020), in practice, this approach begins with the selection of suitable GMPMs by first applying a criteria of quality assurance (Cotton et al., 2006; Bommer et al., 2010). Next, performance tests of the GMPMs with respect to a dataset provide quantitative ranking of the models (e.g., Scherbaum et al., 2009). Sensitivity analyses and expert elicitation (e.g., Delavaud et al., 2012) can provide a final logic tree structure for GMPMs. That said, recent studies (e.g., Mak et al., 2014) have highlighted the inconsistency of a pure data-driven approach, in particular with a lack of independency of the data or incomplete (or biased) datasets that may favor one model over another (e.g. Ghasemi and Allen, 2017).

Beyond the use of multiple GMPMs, the scaled backbone approach (Bommer, 2012; Atkinson and Adams, 2013; Atkinson et al., 2014a; Douglas, 2018) provides an alternative for handling the wide range of uncertainties. In this approach, one GMPM is typically used to generalize the attenuation and magnitude- scaling behavior required for a specific tectonic region type for a range of magnitudes and distances. As explained in Boore et al. (2022), the selected backbone model is first adjusted to match the earthquake source and path characteristics of the target region, and then it is separately adjusted to account for the site- specific geotechnical profile. For a GMPM to be amenable to such host-to-target adjustments, the magnitude scaling of response spectral ordinates should be consistent with the theoretical scaling of Fourier amplitude spectra. In addition, the influence of individual source and path parameters should be clearly distinguished in the model to allow the adjustments to be applied individually, and reliable estimates of the source and path parameters from the host region of the GMPM should be available, as should a reference rock profile for the model. Using data analysis and judgment, upper and lower alternatives about the central GMPM are defined to capture the epistemic uncertainty of a representative suite of published GMPMs. A referenced backbone model allows tuning the size of the alternative branches while preserving statistical independence of the newly predictive models. This approach is gaining ground in recent years and its implementation details are outlined in Boore et al. (2022).

Intensity Prediction Models (IPMs) have been developed to estimate Intensity Scales (e.g. modified Mercalli intensity (MMI)) for a given set of earthquake magnitudes and site distances. Unlike other intensity measures (IMs) such as SAs or PGA, MMI depends solely on observations, such as felt intensities and

structural damage (Wood and Neumann, 1931). Due to their simplified functional form, it is challenging to pair IPMs with specific soil amplification models or focal mechanisms. Therefore, the dataset used in their regression is a key factor for their applicability (Box 4.7). They also require fragility models that are explicitly developed for IPMs, to be paired with a certain exposure model.

BOX 4.7 Examples of IPMs

Popular IPMs have been developed by Atkinson & Wald (2007), later revised by Atkinson et al. (2014b), focusing on North American data above M 3. Allen et al. (2012) developed a globally applicable IPM based on earthquakes with Mw > 5 for active crustal regions. Ahmadzadeh et al. (2020) developed an IPM for Iran, Le Goff et al. (2014) one for Portugal, Baumont et al. (2018) one for France and Dowrick & Rhoades (2005) one for New Zealand. None of the aforementioned IPMs is designed for very shallow small-magnitude earthquakes. A better fit would be the IPM by Teng et al. (2021), which is based on likely-induced earthquakes related to wastewater disposal in Texas, Oklahoma and Kansas, with magnitudes between M 1.5 and 3.5 and hypocentral distances within 30 km. Alternatively, one could compute PGV or PGA estimates using an applicable GMPM, and then convert those to MMI using the conversion-relations of Schultz et al. (2021c), originally derived for Central and Eastern US. That said, doubling the amount of conversion-steps increases the uncertainty of the final output considerably.

4.4 Exposure

When conducting any type of seismic risk analysis, it is important to understand which assets are exposed to the seismic hazard. These assets can be, for example, residential or industrial buildings, special buildings (e.g. schools, hospitals), roads, or critical infrastructure (e.g. bridges, pipelines, energy plants, dams, ports). Each asset has its own fragility against seismic loads and its own replacement cost. Individuals are also exposed entities, although their vulnerability is dependent on the structure they reside in at the time of the earthquake. These assets are aggregated at different spatial resolutions depending on data-availability. Notably, the spatial resolution itself can have an impact on the loss estimates (Dabbeek et al., 2021).

The buildings in the exposure model are classified according to their seismic performance using a building taxonomy that is based on national or international standards (e.g. the GEM Building Taxonomy, Brzev et al., 2013, as updated by Silva et al., 2018; 2022) that allows buildings to be classified according to a number of structural attributes. The main attributes that have been selected for the consistent definition of building classes are as follows:

- Main construction material (e.g. reinforced concrete, unreinforced masonry, reinforced/confined masonry, adobe, steel, timber).

- Lateral load resisting system (e.g. infilled frame, moment frame, wall, dual frame-wall system, flat slab/plate or waffle slab, post and beam).

- Number of stories.

- Seismic design code level (pre-code, low, moderate, high).

- Lateral force coefficient used in the seismic design.

Each building is paired with a corresponding value for its structural elements (e.g. columns, slabs), non-structural elements (e.g. mechanical equipment, windows, cladding) and contents (e.g. furniture). The occupants of each building are also part of an exposure dataset. Furthermore, special structures like bridges, dams, pipelines may also have their own, less standardized, taxonomy classes (Pitilakis et al., 2014; FEMA, 2013).

The SRA should take into account the entire relevant structural portfolio around the site. This can be ensured by including structures within at least a 100 km radius (Baker et al., 2021). Special considerations regarding dams, nuclear plants or other supercritical infrastructure may also be warranted. For both LoCs, the average number of people expected to experience felt seismicity within hundreds of kms (Schultz et al., 2021a) from the site during the stimulation and circulation phase of the EGS project should be evaluated. We suggest adopting the lowest grid resolution possible, with indicative values ranging from 1 to 5 km (Papadopoulos et al., 2024).

Depending on the region, the exposure database could be compiled in an ad-hoc fashion (e.g. from Census or government data). That said, a recent global compilation from GEM could also be utilized (Yepes-Estrada et al., 2017; 2023; Crowley et al., 2020), at least for the building data, if the lowest available spatial resolution meets the needs of the project. It contains information regarding structural and non-structural elements, contents and occupancy.

4.5 Fragility and vulnerability

According to the prevailing terminology, the terms fragility and vulnerability are similar but not identical, the former only captures physical damages, while the latter also captures the losses resulting from such damages. Any risk analysis assigns to each class of structure in its inventory a specific fragility (or vulnerability) curve that estimates the probabilistic distribution of damages (or losses) that this structure is expected to experience when subject to ground motions of different intensities. For the damages, modelers use standardized damage-states as labels, with typical cases being "light- damage", "significant damage", "heavy damage", and "collapse". The direct economic losses are measured in terms of loss ratio, which is defined as the ratio of cost of repair to cost of replacement. Other types of loss include population displacement, fatalities or injuries. Indirect economic losses (such as business interruption or economic disruptions) are more difficult to model and are often neglected, even though they can be very important (Sousa et al., 2022; Markhvida & Baker, 2023). The IMs are usually related to the fundamental period of the structure (Silva et al., 2019), for example 5% damped pseudospectral accelerations (SA) at 0.3s. That said, in recent years, more advanced IMs are gaining traction (Kohrangi et al., 2016).

Established sources of fragility and vulnerability models is GEM (Martins & Silva 2020, Martins et al., 2021) and FEMA (FEMA 2013), but there are numerous individual studies that have produced curves for specific structural typologies (e.g., Kallioras et al., 2019). Importantly, the adopted fragility curves should be compatible with the selected M_{min} and IM.

Notably, most fragility and vulnerability functions were developed for large (tectonic) events, at least larger than magnitude 5, and hence they might be biased towards higher loss estimates, compared to the short duration and high frequency content of induced motions (Grigoratos et al., 2023). In general, these functions also ignore damage accumulation effects that might occur when buildings are subjected to a series of earthquakes (Papadopoulos et al., 2020). If more than one reliable fragility model is available for the exposed assets in question, a logic tree approach can be applied there as well to cover the epistemic uncertainty. This implicitly assumes perfect correlation over all assets, which might lead to skewed results.

4.6 Minimum magnitude for engineering purposes

Notably, depending on the risk metric targeted by the analysis, there is a minimum magnitude (M_{min}), below which there is no engineering interest (Bommer & Crowley 2017). In other words, the rupture is too short (in duration) or limited in frequency-content to cause any damage to the relevant structures, even at close distances. This M_{min} value represents the lower truncation of the magnitude-frequency distribution in the

classical PSHA formulation. Furthermore, if the scenario earthquake adopted by the DSHA is lower than Mmin, then no calculations are needed for the specific risk-metric in question.

Naturally, structural damages require a slightly larger M_{min} than non-structural damages, with the latter requiring a significantly larger M_{min} than nuisance calculations. When it comes to damages, the representative seismic design code level of the built environment plays a crucial role in determining a suitable M_{min} value. For example, the M_{min} value for structural damages in Groningen (no seismic code penetration) should be much lower than the one in Japan (very high seismic code and adoption levels).

BOX 4.8 Minimum magnitude values

M_{min} values linked to structural damages are to an extent typology-dependent; for example, an unreinforced-masonry building should be paired with a lower M_{min} than a reinforced-concrete wall building of similar height. Therefore, ideally one would use M_{min} values specific to both the taxonomy and the risk-metric, increasing considerably the complexity of the calculations for little real benefit. A more pragmatic approach assumes that a specific structural typology will dominate the risk results and chooses as M_{min} the value that corresponds to that typology.

Although exceptions may apply, typical indicative values for M_{min} are: 4 to 5 for structural damages (and fatalities), 3.5 to 4.5 for non-structural damages (Nievas et al., 2019) and 2 to 3 for nuisance estimates (Schultz et al., 2021c). That said, in practice, for simplicity, a uniform M_{min} value is usually selected for both structural and non-structural damages, with a different one only for nuisance.

4.7 Risk metrics

We propose the following risk-metrics as variables in decision making related to the permitting process, designing the TLP thresholds and in general regarding a project should be deemed too risky or not (Grigoratos et al., 2023):

- aggregate nuisance level: mean total number of people feeling an earthquake.

- aggregate structural damages: mean total number of structures with at least "moderate" structural damages.

- aggregate non-structural damages: mean total number of structures with at least "severe" non-structural damages.

- local personal risk: mean probability of fatality for a person, who is continuously present without protection at a location.

These metrics refer to the entire duration of the human activity in question. Obviously, if a human activity is to be repeated multiple times (e.g., several stimulations over a number of weeks) then this should be taken into account. Both the list of risk metrics and their tolerance thresholds should be defined prior to the first SHRA by the regulator. Notably, local personal risk thresholds are mandated by law in certain countries (e.g., Netherlands).

To better contextualize these decision variables, one could express them as ratios of the equivalent ones for tectonic hazard. However, this assumes that the tectonic estimates are not only available, but that they have also been computed with similar enough model components (e.g., GMPMs, fragility curves, etc). This might be quite a challenging task.

