DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

Deliverable D3.5: Rational guidance to governments and regulatory authorities

WP3 Risk management workflows for deep geothermal energy

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1 Introduction

This public report entitled "***Rational guidance to governments and regulatory authorities***" corresponds to the Deliverable 3.5 of the European ***Destress*** project. This comprehensive report is done on the framework of the WP3 dealing with "***Risk management workflows for deep geothermal energy***" and involved contributions from ESG (France), ETH (Switzerland), and KICT and SNU (South Korea). This deliverable relates specifically also to DESTRESS deliverables 3.3 *Risk governance strategy report* and 6.4. *Environmental performance monitoring and control.*

State of the art of the environmental monitoring has been done on several EU countries exploiting deep geothermal energy and more specifically EGS (Enhanced Geothermal Systems) operational plants. This environmental monitoring is mainly imposed by the local mining authorities under the umbrella of rational governmental authorities. Thus, on-going geothermal projects dealing with soft stimulation and operational plants in Belgium (Flanders), France (Northern Alsace), and in Germany (Rhine Palatinate, Bad Wurttemberg) have been evaluated based on published documents (**Figure 1**). Some EGS or deep geothermal projects being in development in The Netherlands and Switzerland have been also considered even though no EGS plant is operating yet in those countries. Regulations of geothermal plants related to volcanic reservoirs like Italy or Turkey have not been considered, except for a recent pilot project in Iceland.

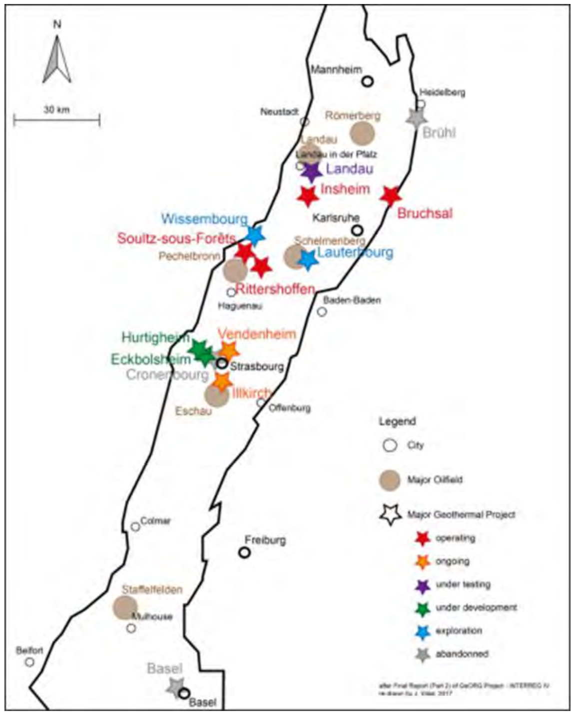

Figure 1. The different geothermal sites located in the Upper Rhine Graben (Vidal et Genter, 2018)

The Basel project located in the Swiss part of the Upper Rhine Graben (**Figure 1**), aimed to create one of the first commercial EGS plants in Europe and providing electrical and thermal energy directly within the city of Basel. To create an EGS reservoir at depth, fluids are pumped under high pressure into the rock mass to cause hydro-shearing, which eventually increases its permeability for subsequent water circulation. In Basel, this hydraulic stimulation started on 02^{nd} December 2006 with an injection of 11,570 m^3 of water during 5 days at increasing flowrates (Häring et al., 2008). The stimulation was accompanied by an increasing seismic activity, including a M_L=2.6 event, which prompted the operator to stop the injection on 08^{th} December 2006. Only a few hours later, during the shut-in period, a M_L=3.4 event occurred, the largest event in this sequence. It was felt by the population up to 20 km away, that means in Switzerland but also in Germany and France, the two neighbouring countries (

Figure 2). It caused minor non-structural damage within the city of Basel, lead to increased awareness of the public, and attracted international attention (Giardini, 2009; Edwards et al., 2015; Mignan et al., 2015). In late 2009, a seismic risk assessment concluded an unacceptable risk for a continued geothermal operation (Baisch et al., 2009), the results being subject to high uncertainties (Mignan et al., 2015). The public authorities suspended the geothermal project and the deep well Basel 1 was closed in April 2011.

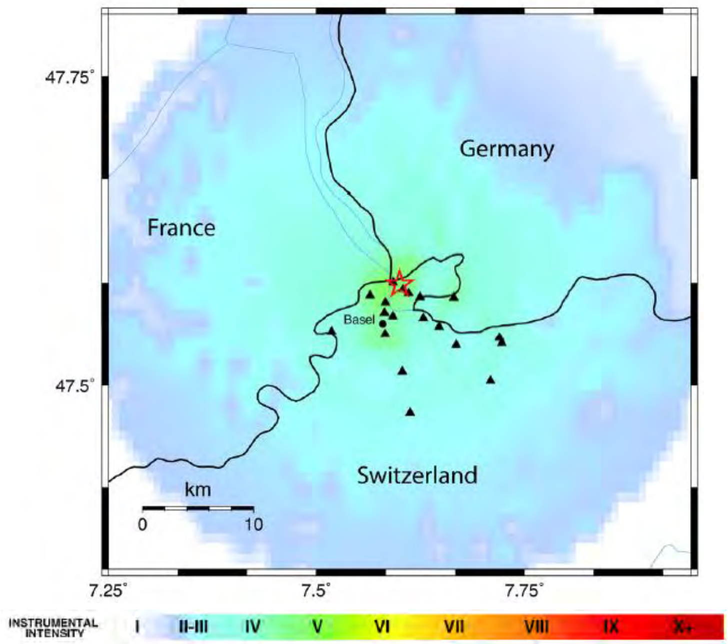

Figure 2. Shake Maps for the Basel 2006 Mw = 3.2 event (Edwards et al., 2015). The red star is the location of the epicentre and the triangles represent the seismic stations recording the event. Administrative boundaries are depicted as black solid curves. Colours are proportional to European Macroseismic Scale (EMS-98) intensity levels.

It turns out because of previous geothermal counter references like the Basel felt earthquake happened in 2006, that geothermal operators are obliged by local or national regulations to monitor various physical and geochemical parameters before and during drilling, during stimulation and/or geothermal exploitation. Therefore, regulators, from France and Germany, have imposed to many geothermal plants similar policies for operating existing geothermal facilities. The main common monitoring system deals with induced seismicity, slow deformation, radiation protection and various emissions like noise or geothermal fluids.

Induced seismicity which is the major concern for developing EGS-like projects is regulated at state or and municipal levels and primarily on a project-by-project basis. The European Union defined some directives on environment, hydrocarbon licensing or ground-water protection for using the deep underground resources, but there is no European regulatory framework yet on induced seismicity, and because permitting is strongly depending on national or regional legislation, this may not be possible in the short and medium term. The guidance reported on in this deliverable this is starting from considering the nation- and sometimes region-specific point of view. We also outline recommendations in order to harmonize EGS geothermal plant exploitation in terms of seismic monitoring, traffic light system and transparency measures in order to inform local population.

2 Rational guidance to governments and regulatory authorities in France

2.1 Introduction

The future development of deep geothermal energy worldwide and especially in Europe is highly dependent on the public acceptance of currently exploited plants and new projects. Major concerns of the population are related to the environmental impacts of geothermal projects or plants in the surroundings, from the drilling phase to the continuous exploitation phase.

2.2 Site presentation

In France, the development of deep geothermal energy has increased since a few years. Around 20 exploration licenses have been granted by the French government, mainly in the Upper Rhine Graben, in the Massif Central, in the Rhône Valley and in the South-West France. Currently, there are two geothermal plants in operation and two projects at the drilling phase, all located in the Upper Rhine Graben:

- **Soultz-sous-Forêts power plant**: it is located in northern Alsace and was commissioned in July 2016 and has been operating continuously since then. The power plant produces electrical power through an ORC cycle of 1.7 MW_e (gross power). The plant is based on a 3 wells system (1 production and 2 injection wells), which were drilled down to 5 km depth in the crystalline basement. Production flowrate is around 30 L/s for a production temperature of about 150°C.
- **Rittershoffen heat plant**: it is also located in northern Alsace and was commissioned in May 2016. The plant provides heat for an industrial bio-refinery. Thermal power of about 25 MW_{th} is produced through a doublet (1 production well and 1 injection well), drilled down to 2500-2700 m, at the interface between sedimentary cover (Buntsandstein sandstones) and the crystalline basement. Production flowrate reaches around 85 L/s and the production temperature is nearly 170°C.
- **Illkirch project**: it is located in the South of Strasbourg. Drilling of the first well has recently been achieved. It has been drilled down to 3300 m into the Buntsandstein sandstones and the crystalline basement. The plant is aimed at co-producing heat for district heat system and electrical power.
- **Vendenheim project**: it is located in the North of Strasbourg. The two-well system has been drilled down to 5 km depth in the crystalline basement. The aim of the

project is also to provide heat for a district heating system and to produce electrical power.

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2.3 License legal framework in France

In France, the legal framework is today well established. The regulation about all types of geothermal energy is governed by the French Mining Code. In the case of deep geothermal energy, there are several steps before getting the final authorization for long-term exploitation. The life-time of a project requires then to get several permits or authorization, that are presented below in chronological order:

2.3.1 Exclusive Exploration License (in French: PER, Permis Exclusif de Recherche)

The first license to be obtained by an applying company is the Exclusive Exploration License for high temperature resources. It is delivered by the French government, through a ministerial decree. It defines an area over which the granted company owns the exclusive rights to perform any exploration works and subsequent drilling. This license is granted for 5 years and can be renewed twice. The application file must contain the technical and financial capabilities of the applying company, as well as a work program and the planned investments. The examination of the application cannot exceed 2 years. Figure 3 presents the current licenses in metropolitan France with a focus on Alsace.

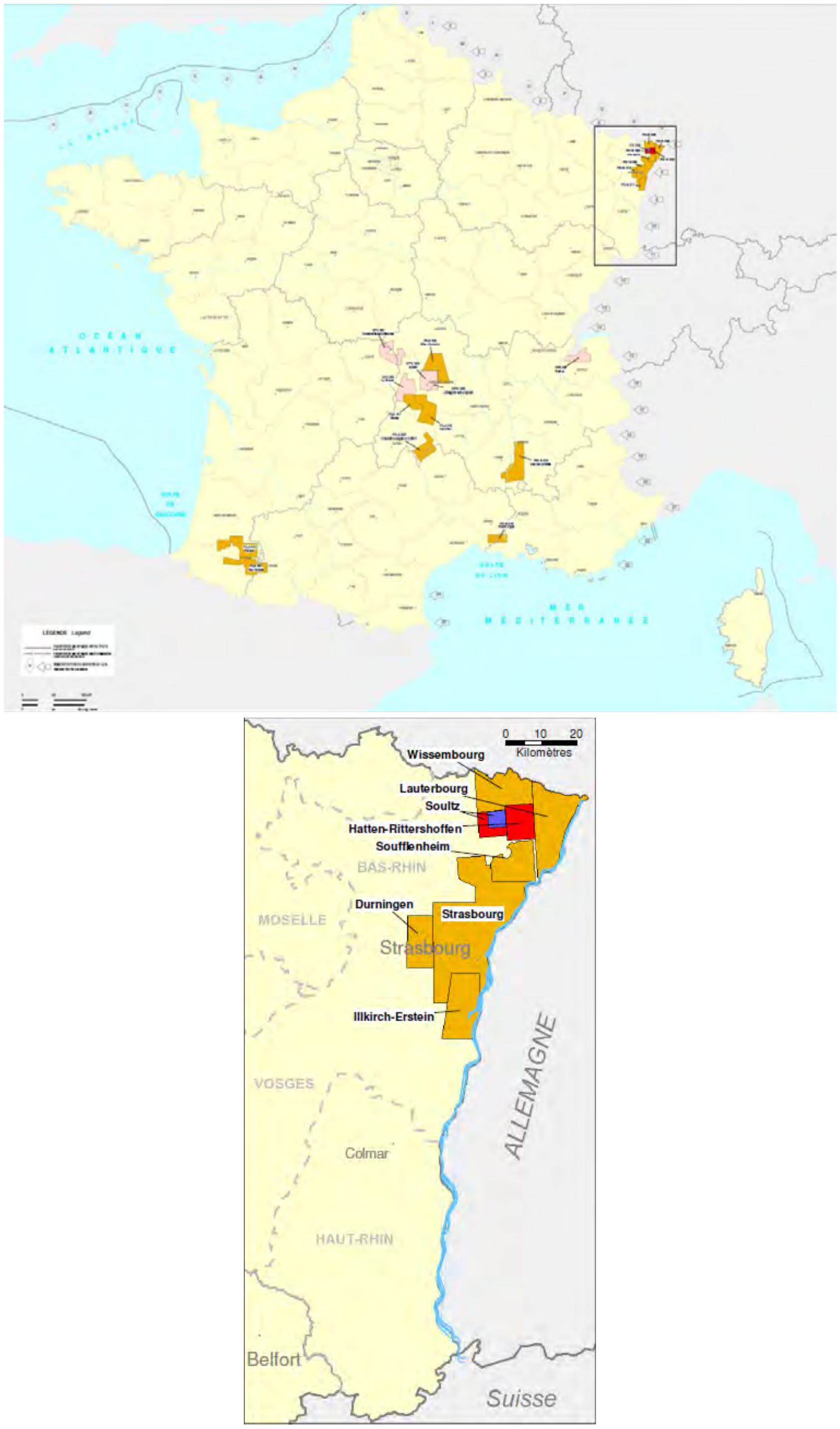

Figure 3. Exclusive Exploration Licenses (in orange, pink and red) and Exploitation Licenses (in blue) in metropolitan France (left) and in Alsace (right), dated January 2016. Source: French Ministry of ecology, sustainable development and energy.

2.3.2 Drilling Permit (in French: AOTM, Autorisation d'Ouverture de Travaux Miniers)

Once a company has defined a drilling target within its exploration license, it has to apply for a drilling permit. The drilling permit is also governed by the Mining Code, but needs to conform to other national regulations, such as mainly the Labour Code, the Public Health Regulation and the Environmental Code. The drilling permit is delivered by the regional administrative authorities through a prefectural decree. The application file must contain the complete drilling program, a full survey on environmental impacts, a document defining the rules in terms of safety and health, and the conditions defining the potential interruption of the drilling. It is also submitted to a public consultation which maximal duration is 1 month.

2.3.3 Exploitation License (in French: Concession)

Although the commissioning of a plant and beginning of exploitation can be performed under the Exclusive Exploration License, the long-term exploitation of a geothermal resource requires the company to get an Exploitation License, which is granted by the government through a ministerial decree. As for the Exclusive Exploration License, it defines an area within which the company owns the exclusive rights to exploit the geothermal resource for a maximal duration of 50 years, which can be extended several times by periods of maximum 25 years. The application file must include information about the applying company, regulatory cartographic documents, description of the geothermal plant facilities, description of the process and a survey on environmental impacts. It is also submitted to a 1-month public consultation. One important issue is that the decree defines annual production commitments in terms of gross thermal and/or electrical power that must be achieved by the operating company. In Figure 3 is shown the "Soultz concession", which is the only exploitation license in metropolitan France to date.

2.3.4 Exploitation authorization

The Exploitation License is completed by a prefectural decree which authorizes the exploitation of geothermal plants and defines the rules that must be followed by the operating company. In particular are described: general exploitation conditions, definitive cessation of exploitation, safety on the facilities, prevention against pollution and nuisances, seismological monitoring, boreholes and pipes monitoring, relationships with and information to local mining authorities, regional and national administrative authorities.

2.4 Environmental monitoring

The prevention against environmental impacts, pollution and nuisances is the main principle, together with safety at work, on which are based the drilling and exploitation authorizations. The definition of well-established procedures and measures aiming at minimizing the environmental impacts is also a way to increase the acceptability of the population. Indeed, the environmental effects and nuisances are usually the main concerns of the population living in the surroundings of a geothermal plant or project (e.g., Chavot et al., 2018). Several topics are addressed that are presented below.

2.4.1 **Integration into the landscape**

The operating company must take all possible measures to minimize the visual impact of facilities.

2.4.2 **Noise and vibration**

Exploitation and drilling works must be performed so as to minimize noise emissions and mechanical vibrations, which could disturb the surrounding population or have an impact on the close environment. Day- and night-time noise measurements must be performed before the start of exploitation/drilling near the closest houses to determine the level of background noise. Those measurements must be repeated several times during exploitation/drilling, to check if noise emissions exceed the regulatory levels of emergence (that is, above the determined background noise). In that case, it is mandatory for the operating company to take measures or establish procedures to decrease the level of generated noise. In particular, during the drilling phase, any loud operation is forbidden during the night-time (22h – 7h). Figure 4 presents the locations where noise measurements are regularly performed around the Soultz-sous-Forêts power plant.

2.4.3 **Protection of water resources**

The general principle states that the operating company must take all possible measures or apply specific procedures in order to guarantee the protection of surface and underground water and minimize the risk of accidental pollution. Some specific concerns are related to:

- management of rainwater: the company must make sure that the rainwater drained on platform is not polluted;
- any discharge of any type of water/fluid into the environment can be strictly forbidden. If not, the discharged water/fluid must respect maximal concentration values for specific parameters;
- discharge of geothermal fluid into the environment is strictly forbidden. It must be stored in dedicated ponds;

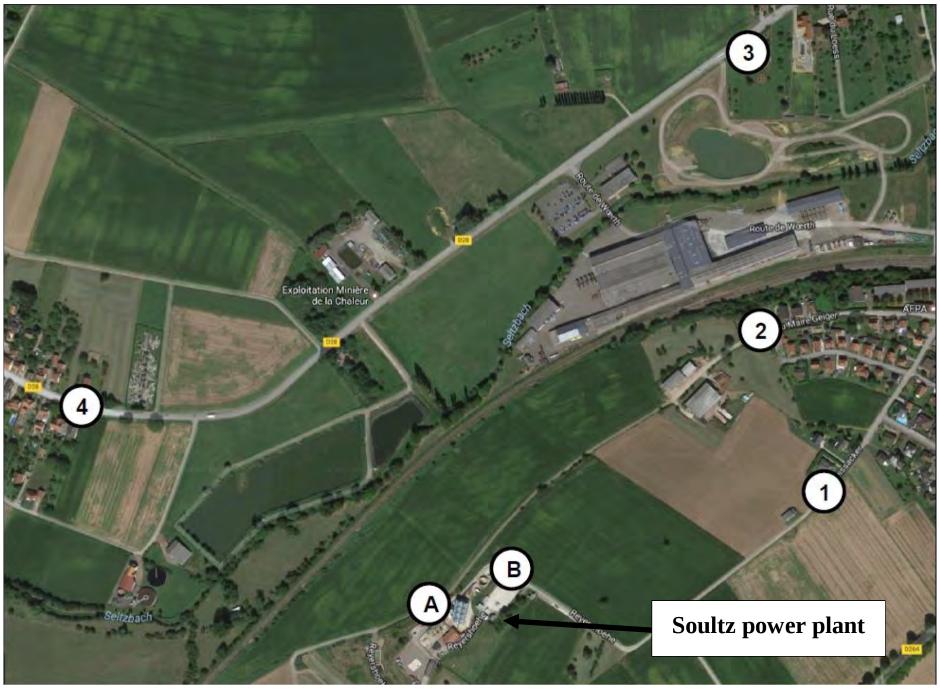

Figure 4. Location of places around the Soultz-sous-Forêts power plant, where noise emissions are repeatedly measured (OTE, 2017, courtesy of GEIE Exploitation Minière de la Chaleur). A and B are located at the plant; the other spots (1, 2, 3, 4) are located near the closest habitations.

- management of accidental pollution;
- protection of underground water: boreholes' completion must guarantee the protection of potential permeable layers. Moreover, the exploitation authorization defines a program of regular inspection of wells' integrity (control of casing and cement quality). Inspections shall be performed every 6 years for production wells and every 3 years for injection wells;
- presence of groundwater table: in this case, the operating company must install a network of piezometer into shallow observation wells. At least, one piezometer must be installed upstream from the facilities and 2 piezometers downstream of the facilities. Regular measurements of the groundwater table's level, conductivity, temperature, pH, reduction potential. In addition, water samples are monthly taken and analysed. The concentration in main anions, cations, metallic species, pollutants and the radiological activity of main natural radionuclides are then characterized. All these measurements aim at detecting any pollution of the groundwater table by geothermal fluid. The location of the shallow observation boreholes around the Illkirch drilling platform, as well as the installation of piezometric sensors are shown on Figure 5.

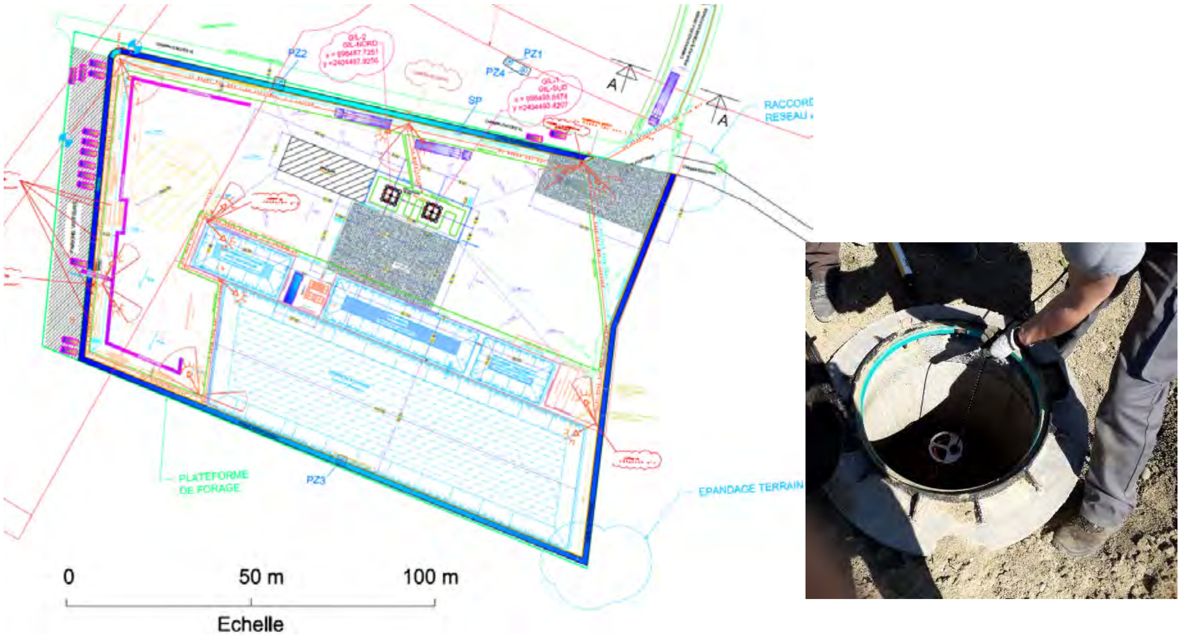

Figure 5. Left: Location of the shallow observation wells around the drilling platform at Illkirch (PZ1, PZ2, PZ3, PZ4); Right: piezometric sensor (top) and installation of the sensor (bottom).

2.4.4 **Radioactivity**

In the case of geothermal plants exploiting a reservoir containing natural radionuclides, the probability exists that some of the radionuclides could be washed out by circulation of geothermal fluid and then trapped during the formation of scales in the plant's surface equipment. This type of slightly radioactive scales is called “NORM” (Naturally Occurring Radioactive Material). Typically, the geothermal plants developed in the Rhine Graben have to face this issue: indeed, they exploit a geothermal fluid circulating in granite, a rock containing small amounts of radionuclides, for instance Uranium 238, Thorium 232, Potassium 40 and the products of their decay chain. On surface, enhanced concentration of Radium 226, Radium 228 and Lead 210 can be found in sulfates and sulfides scales, as shown on Figure 6 (Cuenot et al., 2013, 2015; Scheiber et al., 2012; Eggeling et al., 2013; Mouchot et al., 2018).