BOX 4.9 Definition of damage-states and nuisance levels

The damage-states adopted by the global risk map of GEM (Silva et al., 2020) or the ones from HAZUS (FEMA, 2013) could be used as reference points. Majer et al. (2016) also lists damage-states for civil and buried structures. If the

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consequence function assumes different fatality ratios for daytime and nighttime, the mean of the two should be used. Indirect economic losses (such as business interruption or economic disruptions) are more difficult to model and are neglected here.

The nuisance levels can be taken as equivalent MMI scales above III or following the considerations outlined in Majer et al. (2016).

4.8 Deaggregation and component analysis

Deaggregation provides a breakdown of the modeled seismic risk estimates, allowing engineers and decision-makers to better understand the relative contributions of different earthquake sources (McGuire, 1995). It is the statistical decomposition of the probability of exceeding a certain hazard or risk metric, into the contributions from individual seismic sources or earthquake scenarios (Bazzurro & Cornell, 1999; Hong & Goda, 2006; Goda & Hong, 2009). The results are usually plotted as probability mass functions for different values of magnitude and/or (hypocentral) distance, or are mapped along latitudinal and longitudinal surface coordinates. The spatial dimension of the deaggregation results might be relevant in case the EGS comprises multiple wells over a sizable geothermal play. If the EGS consists of just a few closely spaced wells, then only the decomposition in the magnitude domain is relevant. Notably, the latter is conceptually similar to how different scenario earthquakes are simulated to configure the red-light magnitudes in TLPs (§5.1.4).

One-at-a-time sensitivity analyses can also highlight whether the risk results are particularly sensitive to a specific logic tree branching level, e.g. to the GMPMs or the seismic source models. This would be an indication that additional effort should be put into reducing the uncertainty associated with this model-component. Furthermore, component analysis could be utilized to highlight parts of the seismic risk model that are responsible for a significant portion of the losses. For example, if a specific building typology dominates the loss estimates, targeted retrofitting options or insurance coverage could be considered.

5. Traffic Light Protocols (Module 5)

The design of a Traffic Light Protocol (TLP, synonymously called a Traffic Light System) depends on a cross-examination and cooperation between the regulator, operator, and independent expert groups, as shown in Table 5.1. The operator then implements a plan to mitigate induced seismicity, which includes the seismic monitoring network and a reactive TLP (Module 5).

Table 5.1. Roles of operator, regulator, and independent expert group on the TLP.

Participants	Roles
Regulator	Defines acceptable risk tolerance, uses risk principles to inform TLP design, ensures that the operator complies with regulations, enforces red-lights.
Operator	Defines effective yellow-light mitigation strategies, complies with regulations, reports compliance to the regulator. Installs and maintains a monitoring network to ensure the efficacy of the TLP (and optionally ATLP). Optionally defines its own (lower) TLP thresholds.
Independent expert group(s)	Provides authoritative seismic monitoring services and impartial scientific advice (e.g., calibrated M_L-M_W relationships).
Vendors	Provide seismic monitoring services and design/operate the TLP

In general, the TLP uses a three-stage response plan that governs the injection/extraction of fluids (Bommer et al., 2006):

- Normal (green): operations continue as planned;

- Caution (yellow): operator implements seismicity-mitigation strategies;

- Stop (red): operation is (indefinitely) suspended.

Note that the yellow-light can be further subdivided into sub-stages that implement increasingly effective mitigation strategies as the red-light is approached. Herein, (seismicity) mitigation strategies are defined as any operational changes made with the intention of reducing the growth in earthquake magnitude and frequency - in order to avoid encountering the red-light.

Goals of the TLP

1. The intention of the red-light is to provide the last possible stopping point, before exceeding an agreed upon tolerance to risk.

2. The intention of the yellow-light is to provide an adequate buffer, before the red-light, for an operator to enact their mitigation strategies - to ensure that the red-light is avoided.

Recommendations for the TLP

1. The construction of a TLP must be informed by seismic risk estimation methods.

2. Red-lights need to account for trailing seismicity: aftershock-like earthquakes that continue to occur after an operation has stopped, which can be larger in magnitude than the events during

stimulation. In this sense, the red-light should trigger the operational stop an adequate 'distance' before the agreed upon risk tolerance.

3. Yellow-lights need to account for magnitude jumps: sudden increases in the largest event in a sequence - to minimize the chance of moving straight from green-to-red.

We note that any event size (magnitude or ground motion) based TLP has uncertainty and cannot 100% prevent intolerable events, thus supplementary measurements should be considered in the decision making (see §5.2).

These core recommendations are illustrated in Figure 5.1. Risk-based approaches are used to estimate M_{TOL}, a threshold magnitude that is expected to exceed a tolerance to risk (if it occurs). The red-light threshold (M_{RED}) is then stepped back from M_{TOL} by an amount we anticipate that magnitudes could change after an operation has stopped (ΔM_{TRAIL}). The yellow-light threshold (M_{YELLOW}) is then stepped back from M_{RED} by an amount we anticipate that magnitudes could jump during an operator's mitigation (ΔM_{JUMP}). We note that this figure is a simplification, in order to illustrate these concepts.
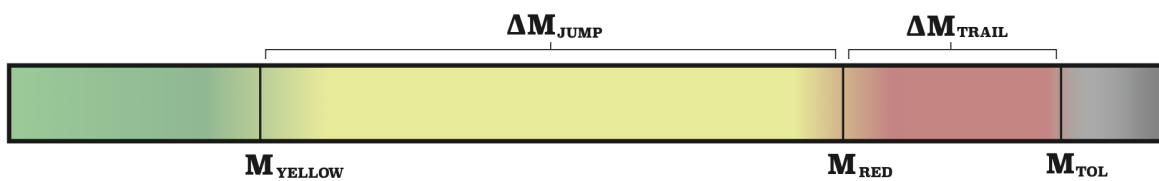

Figure 5.1. Schematic framework for a risk-based traffic light protocol, using magnitude thresholds.

5.1 Risk-based Traffic Light Protocols

In the following, we provide justifications and examples that illustrate how a risk-based TLP could be designed for EGS operations in a geothermal setting. We organize these points based on questions and answers to TLP design.

5.1.1 How to select risk tolerances?

Seismic risks are multifaceted and can include nuisance, infrastructure damages, economic losses, and personal safety. Seismic risks can also vary by local or aggregate types: being either the impacts to an individual or the group, respectively. Using risk to decide when an operation needs to stop is justified, since these metrics are most closely tied to the consequences of induced seismicity and most easily understood by the impacted stakeholders.

Tolerances to each of these risks need to be clearly defined and communicated for a region/project - preferably in cooperation with all the affected stakeholders. Ideally, tolerances are defined via legislation or policy direction, which gives the regulator mandate or authority to govern industrial activities. Alternatively, tolerances can be inferred from prior TLPs or operation-ending earthquakes. The risk metrics, types, and tolerances that are relevant for a region/project might vary depending on:

*   Familiarity and willingness of the local communities to cope with earthquake ground shaking risks.

*   History of regulation, energy projects, and induced seismicity in a region.

*   Policy orientation and social/cultural norms.

*   Criticality of the energy project.

5.1.2 Why are magnitudes used for thresholds?

The majority of thresholds used in conventional TLPs are magnitude-based, given that magnitude can be calculated rapidly from a coarse network (or even a single station, under special circumstances). Often this arises due to practical needs and considerations: regulatory/mitigatory decisions need to be made robustly, in rapid response to incoming (and uncertain) information. Induced seismicity tends to occur in seismically quiescent regions that are (initially) poorly monitored. As well, operations (like EGS stimulations or hydraulic fracturing) are transient and may become numerous - targeting plays and then moving on. Magnitude is also a more homogeneous metric compared with ground motions, which are only available at the measurement point. It is likely that these reasons also play a role in why local magnitude (M_L) is most often used to define TLP thresholds, rather than moment magnitude (M_W), which requires additional subsurface information (e.g., velocity model) and complex models. That said, a well-calibrated magnitude scale is essential for an effective TLP, because the link between magnitude and potential risks should be as accurate as possible (Roy et al., 2021).

In cases where there are monitoring stations co-located either with the operation or exposed assets, ground shaking measurements can be used to supplement the TLP decision making process. Better yet, direct measures of risk impacts could also supplement the TLP decision making process. We note that seismic risk estimation approaches (Chapter 4) can be used to translate magnitudes into seismic hazards or risks, and vice versa. There, uncertainties in geophysical parameters can be taken into account when designing a magnitude-based TLP threshold.

Similarly, M_W could be implemented as the magnitude scale used for the TLP if robust and reliable real-time estimation is available down to the monitoring thresholds. Practical issues aside, M_W would be preferable to M_L since it is based on the physical quantity of seismic moment from the earthquake, is used pervasively throughout hazard/risk estimation approaches, and does not saturate at large magnitudes.

5.1.3 Simplified examples of designing red-light magnitude thresholds

When M_{TOL} has been determined for a given risk tolerance, models of magnitude jumps and trailing seismicity can be used to inform how far back (in magnitude) an operator needs to stop. These concepts were previously illustrated in Figure 5.1, where M_{RED} needs to be set back from M_{TOL} (by ΔM_{TRAIL}) and M_{YELLOW} needs to be set back from M_{RED} (by ΔM_{JUMP}). Two simplified examples are described in Boxes 5.1 and 5.2.

BOX 5.1: Example for a High LoC project

If a $M_{TOL} = 3$ was determined to be associated with an operation-ending amount of nuisance or social unrest, then a red-light threshold of $M_{RED} = 2$ could be chosen. This is 1 magnitude lower than the risk-based target, considering that 90% of historical projects with hydraulic fracturing have trailing event magnitude differences smaller than magnitude +1 ($\Delta M_{TRAIL} = 1$) (Schultz et al., 2022a). Similarly, the yellow light could be $M_{YELLOW} = 0$, considering 90% of historical projects have magnitude jumps lower than 2 ($\Delta M_{JUMP} = 2$) (Verdon & Bommer, 2020); or 99% chance based on a Gutenberg-Richter distribution, with a b-value of 1 (Schultz et al., 2022a). So there is a 90-99% chance the project doesn't encounter a green-to-red jump.

BOX 5.2: Example for a Low LoC project

If a $M_{TOL} = 4$ event could be associated with intolerable housing damage, then a red-light threshold of $M_{RED} = 3.3$ could be chosen. This is 0.7 magnitude lower than our risk-based target, considering ~75% historical projects have trailing event magnitude differences smaller than +0.7 ($\Delta M_{TRAIL} = 0.7$) (Schultz et al., 2022a). The yellow light could then be $M_{YELLOW} = 2.3$, considering 60% historical projects have magnitude jumps lower than 1 ($\Delta M_{JUMP} = 1$) (Verdon &

> Bommer, 2020); or a 90% chance based on a Gutenberg-Richter distribution, with a b-value of 1 (Schultz et al., 2022a). So there is a 60-90% chance the project doesn't encounter a green-to-red jump.

These two simplified examples highlight how the basic concepts of trailing seismicity and magnitude jumps can be used to define TLP red- and yellow-light thresholds. In practice, we want to unify these concepts in a rigorous method that simultaneously considers risk-based tolerances, magnitude jumps, and trailing seismicity.

5.1.4 How are risk tolerances transformed into red-light magnitude thresholds?

By constructing models to estimate seismic risks from any scenario earthquake magnitude, the risk tolerance can be converted into a red-light magnitude (Douglas & Aochi, 2014; Ader et al., 2020). Typical risk concerns are nuisance, damage, and a probability of personal risk concern. An example of a detailed workflow is developed by Schultz et al., (2021a), and illustrated in Figure 5.2 and the Box 5.3 below. In prior work, these concepts have been applied to prospective EGS induced seismicity (Schultz et al., 2022b; Yaghoubi et al., 2024). The approaches used draw from the previously described seismic risk/hazard estimation concepts (Chapter 4). We anticipate that there may be additional methods developed to assist in the construction of risk-based TLP thresholds. For example, by estimating magnitudes of intolerable events (M_{TOL}) for a given location or using the mathematical framework of deaggregation of seismic risk (§4.8).

BOX 5.3. A risk-based red-light workflow (Schultz et al., 2021a)

To determine a red-light magnitude, we can use a workflow that simultaneously incorporates concepts of trailing seismicity, risk estimation, and risk tolerances.

Assuming a red-light threshold, scenarios of earthquake magnitudes are randomly drawn from a trailing seismicity model. Trailing seismicity models are used in place of seismogenic rate models (which are difficult to constrain a priori), since we are only interested in the last possible stopping point before exceeding an amount of risk.

The remaining steps straightforwardly use concepts from PSHRA (Chapter 4). Trailing events are translated into an expected amount of hazard, via a GMPM (§4.3). Given a proposed location for the operation (and simulated trailing magnitudes), we can estimate ground shaking intensity. Ground shaking is then translated into risk via a combination of exposure (§4.4) and vulnerability/fragility models (§4.5). Essentially, if we know where assets are and how they respond to ground shaking, we can estimate the impact. These impacts can be of various risk types (e.g., nuisance, damage, or fatality) and various risk scopes (e.g., aggregate amounts to a crowd or local chances for an individual). The process is probabilistically repeated to estimate median/mean amounts of potential risk impacts and provide a measure of uncertainty (e.g., §4.1) as a function of the red-light magnitude. For this location, as the red-light threshold increases, so does the level of 'acceptable' risk implicitly taken. This process quantifies the amount of risk taken, as a function of red-light magnitude. Since the earthquake location, wave propagation, and exposure profile are physically constrained (for a given/potential site), the red-light magnitude becomes the critical variable.
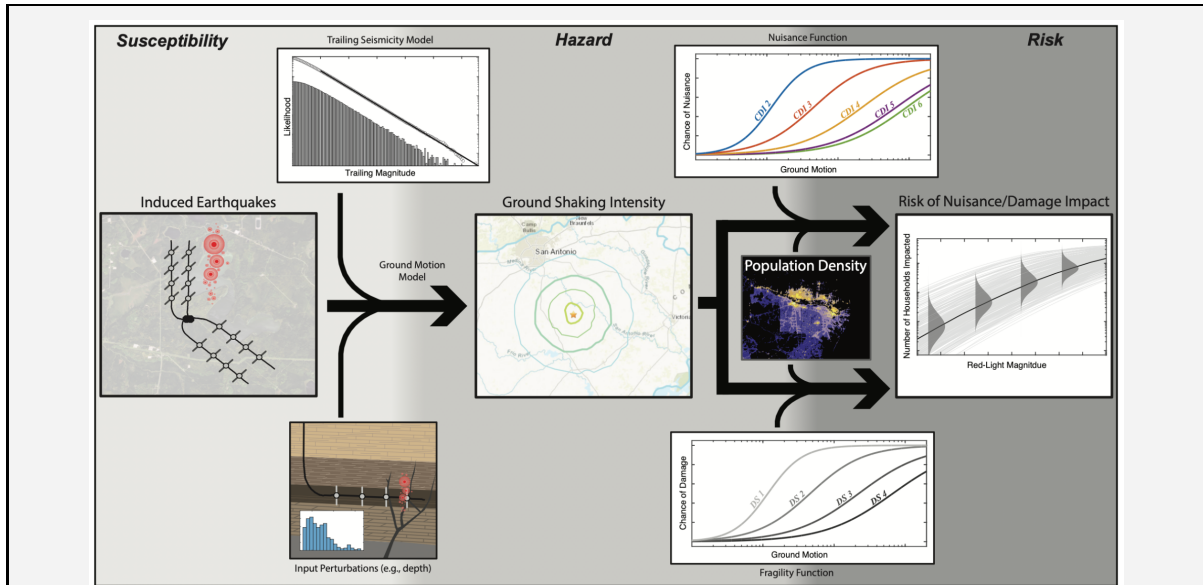

Figure 5.2. An example workflow of a risk-based TLP. Scenarios of earthquake magnitudes following a red-light event are randomly drawn from a trailing seismicity model. These scenario red-light events pass through the hazard/risk workflow to estimate the amount of expected risk. Figure is adapted from Schultz et al., (2021a; 2021b).

Given known tolerances to risk (§4.7), it is possible to use this approach to determine the appropriate red-light for when an operation would need to stop - to ensure that these risk tolerances are not exceeded. This can be accomplished by observing the graphical intersection between the risk tolerances and estimated risk curves (Figure 5.2). In this sense, we can work backwards from risk tolerances (using risk modeling) to infer an appropriate red-light threshold for any possible site (Figure 5.3).
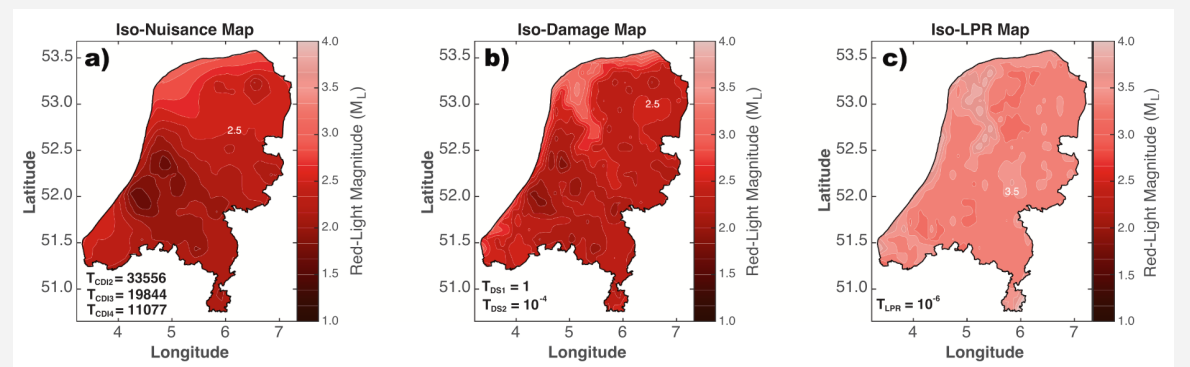

Figure 5.3. An example of TLP red-light thresholds determined using risk-based methods. Given known/inferred tolerances to risks of nuisance (a), damage (b), and fatality (c), an appropriate stopping point is determined for all EGS locations in the Netherlands. Multiple metrics of risk could be considered by using the lowest red-light estimate (at a given site location). This approach automatically considers the potential for trailing seismicity. Figure is adapted from Schultz et al., (2022b).

5.1.5 Can red-light thresholds vary for the same risk tolerance?

Currently, many countries have adopted TLP thresholds at a national or regional scale, with values ranging between M_L 0.5-4.0 (Verdon & Bommer, 2020; Braun et al., 2020; Schultz et al., 2021b; Maury et al., 2023). Ideally, TLP thresholds should be informed by risk-based principles. Notably, the same risk tolerance can mean different red-light thresholds from region-to-region, since assets and their exposure to risk can vary spatially.

Firstly, the red-light magnitude can vary, depending on:

- The tolerance of the local population to seismic risks;

- Location and fragility of exposed assets (exposure factors, population density, critical infrastructures);

- Regional physics of wave propagation, ground motion, and site amplification;

- Variations in the anticipated amount of trailing seismicity.

Secondly, the magnitude of the largest trailing event also varies, depending on:

- Spatial variations in seismogenic model: b-values and the productivity of trailing seismicity (Verdon & Bommer, 2020; Schultz et al., 2022a).

5.1.6 What are the limitations of a TLP?

The framework of a TLP is based on the assumption that induced earthquake magnitudes will grow with time, providing some warning or reaction time for an operator to enact mitigation strategies.

We emphasize that the TLP for the stimulation phase of the EGS project can differ from the TLP during the production (circulation) phase of the geothermal project. Currently available magnitude jump and trailing seismicity models (Verdon & Bommer, 2020; Schultz et al., 2022a), are developed for stimulation, which might also be used for the circulation phase with caution. Future developments on seismogenic models are needed to properly address the circulation phase.

5.1.7 Lower TLP thresholds from the operator's perspective

An operator may opt to take a more conservative approach than the regulator's regionally defined guidelines. This could be informed by additional information the operator has regarding the subsurface conditions for induced seismicity susceptibility, the severity of earthquake impacts/consequences, or simply the operator's (lack of) appetite for risk. Note that the seismic monitoring network's design should be adjusted to meet the revised yellow-light threshold (Table 6.1).

5.1.8 Mitigation strategies for TLPs

Mitigation strategies are the reactive measures employed by the operator to ensure that induced seismicity does not continue to grow to unacceptable levels. Currently, there is no consensus or rigorously established approaches on how to most effectively mitigate induced seismicity. Said another way, there is no 'silver bullet' to prevent further earthquakes. Here, future research would be beneficial; specifically, to disentangle and quantify the efficacy of mitigation in a variety of geological, seismotectonic, and operational settings. Openly accessible datasets will be crucial to establish scientific consensus on mitigation.

Typical mitigation strategies include reduction of stimulation rate/pressure, implementing gradual changes to pumping rates, operational pauses, reorganizing the stage stimulation schedule, changing stimulation designs (e.g., soft 'cyclic' stimulation (Hofmann et al. 2019)), flowing back between stages, reducing total injection volume, skipping problematic stages, or ultimately pad/well abandonment. Other non-operational mitigation measures can include public outreach, relocation of infrastructure/personnel, building retrofitting, or financial compensation schemes (Bommer, 2022). Yellow-light mitigation strategies (and the communication channels to execute them) should be outlined and agreed upon before the operation begins. Ideally, test case scenarios would be practiced in a hypothetical setting before the operation begins. Examples of detailed mitigation strategies are available in prior documents (Majer et al., 2016; Gischig et al., 2019; Ader et al., 2020; Braun et al., 2020; Pankow et al., 2023; Yaghoubi et al., 2024).

The design of mitigation plans/strategies can also straightforwardly adapt from the analogs in hydraulic fracturing for shale gas (CAPP, 2019; Schultz et al., 2020a).

Operators encountering a red-light should shut-in their operation as soon as reasonably practicable. They should follow jurisdictional shut-in safety guidelines to avoid causing any other operational risks/concerns (e.g., well integrity issues). Details of a 'generic' red-light shut-in procedure should be previously agreed upon, at the discretion of the regulator. This may include mitigatory strategies such as a gradual shut-in procedure or well flow back. Specific details of the shut-in procedure could vary on a case-by-case basis, again at the discretion of the regulator.