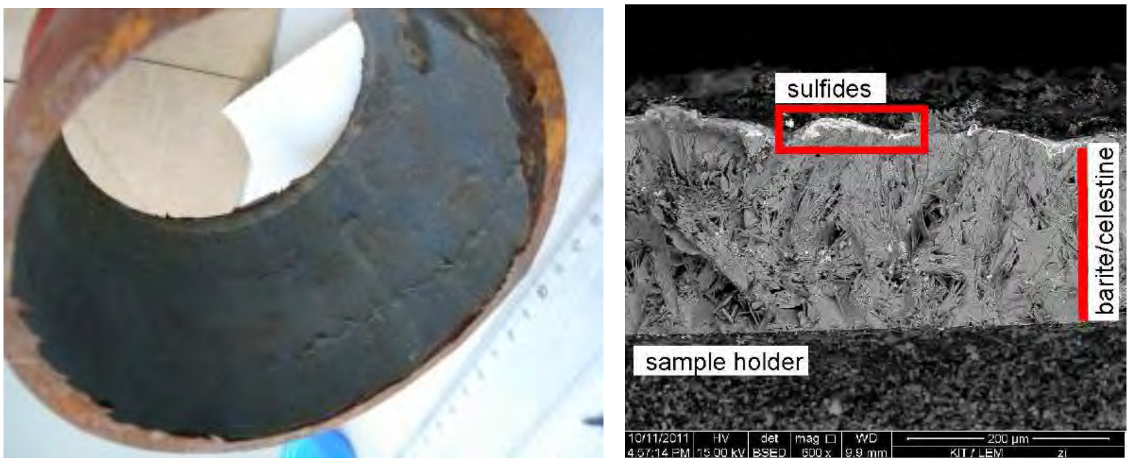

Figure 6. Left: Barite scaling covering the inner surface of a pipe (Scheiber et al., 2012); Right: Electron microscopy oft he cross-section of a scaling layer showing sulfide and sulfate scaling (Scheiber et al., 2012).

Radioactivity is one of the main environmental concerns among the population. Thus, the drilling and exploitation authorizations require that the operating company at least performs measurements to check the level of radiation on the facilities and to monitor its evolution. Last year, the French Mining Code was modified to take into account the problem of NORM: a new chapter was added, mainly dedicated to the protection of environment and population. It defines the measurements that are mandatory for the operating company. Radiological characterization is asked for all kinds of solid, liquid and gaseous effluents, to be sure that no radioactive material could be spread into the environment and could be harmful for the surrounding population. In addition, in France, the regulation regarding radioactivity is defined in the Labour Code and the Public Health Regulation, which defines the measures and procedures that must be followed by employers for the protection of workers. The basic principle of radiation protection states that every exposure to radiation, even the lowest, could have potential, harmful effects on human's health. Thus, the regulation imposes that at least, the level of radiation has to be measured and the potential exposure of workers should be calculated. Depending on the results, radiation protection measures have to be implemented, in order to respect the following principal law: the maximal cumulative dose that can be received by workers and population over 12 consecutive months is 1 mSv (one milli-Sievert). As an example, are listed some of the measures that are applied on the geothermal plants of Soultz-sous-Forêts and Rittershoffen.

<u>Monitoring</u>

- Quarterly measurement survey: every three months, ambient and contact dose rate measurements (Figure 7, left) are performed on several tens of locations over the plants' surface equipment. This allows to accurately monitor the evolution of radioactivity, which has to be reported to the Mining Authorities.

- Characterization: regular sampling of geothermal fluid and scaling is performed. Samples are then fully analysed in terms of geochemical content and radiological characterization. This is explicitly asked by the regulation, at least once per year.
- Aerial emission: quantification of Radon emission on the plant, but also, in the environment around the plant (typically, near the closest habitations) is mandatory, as well as radiological measurements on the dusts that can be emitted on the plant (Figure 7, right). It has to be done once per year and reported to the Mining Authorities
- Effluents: sampling and radiological analysis of liquid and solid effluents that can be released into the environment or stored on site (for example, rainwater, mud, …) must be performed once per year. In addition, if some effluents are released in the environment, soils, flora and fauna located near the discharge place must also be sampled and analysed to check for the presence of radionuclides.

Figure 7. Left: Dose rate contact measurements on a pipe; Right: Planned radon measurements around the Rittershoffen plant (Bosia et al., 2020).

<u>Radiation protection (only if radiations have been measured on site)</u>

- Appointment of a radiation protection expert: the expert will be in charge of the monitoring described above, but also to all actions related to radiation protection
- Estimate of individual exposure: from the list of all possible works that employees are likely to perform on the plant, duration of each work and dose rate measurements on facilities, a calculation of the possible received dose for each worker has to be made and compared to the maximal permitted dose over 12 consecutive months (1 mSv).
- Workers’ dosimetry: each worker must wear a passive dosimeter during its working time if he works on the plant’s facilities. The dosimeters are analysed every three months to check the value of the cumulative dose (Figure 8, left).
- Installation zoning: if the measured ambient dose rates exceed given thresholds, it is required to proceed to a zoning of the installation (Figure 8, right), according to the procedure defined in the regulation. It has to be noticed that, as soon as an area is

determined and reported, workers must compulsorily wear their passive dosimeter when entering the zone. It is applicable even for the first zone defined in the regulation (“blue” or “supervised” area).

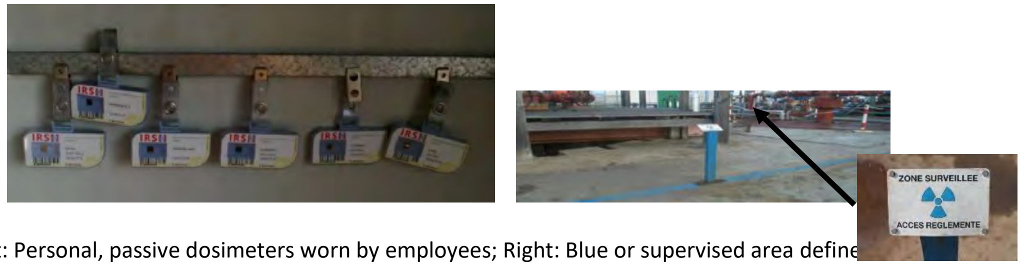

Figure 8. Left: Personal, passive dosimeters worn by employees; Right: Blue or supervised area define
sous-Forêts power plant (Cuenot et al., 2013).

- Work procedures and authorization: specific work procedures have to be defined for the work in supervised or controlled area (including the access authorization), or for work where the risk of exposure is higher (for example, when opening a contaminated equipment implying a risk of contact with radioactive material). A particular attention should be paid to the collective and individual protective equipment that is required regarding the type of operation (Figure 9).
- Employee’s training: each employee who is likely to be exposed to radiations must be trained, or at least informed, about radioactivity in general, but especially about all related issues in its framework.

Figure 9. Example of individual protective equipment worn for the opening of a heat exchanger.

<u>Waste management</u>

- Scaling residues: the radioactive scales, coming from filters or equipment cleaning are first stored in a dedicated, isolated place. The Mining Authorities require that these wastes cannot stay on site for a long time. In France, all radioactive wastes have to be collected by ANDRA (French national agency for nuclear waste management) for a long-term storage (depending on the type of radionuclides). This process is, by the way, very expensive for the operator.

- Contaminated equipment: other contaminated equipment (heat exchanger, pipes, valves,…) should normally be also collected by ANDRA. Due to the large weight of these metallic components and consequently, very high costs associated with their management by ANDRA, several research projects are currently running to develop decontamination processes in order to reduce the costs.

2.4.5 Seismological and geodetic monitoring

The issue of induced seismic activity and ground deformation is the major environmental concern among the population. Thus, this topic is fully addressed in a separate chapter (next chapter).

2.5 Seismological and geodetic monitoring

The monitoring of induced seismicity associated with geothermal energy started very early in France through the development of the Soultz-sous-Forêts EGS project. Indeed, the first seismological network was installed in 1988 for the stimulation of the first drilled well GPK1. Since then, the seismological monitoring, with either temporary or permanent networks, has been performed for every operation, hydraulic activity and continuous exploitation at all French EGS geothermal plants or projects. However, for a very long time, the seismological monitoring has only been performed for research and development purpose, without any legal framework. The first mention of seismological monitoring in the regulation appeared in the drilling authorization of the Rittershoffen boreholes, which also covered the well testing, stimulation tests and inter-well circulation tests in December 2011.

Historically, from 1988 to 2002, only temporary downhole and surface networks were installed for the monitoring of hydraulic operations at the Soultz-sous-Forêts EGS project (Cuenot et al., 2008). At that time, there was no obligation from the Mining Authorities to monitor the induced seismicity. In 2000, during the hydraulic stimulation of the first deep well of the Soultz-sous-Forêts EGS project occurred the first felt event linked with geothermal energy in France (ML = 2.6, Cuenot et al., 2008). Afterwards it was decided to install a permanent surface monitoring network of 9 short-period stations, which was completed by additional downhole and surface temporary stations (Dorbath et al., 2009). But again, this was based on the goodwill of operators, for research purpose, but also to be able to transparently communicate with the population and local authorities in case of a further felt event. Then the largest recorded event at the Soultz-sous-Forêts project (ML = 2.9), occurred in 2003 during the hydraulic stimulation of the well GPK-3 (Charléty et al., 2007), and the earthquakes series ($3 \leq ML \leq 3.4$) occurred at the Basel project in 2006 (Häring et al., 2008) were widely felt and contributed to make induced seismicity the major environmental concern associated with the development of EGS projects. This also led the mining authorities to include the seismological monitoring and the procedures to be followed in case of earthquakes. Below are presented three examples of recently published prefectural decrees, into which the seismological issue is addressed. The decrees are presented in chronological order, so that the evolution of regulation regarding induced seismicity can be observed here.

2.5.1 Prefectural decree authorizing the drilling of Rittershoffen boreholes (2011)

This decree was the first in France to explicitly address the issue of induced seismicity. It covers the drilling phase, well-testing phase, stimulation and circulation tests. The main obligations for operators were the following:

- Information of the population about the hydraulic activities and the probability of induced seismicity;
- Progressive decrease of injection pressure during the shut-in period of hydraulic stimulation, in order to minimize the probability of larger magnitude event, as the felt events in Soultz and Basel occurred after the stop of injections;
- Reinforcement of the existing, permanent, seismological networks by temporary stations
- Information to administrative authorities, press, population about the parameters (location, magnitude,...) in case of a felt event;
- Interruption of operations in case of a felt event and analysis of the situation by the BCSF[1]. It has to be noticed that there is no mention of the conditions for a restart of operations;
- In case of damages consecutive to an earthquake, an expertise from the operator's insurance is mandatory.

2.5.2 Prefectural decrees authorizing the drilling of Illkirch-Graffenstaden and Vendenheim boreholes (2015)

This decree is applicable to the drilling phase, well-testing phase, stimulation and circulation tests.

- Information of the population about the hydraulic activities and the probability of induced seismicity;
- Installation of a monitoring network at least 6 months before the start of drilling, in order to observe the local, natural seismicity. For the first time, a detailed description of the characteristics of the required network are given:
    - At least, 4 short period seismometers;

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1 BCSF : Bureau Central Sismologique Français

- 1 "multi-sensor" station including a broad-band seismometer, an accelerometer, a GNSS receiver and a corner-coin reflector for InSAR studies. All data from this station should be transmitted to and archived by RéNaSS[2] (French National Seismological Network, hosted at EOST[3], Strasbourg University). The RéNaSS is in charge to publish online the data from this station, which are freely accessible by the public; a convention was signed in 2016 between EOST, Strasbourg University and geothermal operators to regulate this topic, under the control of Mining Authorities.

The frequency range of short period seismometers allows the detection of microseismic events. The use of a broad-band sensor aims at observing slow deformation or aseismic movements, which were highlighted by other methods (Cornet et al., 1997; Cornet, 2016; Bourouis and Bernard, 2007; Schmittbuhl et al., 2014). The demand of a geodetic station followed the surface ground deformation observed at the power plant of Landau in Germany, due to a leak in the injection well (see chapter 8.4). The ground deformation was only detected when damages on surface started to appear and evidenced afterwards by the treatment of SAR data. Thus, the installation of a permanent geodetic station whose data are monthly analysed should allow to detect any surface ground deformation, as soon as it may start.

- Definition of magnitude-based thresholds and associated procedures:
  - **M_L ≥ 1.5**: the occurrence of a magnitude 1.5 event launches the "increased vigilance threshold", meaning that the operator has to follow more accurately the induced seismicity, in terms of activity and magnitude, to check a further event of magnitude ≥ 1.5 occurs, which would lead to take operational measures (decrease of injection pressure for instance);
  - **M_L ≥ 2**: the occurrence of a magnitude 2 event (threshold above which some events could be felt by the population under certain conditions) launches the progressive shutdown of hydraulic operations. All the seismological data from the 4 short period stations must be sent to the RéNaSS, within 24 h after the event and this, for a period covering 7 days before the event. The RéNaSS is then in charge of precisely characterizing the event. Depending on the results of this analysis, the Mining Authorities will authorize or not the restart of hydraulic operations;
- During stimulation operations, real-time monitoring must be implemented with the permanent presence of an operator;
- Progressive decrease of injection pressure during the shut-in period of hydraulic stimulation;

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2 RENASS : RESEAU NATIONAL DE SURVEILLANCE SISMOLOGIQUE

3 EOST : ÉCOLE ET OBSERVATOIRE DES SCIENCES DE LA TERRE, DEPARTMENT OF STRASBOURG UNIVERSITY

- Information to administrative authorities, press, population about the parameters (location, magnitude,…) in case of a felt event;
- In case of damages consecutive to an earthquake, an expertise from the operator's insurance is mandatory.

2.5.3 Prefectural decrees authorizing the exploitation of the Soultz-sous-Forêts and Rittershoffen geothermal plants (2016)

The two last decrees published in France corresponds to the exploitation authorization of the Soultz-sous-Forêts and Rittershoffen geothermal plants. They cover the exploitation period of both plants and the potential, temporary hydraulic operations that could be performed during the life-time of exploitation (well stimulation for example). The operator's obligations remain unchanged, compared to the decrees described above, except for the definition of threshold. Indeed, the thresholds based on magnitude were found to be rather restrictive for the operators. For example, a M = 2 event occurring at 5 km depth has very low probability to be felt on surface and even a lower probability of generating damages to constructions. Nevertheless, the previous regulation obliged the operator to stop any operations and would have been the same for the exploitation of the plants. So, considering the regulation for mines and quarries, as well as regulation from other European countries (see following chapters), and after fruitful discussions between operators and Mining Authorities, the latter decided to express the threshold in terms of Peak Ground Velocity (PGV) rather than magnitude. PGV is indeed a physical measure of the real vibration that is recorded on surface by a seismological sensor and thus, better indicates the potential effects of an event on surface. It must be noted that this is not retroactive to the previous decrees, for which the magnitude-based thresholds are still applied.
The PGV-based threshold described below apply only if an event is located within the perimeter of exploitation or exploitation license and the threshold is reached on at least 2 stations. These conditions allow not to trigger an alert in the case of a fake event or a natural large event.

- Definition of PGV-based thresholds and associated procedures:
  - **PGV ≥ 0.5 mm/s:** an event reaching this threshold triggers the "vigilance threshold". The operator must continuously follow the seismicity in order to check if a further event reaches the threshold and eventually adapt the operating conditions of the plant;
  - **PGV ≥ 1.0 mm/s:** this value triggers the "increased vigilance threshold". The operator must follow the seismicity in order to check if a further event reaches the threshold. All the seismological data from the 4 short period stations must be sent to the RéNaSS, within 24 h after the event and this, for a period covering 7 days before the event. The RéNaSS is then in charge of precisely characterizing the event. In the same time, the operator must take the appropriate measures in terms of operating conditions in order to avoid the occurrence of a further similar event.

- **PGV ≥ 1.5 mm/s:** an event reaching this value triggers the mandatory, gradual shutdown of the plant. All the seismological data from the 4 short period stations must be sent to the RéNaSS, within 24 h after the event and this, for a period covering 7 days before the event. The RéNaSS is then in charge of precisely characterizing the event. The Mining Authorities must be immediately informed about the event and the plant's shutdown. Depending on the results of the event's analysis, the Mining Authorities will authorize or not the restart of the plant.

2.6 Examples of application of regulation to the current seismological and geodetical monitoring of the Soultz-sous-Forêts and Rittershoffen plants.

As seen before, the regulation gives the operators several guidelines to be respected. Nevertheless, it is often necessary for operators to translate these guidelines into proper and efficient working and monitoring procedures. The seismological monitoring of the Soultz-sous-Forêts and Rittershoffen plants is regulated by the latter decree described above. Following are examples of what has been done so far to fit with the regulation.

2.6.1 Seismological networks and data processing

Figure 10 presents the permanent seismological networks installed around the Soultz-sous-Forêts and Rittershoffen plants since 2002 and 2012 respectively (Maurer et al., 2020).
Originally composed of 9 surface stations, the Soultz network (in blue on figure 10) currently consists of 7 stations:

- Four 3 components short period (1 Hz) velocimeters
- Two 1 component short period (1 Hz) velocimeters
- One 3 component broad-band (120 s) velocimeter
- One 3 component accelerometer (2 g), located at the same place as the broad-band sensor

The sampling rate for all stations is set at 200 Hz.
The multi-sensors public station is the one called "OPS" located with a blue star on Figure 10.
The Rittershoffen network was initially composed of 4 stations. The station named "KUHL" was recently transferred from the Soultz network to the Rittershoffen network comprising today 5 stations.

- Four 3 components short period (1 Hz) velocimeters
- One 3 component broad-band (120 s) velocimeter
- One 3 component accelerometer (2 g), located at the same place as the broad-band sensor

The characteristics of the sensors and the sampling rate are the same as the Soultz network. The multi-sensors station is the one called "BETS", marked with a red star on Figure 10.

In case of specific operations such as chemical and/or hydraulic stimulations, the permanent networks are densified by temporary stations (Maurer et al., 2015).

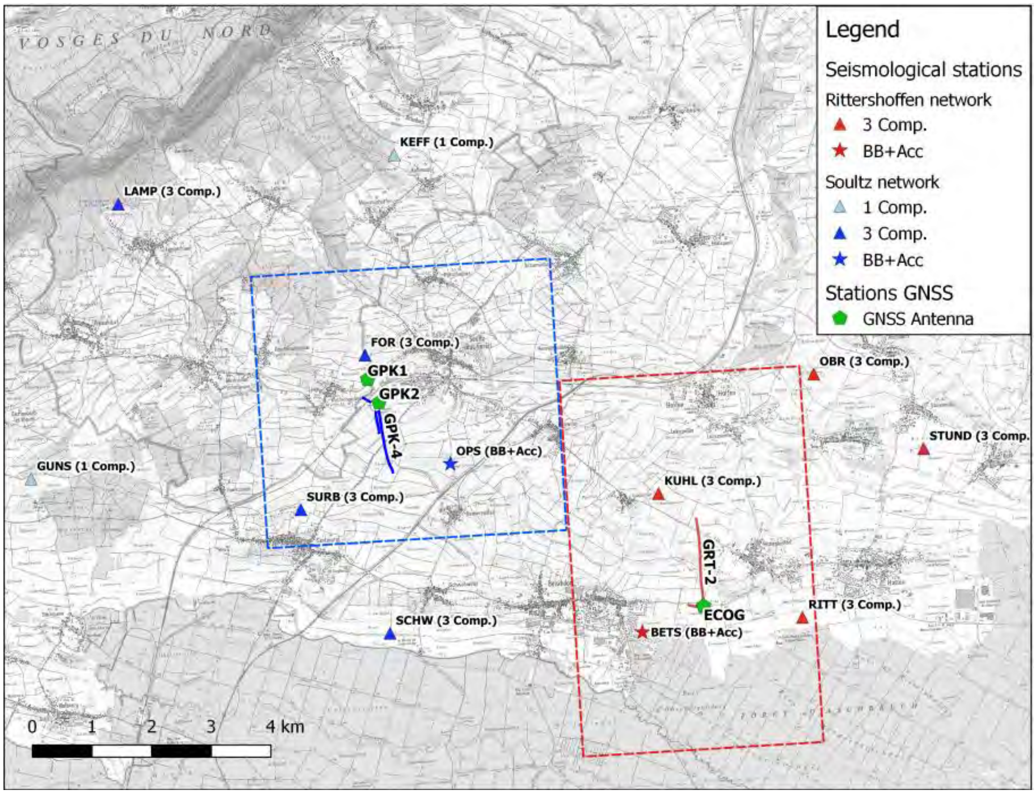


Figure 10. Seismic networks of Soultz-sous-Forêts (in blue) and of Rittershoffen (in red) and geodetic network (in green). Trajectories of wells are also displayed. Dashed rectangle shows Soultz-sous-Forêts (in blue) and Rittershoffen (in red) exploitation license (concession).

For both networks, the data from the individual stations are transmitted in real-time by radio or WiFi link to a central acquisition place, where the data are compiled and stored. From this place, the data from all stations are transmitted through an ADSL connection to a server hosting the archiving and processing software. A view of a station is given on Figure 11.

Figure 11. View of a permanent station from the Rittershoffen network.

The detection, phase picking, location and magnitude estimate are processed automatically. Then a seismologist manually reprocesses the detected events to improve the accuracy of location and magnitude. The detection magnitude is close to 0, depending on the overall background noise. In case of a detected seismic crisis, it is often necessary to manually review all the waveforms as the automatic detection system may have missed some of the weakest events.
The seismological observations are monthly reported to the Mining Authorities, together with the monthly exploitation report.

2.6.2 Alert system

To be able to quickly:

- manage the occurrence of an event, exceeding one of the thresholds defined in the regulation,
- meet all legal obligations demanded by the regulation,
- avoid any further event,

an alert system together with a decisional chart has been set up. In the case of an automatically detected event, reaching or exceeding a magnitude of 1.7, an automatic alert e-mail and phone call is sent to the on-call duty person (in the frame of the plants' exploitation, there is permanently an on-call duty person, 7 days a week, 24h/24), who may contact if necessary a seismologist. Then the event is manually reprocessed and the PGVs at each station estimated. If the first threshold is reached on at least two stations, then the procedure described on figure 12 is launched.
This procedure aims at translating the main, general obligations defined in the regulation, into practical decisions and actions to be followed. For example, it was decided to:

- re-evaluate the periods of vigilance and increased vigilance every 6h, as no time frame for the vigilance is defined in the regulation;
- in case of reaching the second PGV threshold, it was decided to decrease the flowrate by iterative steps of 20 m^3/h, as “an appropriate measure in terms of operating conditions in order to avoid the occurrence of a further similar event”, which is stated in the regulation.

This procedure has never been launched since the commissioning of both geothermal plants, as no event has been felt nor reached the first PGV threshold on more than one station.

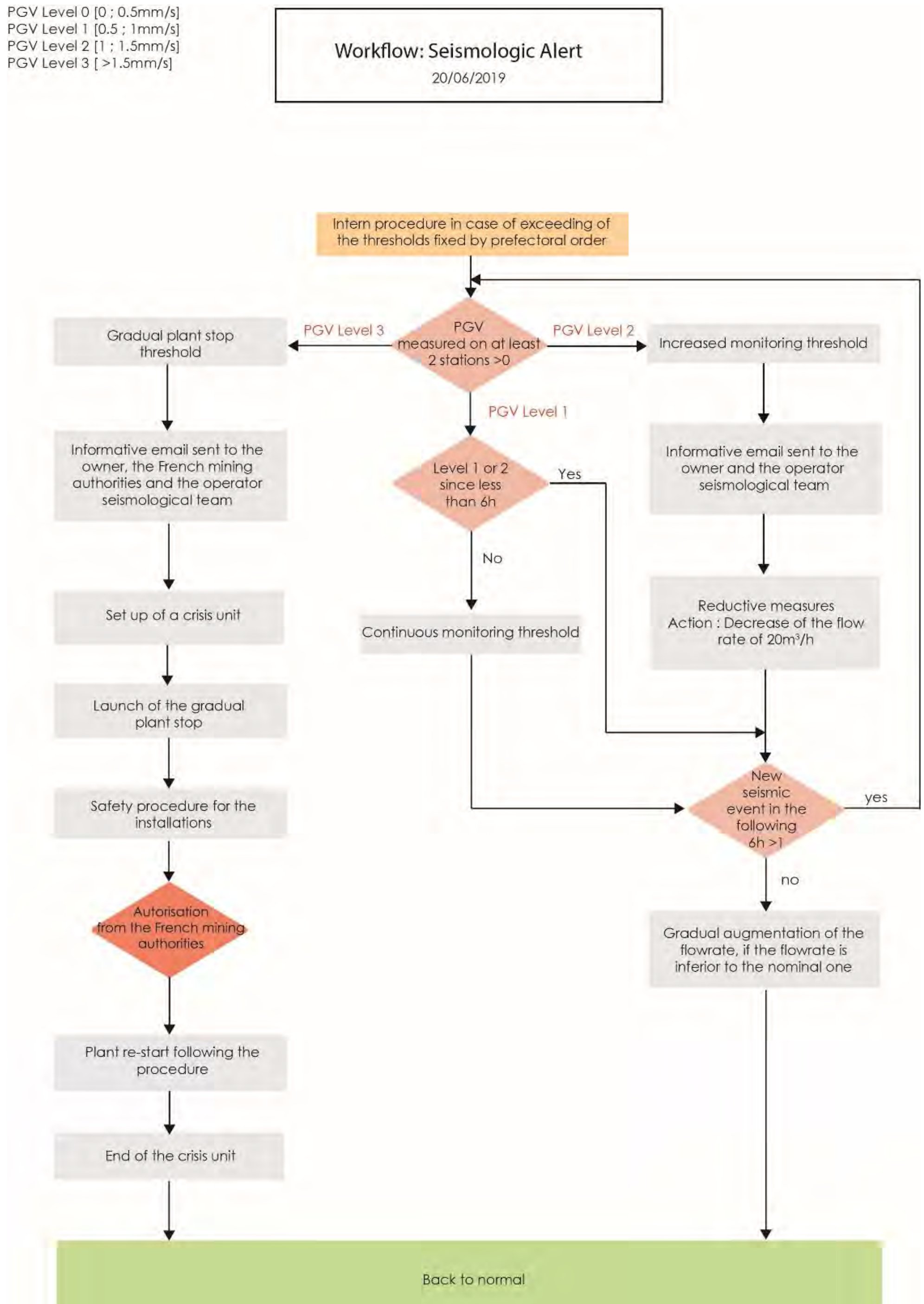


Figure 12. Decisional chart designed by operators in case of occurrence of induced micro-seismic activity, based on French mining authority regulation.

2.6.3 Results of the seismological monitoring

Since 2016, the geothermal plants of Soultz-sous-Forêts and Rittershoffen have been almost continuously operating, with an availability higher than 90%. The micro-seismic activity has been carefully monitored in real–time since the beginning of the production. Since then, a couple of thousands of induced low magnitude earthquakes were detected (maximal reached magnitude M_L = 1.7), all located in the vicinity of the injection wells, GRT-1 for Rittershoffen and GPK-4 for Soultz-sous-Forêts (Maurer et al., 2020).

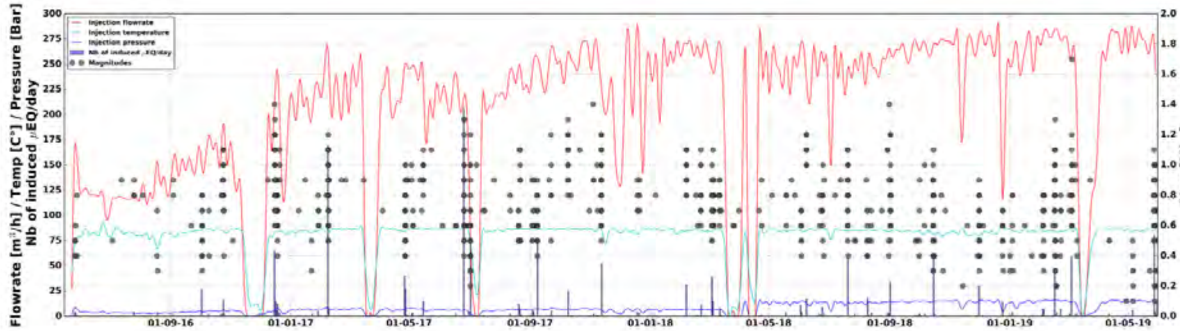


Figure 13. Induced seismicity associated with the injection parameters since the commissioning of the Rittershoffen plant (Maurer et al., 2020).

For the Rittershoffen plant, since the commissioning of the plant, a total of 1680 microseismic events have been automatically detected and located in the direct vicinity of the project by the local seismic network (Figure 13). All events have been then manually relocated. Most events are located within a radius of 1 km around the open-hole section of the injection well GRT-1 (Figure 14). The maximum recorded local magnitude M_L was 1.7 for an event occurred on the 04th of March 2018. The maximum PGV recorded for this event was 0.506 mm/s. No induced seismic event has been felt by the local population around the Rittershoffen plant since operation has started. The lowest PGV threshold value (0.5 mm/s) was only reached once, but only on one single station, so that the alert procedure has not been launched. The induced microseismic activity during exploitation is shown in Figure 14.

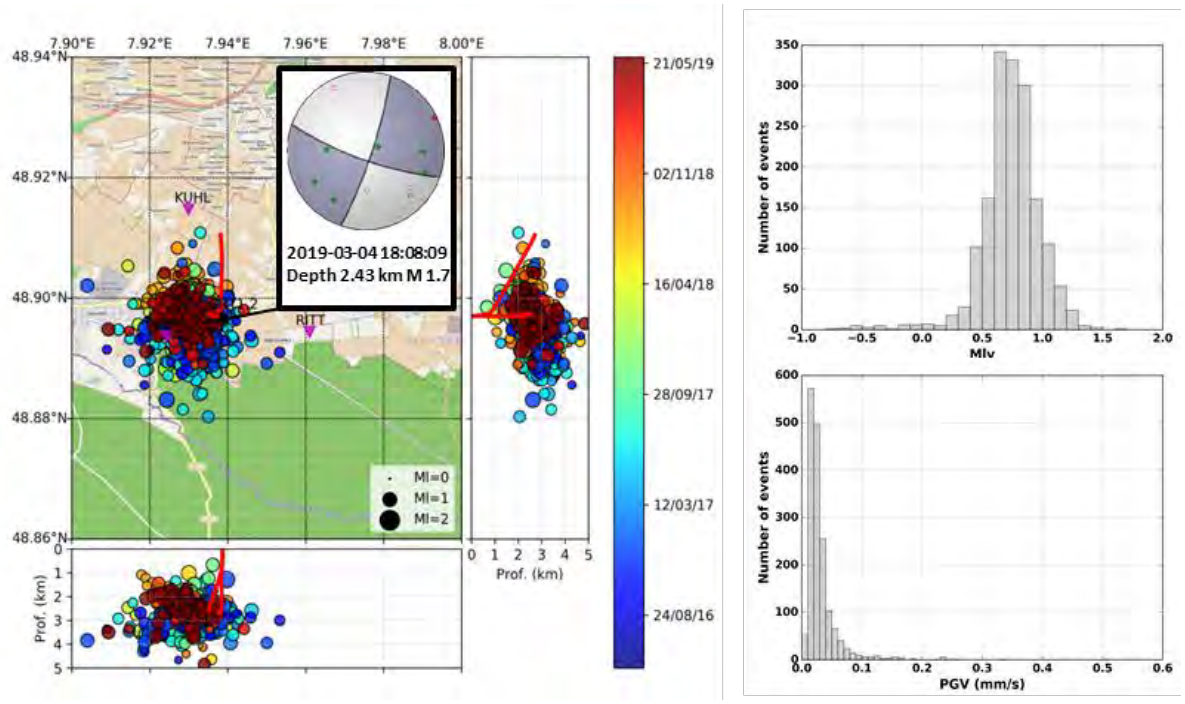


Figure 14. Induced seismicity during geothermal exploitation located around GRT-1 since the commissioning of the Rittershoffen plant (Maurer et al., 2020).

In Soultz-sous-Forêts, induced seismicity has been observed since injection has started in GPK4 (Figure 15). A total of 156 events could be located in the vicinity of the project since the commissioning of the plant in July 2016. The maximum local magnitude M_L was 1.7. The maximum PGV recorded for this event was 0.173 mm/s. The lowest PGV threshold value (0.5 mm/s) was never reached and no induced seismic event has been felt by the local population around Soultz-sous-Forêts since operation has started in 2016. The generated micro-seismic activity during exploitation is shown in Figure 16.

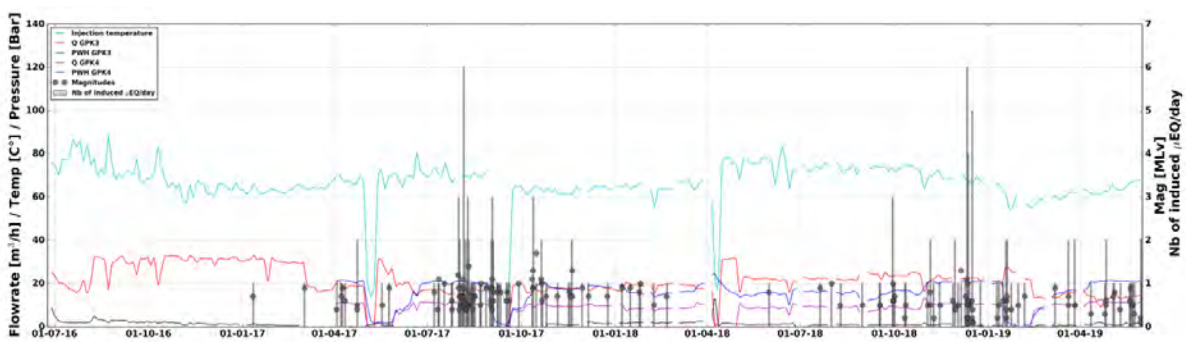


Figure 15. Induced seismicity associated with the injection parameters since the commissioning of the Soultz-sous-Forêts plant (Maurer et al., 2020).

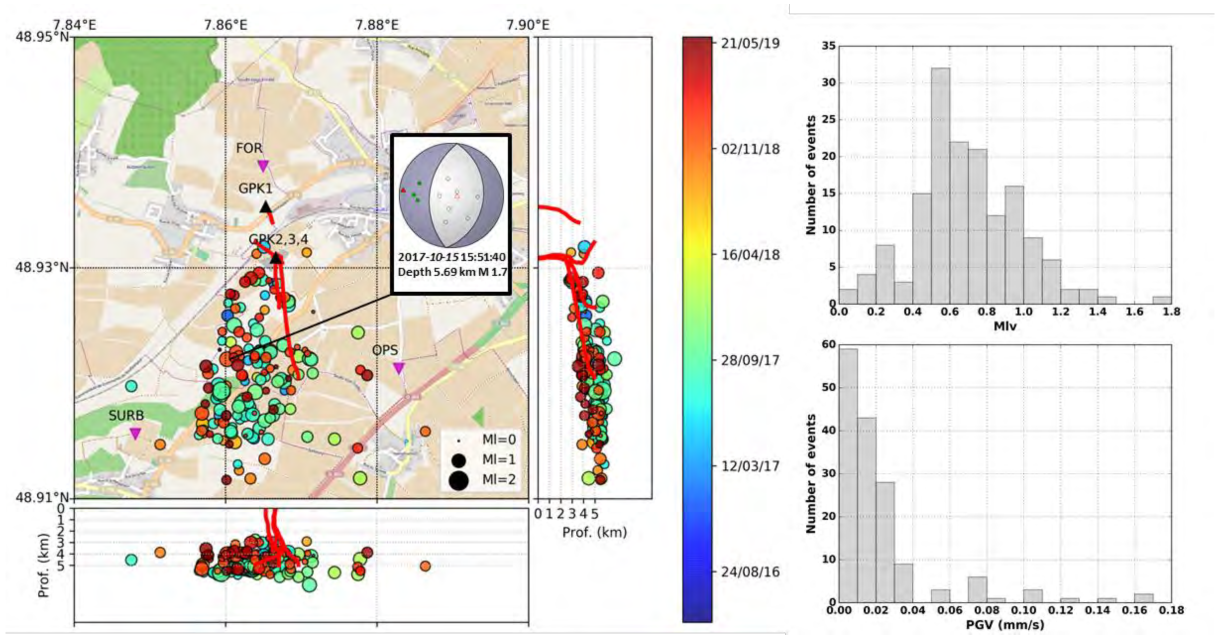


Figure 16. Induced seismicity during geothermal exploitation located around GPK-4 since since the commissioning of the Soultz-sous-Forêts plant (Maurer et al., 2020).

2.6.4 Geodetic monitoring

In accordance with the specifications of the Mining Authorities, a geodetic station was installed on each platform in Soultz-sous-Forêts and Rittershoffen. A geodetic station was installed on the GPK-1 platform in July 2013, and in April 2014 on GPK-2, -3, -4 platform (Soultz-sous-Forêts) and on GRT-1, -2 platform (Rittershoffen). The geodetic stations named GPK1 and GPK2 at Soultz and ECOG at Rittershoffen are indicated by green stars on Figure 10.

The evolution of surface ground deformation is also monthly reported to the Mining Authorities. Figure 17 presents the evolution of the relative position of the station ECOG and GPK2, in the horizontal and vertical directions, as well as the baseline, which is the distance in 3D between both stations. It shows that the relative position varies of about ±2.5 cm in the Northern and Eastern direction and ±1.0 cm in the vertical direction. The baseline oscillates between ±0.5 cm on a mean distance of 6 435.210 m between the two stations. The year 2015 was taken as a reference, as both plants were under construction and no hydraulic activities were performed. The comparison with the reference shows that no significant vertical and horizontal ground motions can be observed at the surface of each plant.

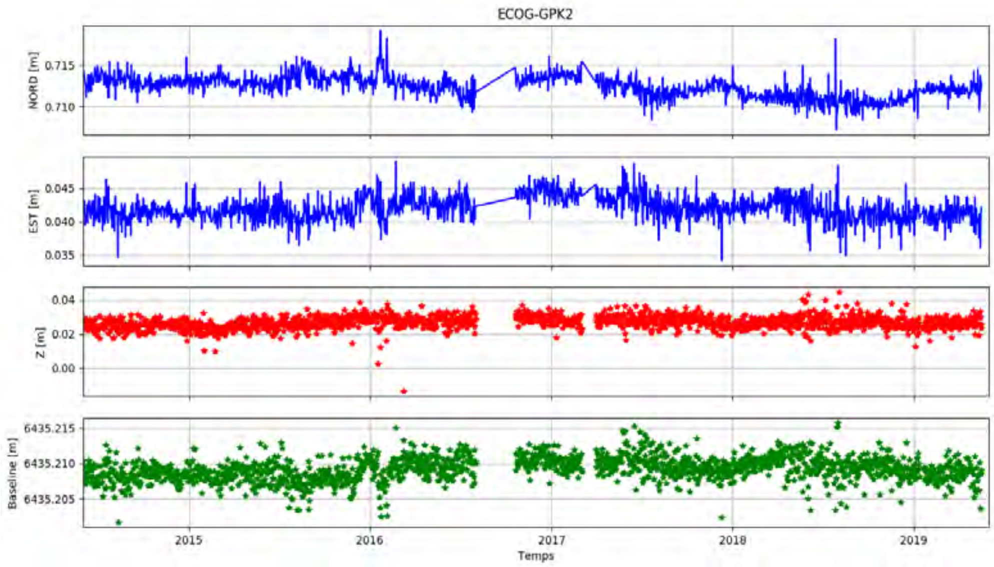


Figure 17. Position of the ECOG station (Rittershoffen plant) relative to the GPK2 station (Soultz-sous-Forêts plant). Results are shown horizontally (blue lines), vertically (red dots) and in baseline (green dots).

3 Rational guidance to governments and regulatory authorities in Switzerland

3.1 Introduction

To date, Switzerland has no federal laws or regulations specifically related to geothermal induced seismicity (Hirschberg et al., 2015; Dumas et al., 2013). In Switzerland, the use of the underground is not managed at federal level but is under the responsibility of the cantons (Hirschberg et al., 2015). Excepted the geothermal plant of Riehen which is operating a district heating close to Basel, there is no running geothermal site exploiting the heat from a deep reservoir for producing heat and/or electricity. In Switzerland, there were several geothermal projects which drilled at great depth like Basel or St Gallen, but both generated felt induced seismicity in 2006 and 2013 respectively, and then, their respective activity stopped.

3.2 Induced seismicity

A comprehensive report about deep geothermal energy in Switzerland based on worldwide case studies was done by a group of experts in 2015 (Hirschberg et al., 2015). For considering induced seismicity during the life cycle of a deep geothermal project, they proposed the following flow chart (**Figure 18**). Risk studies must be conducted at the early stage of a project (planning, drilling, well testing). In parallel, a seismic monitoring must be implemented as soon as the earliest phase of the project when the drill pad location is defined and must operate during all the life cycle including post-exploitation phase (**Figure 18**).

Figure 18. Risk chart for induced seismicity during the life cycle of a geothermal project (Hirschberg et al., 2015)

The main conclusions of this report (Hischberg et al., 2015) are compiled below.

- Deep geothermal energy projects in Switzerland carry a certain degree of seismic risk. Operators and regulators should accept this fact and discuss it openly with the public and decision makers. The seismic hazard and risk can be assessed, albeit with uncertainty, and limited through mitigation strategies. Whether such a risk is acceptable, and when the potential benefits outweigh the risks, is ultimately a political decision.
- Adequate seismic monitoring and real-time data analysis is a key element of the safety of an operation. Experiences of past geothermal projects imply that real-time monitoring and traffic light systems (TLS), coupled to hydraulic operation management, can significantly mitigate the seismic risk and contribute to the safety of the operation.
- An open data policy will contribute to the public acceptance of the project and can help significantly to improving the knowledge and understanding of induced seismicity, and at the same time contribute to public acceptance. Thus, relevant datasets for a given project should ideally be well documented and accessible for science and teaching.
- A more harmonized approach to induced seismicity risk governance is needed across both technologies and cantonal boundaries.
- For Switzerland, industry, permitting and licensing authorities as well as regulators and enforcers need to understand their roles, responsibilities and accountabilities. Induced seismicity risks can be assessed and mitigated, albeit not to zero.

3.3 **Pre-screening seismic risk as an entry point to risk goverance**

Not all geothermal projects carry the same seismic risk. To address this basic fact at an early stage in project, a methodology, GRID (Geothermal Risk of Induced seismicity Diagnosis), has been develloped for minimizing the seismic risk during the life cycle of a given project (Figure 19). GRID is a transparent, reproducible and transferable approach for the initial screening of geothermal energy projects in terms of induced seismicity concerns (Trutnevyte et Wiemer, 2017). GRID is based on indicators of seismic hazard, risk, and social concern. GRID reflects the concern level rather than the hazard or risk level, assuming that higher concern requires more involved measures of risk governance. For example, the lack of trust in the operator or widespread public worry about induced seismicity, increase GRID scores. That means that projects with relatively low hazard and/or risk, but high social concern would still need some type of hazard and risk assessment or monitoring in order to address the social concern.

Another example is the separation between natural and induced seismicity. The influence of natural seismicity on the induced seismic hazard is debated. Higher back-ground seismicity is still assumed to increase GRID scores because more measures are required to distinguish an induced event with confidence for liability purposes. Seismic monitoring provides essential information for trying to distinguish between natural and induced seismicity, which may be important in cases of legal dispute.

Trutnevyte and Wiemer (2017) recommended that GRID scores be evaluated at an early project planning stage, before the drilling or communicating with the affected members of society. However, GRID scores can be revisited throughout the different project stages as new knowledge emerges. At least three parties would ideally be involved: the project operator, the licensing authority/regulator, and one or two independent experts. The Swiss Seismological Service uses the GRID score also as one part of its best practise guidelines for managing induced seismicity (http://www.seismo.ethz.ch/export/sites/sedsite/research-and-teaching/.galleries/pdf_products_software/Good-Practice-Guide-for-Managing-Induced-Seismicity-in-Deep-Geothermal-Energy-Projects-in-Switzerland_v1.0.pdf)

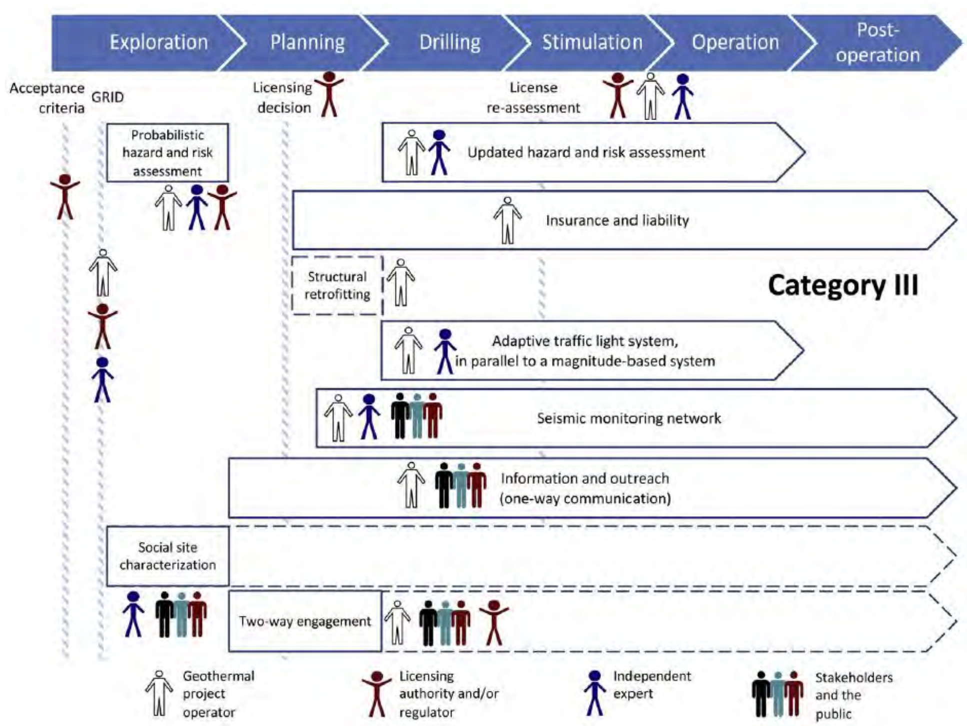


Figure 19. Geothermal Risk of Induced seismicity Diagnosis from Trutnevyte and Wiemer (2017).