Triggering a red-light likely means the end of an operation, so the urgency of yellow-light mitigation strategies should reflect this finality. A reduction of the TLP level after triggering a red-light should be properly investigated (and only considered in exceptional cases), with input from the independent expert group, acceptance from the regulatory authorities, and with consent from the impacted community/stakeholders.

5.2 Supplementary TLP considerations

The threshold of a conventional TLP is magnitude based. A risk-based red-light threshold must choose some probabilistic value of risk tolerance (e.g., a median amount of nuisance impacts or mean fatality chances) and is based on empirically/statically derived models - guaranteeing that it will never be completely effective. Furthermore, magnitude isn't a complete indicator of earthquake physics and risk consequences. Thus, other supplementary indicators should be used when available. These supplementary considerations are aimed at better understanding how the underlying geophysics, geology, or monitoring uncertainties could impact the earthquake sequence(s); this information should inform how the operator reacts during the yellow-light.

The following are important to consider:

1. Spatial distribution/orientation of seismicity. Well-resolved clouds of seismicity (after accounting for location uncertainty) generally indicate the least problematic scenario of stimulated fracture networks. Plane-like features can be more concerning, depending on their orientation within the stress field. For example, planes subparallel to the maximum stress direction are likely hydraulically stimulated fractures in tensile failure. On the other hand, planar features oriented along critically stressed directions indicate fluid is reactivating a larger fault in shear slip. Operations encountering fault reactivation in shear slip should proceed with heightened caution, especially if multiple stages intersect different points of the same fault. Suggestions here are analogous to those for hydraulic fracturing for shale gas (CAPP, 2019; Schultz et al., 2020a).

2. Events with a large distance from the injection point should raise attention, as that likely indicates pressure conduits linked to distant faults. Faults that are distant from the operation will be more difficult to control, due to relatively larger lag time between operational changes and induced earthquakes.

3. Rates of seismicity are often used as a supplementary metric within existing TLPs. This is often included to account for cases where a large event was statistically expected to occur, but still has yet to be observed. For example, by triggering a yellow-light either if an M_{YELLOW} event is encountered or if ten M_{YELLOW}-1.0 events are recorded within a given timeframe.

4. Proxies for the seismic response of the reservoir like the seismogenic index (Shapiro et al 2010), the seismic injection efficiency (Kwiatek et al., 2019), and the seismic moment release (Bentz et

al., 2020). These metrics have implications for the growth of earthquake magnitudes during injection.

5. The Gutenberg-Richter b-value. Often hydraulic fracturing operations observe larger b-values (~2.0) during fracture stimulation. Fault reactivation is usually associated with smaller tectonic values (~1.0). This transition in b-value has been observed in hydraulic fracturing cases where fracture stimulation inadvertently reactivates faults (Maxwell et al., 2009). Generally speaking, the smaller the b-value the greater the seismic risk.

6. The amount of trailing seismicity observed. The initial TLP design will have made assumptions about the productivity of trailing events. How this deviates from the initial assumption will have important implications for the current operation (Schultz et al., 2023b). Generally speaking, more trailing events means that operations would need to mitigate (or end) further back from the tolerance threshold M_{TOL} (i.e., the red-light would need to be lowered).

7. Additional risk or hazard related information: like felt reports, damage/loss reports, or ground shaking metrics.

5.3 Updating the TLP

The uncertainty of the TLP thresholds predominantly lies within accurately estimating the seismogenic model (§4.2), ground motion prediction model (§4.3), exposure (§4.4), and vulnerability/fragility model (§4.5), which are also key components of the risk analysis workflow (Chapter 4). As development within a project or play progresses, new data will become available, which could be used to update the SHRA and TLP (Figure 5.4).
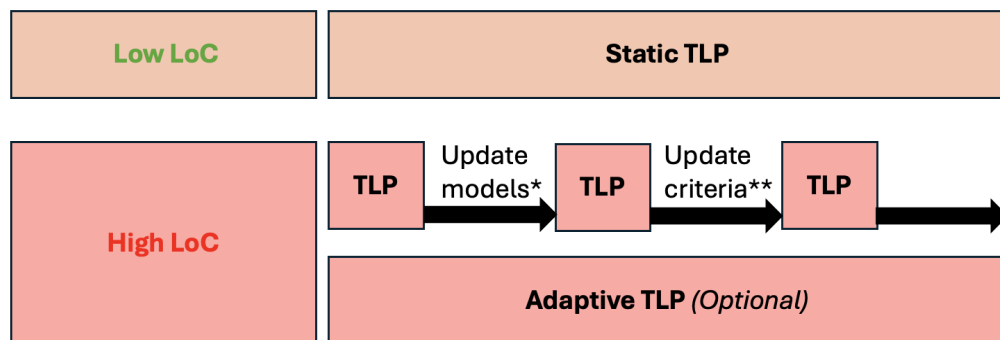
Figure 5.4. Schemes on updating a TLP or ATLP. *The TLP should be updated each time significant improvements are made to underlying models or criteria (e.g., ground motion prediction, trailing seismicity, risk tolerance). **Appropriate yellow-light reactions to supplementary considerations should be updated as information is shared amongst the operators on how the play responds to injection.

BOX 5.4. Research considerations for improved TLP updating

The probability of magnitude jumps used in the TLP are statistically obtained from large data sets. It is possible to achieve site specific estimation, if seismicity data is available, through an ensemble (logic tree) of various models available in the literature, such as Shapiro et al. (2013), McGarr (2014), Galis et al. (2017), van der Elst et al. (2016), and Cao et al. (2020). Some of these models incorporate the injection strategy, others use the extent of the seismicity cloud as a proxy for the largest possible rupture, and others use purely statistical methods based on the magnitude frequency distribution. Research into the efficacy of models will be required (Schultz, 2024).

Additionally, at the early stage of the stimulation operation, operations could consider incorporating information from a seismogenic fault injection test (SFIT) as proposed by Schultz et al., (2022a) to constrain the site specific ΔM_{TRAIL} following well shut-in. This parameter is one of the most sensitive to perturbing red-light thresholds (Schultz et al., 2021a) and site specific measurements have been suggested as a TLP correction metric (Schultz et al., 2023b). Note

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that constraining trailing seismicity through SFIT is currently being developed and its limitations are not yet fully understood, e.g., it involves a small volume, which might not be representative for the entire reservoir. Alternatively, if multiple stimulations are involved, the seismicity during and after the early stage stimulations could be used to constrain the ΔM_{TRAIL}.

For a low LoC project, we suggest that a TLP is designed. For a high LoC project, we suggest periodic updates to the TLP alongside gains in knowledge and the progress of the project, following the recommendations in Chapter 2. Optionally, high LoC projects can consider updating their TLP in real-time, which is accomplished through the Adaptive Traffic Light Protocol (ATLP).

5.4 Adaptive Traffic Light Protocols (ATLP)

The TLP has its simplicity for implementation and regulation, thus should always be conducted for EGS projects. But some of the shortcomings of traditional TLPs are that they are reactive, they do not forecast future seismic activity or risk, and there is limited application for real-time monitoring optimization. Thus, continued research and development into both traditional TLP and ATLP are advised. ATLPs are an alternative decision-support tool that aims to provide operators with continuously updated estimates of seismic hazard and risk forecasts during reservoir operations (Figure 5.5; Box 5.5). This approach is currently at a low technology readiness level, as it has not been tested in a real project so far.
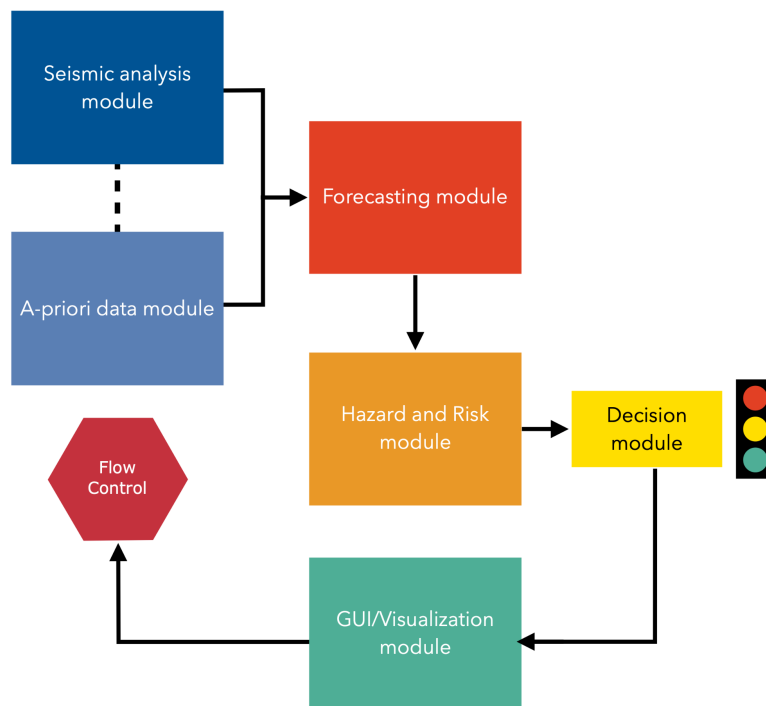

Figure 5.5. Simplified scheme of the ATLP workflow.

BOX 5.5. Adaptive Traffic Light Protocols (ATLP)

ATLP are built to capture the reservoir evolution based on a range of key parameters (e.g., permeability, pressure, temperature, seismicity, injection rates, etc.). They are fully probabilistic, data-driven (in the sense that microseismic data are integrated in real-time to update geomechanical and statistical seismicity forecasting models) and risk-based by integrating hazard, exposure, and vulnerability (Wiemer et al., 2014; Mignan et al., 2017; Langenbruch et al., 2020; Grigoratos et al., 2021). The ATLP should therefore, at any point in time, integrate all available information on the reservoir evolutions into the best possible forecast.

Below, we suggest the following protocols if ATLPs are deployed:

- An ATLP Expert Panel, selected by the operator and the regulator, composed of independent subject matter experts and communication experts, should be created whose purpose is to provide thresholds for the ATLP, run the ATLP, and communicate response levels of the ATLP to the public and other project stakeholders. ATLP updates should be given through the online web interfaces dedicated to seismic monitoring, as outlined in §6.3 on data sharing.

- Clear threshold level criteria defining when an increase in response level is necessary needs to be defined in advance. Threshold criteria include (but are not limited to): probability of exceeding certain earthquake magnitudes, the probability of a felt/damaging/fatal event, or a ground shaking intensity (Bommer et al., 2017; Gischig et al., 2020).

- A clear description of the mitigation actions and emergency response plans at each of the TLP levels should be agreed upon before the start of operations.

- Sensitivity pre-testing of the ATLP for the minimum amount of data needed.

- Adequate near-real-time data input (including fast data transfer) from the seismic monitoring system must be in place. Hydraulic and seismic data acquisition systems must be synchronized to one reference time base to allow for the forecasting models to run.

6. Seismic Monitoring (Module 5)

In this Chapter, we aim to harmonize the monitoring guidelines that are currently available at national levels. These new standards are designed to encompass the different phases of an EGS project lifetime (ranging from initial planning and drilling to stimulation and post-operation stages) as well as the different project categories as assessed by the available methods discussed in Chapter 3.

Goals of seismic monitoring

1. To provide supporting earthquake information, at a resolution sufficient to inform safety-relevant, decision making processes (e.g., TLP).

2. To reduce the uncertainties in seismic risk estimates, through measurements that update a priori assumptions.

3. To demonstrate an operational transparency that fosters trust with the impacted community and stakeholders.

4. To provide guiding subsurface information for future operations.

5. To characterize the properties of the reservoir for production optimization.

Recommendations for seismic monitoring

1. Seismic monitoring networks must be designed to detect sufficiently small earthquakes, well before decisions need to be enacted (e.g., the yellow-light).

2. Seismic monitoring networks must be designed to spatially resolve earthquakes (e.g., identifying pre-existing faults and event migration patterns) to adequately aid mitigation decision making.

3. Seismic monitoring networks must be designed to reduce measurement uncertainties for updating risk estimates.

4. Seismic monitoring protocols need to be tailored towards both short-term and long-term risk scenarios.

5. All seismic monitoring data should be shared using open and FAIR (Findability, Accessibility, Interoperability, and Reuse) data practices. Sharing could occur after a brief (and optional) embargo period.

6. Seismic monitoring is the responsibility of the operators, with the requirement that information is shared with all the other groups. This is to ensure that the operator is meeting their monitoring targets.

We note here that the provided recommendations do not include guidelines regarding the acquisition of active source seismic data (e.g., reflection seismic, vertical seismic profile, or mutil-channel surface wave survey), which should be considered when risk screening and site-specific SHRA analysis is required (as described in Chapters 3 and 4). We also note that for a low LoC project, if a red-light event (or an unexpectedly high level of seismicity) occurs, it would require a re-assessment on the monitoring level.

For each of the LoC categories, a different level of monitoring sensitivity is required. Two critical measures of monitoring sensitivity are the magnitude of completeness (Mc, see Box 6.1) and spatial resolution. To

avoid non-uniform spatial completeness, Mc targets must be reached before advanced techniques such as template matching and/or repeater detectors are applied.

BOX 6.1 Magnitude of completeness (Mc)

In an earthquake catalog, the magnitude of completeness (Mc) is defined as the minimum magnitude above which the overwhelming majority of earthquakes in a space-time volume are detected. This minimum magnitude depends on the number and spatial density of seismic stations (Mignan et al., 2011). Mc can be estimated with a variety of statistical methods (Wiemer & Wyss, 2000; Woessner & Wiemer, 2005; Schorlemmer & Woessner 2008; Zhou et al., 2018); some of these methods assume a Gutenberg–Richter law (Gutenberg & Richter, 1944) for the magnitudes above the completeness threshold.

Below, we list our justifications for and quantifications of Mc thresholds that a seismic monitoring network should reach to accommodate risk assessment studies and risk mitigation measures (e.g. traffic light protocols, see Chapter 5). Seismic monitoring must reach detection thresholds based on:

(a) Felt ground shaking: Felt ground shaking is one of the first undesirable impacts encountered by stakeholders from an induced earthquake. Thus, adequately resolving felt events should be one of the monitoring objectives. Here, we define the size of the minimum felt event (M_{felt}) as the smallest magnitude expected to cause nuisance to stakeholders. M_{felt} depends on the site conditions, focal depth, population density, and time of occurrence. Most felt events are usually larger than M 2.5, under rare circumstances they might be as low as M 1.0. However, in areas with no exposed population this value could be arbitrarily large. The network Mc should be equal or smaller than M_{felt}. For example, shaking intensity data could be used to inform when felt events are being approached, through calibration of IPMs or GMPMs.

(b) Yellow-lights: Yellow-lights define the period when mitigation strategies should be enacted. Thus, adequately resolving yellow-light events should also be a monitoring objective. The Mc should be small enough to allow enough data to be collected and used for yellow-light mitigation strategies. For example, the data may be used to inform earthquake recurrence models, namely the parameters of magnitude frequency distributions (e.g., b-value, seismicity rate, seismogenic index), magnitude jumps, and maximum magnitude after shut-in (trailing magnitude). This could be achieved by setting the Mc lower than the yellow-light, depending on the LoC category.

The event spatial resolutions are supplementary considerations for the SHA or magnitude-based TLP. Below we list our justifications for and quantifications of spatial resolution thresholds that a seismic monitoring network should reach for mapping pre-existing faults and accommodate other supplementary TLP measures (§5.2):

(a) The orientation of a fault within the ambient stress field is a key factor for determining the susceptibility for slip reactivation. Thus, adequately resolving relative hypocentral trends of induced earthquakes should be a monitoring objective. For example, this data could be used to inform in situ stress information or fault frictional parameters.

(b) Spatial information is important for distinguishing between natural or competing anthropogenic operations. Thus, adequately resolving absolute hypocentral locations should also be a monitoring objective.

Note also that the event focal mechanism is also an important parameter for stress estimation, reservoir characterization, and seismic hazard. Here, we assume the network capacity on resolving event location is correlated with resolving focal mechanism, and do not take it as an independent measure.

We also note that for reservoir characterization, seismic monitoring is pivotal for reconstructing a detailed map of faults, fractures and fluid pathways being developed during stimulation/production phases. To illuminate such structures, a seismic network should be able to characterize very small events

(microseismicity). We provide the caveat that over-focusing on the spatial domain sometimes results in discarding events with higher location uncertainty, affecting catalog completeness in the magnitude domain. Within reasonable constraints, the latter should remain a priority for the catalogs to remain useful for the development of earthquake recurrence models (a/b-value, magnitude jumps).

6.1 Seismic Network Design

Concerning the technical specifications for a microseismic monitoring network, a universally recognized standard practice has not yet been established. Various thresholds such as the number of stations, azimuthal gap, location accuracy, magnitudes, dynamic range, sampling rates, etc., differ significantly and are tailored based on specific project requirements, highlighting a considerable reliance on a project-to-project basis (e.g., Maury et al., 2023). Here, we propose a standardization of practices based on the Mc and event spatial resolution as a function of the LoC categories (Table 6.1).

Note that if the LoC changes with time, the monitoring targets will change and thus the network sensitivity should also change accordingly.

Low LoC category

For this category, the seismic monitoring network should ensure accurate/precise locations and source parameters of induced earthquakes, as well as the operation of a conventional magnitude-based Traffic Light Protocol (TLP, see Chapter 5). This data is also collected to validate/refute the hypothesis that the operation is indeed low LoC. Thus, monitoring standards must be adequate enough to perform a causation/risk assessment in the case that unexpectedly high levels of seismicity/risk is encountered.

Below we list the targets for the network-Mc and spatial resolution thresholds (Table 6.1):

- **Mc threshold:**
  The seismic network should be able to detect and characterize seismicity at a Mc lower than the yellow-light or M_{felt} within the expected source region. However, if induced seismicity occurs beyond the expected source region, the latter should be reassessed and enlarged to include greater distances. The target Mc threshold value can be obtained through numerical simulation scenarios where different numbers of sensors and array geometries are tested (e.g., Kraft et al., 2020, §6.1.1).

- **Spatial resolution threshold:**
  The choice of a target location accuracy/precision should be set so that stimulation fractures can be clearly distinguished from shear fault reactivation for events of magnitudes approaching the M_{RED} threshold. Moreover, the location accuracy should allow for distinguishing between competing anthropogenic operations (inter-pad spacing). To achieve this, numerical simulation scenarios to calculate the location accuracy/precision of earthquakes down to the completeness level should be performed (see §6.1.1). As location uncertainties are highly dependent on the velocity model used in their calculation, we suggest, for this category, to use locally-derived 1-D or 3-D velocity models.

We suggest planning the network taking into account the existing national monitoring network as, depending on the local density of the stations, the number of new stations to be deployed could be reduced (Kraft et al., 2020). Included stations from the national network should be accessible in real-time and incorporated in the calculation of magnitudes and locations. We also suggest to co-locate accelerometers at the station closest to the expected injection point, and close to the exposed community. Apart from dedicated high-quality instruments, budget instruments e.g., RaspberryShake seismometers/accelerometers, might be also used to further improve the network performance.

An example scenario for designing a seismic network for a project in the low LoC category is provided in Box 6.2.

BOX 6.2. Example scenario for a Low LoC category

If we had a case where the red-light was set at M 4.0 and the yellow-light at M 2.0, then the seismic network should be able to spatially resolve M4 faults of this size and detect events down to M 2.0. Earthquakes of M 4.0 have an average fault length of ~500 m (Zoback & Gorelick, 2012). Thus, the seismic network should be able to achieve a location accuracy of ±0.5 km horizontally and ±2.0 km vertically.

Generally, for a low risk area (e.g., rural), and a field-scale EGS project in a strike-slip stress regime, the seismic network is composed of at least five regional/local stations with a geometrical configuration to allow an azimuthal gap smaller than 120°. This should ensure a minimum redundancy in case of station failure. For the same general case, Kraft et al. (2020) recommended that the epicentral distance of the stations to the expected injection point should be about two times the planned operation depth, but less than ~10 km. This is to guarantee good sensitivity (e.g., detection capability) while allowing to constrain earthquakes depth.

High LoC category

For this category, the seismic monitoring network should ensure near real-time accurate/precise locations of induced earthquakes, as well as the operation of a risked-based Traffic Light Protocol (see Chapter 5) or, if possible, an Adaptive Traffic Light Protocol (ATLP). This data is also collected to improve the understanding of induced seismicity: to improve source/forecast models, to accurately model hazard/risk and react to recorded events. Thus, monitoring standards must be adequate enough to reduce relevant uncertainties.

Below we list the targets for network-Mc and spatial resolution thresholds (Table 6.1):

- **Mc threshold:**
  The network design should include a comprehensive numerical modeling study to infer the minimum magnitude of completeness level needed to fulfill the microseismic monitoring as well as reservoir characterization targets. The derived Mc should be at least 1.0 magnitude units less than the yellow-light set in the TLP within the source region. The choice of decreasing the Mc thresholds by at least one magnitude lower than the yellow-light enables the consideration of magnitude jumps and still provides adequate room to execute operational changes. The modeling should also include testing different array geometries and different combinations of instrumentation (e.g., surface dense array patches, co-located geophones and fiber optic technologies, i.e. DAS). Comparison of the noise levels at the sites of the different seismic instruments and network design should also be performed.

- **Spatial resolution thresholds:**
  The monitoring network location accuracy/precision target should be sufficient to distinguish between stimulated fractures and shear fault re-activation for events of magnitudes near M_{YELLOW}, so that an appropriate reaction plan can be implemented by the operators. Additionally, the spatial resolution should be able to link each earthquake cluster to its causal stage. To achieve this numerical simulations to check the spatial resolution down to the completeness level should be performed (see §6.1.1). To improve the absolute location accuracy/precision and source depth determination, we suggest performing checkshots and perforations to calibrate the velocity model and to orient the borehole sensors (Akram and Eaton, 2013). Ideally, the velocity model should be calibrated prior to the stimulation. If available, velocity information from active seismic surveys, VSP and crosshole tomography should be integrated into the velocity model used for event location.