3.4 Traffic Light Systems (TLS)

The most widely used tools so far for hazard and risk management and mitigation, and an integral part of 'protocols' or best practice recommendations are so called traffic light systems (**Figure 20**). This approach was also adopted by the EGS projects in Basel (Häring et al., 2008) and in 2013 for the St Gallen hydrothermal project. In both cases, the operators were well aware of the possibility of inducing earthquakes strong enough to be felt. To monitor earthquake activity and to be prepared for hazard mitigation actions, they adapted the 'traffic-light' system to be based on the public response, observed local magnitude and on peak ground velocity values (PGV). A new TLS generation calls Adaptive Traffic Light Systems (ATLS) has been proposed that takes into account modelling as a tool for monitoring the seismic activity. It was a part of the Destress project and fully detailed in Grigoli et al. (2019). A fully quantitative and transparent (closed-formed) ATLS was first proposed in Mignan et al. (2017), with online updating of the underground feedback done with hierarchic Bayesian approach (Broccardo et al., 2017). The method was not only validated in retrospect on the Basel case but also on other deep stimulations worldwide. It was first applied in real-site conditions during operations in Iceland, as described in the respective section (see X.X). Most cantonal authorities in Switzerland follow the recommendations of the Swiss Seismological Service, which suggests the use of such dynamic systems in addition to more classic TLS systems. The Swiss Seismological Service also provides probabilistic risk reports to identify the a-priori risk associated to planned EGS projects in Switzerland. The quantitative, dynamic, approach (see details in deliverable D3.2) is in agreement with the recent conclusions from the South Korea Pohang event review (Lee et al., 2019 - see section 9), which stated that "*it is essential that EGS and related stimulation activities use a risk-based TLS that adapts to evolving hazards.*"

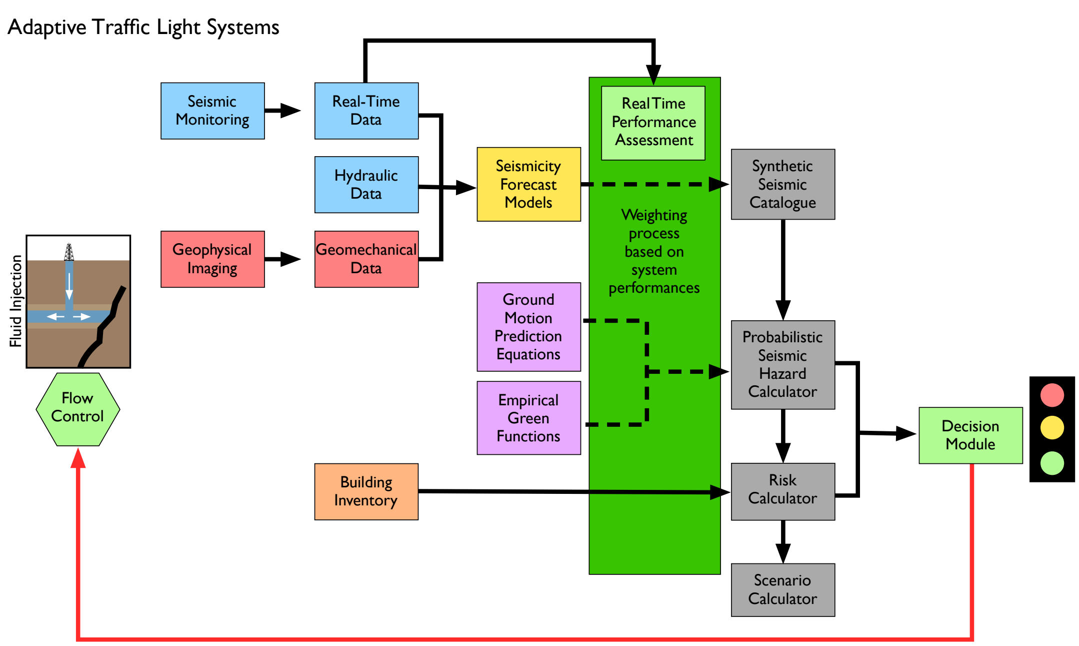


Figure 20. Adaptive traffic light system in Grigoli et al. (2019).

4 Rational guidance to governments and regulatory authorities in The Netherlands

4.1 Introduction

Geothermal energy and more specifically EGS is a relatively new technology in the Netherlands. Most of the heat projects correspond to geothermal doublet with one injection well and one production well (Figure 21). There is no geothermal plant producing electricity yet in The Netherlands.

In Europe, it is known that in a few cases of stimulation operations like the Basel EGS project, induced seismicity has been felt with minor but widespread damage to buildings (Baisch et al., 2009; Mignan et al., 2015). In the Netherlands, due to the geology and the location of drillings, there is a low probability of tangible damage related due induced seismicity. Therefore, for the Dutch geothermal sector, it was challenging to analyze the risks of seismicity resulting from geothermal exploitation of deep reservoirs. Thus, a study was conducted for defining the framework for seismic hazard assessment in deep geothermal faulted reservoirs (Baisch et al., 2016). The outcome would be to clearly propose legal guidelines for regulators and developers in terms of control measures in order to manage safely geothermal projects and improve public acceptance.

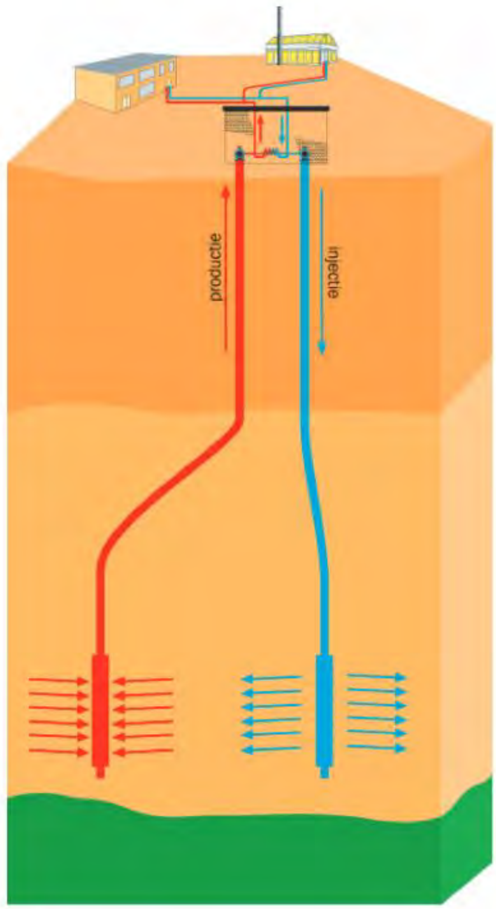


Figure 21. 3D bloc showing a typical geothermal doublet in The Netherlands (source: Kas als Energiebron, 2013)

4.2 Legal framework

The exploration and production of geothermal energy in the Netherlands require a licence from the Minister of Economic Affairs. Under the Environmental Licensing Act, it is also necessary to hold an environmental permit (Geothermie.nl). No costs are associated with the issuing of an exploration licence for geothermal energy, or for the issuing of a production license for geothermal energy. A short explanation regarding the procedure in order to request a license has been published by the Ministry of Economic Affairs. The Dutch innovation programme “Greenhouse as Energy source” has set an extensive roadmap that contains lots of information about legal procedure and licenses. In parallel, the Dutch government is currently preparing a Subsurface Policy Strategy (Structuurvisie Ondergrond) that should ensure sustainable and responsible use of the subsurface (www.nlog.nl).

4.3 **Induced seismicity issue**

To develop deep geothermal projects in a safe and sustainable manner and with the support of the local population in The Netherlands, it is important to mitigate potential hazards related to geothermal operations. One of these hazards, is the occurrence of induced seismicity as a result of the reactivation of pre-existing faults by geothermal operations (Buijze et al., 2019). As there is no EGS geothermal project in The Netherlands yet, a review of existing case studies has been carried out by analysing the responsible physical mechanisms for evaluating the key parameters influencing the occurrences of induced seismicity (Buijze et al., 2019).

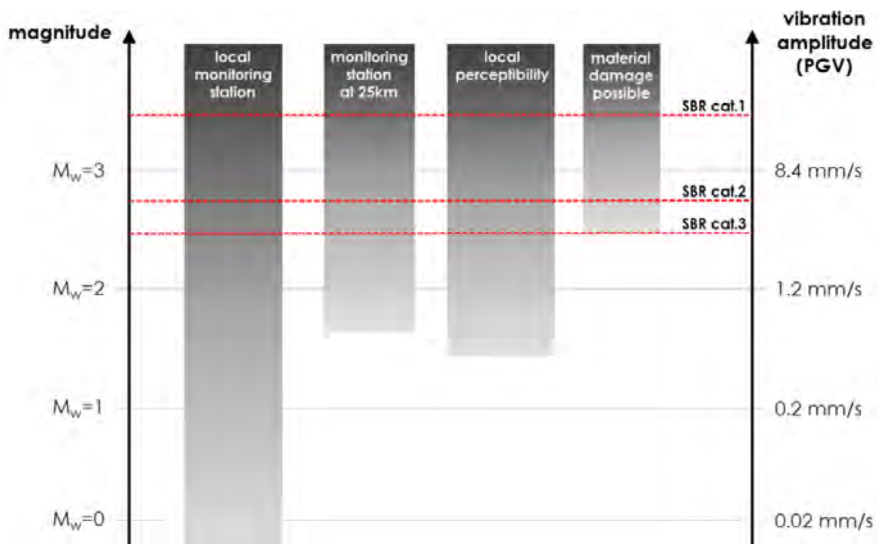


Figure 22. Relationship between PGV and earthquake magnitude (source: Baisch et al., 2016). cat 1: industrial buildings, cat 2: ordinary buildings, cat 3: sensitive buildings).

The KennisAgenda Aardwarmte (Dutch Geothermal Research Agenda) has commissioned experts (Baisch et al., 2016) to develop a protocol for induced seismicity in geothermal reservoirs in the Netherlands. Based on this study, recommendations have been drawn up for a methodology to provide insight into seismic risks and to determine the associated control measures. The research tested the methodology for risk analysis on two geothermal installations in the Netherlands and concluded that for both projects, no tangible seismic activity has been observed to date.

Baisch et al. (2016) defined the relationship between earthquake magnitude and associated peak ground vibrations at the Earth's surface (PGV) for an earthquake located at 3 km depth (Figure 22) Vibration levels above which damage are indicated by dashed lines on **Figure 22**. It includes three categories of buildings ranked according to their sensitivity to structural damage (SBR standard). The typical sensitivity range for a seismometer deployed in the epicenter and at 25 km distance, respectively, is indicated by shaded bars (**Figure 22**).

Seismic hazard assessments are frequently based on peak ground vibrations (PGV) or on peak ground accelerations (PGA, or spectral acceleration, SA). For natural earthquakes, PGA is the most common metric. For induced seismicity where the focus is on higher frequency signals with short duration, PGV is considered a better damage indicator than PGA. Additionally, PGV can be directly compared to engineering standards, providing guidelines at what vibration level damage to buildings and other installations starts to occur. For example, damage to ordinary buildings is considered to be unlikely for PGV < 5 mm/s and human perceptibility is expected to start at 0.3-0.5 mm/s (**Figure 22**). Therefore, for The Netherlands, PGV is proposed as the most suitable metric for addressing seismic hazard associated with geothermal facilities. It turns out that prior to the exploitation license, an evaluation of the seismicity risk is mandatory.

Recommendations for implementing a seismic monitoring to a given geothermal projects have been proposed. The sensitivity and hypocenter location accuracy of a seismic monitoring network is basically determined by the number of monitoring stations and their spatial distribution as well as the type of instruments used. For monitoring geothermal reservoirs, general recommendations are provided by Ritter et al. (2012):

- A minimum number of 5 stations should be operated. An optimized station geometry depends on the number of stations included in the network and can be simulated as part of the network design. Nominal two sigma epicenter location errors should be at the level of +/-500 m or less throughout the region of interest.
- To facilitate the detection of secondary seismic waves, 3-component seismometers should be utilized.
- The eigenfrequency of the seismometers should be ≤1 Hz.
- The I95 noise level at the station locations should be ≤ 2,000 nm/s (vertical component) in the frequency range 5-40 Hz.
- Seismometer recordings should be based upon an absolute time base (GPS synchronization).
- The sampling frequency should be at least 100 Hz.
- Data should be time continuously recorded and stored on a ≥ 24 bit acquisition system.
- Real-time data access is required.

Additionally, it is recommended to operate monitoring instruments at the Earth’s surface to facilitate direct comparison of recordings to engineering standards. To ensure compatibility with seismogram recordings from other operators, it is recommended to use miniSEED as a common data format. It is also recommended to operate TLS (Traffic Light System) as a risk mitigation measure during the geothermal operations.

4.4 Environmental effects

Other environmental impacts are also considered: the auditory and visual nuisance for the surroundings, the decommissioning of a well, and the possible implications of naturally occurring radiative materials (NORM). For these risks guidelines and industrial standards are or will be established by DAGO, the Dutch Association Geothermal Operators. These results and the industrial standards will make it easier to share experiences on the extraction of geothermal energy in the Netherlands, thus reducing risks and possible negative environmental effects (Gonzales, 2017).

4.5 Well integrity

Well integrity management for geothermal wells (low enthalpy) in the Netherlands has historically been based on Oil and Gas Industry standards and procedures. A recent study was commissioned to adapt those standards to the geothermal sector (Ikenwilo, 2016). This study proposes some best practices that could be summarized as follow: a comprehensive review of the entire well system to optimize and minimize cost for best corrosion mitigation over the well life, the need to gather more data to better inform well design, material selection, data logging and sharing of information between operators.

5 Rational guidance to governments and regulatory authorities in Belgium

5.1 Introduction

In September 2015, the Flemish Institute for Technological Research (VITO) started drilling an exploration well, targeting a hot water reservoir at a depth of about 3 km on the Balmatt site near Mol. Finally, three deep wells targeting faulted and fractured limestones from Lower Carboniferous have been drilled (Broothaers et al., 2019).

The construction works for the deep geothermal project at the Balmatt site in Mol are finished. The site in Mol is the very first geothermal doublet in Belgium. The production well will deliver 120°C of very salty geothermal water. Both heat and electricity will be produced (Broothaers et al., 2019).

5.2 Induced seismicity

A seismic network has been installed for monitoring induced seismicity. The seismological network allows us to detect the soil movements to within several tens of metres. Since the first test phase in November 2018, in total 265 events with MI = -1.0 to 2.1 have occurred, all around the injection well. On 21st June 2019 the central has stopped because of a drop of electric tension on the general electricity grid. 2 days after ending the longest operational period, an earthquake has occurred with a magnitude of Ml=2.1 close to the injection well MOL-GT-02. A Traffic Light System (TLS) is also installed and will be updated (https://vito.be/en/news).

5.3 Norm

The formation water is a Na(Ca)Cl brine with up to 165 g/l total dissolved solids. Sodium and chlorine sign for 90% of the dissolved ions. Besides, the water contains minor amounts of Ca^{2+}, Mg^{2+}, K+, and SO_4^{2-}. Geothermal hot water contains naturally occurring gases, chemicals and radionuclides at variable concentrations. The actual concentrations and potentially related hazards strongly depend on local geological and hydrogeological conditions (Vasile et al., 2017). The results of analyses show low values for the activity concentration for uranium and thorium in the formation water and in the precipitate/sediment fraction (Vasile et al., 2017). This study also shows that the activity concentrations of ^{210}Pb and ^{210}Po are low in these samples and the activity concentration of ^{226}Ra is dominant.

6

7 Rational guidance to governments and regulatory authorities in England

7.1 Site presentation (UDDGP)

The United Downs Deep Geothermal Power (UDDGP) project is the first geothermal power project in the United Kingdom. It is located near Redruth in west Cornwall (see **Figure 23**), UK and is part-funded by the European Regional Development Fund and Cornwall Council. The project consists of two deviated wells; a production well to a target depth of 4,500m and an injection well to a depth of 2,500m. Both wells target a sub-vertical, inactive fault structure that is thought will provide enhanced permeability relative to the surrounding granitic rock, sufficient to support circulation of between 20 and 60l/s. Geothermal gradients in Cornwall are relatively good and the bottom hole temperature is expected to be in the region of 190°C, allowing anticipated production to surface at greater than 175°C, which should allow electricity generation of between 1 and 3WMe.

Figure 23. Location of the UDDGP site within the United Dows Industrial Estate (Ledingham et al., 2019)

Site preparation began in early 2018, and the drilling of the first (production) borehole, UD1 commenced in November 2018 following installation of the shallow conductor casing. TD was reached in April 2019 at a measured depth of 5275 meters, (5075m TVD) with a down-hole temperature of approximately 180 - 185°C (awaiting full recovery before final temperature is known). Following logging and preliminary hydro-testing, the rig will be slid on the drill pad to commence the drilling of the shallower injection well, UD2 in early May 2019 (**Figure 24**). The second well is over from summer 2019 and next phase aims to develop and connect the wells for producing enough flow.

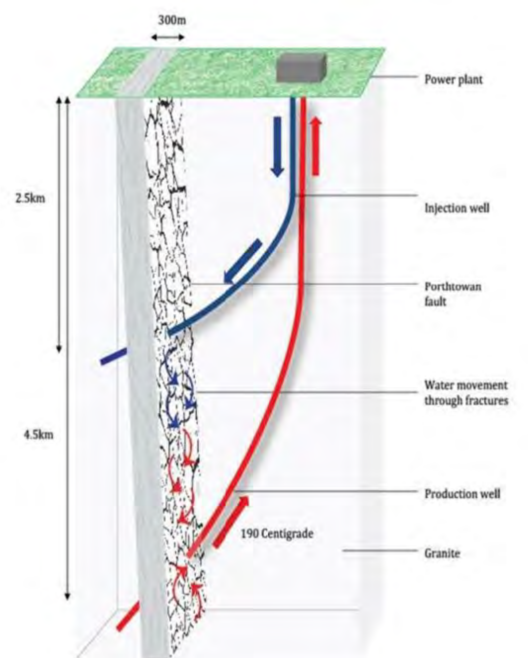


Figure 24. (Left) UDDGP concept showing theoretical well intersection with the targeted fault. (Right) The Anger's Sohne Innovating with hydraulic pipe handling system use to drill both UDDGP wells (Ledingham et al., 2019 and Law et al., 2019).

7.2 Licence legal framework in UK

Detailed planning permission for a 3 wells system on this site was obtained in 2010, together with outline planning permission for a 10MW power plant.
There is still no official licensing scheme for deep geothermal development in the UK (Curtis et al., 2019).

Because of the increasing interest in geothermal energy in the UK, The British Geological Survey published a Briefing Paper in November 2018 on the topic of geothermal heat ownership. (Abesser et al, 2018).

7.3 **Environmental monitoring**

Noise monitoring

The drilling site is located within an industrial estate which is noisy during the day but does not operate at night or at weekends. It is in a generally rural location and therefore otherwise quiet. There are private houses along the western, northern and eastern edges of the state, as close as 300m to the site, and the village of Carharrack is less than 1km to the west. The planning consent for the drilling phase requires noise levels at any receptor to be kept below 65dB during the day and 45dB during the night.

During the drilling rig selection process, the noise signature was one of the most important criteria used and the rig selected is one of the quietest of its size in Europe. Additional noise mitigation and attenuation measures were also put in place around the site and background monitoring and predictive modelling was carried out to predict noise levels in the surrounding area.
Continuous noise monitoring is being carried out during the drilling operation with one monitor on site and three more in nearby locations. The monitors send automatic alerts if noise levels approach or exceed the present limits so that action can be taken if appropriate. The public have access to live noise readings.

The large majority of alerts received since monitoring began have been caused by environmental noise, primarily the weather, trees, animals and traffic. Only a handful of alerts has been the result of drilling noise. An objective, fast and transparent procedure is in place to deal with complaints. Although some nearby residents have complained about being able to hear the drilling rig, even when the noise levels are below threshold, the number of complaints has been very low.

Microseismic monitoring

The micro-seismic monitoring networks installed at the original HDR project in Cornwall, and at other HDR and EGS sites since then, have provided valuable information about the distribution of injected water and the shape and size of the geothermal reservoir. There is therefore an ‘engineering’ imperative for installing such a system at UDDGP to understand how the reservoir develops within the Porthtowan Fault referred to as the local fault calls ‘PTF’.

However, there is also an ‘environmental’ imperative to carry out monitoring because of public concern over induced seismicity. In the UK, this concern began following the occurrence in 2011 of two induced events associated with shale gas exploration in Lancashire. They were very small events (magnitude 1.5 and 2.3) but were widely reported as earthquakes and contributed to very negative media reporting and the subsequent public objections to 'Fracking' projects. Although UDDGP is not a Fracking project, there is still public concern and a degree of mistrust about any projects that involve deep drilling and the circulation of water through underground fractures. As a result, the Local Authority included a requirement both for seismic monitoring and for a monitoring and control protocol in the planning consent for the project.

7.4 **Seismic network**

Geothermal Engineering Ltd (GEL) is installing an integrated Microseismic Monitoring System (MMS) and Ground Vibration Monitoring System (GVMS) designed to detect events down to magnitude 0.0 at a depth of 5km within the immediate vicinity of the reservoir, and to magnitude 1 within a larger 10km by 10km area. Seismometers had been installed by May 2018 to begin background monitoring and several months of data were collected before drilling began (see **Figure 25**). Detection and location of local quarry blasts and natural seismicity demonstrated that the system was working, noise levels were acceptably low and that events as low as magnitude 0 could be detected over a fairly wide area. The full system installation will be complete before the drilling of the first well is complete.

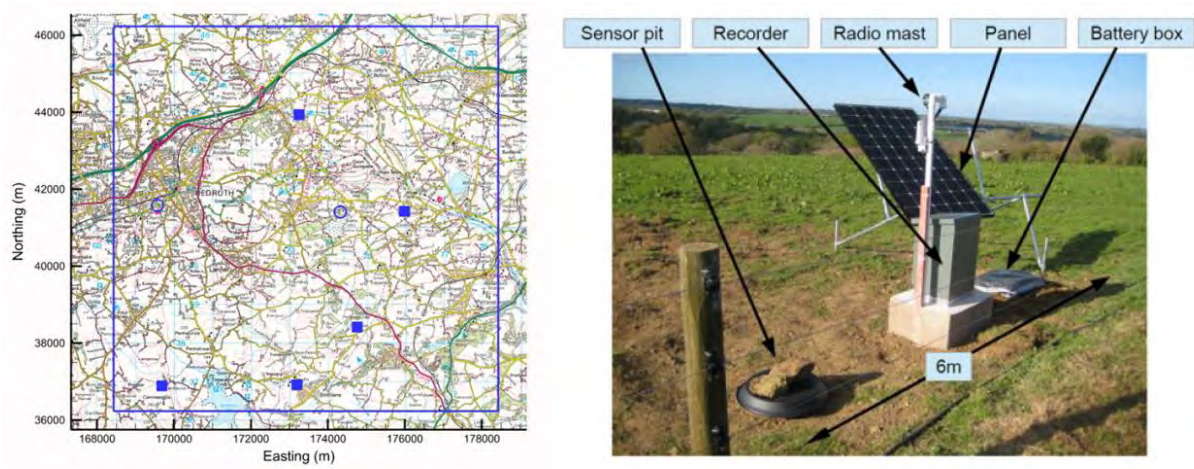


Figure 25: Current (solid circles) and planned (open circles) seismic sensor locations and photograph of a typical installation (Ledingham et al., 2019)

The monitoring and control protocol being put in place to manage any induced seismicity is based on both measured seismicity and surface ground vibration. Therefore, ground vibration motion sensors are also being installed as part of the monitoring system, in locations close to the site, within population centres and adjacent to sensitive structures. This data is acquired, transmitted, processed and stored in the same way as the seismic data (see **Figure 26**).