The baseline network should include surface stations (a mix of high-gain sensors and low-gain accelerometers) in a number as indicated by the Mc numerical modeling. A possible add-on to the baseline monitoring at the surface is the installation of dense surface arrays which have been demonstrated to reduce the noise level, and thus reducing the magnitude of completeness significantly (Fiori et al., 2023). In addition, during stimulations, geophone chains in one deep borehole have demonstrated to lower the Mc levels. Boreholes are crucial for establishing a detailed high-precision catalog of the induced seismicity produced during the stimulation phase. This is because by going closer to the source and away from the near-surface, the effect of noise is reduced and smaller events are more easily detected. If high temperature graded sensors are available, their deployment shall be attempted, however we caution that Mc numerical modeling should not solely depend on the performance of these sensors until the technology is proven to be reliable. This is also due to the fact that such equipment is typically deployed in certain (critical) phases of the project only. Additional instrument types (e.g., shallow borehole stations, surface DAS and borehole DAS cables) may be also necessary depending on the noise levels and results from the numerical modeling of Mc.

An example scenario for designing a seismic network for a project in the high LoC category is provided in Box 6.3.

BOX 6.3. Example scenario for a High LoC category

If we had a case where the red-light was set at M 4.0 and the yellow-light at M 2.0, then the seismic network should be able to spatially resolve M2 faults of this size and detect events down to M 1.0. Earthquakes of M 2.0 have an average fault length of ~60 m (Zoback & Gorelick, 2012). The combined seismic network (surface + boreholes) should be able to achieve an absolute location accuracy of ±60 m horizontally and ±0.2 km in depth within 2-3 km around the injection well.

Generally, for a high risk area (e.g., urban) and a field-scale EGS project in a strike-slip stress regime, the seismic network should include at least 5 surface stations to ensure redundancy in case of failure and an azimuthal gap smaller than 90°. At least one geophone chain in a deep monitoring well is recommended.

Table 6.1. Mc threshold and location precision/accuracy targets and their corresponding network parameters for a general case featuring a field-scale EGS project in rural, and urban contexts.

LoC	Detection threshold suggestions (Mc)[1]	Locations accuracy/precision suggestions[1]	Example of backbone instrumentation for detection, location, & magnitude determination[2]	Example of accuracy/ precision of locations[2]
LOW	Mc < M_{YELLOW} & Mc < M_{felt}	Resolve fault/fracture at ~M_{RED} & Spatial resolution < half the inter-pad spacing[3]	– 3C broad-band sensors at the surface; – Typically, at least 5 stations – Typically, at least 1 strong motion sensor in the center of the array – Optionally shallow borehole stations	horizontally: ± 0.5 km vertically: ± 2.0 km
HIGH	Mc < M_{YELLOW} - 1.0 & Mc < 1.0	Resolve fault/fracture at ~M_{YELLOW} & Spatial resolution < half the inter-stage spacing[4]	– 3C broad-band sensors at the surface; – Typically, at least 7 stations – Typically, at least 1 strong motion sensor in the center of the array – Shallow borehole stations – Geophone chains in deep wells	horizontally: ± 0.06 km vertically: ± 0.2 km

[1] Refer to the text for examples of numerical simulation approaches for modeling Mc levels and location accuracy.
[2] Note that the two example columns can change on a case-by-case basis, thus we advise to follow the Mc and locations accuracy targets rather than the given (example) prescription.

[3] Only valid in case of multiple pads.

[4] Only valid in case of multiple stages.

6.1.1 Numerical modeling tools for network design and optimization

The Mc determination is a function of the attenuation and the noise conditions at the recording sites (Kraft et al., 2020). Below we list few well-known numerical or statistical approaches to calculate either noise levels, variations of Mc, station accuracy, location accuracy, or a combination of these four:

- Optimization method for regional-scale microseismic monitoring networks (Kraft et al., 2013). This method is based on the simulated annealing approach proposed by Hardt & Scherbaum (1994), which aims to minimize the volume of the error ellipsoid of the linearized earthquake location problem (D-criterion). The method samples the solution space for the optimal network configuration by testing many different sizes and geometries of D-optimal networks; it can handle 3-D velocity models, and directly incorporate the calculation of seismic body-wave amplitudes at arbitrary stations.

- Seismic Network Evaluation through Simulation method (D'Alessandro et al., 2011). This method uses numerical simulations to evaluate the performance of hypocenter location of a seismic network. Inputs needed are the station locations and their noise levels, a velocity model, and empirical laws to estimate the variance in residual travel times.

- Probability-based magnitude of completeness (Schorlemmer & Woessner, 2008). This empirical method estimates both station-specific and regional time-dependent Mc values as a function of network properties (e.g. phase data, attenuation relations) instead of earthquake samples (e.g. event-size distribution).

- Bayesian magnitude of completeness (Mignan et al., 2011). It provides network-specific spatial relationships between Mc and the proximity to the nth nearest seismic stations. The statistical regression behind the method was later improved, in line with hierarchical bayesian modeling (Feng et al., 2022).

Additional comments regarding noise levels:

- To select best surface sites, bedrock installations should be preferred over sediment/alluvial layers. A quantitative site selection procedure is described in Plenkers et al. (2015).

- Noise analysis before the final installation of a seismic station should be conducted (preferably over a 7 day period). The noise level should also be continuously addressed during the operational phase of the project.

- If the required noise level conditions are not met, it is suggested to use shallow boreholes (80 - 150 m depth or as a function of the site conditions).

- To enhance signal-to-noise ratio (SNR), and as an alternative to shallow boreholes, surface dense arrays can be employed as it enables stacking over closely located stations which have coherent waveforms. When designing dense arrays, it is important to consider noise frequency content, target Mc, and source depths.

- Indicatively, for baseline surface monitoring, to resolve felt nearby events, Kraft et al. (2020) recommended that seismic stations should be located on sites such that the noise level in the 5-40 Hz frequency band should not exceed an amplitude of 100 nm/s, and the ground velocity of 600 nm/s can be recorded with SNR of at least 6 in this frequency range (see also Box 6.4).

BOX 6.4. Noise Levels

The SNR is sometimes set in order to accurately time the phase arrival onsets (Zeiler & Velasco 2009; Ruigrok et al., 2023). We note that the numerical modeling softwares for modeling location precision/network performance usually use the maximum amplitude of the body wave onset rather than the arrival time which is the first break of the wavetrain onset (Kraft et al., 2020). If the signal is not impulsive, which is often the case, the onset will have much smaller SNR than the one estimated from the model.

Additional suggestions for all risk levels, deployed at the field scale for a single pad:

- 3-component seismic instruments should be preferred to allow for a clear distinction of seismic wave types (P and S waves) and orientation (particle motion); this should provide better earthquake locations, especially for small events that are recorded/visible only at a single station.

- In case of sensitivity saturation of the recording instruments, we suggest co-locating an accelerometer at the station closest to the expected source region. The accelerometer should be able to measure strong ground motions up to at least 1 g.

- Seismic stations must be synchronized to a common time reference with a precision of 1 ms. Hydraulic data and other geophysical measurements should be also synchronized to the same time reference with the same precision. Recommendation is for using a digital data acquisition system of 24-bit and a global position system (GPS)-based field timing system.

- Performing tests recording for new instruments besides an existing calibrated instrument, to ensure manufacturing parameters are reliable, gains and dynamic ranges are set propers, and instrument 3 components are correctly responding to its design.

- During instrument deployment, ensure that the instrument orientation has been accurately determined.

- Real-time transfer of continuous waveform data should be implemented. This implies setting up a telemetry system.

- The surface monitoring system should be in place and operational before the start of the project drilling phase to test data workflows and procedures (see next §5.3) and establish background levels of seismicity. We suggest at least 6 months of seismic measurements for all risk categories. However, this value can vary between operations, projects, and jurisdictions (e.g., 3-12 months).

6.2 Seismic Monitoring Protocols

Baseline seismic monitoring and reservoir characterization networks follow different monitoring protocols as they are tailored to long-term and short-term risk, respectively. The following guidelines focus on the reservoir monitoring protocols and recommendations for deep geothermal projects in the different LoC categories.

Before the start of operations (drilling, stimulation, circulation), it is important to plan discussions and coordination meetings with all the parties involved in order to detail the monitoring activities and data acquisition parameters (see §6.3). Instruments should be tested and assembled beforehand. We suggest implementing TLP for all LoC projects. Chapter 5 includes recommendations to design thresholds for yellow and red-lights, which should be the responsibility of the regulators. Proper sensitivity (Mc) targets for each LoC category are outlined in §6.1. We remark here that for high-risk categories it is suggested to have an operational manager on site that is responsible for integrating the seismic and hydraulic groups, so that all groups are always fully informed of timing and changes in operations. In general, network operations are the primary responsibility of the operators with external surveillance and collaboration with the operators of the national networks (for baseline monitoring).

Below we report in detail the seismic monitoring protocols for both low and high LoC categories (see also Table 6.2).

Low LoC category

During the drilling and operational phase of the project, personnel tasked with providing real-time seismic monitoring (e.g., generating earthquake catalogs) can operate remotely. A TLP is recommended, and it can also be run remotely. Seismic waveform data should be analyzed in near-real time (within 1 hour) to detect, associate, locate, and determine magnitudes of seismic events. If any additional station is added to the baseline seismic network by the operator in order to reach the sensitivity level (Mc) required for this category, the operator should ensure continuous recording. This task should be performed by the operator. Reporting to regulators and the public during and after the stimulation should follow the data policies outlined in §6.3 and the communication guidelines described in Chapter 7.

High LoC category

During the drilling and operational phase of the project, personnel tasked with providing real-time seismic monitoring (e.g. generating earthquake catalogs) need to be on-call. The responsible personnel running the TLP should be also on-call. ATLP is not mandatory. If ATLP is to be implemented, details regarding the ATLP should be established with the operations team. The expectations for the ATLP should be established and there should be a process to decide the probabilistic thresholds (e.g., exceeding probability of a felt/damaging event or as a function of nuisance). The ATLP groups should also test the sensitivity of the system for the minimum amount of data needed, given the variety of datasets. Importantly, a plan for exchanging data and communicating between the different groups needs to be established and tested in advance to the stimulation activity. Further guidelines specific to ATLP protocols are described in §5.4.

Seismic waveform data should be analyzed in near-real time (within 10 minutes) to detect, associate, locate, and determine magnitudes of seismic events. This task should be performed by the operator. As previously mentioned, for this category, it is important to appoint an operational manager to oversee all the monitoring (seismic and hydraulic) groups, so that all groups are always fully informed of timing and changes in operations. Reporting to regulators and the public at all phases of the project should follow the data policies outlined in §6.3 and the communication guidelines described in Chapter 7.

Table 6.2. Seismic monitoring protocols by LoC category.