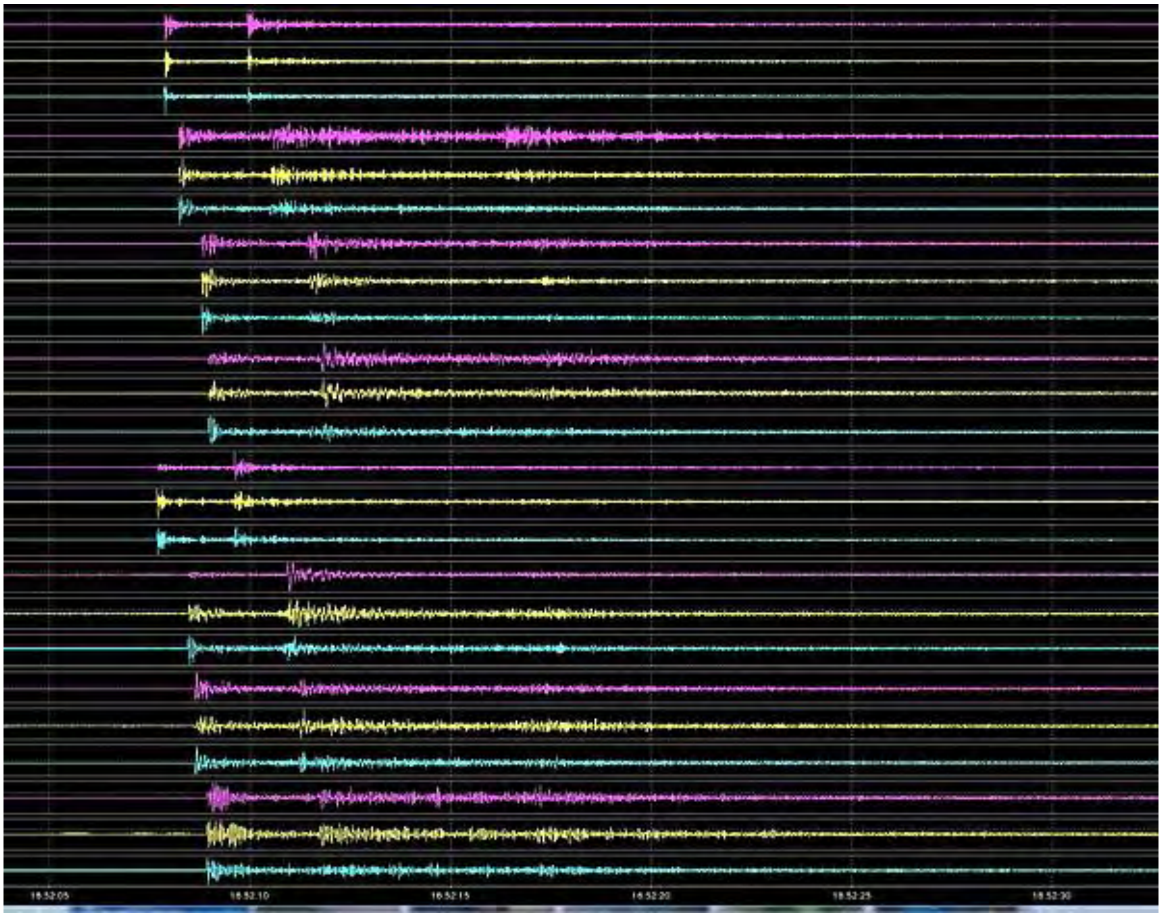


Figure 26: Waveforms of an regional natural earthquake detected on the seismic monitoring system in place and on the British Geological Survey (BGS) national monitoring network.

GEL has also set up a ‘seismicity for schools’ programme, installing simple ‘Raspberry Shake’ seismometers in nine local secondary schools and connecting them to a global network of stations, allowing students to study seismicity on both a global and local scale. This aspect of the education programme provides a link between the national curriculum and the project and gives local students a chance to get involved directly.

7.5 BGS control

Data is transmitted from each station to the data acquisition and processing centre using the SEEDlink protocol and continuous data records are stored on a remotely hosted server, with a duplicate backup system in a separate location. The data acquisition system provides online event detection, processing and also remote database access and visualisation.
Data is transferred to, and then managed by, the British Geological Survey who maintain all seismic records for the UK and make them available to the public.

7.6 PGV scale

The protocol is based on maintaining satisfactory magnitudes of ground vibration with respect to human response. It aims to minimise the ground vibrations that might be considered disturbing by the population in the area. In doing so it also aims to prevent any larger vibrations that might result in damage to buildings. The satisfactory magnitudes are defined in terms of the Peak Ground Velocity (PGV) measured at surface and are based on British Standard (BS) 6472-2:2008, which provides a guide to evaluation of human exposure to vibration in buildings. Cornwall Council already implements BS 6472 within the local planning framework to define the acceptable magnitude and frequency of vibrations due to mine and quarry blasting within Cornwall. This planning framework is the one under which the UDDGP operating permissions are issued.

It is generally considered that a PGV of 2mm/s is the threshold for human perception, but higher values are permissible before disturbance or cosmetic damage results. GEL is implementing a Traffic Light System (TLS) consisting of Green, Amber and Red zones, where each zone indicates a different level of ground vibration, operational intervention and reporting to Cornwall Council.

7.7 UK, EGS and fracking

Geothermal energy in UK is not only disassociated to fracking in the media, this is also the case for legislation. In the UK, induced seismicity caused by ‘fracking’ for hydrocarbons is very tightly regulated, while, induced seismicity caused by hydraulic fracturing for other purposes, such as EGS development, is exempt from this regulation. It is covered in the UK only by default regulations affecting all forms of vibration nuisance caused by industrial activity; as Westaway and Younger (2013) have discussed, the regulations for this, expressed in terms of thresholds of peak ground velocity, probably equate to magnitudes of ≥3 for typical depths of injection. This apparent anomaly has been raised in the media (Willems e al., 2020). Westaway and Younger (2013) suggested that the existing regulatory limits applicable to quarry blasting can be readily applied to cover such induced seismicity. They mentioned that it could correspond to peak ground velocities (PGV) in the seismic wavefield incident on any residential property of 10 mm/s during the working day, 2 mm/s at night, and 4.5 mm/s at other times. Westaway and Younger (2013) discussed that levels of vibration of this order do not constitute a hazard but are rather similar in magnitude to the ‘nuisance’ vibrations that may be caused by activities such as large vehicles passing on a road outside a building. Using a simple technique based on analysis of the spectra of seismic S-waves, Westaway and Younger (2013) show that this proposed daytime regulatory limit for PGV is likely to be satisfied directly above the source of a magnitude 3 induced earthquake at a depth of 2.5 km.

8 Rational guidance to governments and regulatory authorities in Germany

8.1 Introduction

There are several EGS projects running in the German part of the Upper Rhine Valley (**Figure 1**). Some of them had some issues with felt induced seismicity during exploitation (Groos et al., 2013). In Southern Germany, there are no laws specific to geothermal energy, but the projects require mining and building permits as well as a license under the Water Act (Dumas et al., 2013). The permitting process includes an operation plan, where the mining authority can add conditions. For example, after seismicity increased in the Landau geothermal plant, the mining authority requested an adjustment of the operation plan and the installation of a monitoring system, a reduction of injection pressure, and the acquisition of higher level of insurance coverage (Dumas et al., 2013). It is the reason why a seismic network for monitoring induced events is systematically installed for EGS project in Southern Germany.

Generally, the geothermal concept is made of two wells, one for production with a down-hole pump and one for reinjection in the deep reservoir (**Figure 27**). Because low initial natural permeability, the geothermal wells are thermally, chemically and hydraulically stimulated in order to improve the connection between the well and the reservoir. Such projects are targeting local nearly vertical normal faults intersecting the Muchelkalk limestone, the Buntsandstein sandstone and the top granitic basement (Vidal and Genter, 2018).

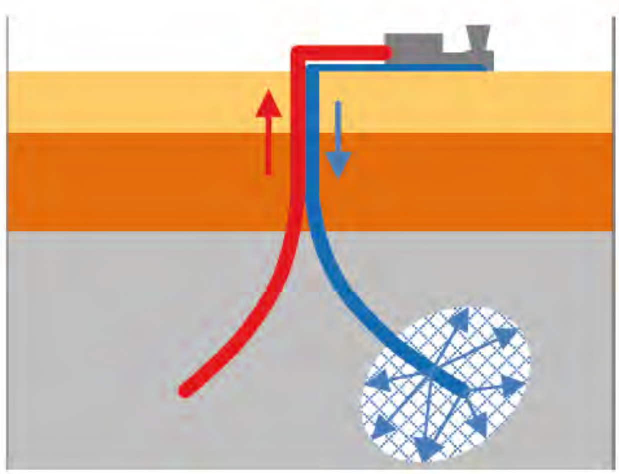


Figure 27. Geothermal concept at Landau, Rhine Palatinate, Germany (Groos et al., 2013)

8.2 Induced seismicity in Southern Germany

Seismic events with local magnitude M_L <1 during the hydraulic stimulation of the geothermal wells in Landau in the Rhine Palatinate area were recorded in March and April 2006. During the geothermal exploitation of the plant, the two strongest seismic events took place on 15th August 2009 (M_L = 2.7) and 14th September 2009 (M_L = 2.4).

Groos et al. (2013) studied relationships of local magnitude with perceptibility and potential to cause damages to buildings in the area of Landau (**Figure 28**). The assessment of the observed ground motions is based on the concepts and indicative values of the German industry standard DIN 4150 which is dealing with the impacts of vibrations caused by construction activity on humans and buildings. They show that the ground motions of the analyzed induced seismic events with local magnitudes exceeding M_L ~ 1.3 can be perceptible in Landau. The ground motions due to the two strongest seismic events with local magnitudes of M_L = 2.7 and M_L = 2.4 reach the indicative value (3 mm/s) for potential damages at very sensitive buildings in Landau. Since the commissioning of the geothermal power plant in Landau In 2007, this site operates with a seismological network with up to eight measuring stations for continuous micro-seismic monitoring (blue circles in **Figure 29**). From 2009, the Insheim power plant and the Landau power plant operated with several seismic monitoring networks belonging to various organizations. They also follow the standard DIN 4150 with up to 16 stations (squares in **Figure 29**). They are equipped with standard precise seismometer, which are able to measure the ground vibration velocity in three orthogonal spatial directions.

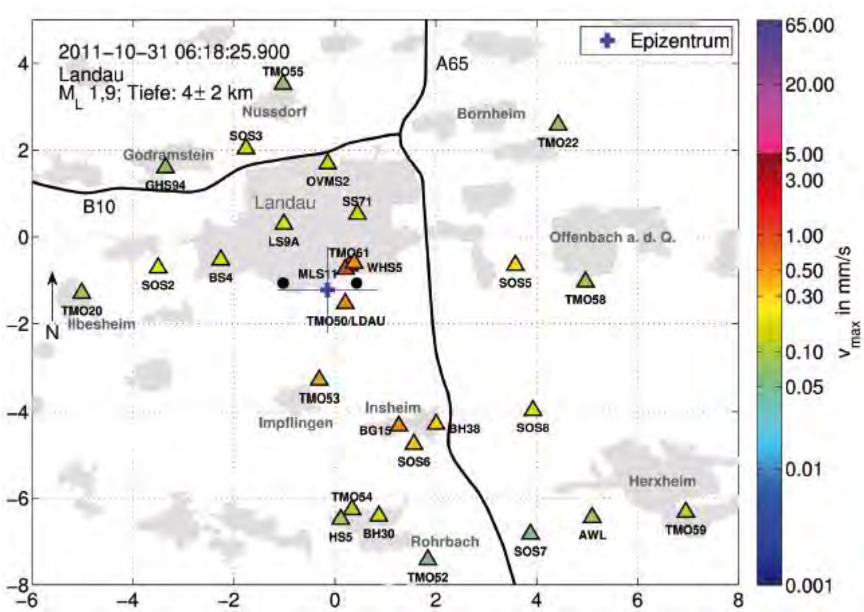


Figure 28. Peak ground velocities observed for the earthquake 2011–10–31 06:18:25 UTC with a local magnitude of 1.9 (Groos et al., 2013).

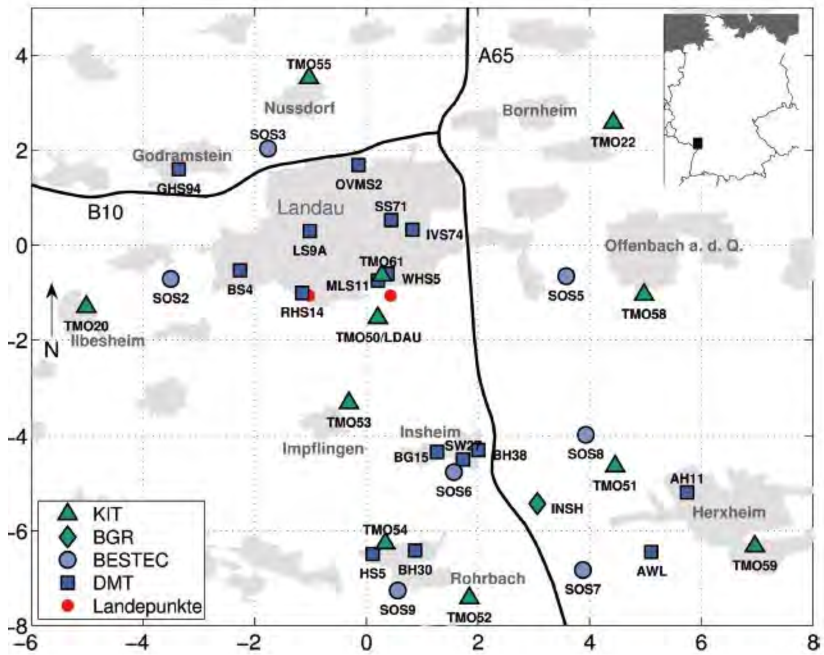


Figure 29. Seismic stations operated by the geothermal power plant operators (blue) as well as public research institutions (green) in the Rhine Palatinate area. Red dots mark the end points of the production well (west) and the reinjection (east) well located at about 3 km depth (Groos et al., 2013).

In the same area, a dense local seismic monitoring network was deployed around Insheim, consisting of a high-gain network for monitoring microseismicity and a low-gain network for vibration measurements in buildings, in case of larger events. The low-gain network consists of 13 stations with 4.5Hz three-component geophones and a dedicated acquisition system. A seismic event is detected by the low-gain network if a certain threshold is exceeded (between 0.01 mm/s and 0.1 mm/s). Thus, these stations provide waveforms only for larger events that might be felt by the population. The permanent high-gain network consists of nine permanent three-component stations (reduced to six permanent stations since March 2014) operated by site owner and three permanent borehole stations operated by the regional earthquake survey. About 15 temporary stations were deployed at Insheim by the Federal Agency for Geosciences and Resources i a framework of a research project. The permanent stations operated by the site owner are equipped with Güralp 1Hz Seismometers (CMG-6T) and Güralp acquisition systems (Küperkoch et al., 2018).

There is a clear correlation between seismicity rate and operational status of the Insheim plant (**Figure 30**). Downtimes and corresponding starting times of the Insheim plant are followed by an increase of the seismicity rate (Küperkoch et al., 2018).

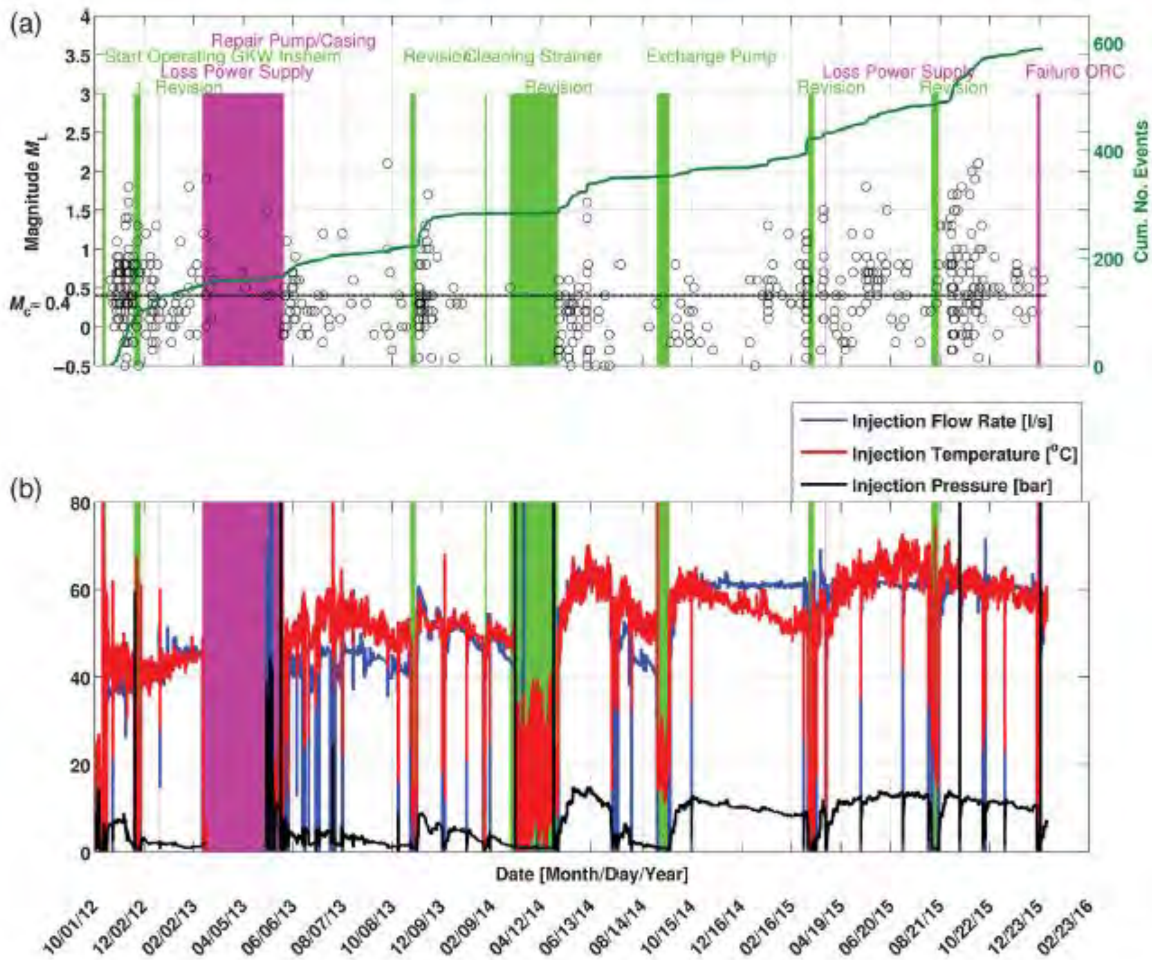


Figure 30. a) Temporal distribution of seismic events and (b) corresponding operating parameters injection flow rate, injection temperature, and injection pressure. Shaded areas are planned (green) and unplanned (pink) downtimes of the geothermal site. The cumulative number of events is plotted on the right y axes (Küperkoch et al., 2018).

In Baden Württemberg, a permanent seismic network which is monitoring the Bruchsal plant since June 2010 is composed of four seismic stations located maximum 4 km away from the production and injection wells (Gaucher et Kohl, 2013). Each station contains a 3C-geophone of 4.5 Hz natural frequency installed at 100 m depth in a dedicated well. The primary target of the monitoring is the volume located between the injection and the production intervals, from ~2.5 km depth up to the surface. As soon as the network was operating, a detection procedure to automatically select seismic event candidates was defined. Then, an operator periodically reviews all seismic candidates to confirm whether they are events induced in the reservoir or not. There was no felt seismicity associated to Bruchsal plant operation.

8.3 German regulations for Southern Germany

The mining authorities of Southern Germany created guidelines for geothermal plant operators which are obliged by law to follow. They have to consider vibrations and induced seismicity. The geothermal installations must be operated in such a way that the admissible values of the effects caused by floor vibrations on structures are following the standard DIN 4150. The measuring networks are to be adapted to the state of the art. Detailed about thise guidelines are not in the public domain but the paper of Groos et al (2013) and Küperkoch et al. (2018) described the technical characteristics of the seismic network. Seismic and vibration networks are to be maintained and operated in accordance with the state of the art. Modification of the monitoring networks require the approval of the local authorities.

8.4 Slow deformation related to geothermal activity

Mid 2013, an uplift began centered on the geothermal power plant of Landau due to a leak in the reinjection well. The uplift has an extension at kilometer order (**Figure 31**). This uplift occured until mid March 2014, followed by a subsidence centered at the same location. Observation and analyze of the surface displacements during the whole 2013-2014 period, including the subsidence after the power plant shutting down in March 2014 were analysed by SAR images and leveling measuring (Heimlich et al., 2016). They processed Synthetic Aperture Radar (SAR) images from TerraSARX satellite, covering January 2013 to January 2015 and produced velocity maps. At 500 meters from the power plant location, the uplift reaches 4.5cm. It was assumed that the vertical displacement was higher at the power plant location. But at this place, the satelitte data suffer of decorrelations due to the large displacement rate. Moreover, the occurrences of vegetation surrounding the power plant hinder difficult to quantify properly the full displacement in this area.

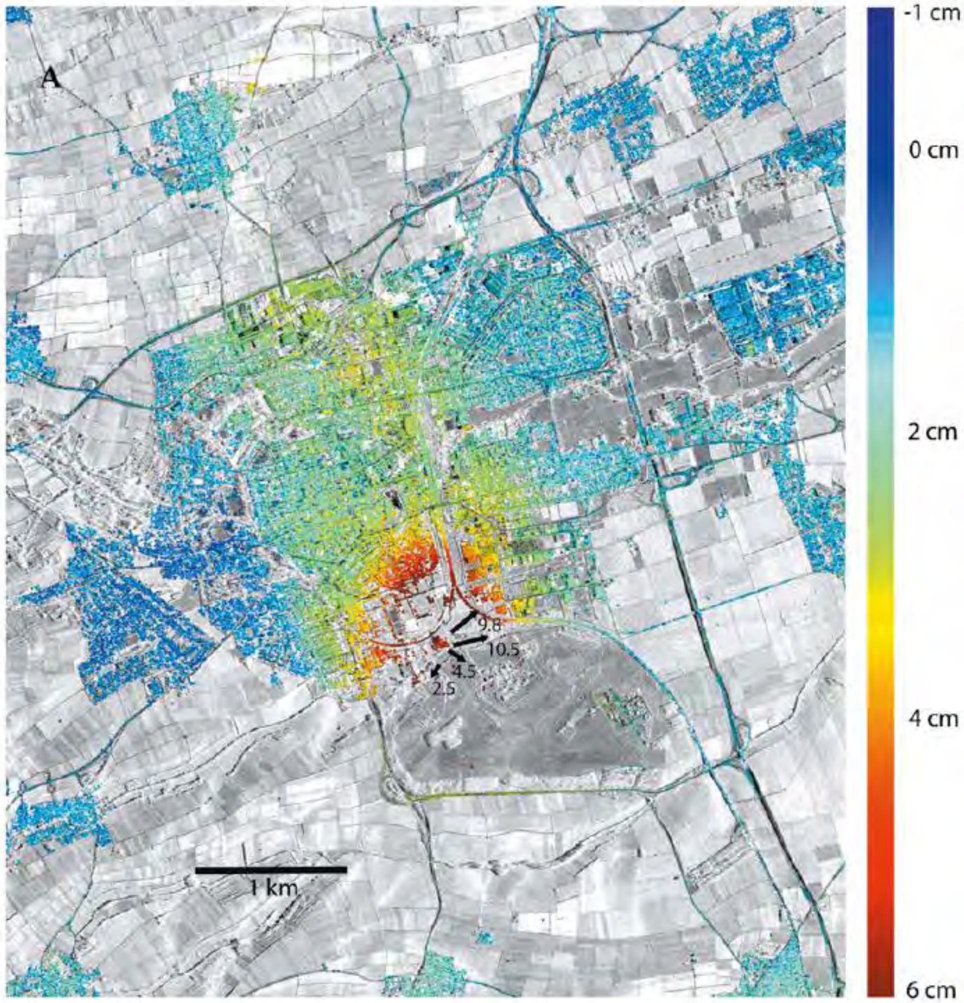
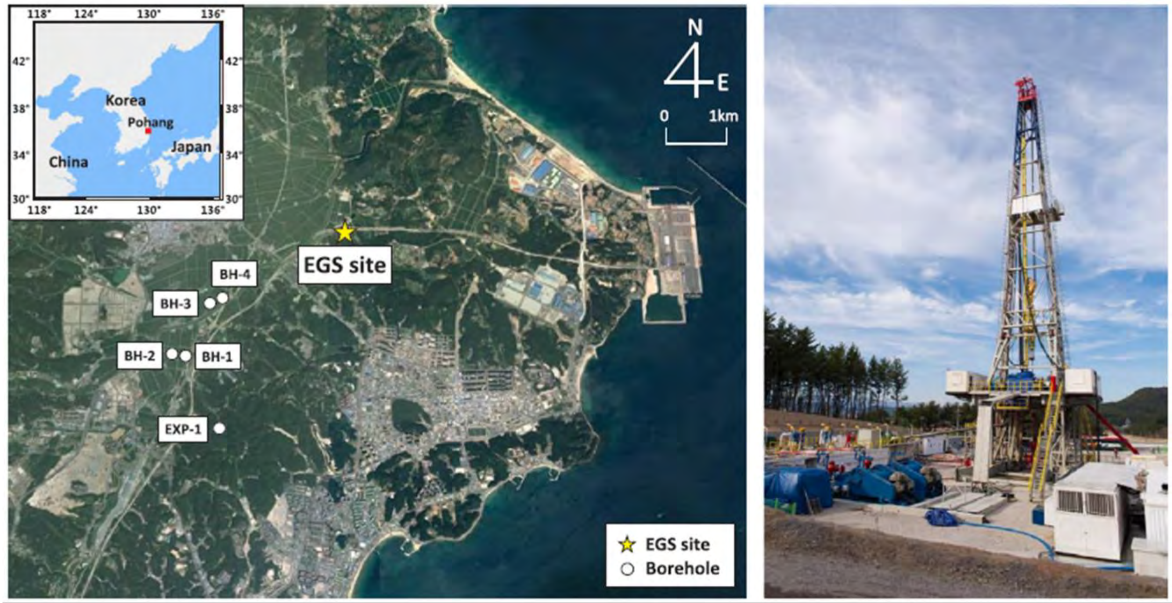


Figure 31. Surface displacements over Landau area from April 2013 and March 201 4 satellite images (Heimlich et al., 2016). Horizontal displacements are indicated by a black arrow which start at the geothermal plant location.

9 Rational guidance to governments and regulatory authorities in Korea

9.1 Introduction

The first EGS pilot plant project in South Korea was initiated in December 2010 in Pohang. The site is located at the south eastern part of Korea at 36°06'24"N, 129°22'42"E (Fig. 32). The ultimate goal of the Pohang EGS project was to construct a geothermal power plant with an installed capacity of 1 MW. The project was conducted by a consortium of six organizations from industry, research institutions, and a university, led by NexGeo, Inc., which specializes in geo-engineering and geo-energy. Two drill holes have been completed to depths of 4217m (PX-1) and 4348m (PX-2) as total vertical depth. Prior to the initiation of the Pohang EGS project in 2010, there were already four boreholes that were drilled in early 2000 to determine the geological conditions and thermal properties. The first large-scale hydraulic stimulation for EGS development in South Korea was conducted through a 140m open-hole section of PX-2 in January and February of 2016, and four other stimulations were performed in PX-1 and PX-2 by September 2017 resulting in the injection of 12,798 m3. In November 15, 2017, earthquake magnitude 5.4 ML occurred at the EGS site two months after the last hydraulic stimulation. The government-appointed commission concluded after one-year study that the Pohang earthquake was triggered due to the hydraulic stimulations conducted at the site (Lee et al., 2019). Relatively large magnitude compared to injected fluid volume, and the range of the magnitude of induced seismicity (< 3.1 ML) during hydraulic stimulation remains questions to be answered in order to unveil the exact mechanisms of how this earthquake can be triggered.



(a) (b)

Figure 32. Map showing the location of Pohang EGS site and five boreholes; (b) Photo of the Pohang EGS site (Kim et al., 2018).

9.2 Main regulations for a deep geothermal project

To date, no laws or regulations specifically related to a deep geothermal project and induced seismicity exist in Korea. On the other hand, ground vibration criteria for blasting operations exists (Table 1, MOCT, 2002). The consortium of the Pohang EGS project developed a protocol and traffic light system to manage the risk of induced seismicity from hydraulic stimulation (Kim et al., 2018). Three version of traffic light systems were applied to the five hydraulic stimulation campaigns (Figure 33). Figure 33 (a) was designed before the first hydraulic stimulation. After the first stimulation, the consortium made the modified version of traffic light system based on the experience of the first hydraulic stimulation which was officially notified to the Korean government (Figure 33 (b)). Figure 33 (c) was used for the fourth hydraulic stimulation in PX-1 hole which was operated by the DESTRESS consortium (Hofmann et al., 2019).

Table 1. Criteria on ground vibrations for different types of buildings (MOCT, 2002)

Type of buildings	Threshold of ground velocity (cm/s)
Cultural heritage	0.2
Structures with masonry wall and wood ceiling	1
Structures with underground foundations and concrete slabs	2
Low storied structures with steel concrete frameworks and slabs	3
High Storied structures with steel concrete frameworks and slabs	5

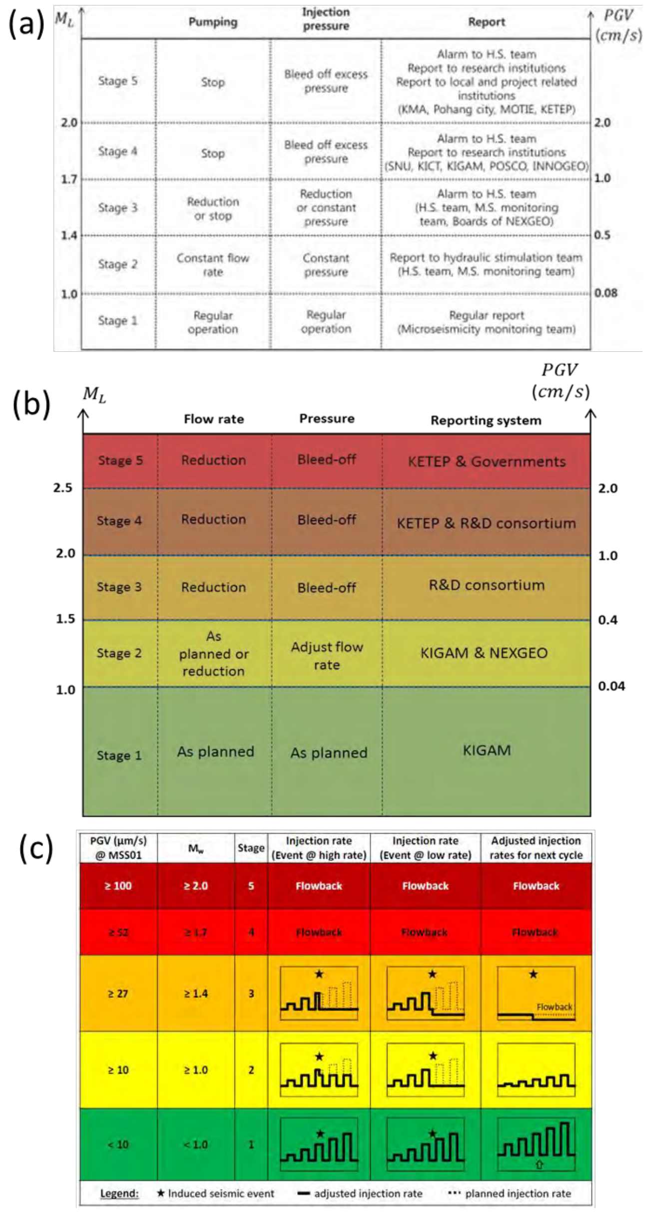
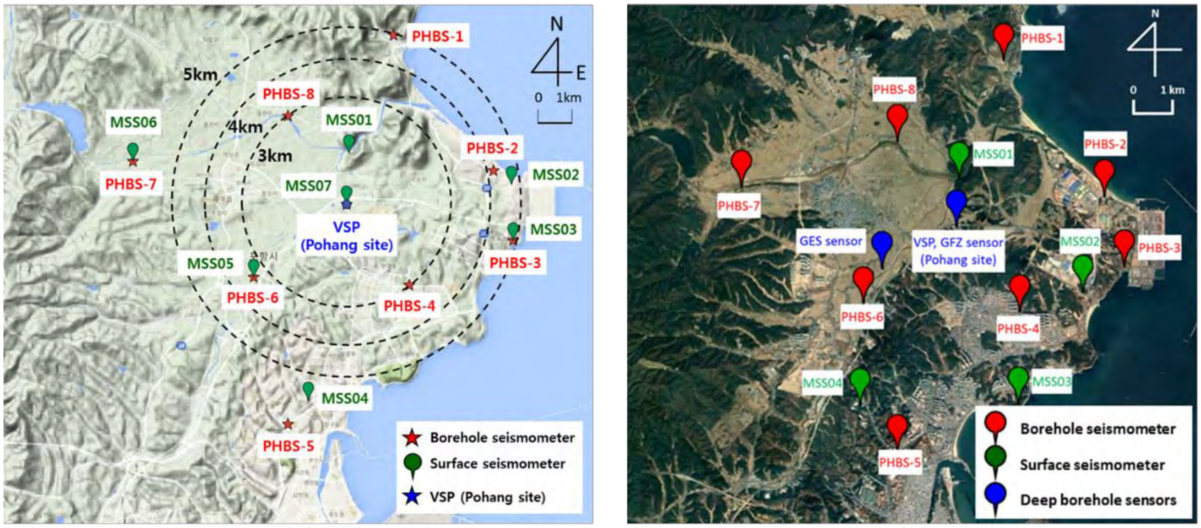


Figure 33. Traffic Light Systems for (a) the first stimulation (Kim et al., 2018) (b) the second, third and fifth stimulation and (c) fourth stimulation (Hofmann et al., 2019).

9.3 **Induced seismicity monitoring**

Local seismic monitoring system has been established to detect background and injection-induced seismicity (Figure 34). Eight shallow borehole seismometers (PHBS-1~PHBS-8) were installed at depths of 120-130 m. A vertical seismic profile (VSP) consisting of three sensors was installed at the PX-1 hole at a depth of 1,360 m by Korea Institute of Geoscience and Mineral Resources (KIGAM). Seven temporary surface seismometers (MSS01~MSS07) were distributed around the Pohang EGS site. A deep borehole sensor from Swiss Seismological Service (SED) was installed at the BH-4 hole at a depth of 2,260 m from the second stimulation. 17-level VSP from GFZ was deployed at the PX-2 well at 1,350 to 1,150 m measured depth (Hofmann et al., 2019).



(a) (b)

Figure 34. A map showing the location of the Pohang EGS site and seismic monitoring stations for (a) the first stimulation (b) second to fifth stimulation (Kim et al., 2018). GFZ sensor was used only for the fourth stimulation.

10 Rational guidance to governments and regulatory authorities in Iceland

10.1 Introduction

The growing population and the number of tourists in the city of Reykjavik (Iceland) are pushing the supply of Geothermal energy at its limit. Despite the surging demand, no new low-temperature wells have been drilled in the last 20 years. It follows that additional sources of low-temperature heat need to be accessed to ensure a reliable heat provision for the city center. To meet this target, the current capacity has to be increased by both drilling new wells and stimulating older inactive wells.

Geldinganes RV-43 well has been identified as a possible source of geothermal energy for increasing the supply of hot water (this project does not target any electricity production). Geldinganes is a peninsula within the city limits of Reykjavik, with an exceptional geothermal gradient (Figure 35). Given these favorable conditions, in 2001, the RV-43 well was drilled. Although the required temperatures were found, the flow rates were insufficient for economic production. However, recently, the Geldinganes site was re-assessed for the development of new and re-stimulation of existing production wells. One of the first targets of this plan was the hydraulically re-stimulation of well RV-43 to improve its productivity to feasible costs.

Geldinganes RV-43 well was re-stimulated in October 2019. The project consisted of two-stage cyclic pulse stimulations in a pre-existing fracture zones penetrated by RV-43 and isolated with straddle packers. This is a technology adopted from the oil and gas industry, which allows isolating selected zones of the well and performing an accurate injection in the target zone. In this re-stimulation, two zones were isolated and stimulated sequentially. In particular, in each of the zones was performed the so-called cyclic injection scheme (“cyclic” stimulation), which consists of a sequence of short-term cycles. The application of short-term cycles is based on the concept of fatigue hydraulic fracturing introduced by Zang et al. (2013, 2017b, 2018). This technology (in general) aims to three major improvements: first, increasing the stimulated reservoir volume by creating a complex fracture growth; second, reducing the breakdown pressure; third, reducing the magnitude of the largest induced seismic event. The concept of cyclic stimulation is one of the soft stimulation techniques evaluated by the DESTRESS consortium. In this project, for the operators, the major concern was the seismic risk related to the injection. As no other risk has been analyzed, the rest of the Section focuses on fluid-induced seismicity.

Similar to most of the other countries, in Iceland, there is not currently a regulatory framework for fluid-induced seismicity. In this regulatory vacuum, it was decided to implement a series of risk studies in line with the current state of knowledge in earth-science and engineering. The implemented risk assessments are beyond the prevailing standards in geothermal projects, but in line with the good practice recommendation of the DESTRESS project (Grigoli et al., 2017), with Swiss good practice recommendations (Trutnevyete and Wiemer, 2017) and the recommendations of the international expert panel investigating the Pohang earthquake (Lee et al., 2019).

In Geldinganes, to the best of our knowledge, it was introduced for the first time an “updatable” a-priori risk analysis. The goal of this analysis was to collect all the possible source information together with the associated uncertainties into a coherent risk analysis framework. Most important, the a-priori risk assessment serves as a prior source of analysis, which must be updated consistently as soon as new data arrives. Because the initial uncertainties were substantially large (see the following of this Section), updating it with in-situ information was a paramount. The a-priori risk assessment presented in Geldinganes is thus also a first and critical step for moving from risk assessment to full risk management. In the following, we describe the main points of the a-priori risk assessment, together with the updating scheme. We also show some of the post-project key results. At this stage it is not possible to provide a full detailed report on the outcome of this project as the data are currently being analyzed.

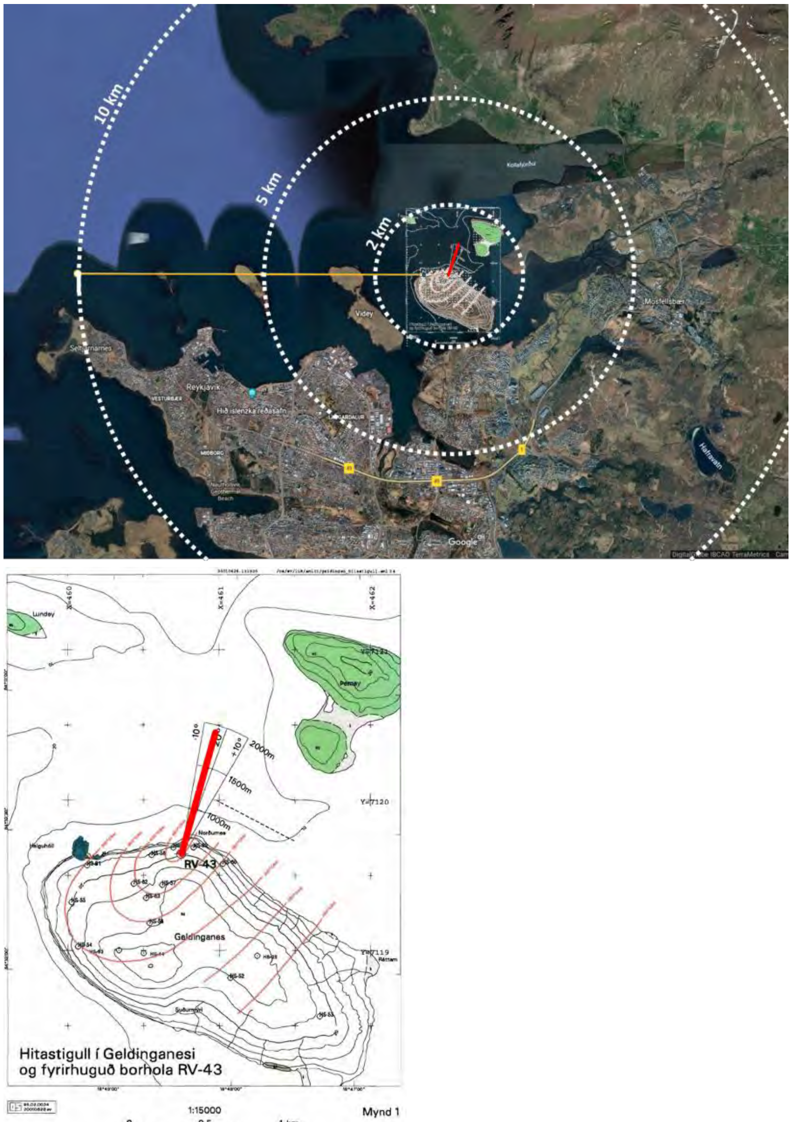


Figure 35. Map view of the Geldinganes island in Reykjavik on the left, where the dashed circles are centered at the head of RV-43 with radii as indicated, and the red solid line represents the deviated RV-43 (figure extracted from Google Earth). On the right, the Geldinganes area is plotted with all its wells, the temperature gradients measured at shallow depths and with the solid red line representing RV-43 at different measured.

10.2 **Probabilistic induced seismic a-priori hazard framework**

The a-priori risk assessment is based on a fully probabilistic approach. The need for the probabilistic-based approach is motivated by the stochastic nature of earthquakes, the many and vast uncertainties associated with the process of inducing seismicity, and the requirements of regulators, the public, and in case insurances. Both hazard and risk approaches follow standards proposed, among others, by the Swiss Seismological Service (SED, 2017) and related references (Broccardo et al. 2017a, Mignan et al., 2015; 2019a-b), which are based on a combination of Probabilistic Seismic Hazard Analysis (PSHA) and the PEER-PBEE framework.

The output of PSHA is the probability of exceeding a given intensity measure (e.g., peak ground acceleration, PGA, peak ground velocity, PGV etc.) at a given distance d from the injection site, based on the number of events above a given minimum magnitude , the frequency distribution of the magnitude (i.e., Guttenberg-Richter distribution), and an empirical ground shaking attenuation function. The last can be an intensity prediction equation (IPE) based on felt intensity, or a ground motion prediction equation (GMPE) based on a physical measure (e.g., PGA, PGV). This probabilistic framework has two main axes to be defined: (i) the probabilistic characterization of the seismogenic source model, and (ii) the ground motion characteristic model (describing the expected ground vibration given the occurrence of an earthquake). The first axis gives the temporal and spatial forecast of the earthquake ruptures, while the second axis is characterized by Ground Motion Predictive Equations (GMPEs) to link the earthquake rupture with the expected ground shaking at the site of interest.

In addition, to include also the epistemic uncertainties, i.e. alternative source models and alternative GMPEs a logic tree structure with weighted branches (indicating the belief in a given model) was defined. Figure 36 shows the proposed logic tree adopted after discussions between experts for this a-priori risk analysis. The first level of the logic tree describes the epistemic uncertainty related differ source models and source model parameters while the second level on the uncertainty relates to the ground shaking model (i.e. choice of the appropriate GMPEs). The upper bound of the Gutenberg-Richter distribution was fixed to .

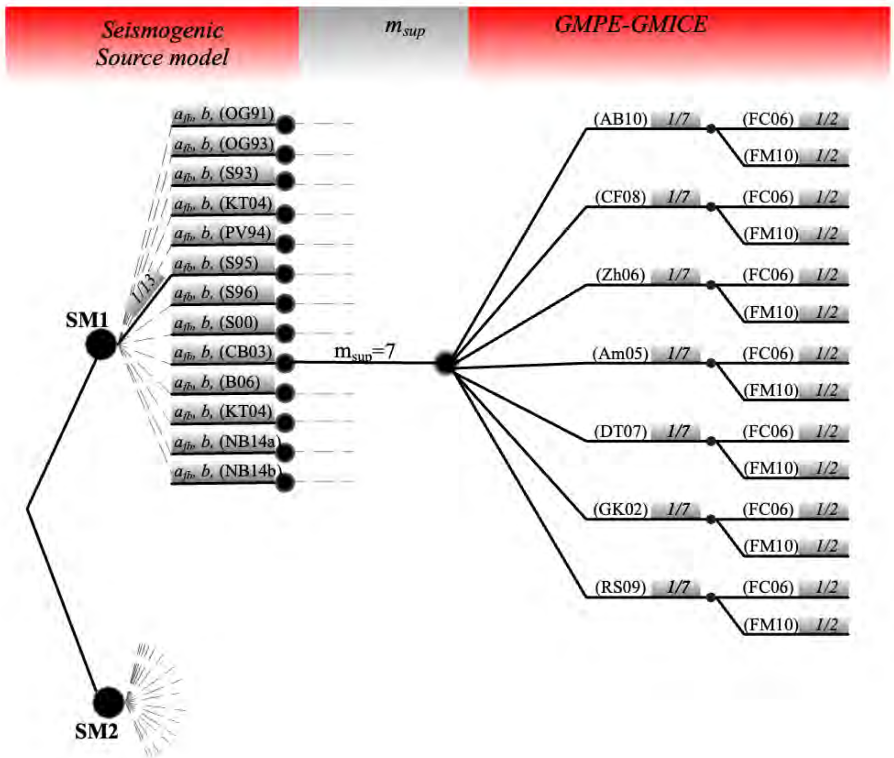


Figure 36 Logic tree adopted for the PSHA analysis. Source (Broccardo et al., 2019) - See Table 2 for GMPE acronyms.

10.2.1 Seismogenic source model, existing analogues and empirical evidences

In the a-priori risk analysis, it is assumed that induced seismicity nucleates and eventually extends in the vicinity of the stimulation. Consequently, a point source located at the coordinates of the injection point was used as unique source model. This implicitly excluded any geometrical uncertainty on the location of the hypocenter.

Forecasting the number of events associated with a reservoir stimulation is a hard task difficult to accomplish robustly. Empirical data from similar sites can be used as a first-order surrogate analysis, but in the case of Geldinganes, only limited experience existed. Considering these vast uncertainties, the a-priori risk analysis was based on simple models since they tend to be more robust and not subject to overfitting. In addition, simple models are more easily updatable with real-time data.

Following these principles, the a-priori risk assessment considered two simple models to analyze the uncertainty and have a first-order crude forecast of the underground response to injection:

- **Model S1** assumes site-specific constant underground feedback, and it is a pure empirical model;
- **Model S2** simulates the fluid and overpressure propagation for the planned injection protocol based on one-dimensional diffusion and stochastically distributed seeds. Therefore, it is a stochastic simulator with a first order physical process incorporated.

These two models captured to a first-order the epistemic uncertainty in forecasting seismicity since they express alternative approaches to forecasting (purely empirical and partially physics-based). Both models were combined in the hazard computation with a weight of 50% each.