	LoC category: Low	**LoC category: High**
Continuous recordings	Yes	Yes
Real-time processing	within 1 hour	within 10 minutes
Seismic Monitoring responsible personnel	Yes, remote	Yes, on-call
TLP personnel	Yes, remote	Yes, on-call
ATLP personnel	Not needed	Suggested, on-call
Operational manager overseeing all activities	Yes, on-call	Yes, on-call[1]
Reporting to regulators and public	Yes	Yes

[1] For critical phases of the operation (e.g., stimulation) it could be advisable to have responsible staff on-site.

6.3 Data management recommendations

In deep geothermal projects, many different activities and parameters have to be monitored and many different expert teams have to be coordinated. In preparation for seismic monitoring for all project

categories, some key elements should be decided in the planning phase before arriving at the field and all groups, both the seismic and hydraulic team, participating in monitoring should participate in this aspect of the planning. It is essential that all data and documents refer to common standards and reference systems. Below we report best practices regarding data acquisition, data sharing and dissemination.

6.3.1 Data Acquisition

Specific data acquisition items to be decided on by all teams involved in monitoring activities include:

- The reference time and any potential timing issues between all the different sensor systems. The universal time (UTC) should be adopted and the accuracy of the measurements should be indicated.

- The coordinate reference system. Relative measurements (e.g. depths) should be clearly described with reference to the chosen coordinate system.

- Reports should use SI units for all quantitative parameters. Otherwise transformation must be indicated.

- Details of data integration, file/waveform formats and archiving procedures should be agreed beforehand. We suggest the SEED format for seismic data. If this is not possible (e.g. for DAS and geophone chains), a procedure and a correspondent conversion tool to transform the data format should be outlined and provided.

- The metadata (and any changes from the initial settings) of all sensors and digitizers must be documented in detail.

6.3.2 Data Communication

An alarm system (via SMS and/or email) should be in place. This system should provide real-time information on automatic event origins (and subsequent manual refinements) to the regulators, as well as independent monitoring agencies. As part of the trust building strategy towards the public and authorities, regulators and independent monitoring agencies should be authoritative for TLP relevant magnitudes (specifically when they reach the yellow or red levels).

6.3.3 Data Sharing

We recommend publishing earthquake catalogs and hypocenter maps in near real-time on a dedicated web interface for all interested parties (operator, regulator and the public). This website can be hosted by the national seismic agency. Besides event origin time, location, magnitude, or event type (e.g., natural earthquakes, induced earthquakes, quarry blasts, landslides), there should be a clear label on whether the event is automatically or manually processed. This can help improve acceptance, support, and trust by the public/local communities. Indeed, including earthquakes not felt by the public will help the public to understand that not every earthquake is a problem and a transparent exchange of information is in place (see also §7.3). Moreover, it facilitates the project oversight and allows scientists to further analyze the data and thus improve the overall state-of-knowledge of induced earthquakes within the research community.

Following the FAIR principles (Findability, Accessibility, Interoperability, and Reusability), hydraulic data, raw seismic waveforms, associated metadata (e.g. instrument locations, instrument response functions), and event catalogs should be archived throughout the lifetime of the project. For the seismic data, the databases should be available in standard seismological data formats such as miniSEED, QuakeML, and data request and transfer schemas, such as SEEDLink and FDSN StationXML should be set up. Similarly, timestamped hydraulic data including flow rates, stimulation pressure, proppant placed, stage locations

should be also accessible openly. It is highly recommended that the data should be made available to third parties immediately or, if necessary, after an embargo period, to allow for verification, quality control and the application of advanced analysis methods (e.g., double difference relocation methods, template matching, moment tensor determination). The length of the embargo period can be agreed upon jointly by the regulator and the operator. We note that however, access to seismic or hydraulic information relevant for the TLP should be made available to analysts immediately, even if an embargo is in place.

Additionally, related information such as the seismic velocity model used for the computation of the event locations, the magnitude calculation method and formulas, scaling relationship between locally established magnitude and moment magnitude, changes to processing routines, equipment failures and changes to network performances, should be shared. Open science data sharing practices have already been successfully implemented in regulatory frameworks that manage induced seismicity in Alberta, Canada (Schultz et al., 2020b).

7. Communication and stakeholder involvement (Module 3)

The aim of this Chapter is to provide good practice guidelines for communication and social engagement for EGS geothermal projects. We define communication here as a multi-way process where all stakeholders receive and provide information. It is crucial to understand that risk communication is a discussion between different stakeholders and not a one-way information provision from the project operator or from experts to the public. The guidelines focus on communication with the local population (i.e., living close to the project site), but also gives an overview of dynamics between the different stakeholders involved in the implementation of a project. The guidelines are informed by a review of academic papers as well as reports from industry in 13 different countries. While these guidelines may be used for any EGS project, the specific measures taken always need to be tailored to the context. There exists no 'one-size-fits all strategy' when it comes to (risk) communication (Trutnevyte & Ejderyan, 2018).

Goals of communication and stakeholder involvement

1. To facilitate open, transparent, and two-way exchange of knowledge between all stakeholders.
2. To provide an impartial and balanced education on the geothermal project, especially around concepts needed to make informed decisions regarding potential risks and benefits.
3. To foster trust and build a sense of community amongst the stakeholders.

While induced seismicity is at the center of challenges faced around the development of EGS projects and has been at the forefront of public debates (Giardini, 2009; Stauffacher et al., 2015), past research and projects have shown that perceived risks of a project (e.g., seismic events) depend on different aspects such as the perceived fairness of the project (McComas et al., 2016), the quality of the relationship with the project developer (Weber & Brian, 2014) as well as the overall quality of the communication strategy (Ejderyan et al., 2019). Therefore, communication guidelines must cover a larger breadth of issues than seismic risk mitigation only.

Stakeholder involvement is a necessary part of risk management and governance, especially when there is uncertainty about a risk which is the case for deep geothermal energy systems (IRGC, 2020). The public is the most important target group. For this target group, risks are assessed on the basis of personal experience (e.g., exchanges with peers), hearsay or media reports (Weber and Brian, 2014). The public includes both, the affected public and the general public (IRGC, 2020). The former are individuals who will directly experience the positive and negative impacts from the EGS project, while the latter are individuals who are not directly affected and are part of the general public opinion on the issue (IRGC, 2020). While most efforts will be directed towards the affected public, attending to the general public is highly relevant as its opinion may affect the view of the affected public.

Recommendations for communication and stakeholder involvement

1. Communication plans must start in the earliest phases of an operation, including an identification of stakeholder networks and an understanding the social context of the region.
2. Communication plans need to understand the social context of the region.
3. Outreach teams must consist of multidisciplinary experts that are providing credible and trustworthy information.
4. Stakeholders should be able to participate in the governance process, including decisions impacting them.

5. Information should be disseminated in regular intervals and tailored for the audience – with monitoring of public perceptions updating the communication strategies.
6. Crisis plans must be prepared/practiced in advance, to ensure that key messages are communicated quickly and received well.

7.1 General guidelines for communication

The proposed communication guidelines consist of nine steps throughout the lifetime of the project (Figure 7.1).
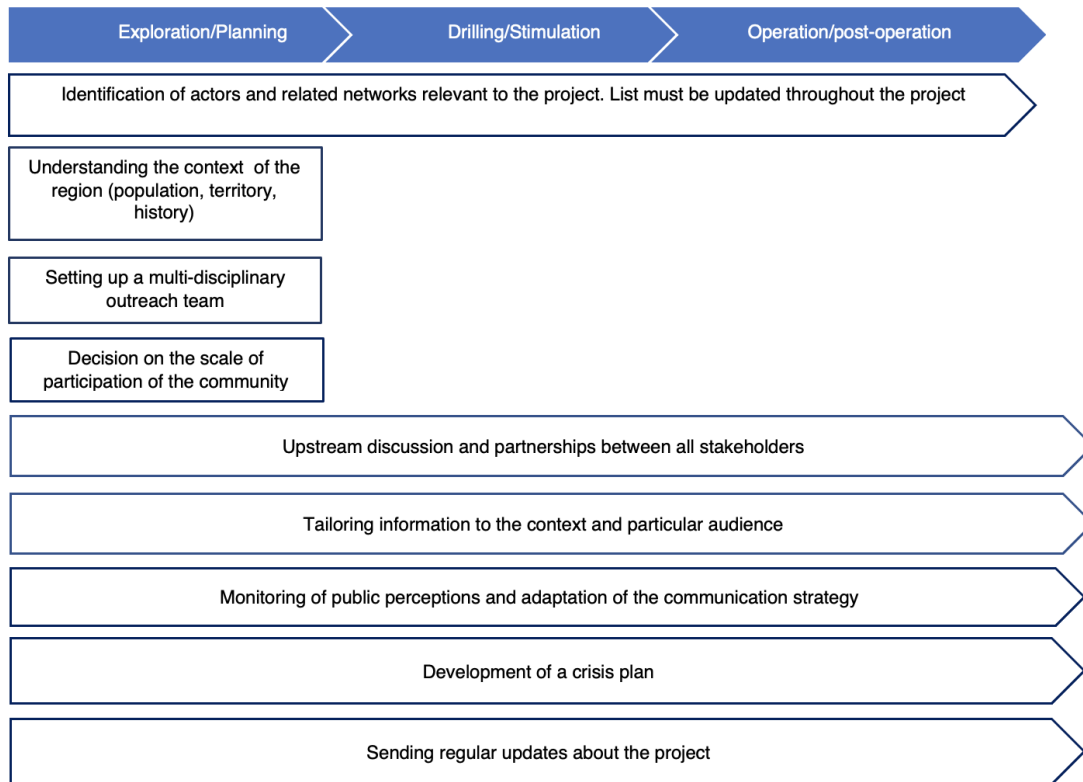

Figure 7.1. Summary of the general communication guidelines

Step 1 - Identification of actors and related networks relevant to the project

Communication efforts should start in the early phases of the project (Cousse et al., 2021). EGS project developers should identify all relevant stakeholders through the connections they have with their project before defining their communication and engagement strategies (Vargas-Payera et al., 2020). These stakeholders may not be directly impacted by the project but yet have a strong weight in its success in terms of acceptance (e.g., NGOs, general public). Among the key stakeholders, local politicians have a strong relevance as the affected population may have high trust in them. Local politicians are often able to build a bridge between the population and the other stakeholders and can give insights on how to communicate to the population. Politicians at the state and national levels have an important role to support the project developers too as EGS can help reach environmental objectives defined at the state or national level. It may however be deceptive to think that it is enough to have politicians on one's side. The legitimacy of a project always requires the approval of the population. Without this approval, politicians may prove to be unreliable partners (Weber & Brian, 2014). The media should further be considered as an important intermediary to the public population. Other important stakeholders are the permitting authorities, the investors, and other special stakeholders, including the chambers of industry and commerce, other geothermal project developers, homeowners' and landowners' associations, non-

governmental organizations (NGOs,) and other associations with local or regional roots (e.g., citizens' climate lobbying groups) (Weber & Brian, 2014).