SM1 assumes that the seismic underground feedback per volume affected by significant pore-pressure change is a site-specific constant. Empirical evidence shows that the volume affected scales with the volume of fluid injected; this implies a relation between the expected number of earthquakes and the volume injected, which is written as

, **(1)**

where is the so-called underground feedback parameter, is the -value in a Gutenberg-Richter distribution, is the injection duration, and is the mean relaxation time of a diffusive process (Mignan et al., 2017). Moreover, one can easily show that the expected total number of fluid-induced earthquakes is . This relation is well accepted in the academic community as a first order model and sometimes also referred to as the Seismogenic Index model (e.g. Dinske and Shapiro, 2013; van der Elst et al., 2016; Mignan, 2016; Broccardo et al., 2017b). This model can also be interpreted in terms of flow rate Qstim (or ΔV) versus induced seismicity rate (Mignan et al., 2017), i.e. (Broccardo et al., 2017), which allows to use a Non-Homogenous Poisson Process (NHPP) as first order stochastic occurrence model. Observe that this model only applies to the stimulation phase and post stimulation phase with no negative flow rate.

The underground feedback parameters and can be calculated during the stimulation (Mignan et al., 2017; Broccardo et al., 2017b). However, a-priori knowledge is very limited, and the range of possible values is vast. Table 10.1 lists a collection of parameter estimates for different sites, which was used as input for the a-priori risk study. Later in this section, we show how the vast uncertainties at rate model parameters, was remarkably reduced by an online monitoring during the stimulation.

Table 10.1 Underground seismic feedback to deep fluid injection.

Site (country*, year)	a_{fb}†	*b*		References
Ogachi OG91 (JP, 1991)	-2.6	0.7	4.3800	Dinske and Shapiro (2013)

Ogachi (JP, 1993)	-3.2	0.8	0.6942	Dinske and Shapiro (2013)
Soultz (FR, 1993)	-2.0	1.4	0.6942	Dinske and Shapiro (2013)
KTB (DE, 1994)	-1.4	0.9	27.6359	Mignan et al. (2017)
Paradox Valley (US, 1994)	-2.4	1.1	1.1002	Mignan et al. (2017)
Soultz (FR, 1995)	-3.8	2.2	0.0003	Dinske and Shapiro (2013)
Soultz (FR, 1996)	-3.1	1.8	0.0087	Dinske and Shapiro (2013)
Soultz (FR, 2000)	-0.5	1.1	87.3925	Dinske and Shapiro (2013)
Cooper Basin (AU, 2003)	-0.9	0.8	138.5078	Dinske and Shapiro (2013)
Basel (CH, 2006)	0.1	1.6	34.7916	Mignan et al. (2017)
KTB (DE, 2004-5)	-4.2	1.1	0.0174	Dinske and Shapiro (2013)
Newberry (US, 2014a)	-2.8	0.8	1.7437	Mignan et al. (2017)
Newberry (US, 2014b)	-1.6	1.0	11.0021	Mignan et al. (2017)

[*] ISO code; [†] referred to as seismogenic index in Dinske and Shapiro (2013).

Model S2 introduced a first-order physical process into the forecasting (Gischig and Wiemer, 2013; Goertz-Allman and Wiemer, 2013). This is achieved by modeling pressure diffusion through a fractured media containing randomly distributed seeds which represent earthquake faults. The pressure propagation can be adopted based on the reservoir properties, as much as they are known. The density of these seeds, and the size distribution, are a-priori unknown site-specific parameters.

In this application, induced seismicity scenarios are stochastically modelled by sampling random hydro-shearing scenarios based on the existing field knowledge. Then, deterministic modeling of flow for a calibrated reservoir model returns which of these scenarios can indeed be realized because of the planned injection. Here, the adaptive Hierarchical Fracture Representation (a-HFR) is employed both for modeling flow in a fracture network with dynamically changing permeability (Karvounis and Jenny, 2016) and for simulating the source times of randomly pre-sampled scenarios of hydro-shearing events at certain hypocenter (Karvounis et al., 2014). This hybrid model is chosen here, as it can integrate several of the field observations, returns forecasts both of the spatial distribution of seismicity and of its focal planes, and can forecast reservoir properties like the expected well's injectivity at the end of the injection. Minimum required inputs to this hybrid model was the initial hydraulic properties, the planned activity, and some knowledge of the stress conditions around the considered well and of the orientations of pre-existing fractures. The resulting seismicity rates can be converted into static equivalents rates (like for SM1) and compared with SM1. In particular, Figure 37 shows the results together with case of synthetic catalogue with predefined parameter matching the Geldinganes conditions.

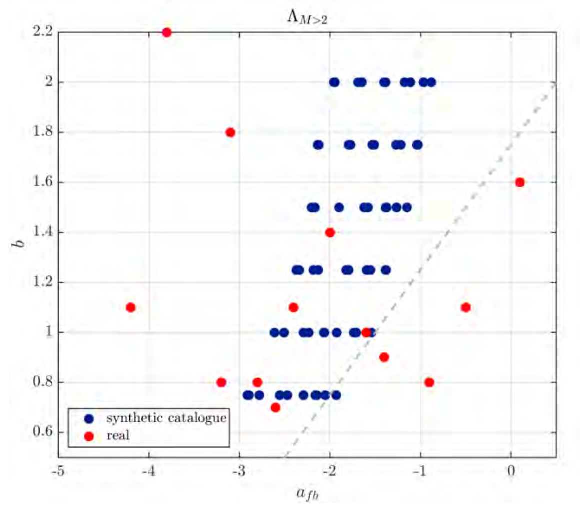


Figure 37 Distribution of - values for the synthetic catalogue together with the dataset of Table 1 Source: Broccardo et al. 2019. The dashed line represents the upper limit of no expected seismicity . Further details can be found in Broccardo et al. 2019.

10.2.2 Ground Motion Prediction Equations

In this project, 7 GMPE models have been selected. This selection was based on the work of Kowsari et al. (2019), which recalibrated existing GMPEs models to the Icelandic strong motion data set. The Icelandic dataset is based on six strike-slip events in the South Iceland Seismic Zone (SISZ), with a range of magnitudes between, and distance km. The intensity measures are reported in Table 10.2, and the value of the functional form and the coefficients can be retrieved directly from Kowsari et al. (2019). From the original list, the GMPE model of Lin and Lee (2008) was replaced with the local GMPE (RS09), Rupakhety and Sigjörnsson (2009). The recalibration has been performed only for PGA. The selected site-to-source distance is the Joyner-Boore metric (). When the distance metric of the original GMPE is different from, the same transformations proposed in Rupakhety and Sigjörnsson (2009) are applied. Figure 38 shows the Trellis Plots for the selected GMPEs models.

Table 10.2 Selected list of GMPEs

GMPE name	Location	Reference
1-AB10	Europe & Middle East	Akkar Bommer (2010)
2-CF08	Worldwide	Cauzzi Faccioli (2008)
3-Zh06	Japan	Zhao *et al.* (2006)
4-Am05	Europe and Middle East	Ambraseys et al. (2005)
5-DT07	Greece	Danciu and Tselentis (2007)
6-GK02	Turkey	Gülkan and Kalkan (2002)
7-RS09	Iceland, Europe and MiddleEast	Rupakhety and Sigjörnsson (2009)

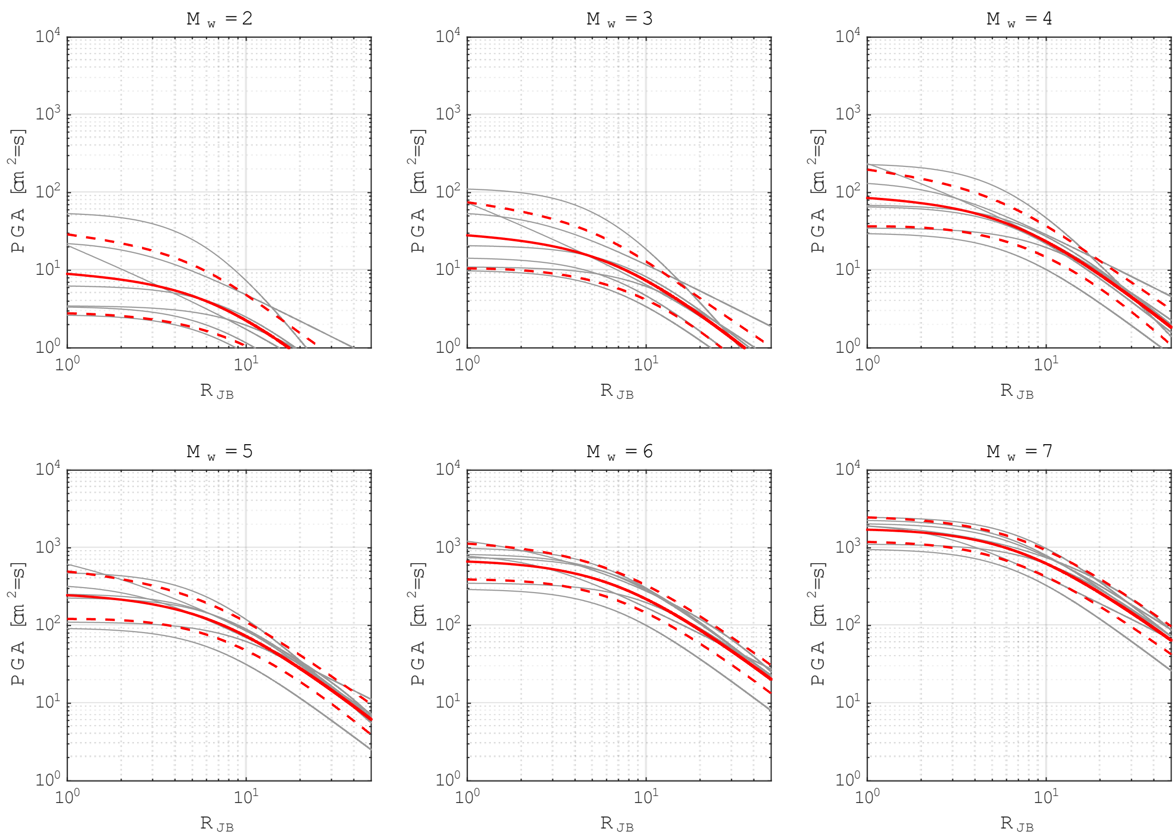


Figure 38. Trellis Plots for the selected GMPEs models.

Then, the was converted into the European Macroseismic Scale (EMS98, Grünthal, 1998) to facilitate an easier interpretability based directly on damage and nuisance to the population. Therefore, the selected GMPEs were converted into expected intensity by using Ground Motion to Intensity Conversion Equations (GMICE) for small-medium intensities. The GMICE used in this work were introduced by Faccioli and Cauzzi (2006) and Faenza and Michelini (2010) (the parameters are listed in Table 10.3). The aleatory variability is then combined into a GMPE-GMICE model with defined as, and values of mean μ, , , and reported in Table 10.3. Figure 39 shows the GMICE epistemic range as function of distance and .

Table 10.3 GMICE parameter list

Faccioli and Cauzzi (2006) Units: [m/s]	0.89	1-AB10	0.175	1.96	0.954
		2-CF08	0.176	1.96	0.955
		3-Zh06	0.391	1.96/ln(10)	0.950
		4-Am05	0.175	1.96	0.954
		5-DT07	0.177	1.96	0.955

	6-GK02	0.403	1.96/ln(10)	0.954
	7-RS09	0.287	1.96	1.053
Faenza and Michelini (2010) Units: [cm/s]	1-AB10	0.175	2.58	0.571
	2-CF08	0.176	2.58	0.573
	3-Zh06	0.391	2.58/ln(10)	0.560
	4-Am05	0.175	2.58	0.571
	5-DT07	0.177	2.58	0.575
	6-GK02	0.403	2.58/ln(10)	0.571
	7-RS09	0.287	2.58	0.819

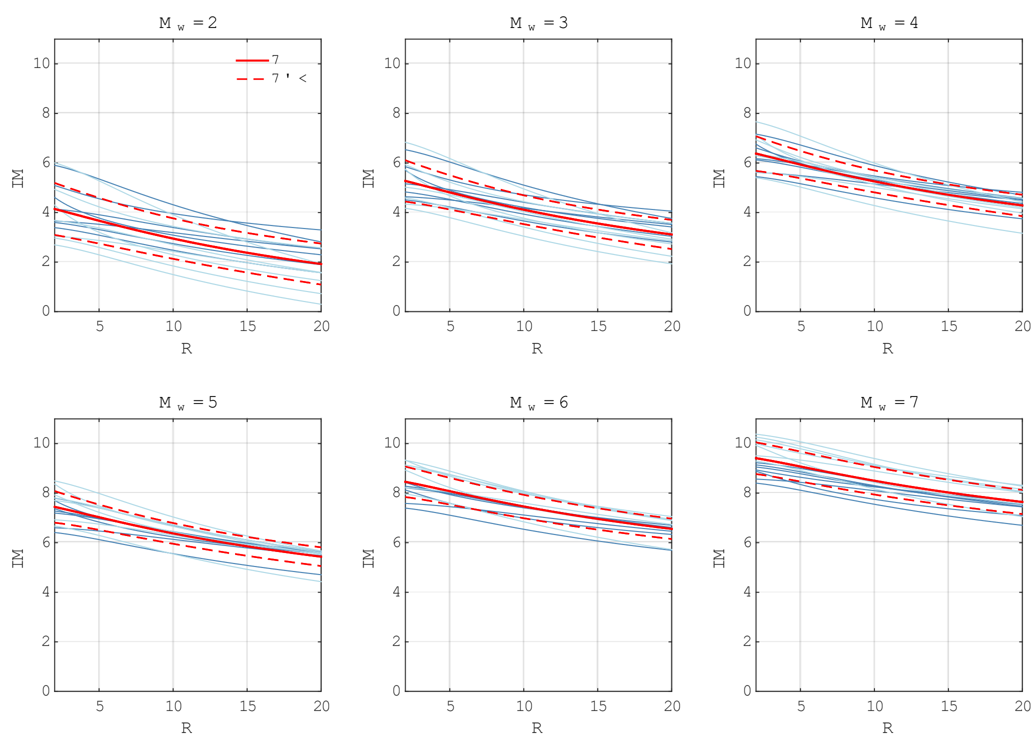


Figure 39 GMICE model. Solid red lines are the epistemic mean and the dash lines the epistemic mean plus minus the epistemic standard deviation.

10.2.3 PSHA results

For a given site, the rate of exceedance (i.e., the output of PSHA analysis) is simply where is the Gutenberg-Richter above magnitude 2. Magnitude below 2 are considered not to cause damage. The probability of exceedance of an intensity, , for a given time period, , (which corresponds to the total duration of the project given the normalization previously introduced), is given by the Poisson distribution as However, is not known a priori (neither an uncertainty quantification based on local condition was possible to carried out a-priori), therefore the risk is computed for each of the and pairs of Table 10.1. Figure 40 and 41 show the PSHA outputs. In red are reported the real data and in blue the model SM2. These curves confirmed the state of deep uncertainty. In fact, for a given probability of exceedance of and distance 2-5 km from the injection point, the macroseismic intensity range between the 10% and 90% percentile is circa.

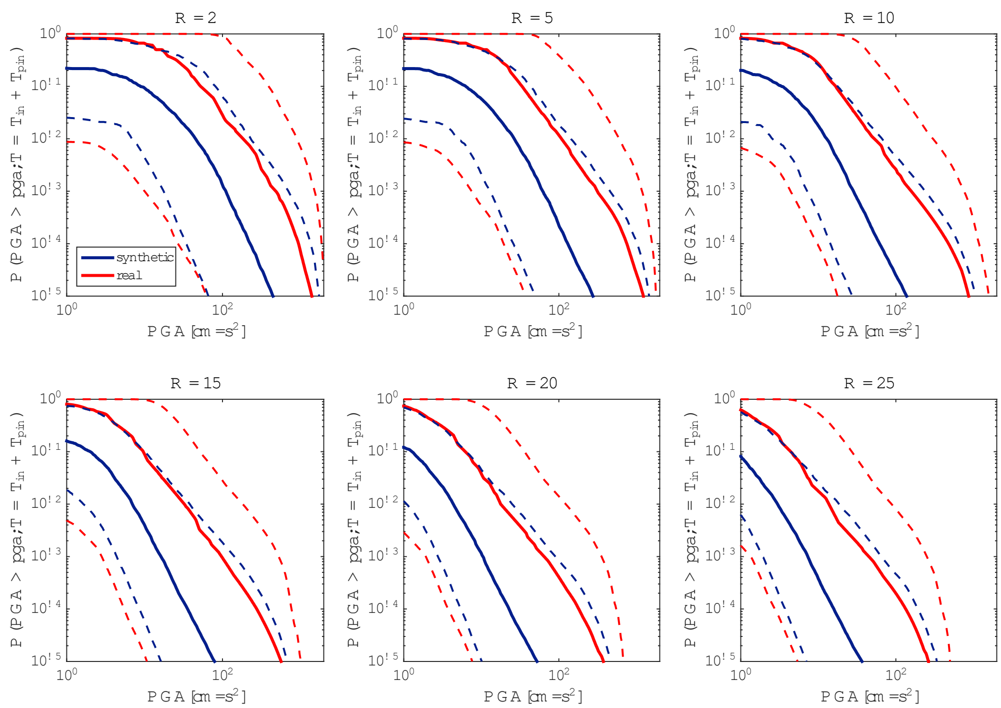


Figure 40 PSHA analysis comparison between source model SM1 (Table 1) and SM2 (synthetic catalogue). Solid lines: medians; dashed lines 10% and 90% quantiles. Intensity measure .

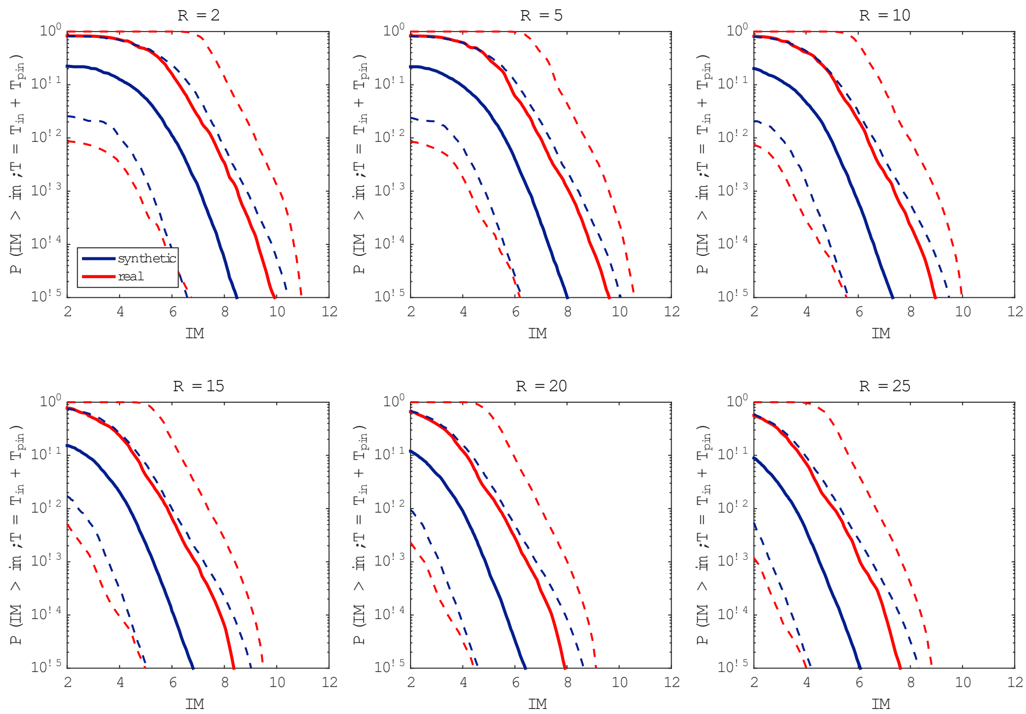


Figure 41 PSHA analysis comparison between source model SM1 (Table 1) and SM2 (synthetic catalogue). Solid lines: medians; dashed lines 10% and 90% quantiles. Intensity measure.

10.2.4 Maximum Magnitude distribution per injected volume

In addition, to the classical PSHA analysis, in the a-priori risk analysis it was determined the probability distribution of the maximum magnitude, observed at fluid injection sites for the total time of observation. Observe that this is fundamentally different from of the Gutenberg-Richter distribution, which is a deterministic upper limit fixed by physical constrains. The probability distribution of the maximum magnitude, can be derived considering the magnitude of events statistically independent. Then simply, where is the classical Gutenberg-Richter distribution, and. Since the number of events is a random variable itself, then, where) is the classical Poisson discrete distribution. Figure 42-a,b shows the equivalent rate of seismicity, for each of the data set reported on Table 10.1 (SM1 model) and for each of the synthetic catalogues (model SM2). One can observe a significant scatter of rate of seismicity reflecting the large uncertainty exiting prior to the project.

In the same Figure, it is reported the envelope distribution computed as the mean value over all the branches of the logic tree. Figure 42-c shows the envelope distribution. Observe that given the sparse dataset (Table 10.1), this distribution is multimodal. The planned effective injection volume was 18,000 cubic meters and based on this envelope distribution was 2.25 and the 5-95% interval is . Observe that these values represent some statistics based on previous projects and not the expected values for this project. In the following, we also report the envelope distribution of based on the synthetic catalogue derived according to the SM2 source model (Figure 42-d). Different from the envelope distribution based on the SM1 source model, this distribution shows a more regular shape, since the synthetic dataset is denser and less sparse. However, this prior distribution can be affected by overfitting since it is based on a crude estimate of the stress measurements without accounting for their uncertainties. The expected , based on this envelope distribution, is 2.09 and the 5-95% interval is . Moreover, since the true injected volume is likely to be different from the planned one, Figure 46-e reports the and [5-95]% confidence bound as function of the effective injected volume. Observe the different nature of the SM1 and SM2 estimates. The one derived from SM1 represents the uncertainties related to all similar projects *but not* this project. Conversely the SM2 prior represents all the uncertainties related solely to this project included in the physics-based model.