It is crucial to identify "local champions", which could support the project as they can indeed considerably influence the public perception (Chavot et al., 2019). For example, in the case of the St. Gallen project, the local city councilor in charge of relaying messages had a positive impact on the communication as he showed personal affiliation and dedication to the project (Ejderyan et al., 2019). It is further important to identify a list of local associations which represent the diverse views and interests of the community (Weber and Brian, 2014). To build a relevant network of stakeholders, a snowball sampling technique can be used. In this technique, participants (i.e. stakeholders already identified) are asked to assist in identifying other potential subjects.

Step 2 - Understanding the context of the region

Where do conflicts (if any) originate from? What can be learned from them? What are the attitudes of local stakeholders? What kind of inconveniences will there be for the population during construction and operation? How far away are the residential areas? Are there any critical facilities nearby? The history of a town or region is very important as well as the experience of the population with similar infrastructure projects. EGS project developers can gain insights on the pulse of the local population by looking at press archives, news, social media or by conducting surveys. Such insights will reveal acceptance issues that could crop up at later stages in the process (Chavot et al., 2020). For example, if a region wishes to assert its autonomy with respect to the country where geothermal energy production is regulated at a national level, opposing geothermal energy may be a way to declare its autonomy while not necessarily implying opposition to the technology per se (Chavot et al., 2020). Understanding the context is also highly relevant to know where potential misbeliefs about the project exist among the population (Spampatti et al., 2022). In situations with high uncertainties, such as it is the case with EGS projects, misinformation is more likely to emerge. Distinguishing the nature and origins of misinformation can be very useful to initiating a debunking strategy and to address the public's misconceptions appropriately (Dallo et al., 2022).

Step 3 - Setting up a multidisciplinary outreach team

The choice of the outreach team is critical as the latter will be the "face of the project" and, consequently, will have a direct impact on how the community perceives the project and its operators (Majer et al., 2013). Providing information about the project is important but good communicators or moderators are needed for this and should be identified early on (Ruef et al., 2020). The outreach team should consist of communication specialists who consult with management, the industry, scientists, government officials, company stakeholders, and citizens groups (Majer et al., 2016; Chavot et al., 2018). The outreach team should clearly define the processes for both internal and external communications for the project. A community liaison group should be set up that represents different positions and needs from the population (e.g., Parish, local councilors, local residents and business representatives, or other interested agencies). This group not only creates requirements but is also a liaison as it has direct links with the population and can favor trust. In addition, a community liaison manager may be assigned to oversee the interactions with local residents to ensure that any problems or concerns are addressed quickly and personally (Law et al., 2019). To fit the project into the social environment, the outreach team should have considerable knowledge of politics, the population, and of the media landscape, in addition to social and technical skills (Weber & Brian, 2014).

Step 4 – Decision on the scale of community participation

Considering population's preferences for specific participation formats allows the anchoring of a project to the context and for appropriate ways of engaging the population (Chavot et al., 2018). Possible participation formats are highlighted in Table 7.1, according to their degree of participation based on

Weber & Brian (2014) and Trutnevyte & Wiemer (2017). If participation is offered, there should be room for adaptation, leading to acceptance compromises in the project design (Chavot et al., 2019, Dallo et al., 2022). A problematic approach is to promise cooperation and participation when the population in the end has no say or is not involved (Hirschberg et al., 2014; Holenstein, 2016). When the scale of participation is selected, formal commitments to the local and wider population should be made. Formal commitments can relate to information exchange, transparency, mitigation measures, addressing concerns, promoting cooperation, and additional benefits (Law et al., 2019). Together with these formal commitments, the mandates and responsibilities of all stakeholders should be made transparent (Majer et al., 2016).. The population needs to be told i) what kind of information they can expect, ii) what is not possible to communicate, iii) why, when and where they can have access to the information, iv) and who is going to distribute the information (Dallo et al., 2022).

Table 7.1: Opportunities for participation based on Weber and Brian (2014) and Trutnevyte and Wiemer (2017)

Degree of participation	Type	Description
Low ↓ High	Consultation procedures (two-way)	Opportunity is offered to the population to have a stake in the decision-making process through a moderated dialogue. It is particularly important here to clearly communicate in advance how much leeway is available to take into account preferences from the population.
	Cooperation	Project is planned jointly by consensus and moderated by a neutral party. This option is mostly used when conflicts exist or are expected.
	Financial participation	Financial participation is offered to the municipality and its citizens during the phase where the project is less risky.

Step 5 - Set up upstream discussions and partnerships between all stakeholders

For building trust with the community and subsequently having constructive exchanges, communication strategies should not only aim to inform relevant stakeholders , but should enable them to become involved in the governance process (Trutnevyte & Wiemer, 2019; Dallo et al., 2022). Trust requires personal contact, genuine interest in the opinion of others as well as reliable and transparent action (Weber & Brian, 2014). Projects that proceed without upstream consultation involving local populations may expect strong opposition from elected officials and inhabitants (Chavot et al., 2019). Stakeholders of a project, who have good knowledge of their population as well as of the overall context (e.g., employment, economy, education) will be better equipped to demonstrate how the project can support the community (Majer et al., 2013) and to understand negative public perceptions and to remedy those (e.g., screening the risk of local concern). Connecting the project to the local environment, social identity, and local politics will favor trust and relation building (Chavot et al., 2019), which are essential for the success of the project. In

addition, multi-way stakeholders engagement may allow to reveal challenges linked to the project that experts may have not thought of.

These upstream discussions should start in the planning phase and close attention should be paid to raising interest in the project in order for all interested stakeholders and members of the community to have a chance to participate. In cases where the population was involved too late, communication efforts tended to be not successful (Weber & Brian, 2014). At the same time, efforts should be made to present and discuss mitigation measures to deal with the risks evoked to the population (Trutnevyte & Wiemer, 2017). It is a matter of negotiating how great the risk is and what safety measures are to be taken. Importantly, communicators need to be aware that perception of risks is different between laypeople and experts. Forums for dialogue need to be created where the different stakeholders can express their perspectives, concerns and fears about the information received. For these discussions, face-to-face meetings should be used as a core tactic whenever it is possible.

Step 6 - Tailoring information to the context and particular audience (i.e., target group)

Rather than trying to convince the population, information should be geared to the needs and concerns of the population (Weber & Brian, 2014; Dallo et al., 2022) and should be consistent between the different actors providing information (Majer et al., 2016). Information that does not address the risk perceived by the population will not be effective. Specifically, the information must address the concerns, misconceptions, needs of the population and be tailored to socio-demographic aspects, practical knowledge, beliefs, and motivations (Karytsas & Polyzou, 2021; Dallo et al., 2022). The dialogue process must correspond exactly to the region and the project being analyzed (Holenstein, 2016).

It is better for project developers to provide information about particularly relevant topics at an early stage and on their own initiative, induced seismicity, noise, steam hazards, radon etc. (Weber & Brian, 2014). Openly talking about the risks will give less room to interpret them, and thus less room for rumors and misconceptions (Weber & Brian, 2014). It is further important to present the benefits and risks of deep geothermal projects in terms of their overall contribution to energy production (i.e. compared to other energy sources). This will mitigate the risk that the population perceives that the information is provided to them in a biased way.

Step 7 - Monitoring public perceptions and adapting the communication strategy

The outreach team needs to consider the changing aspects of a context when planning communication and engagement processes (Chavot et al., 2020, Trutnevyte & Wiemer, 2017). The changes in perceptions and concerns need to be monitored. This monitoring can be done through public meetings, interviews or surveys. For example, as soon as residents become aware of a project being planned in their neighborhood, they will expect clear answers on the expected benefits and risks (Chavot et al., 2020). To be ready for the latter, demonstrating that the project is well conceived, placing any associated risk in the proper context and developing key messages that resonate with the community is crucial (Majer et al., 2016; Robertson-Tail et al., 2018; Benighaus & Bleicher, 2019).

Step 8 - Developing a crisis plan

To limit the loss of confidence that comes with a crisis, the crisis plan must specify how to react to which type of crisis and the roles assumed by different stakeholders (Weber & Brian, 2014). The plan should also highlight the key messages that are to be communicated to the population in case of crisis because fast reaction will be key. For this, it is recommended to make a list of possible negative events, such as various magnitudes of induced earthquake and associated damage (see §7.3), and prepare how to communicate transparently about each of them (Weber & Brian, 2014).

Step 9 - Giving regular updates about the project

Announcements about the project (positive and negative) should be made regularly. Everyone (local population, politicians, associations, media), should be informed about the project more or less at the same time. Strategically proceeding with the announcement allows the EGS project developers to make full use of communication opportunities, occupying the population space early on, instead of leaving the sovereignty of interpretation to others (Weber & Brian, 2014).

7.2 Guidelines specific to communication around seismicity

Experience from several projects has shown that the population will be more tolerant to induced seismicity if they have been forewarned. This tolerance will be further increased if the benefits of the operation are clearly conveyed (McComas et al., 2016). Continued outreach, education, and communication are thus crucial elements to help the community understand the meaning of induced seismicity and micro seismicity (Pankow et al., 2023). Communication regarding induced seismicity should be conducted with a variety of stakeholders (e.g., population, media, regulators, elected officials) during the various phases of the project and should occur pre-stimulation, during stimulation and post-stimulation. As with general communication about geothermal projects, timing of communication is critical (Dallo et al., 2022). For this, it could be useful to create a publicly available database with up-to-date information recording events. The database should quantify risk, record incidents, build up a record of risks and be made publicly accessible. It may record current activities but also anticipate future operations (e.g., risks of drilling in urban environments should be mapped proactively) (Master Plan Geothermal Energy in the Netherlands, 2018).

Furthermore, it is important to be mindful that technologies are perceived to be riskier, the more their consequences are "unknown" (effects unobservable or delayed) and the more they provoke a sense of "dread" (negative consequences potentially catastrophic and uncontrollable) (Slovic 1987; Bassarak et al. 2017). Based on this, increasing familiarity with the underground and drilling activities appears important. In this regard, Law et al. (2021) suggest arranging events for the population where people are able to visit the underground through videos or virtual reality, providing interactive/live information or classes about geothermal energy in the curriculum.

Research has further shown that it may be most effective to use a combination of both numerical and verbal descriptions of probability when talking about earthquake risk (Dallo et al., 2022; Knoblauch et al., 2018). Verbal descriptions should not be used alone as they are often interpreted in different ways (Dallo et al., 2022). Given that it can take experts some time to analyze whether an earthquake has occurred naturally or was induced, it is crucial for operators to immediately communicate that they investigate the nature of the event while they do not know if the event is related to geothermal activities (Dallo et al., 2022).

A crisis plan specific to seismic risk requires to develop and implement a protocol that specifies the steps stakeholders must take in the event of earthquakes. The traffic light protocol should be used to define the acceptable levels of disturbance and the latter should be presented to all relevant stakeholders, including the population (Trutnevyte & Wiemer, 2017). A 'calling tree' should also be built for the project management to be notified in case of seismicity. The institution responsible for seismic monitoring in the region or country should inform the relevant stakeholders immediately in case of seismic events. The details of this 'calling tree' should also be made available to the population (Pankow et al., 2023).

Acknowledgments

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