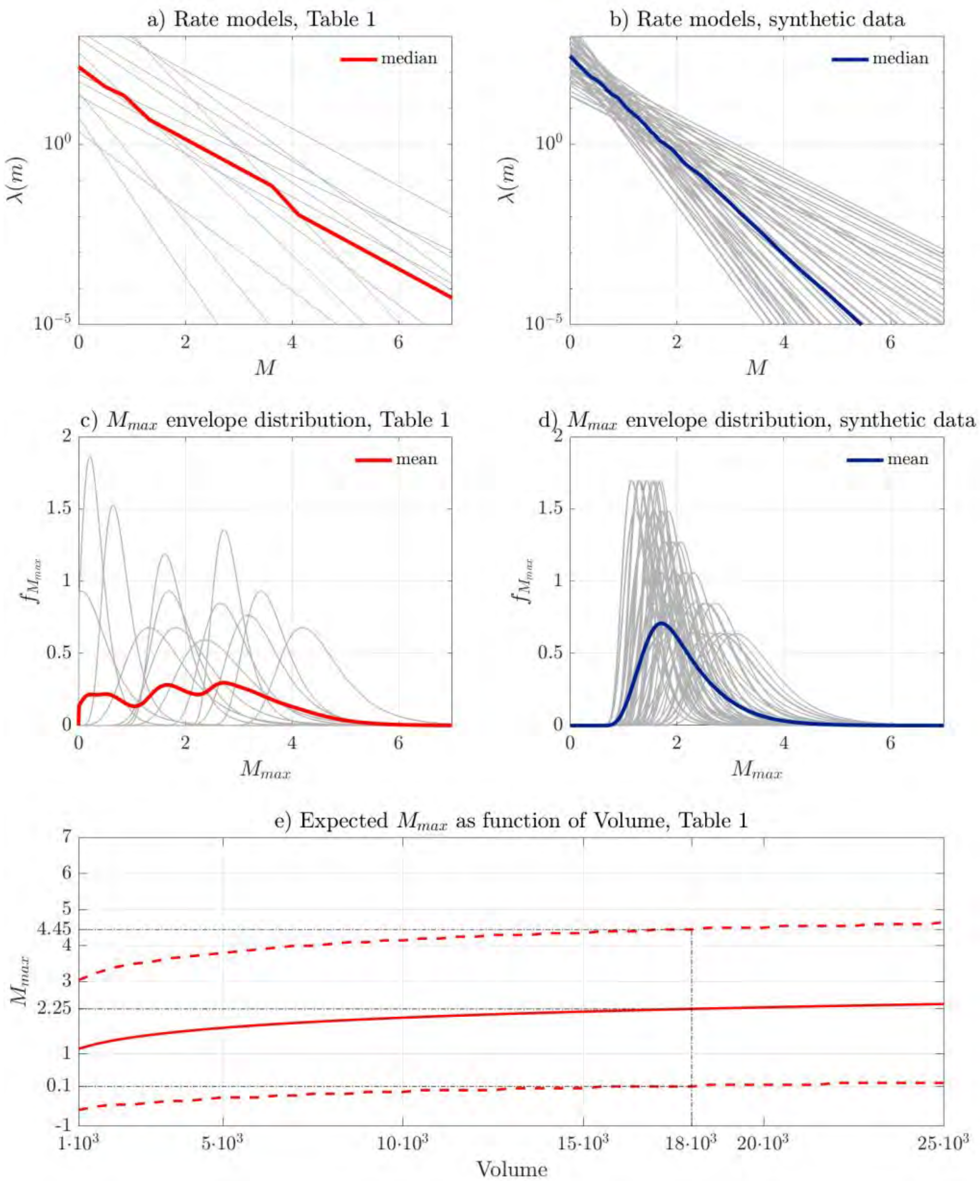


Figure 42 Envelope probabilistic density distribution of the rate model and maximum observed magnitude

a,c) based on Table 10.1, b,d) based on synthetic catalogue (S2 source model). e) Expected magnitude per volume injected, based on Table 10.1. Source Broccardo et al. (2019).

10.3 Probabilistic risk computation framework

The seismic physical risk faced by exposed communities required a quantitative assessment, while non-physical risk which include vibrations felt, noise, opposition by residents, were not considered.

Physical risk is commonly divided into two major categories, i.e., fatalities and/or injuries, and economic losses. The a-priori risk analysis for the Geldinganes project focused on the first risk, while the aggregate economic losses were not computed. However, as a substitute for aggregate losses, it was defined a low damage threshold for statistical average classes of Icelandic buildings. Specifically, two risk measures have been considered: Individual Risk and Damage Risk is defined as the frequency over the time span of the project at which a statistically average individual is expected to experience death or a given level of injury from the realization of a given hazard (Broccardo et al., 2017b). For this project it was defined as the frequency over the time span of the project (including the post-injection phase) at which a statistically average building class is expected to experience light non-structural damage from the realization of a given hazard. This last definition is the first of this kind, and, in the view of the authors, it should be promoted as a standard metric for induced seismicity.

Given the lack of regulatory framework, the following safety thresholds for and have been adopted. The safety threshold was set to This value is in line with the typical standards for induced seismicity in Switzerland or the Netherlands (notice that the original definition the time span is a year). Given the presence of epistemic uncertainties, the median of the distribution was taken as the reference metric to be compared with the selected safety threshold, i.e. (being the epistemic median of the individual risk distribution). The threshold was set to . Again, the median of the distribution is taken as reference metric to be compared with the selected safety standard, i.e .

The computation of and is based on the convolution of vulnerability models for the relevant building typologies with the exposure model. At the present time there exist only local fragility functions for low damage (Bessason and Bjarnason, 2015), which have been used for computations. Given the absence of local fragility function for large damage states, a macroseismic intensity approach (Lagomarsino and Giovinazzi, 2006) was used for computations.

10.3.1 Individual Risk analysis

was computed with a macroseismic approach. The macroseismic model defines the mean damage grade, as function of a vulnerability index , a ductility index, , and a reduction factor introduced in Mignan et al. (2015) to recalibrate low damage states to the damage observed in the Basel 2006 sequence. The vulnerability index depends on the building class and construction specifics, and it includes following Lagomarsino and Giovinazzi (2006) probable ranges, as well as less probable ranges. Following the Icelandic exposure described in Bessason and Bjarnason (2016), three building typologies have been selected, namely: Concrete, Wood and Masonry as a surrogate for Pumice buildings. In addition, Bessason and Bjarnason (2016) reported that (in average) the Icelandic buildings are more reliable than the ones based on Euro-Mediterranean Region. Given that, was selected as vulnerability index for Concrete and Wood, and for masonry. The choice of for masonry was given by noticing that the fragility of this building is close to old (before the 1980s) Icelandic reinforced concrete building. Moreover, there is no detailed information on the ductility index for the different class of building, therefore has been used with a conservatory approach. The first analysis consists in scenarios for different magnitudes, locations and building typologies. The scenarios are derived by using the mean of the GMICE and converted into by using the vulnerability model and the conditional probability of fatalities for a given damage grade. The risk analysis consists in the marginal considering all the couples in a given location, for the total duration of the project. The results are shown in Figure 43 for each building class. Median and quantiles are computed considering a 50% weight for the SM1 model and 50% weight for SM2 model for the selected set of parameters. The results showed that the median is below the selected safety threshold.

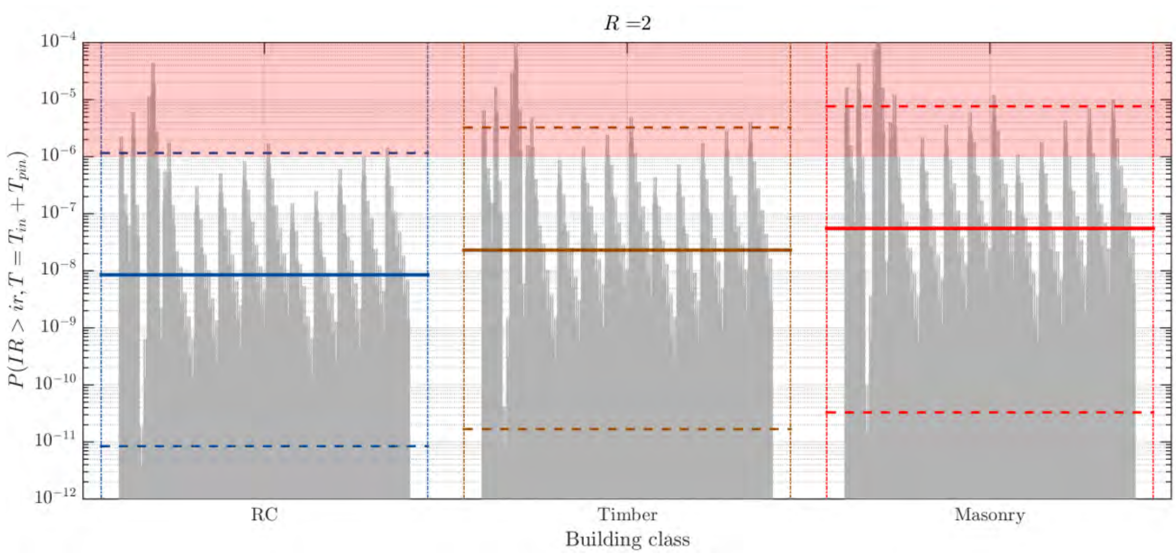


Figure 43 Marginal for 2 km distances based on the final model (combined SM1 and SM2) for a reasonable stimulation fluid volume to create a reservoir. The solid horizontal lines represent the weighted median values of the vertical gray lines. The dashed horizontal lines represent the 10 and 90% epistemic quantiles. Source: Broccardo et al. 2019.

10.3.2 Damage isk analysis

For , the local fragility model developed by Bessason and Bjarnason (2015) has been used. Bessason and Bjarnason (2015) defined the following categories and subcategories:

I. Low-rise reinforced concrete
   RC-b80: Reinforced concrete structure designed before seismic code regulations (before 1980).
   RC-a80: Reinforced concrete structure designed after seismic code regulations (after 1980).
II. Low-rise timber structures
   T-b80: Timber structure designed before designed before seismic code regulations
   T-a80: Timber structure designed after designed before seismic code regulations
III. Hollow pumice blocks (HP)

The marginal considering all the couples, for both SM1and SM2 (with equal 50% weights), are shown in Figure 44 for each class of buildings, for a site located 2[km] from the injection point. The median of is also below the selected safety threshold.

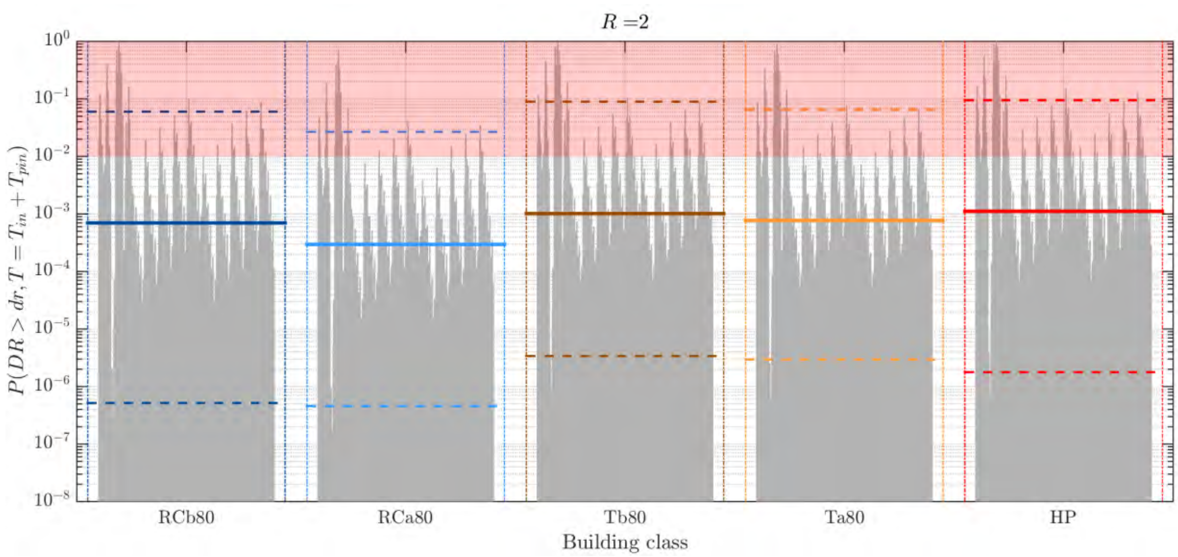


Figure 44 Marginal for the final model for 2 km distance. The solid horizontal lines represent the median values of the vertical gray lines. The dashed horizontal lines represent the 10 and 90% epistemic quantiles. Source: Broccardo et al. 2019.

10.4 Mitigation strategies

The Geldinganes injection was composed of two stages: the first stage started on October 16 and lasted for four days; the second stage, started on October 27 and lasted for two days. Two mitigation strategies were implemented: the classical Traffic Light System (TLS), which was the official approach used by the operators; and, the Advanced Traffic Light System (ATLS), which was implemented and tested parallelly and unofficially. In this deliverable, we do not report on data acquisition and the implemented seismic monitoring strategies. This is subject of DESTRESS deliverable 6.4. Moreover, this document is presenting only the results of the implemented

ATLS, without any interpretation or discussion. In fact, at present, a detailed analysis is undergoing, and no in-depth conclusions are currently available.

10.4.1 Classical TLS

The protocol for the Geldinganes classical TLS was based on a five-steps action plan. First of all the area was divided in two domains: *the internal domain*, which was defined as the volume surrounding the industrial operations where seismicity was monitored and analysed with the highest sensitivity; and *the external domain*, which was a wider volume surrounding the internal domain, where the occurrence of seismicity could be associated with the injection. The geometrical details of the internal and external domain were set as follow. The domains were cylinder-shaped volumes with radii from the injection point of 2.5 km and 5.0 km for the internal and external domain, respectively. The depth range for both domains was [0-10] km. It was planned to manually analyze all the seismic events above in the internal domain and for the external domain, the rest was automatically detected. For all seismic events occurring within the internal or external domain, the TLS system reported in Figure 45 was implemented. Further and in-depth details on the TLS are reported in Broccardo et al. 2019.

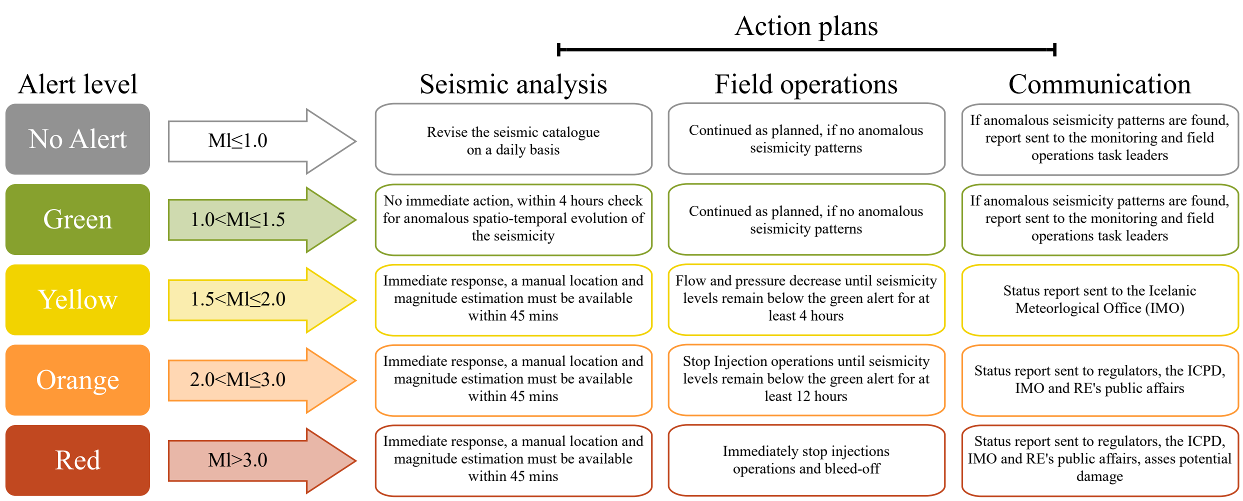


Figure 45 The classic Traffic Light Scheme defined for the Geldinganes project. Source Broccardo et al.

10.4.1 Advanced Traffic Light System

In the following, we describe the updating strategy and the preliminary results of the Advanced Traffic Light System (ATLS), which was tested during the two stages. The implemented ATLS in Geldinganes was based only on SM1 via a fully online Bayesian inversion analysis. In the following, we discuss only the updating of the rate model (i.e., only of [, ,]), while the updating strategy for the coefficient of the GMPEs was not the object of the ATLS. In fact, a detailed sensitivity analysis (Broccardo et al. 2019) showed that most of the epistemic uncertainty was due to the rate model selection. Moreover, the risk team decided to choose only the as reference metric for decision making during the stimulation. Therefore, alternative ATLSs based on or on combinations of and are not discussed here (note that their implementation is "technically" trivial, so the presented ATLS is not limited in its generality).

The ATLS is based on a classical Bayesian inverse framework (Broccardo et al. 2017) for a Non-Homogeneous Poisson process. This framework allows a coherent classification and quantification of the epistemic and aleatory sources of uncertainty. Following SM1, we use the values reported in Table 10.1 to transform the hyper parameters into random variables with a prior distribution. A major advantage of the Bayesian approach is that it enables uncertainties and expert judgments about the model's parameters to be encoded into a joint prior distribution. In this project, we include expert knowledge to determine the bounds of the parameters range. Once the project has started and physical information became available, the Bayesian framework allowed the computation of the posterior distribution for the model's parameters, the formulation of predictive models and a forecasting strategy (in-depth details are reported in Broccardo et al. 2017). Figure 46 shows the joint prior distribution and the joint posterior after data are available for stage I. In this stage, no seismicity was observed. Remarkably, the updating strategy was able to encode this information and update the underground feedback. The correlation between the different parameters is zero because the minimum cut off magnitude was set to zero, and could not be re-set since no seismicity was observed. The same Figure shows both the "safe" and "failure" domain (after the *full* Hazard-Risk computation) and the posterior epistemic uncertainty evolution around the parameters and . This plot, the first of this kind, provide a clear summary of the risk level for the project together with the associated epistemic uncertainties. The authors believe that similar plots should be promoted in future risk analysis frameworks for fluid-induced seismicity. Figure 47 shows the online evolution on together with the epistemic uncertainty reduction on its value. The epistemic uncertainties are reduced after the information "no seismicity" is encoded and the epistemic mean of drop dramatically indicating that the seismic risk was negligible. At the moment, it is not possible to give details on the reasons why no seismicity has been observed during this stage. In addition, the volume injected is not reported here as there was a cross-flow through the packers. The proportion of the effective injection is still being investigated at this time.

In the second stage, the posterior distribution of was encoded within the prior. Therefore, this one was a mixture distribution between the original prior and the posterior at first stage. In this stage, seismicity was observed with magnitudes below zero and circa 0.1. The complete catalogs, together with the magnitudes, are currently under recalculations and, therefore, not reported here. Figure 48 shows the risk evolution in the and domain. Here we can notice a negative correlation highlighting the fact that is negative. Moreover, in this case, we can also update the distribution of . Observe that the epistemic uncertainty dropped considerably after a few events, with the ATLS indicating that the project lied in the safe domain with both median and quantiles of the .

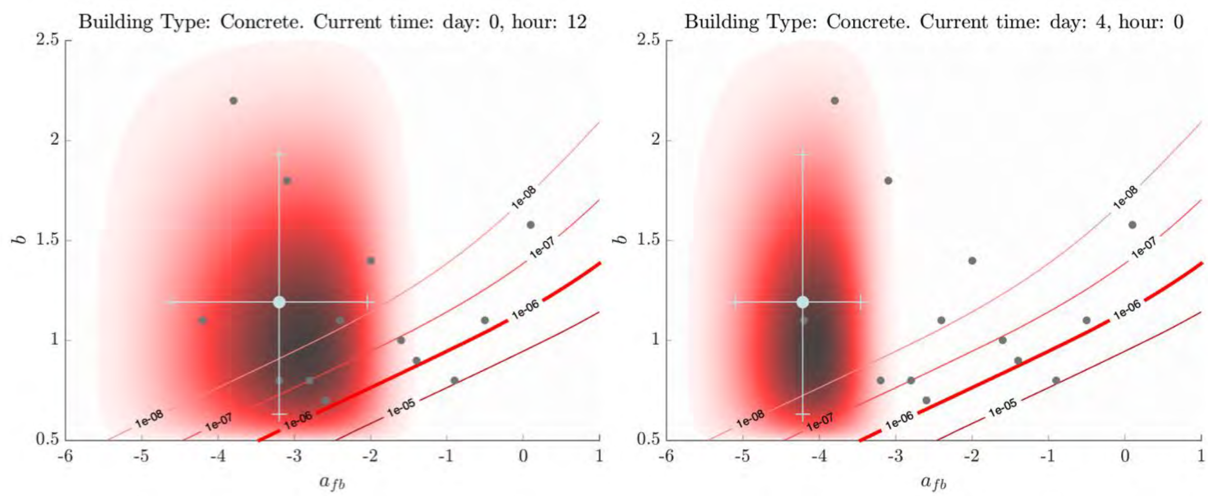


Figure 46 Individual risk evolution for a concrete building. Iso-risk curve and posterior distribution, left panel first updates, right panel last updates

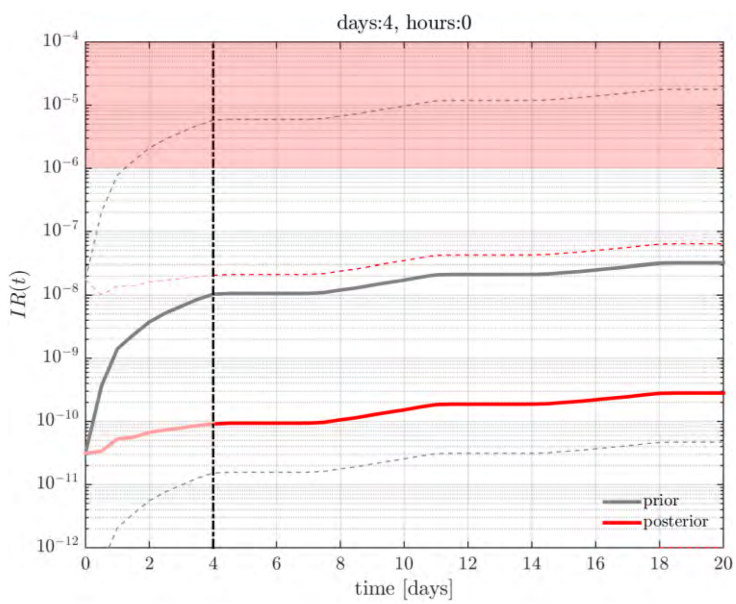


Figure 47 Stage I risk updates and epistemic uncertainty reduction. Solid line mean risk, dashed lines 5-95% quantiles. Grey lines computations based on prior uncertainties; red lines computations based on 5 days posterior.

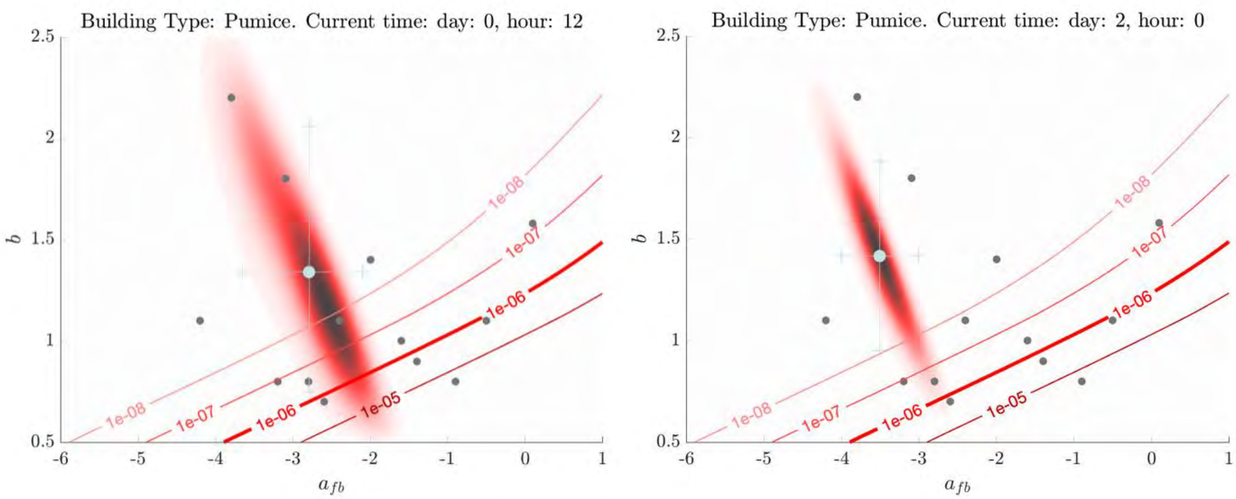


Figure 48 Stage II. Individual risk evolution for the most vulnerable building. Iso-risk curve and posterior distribution, left panel first updates, right panel last updates

11 Conclusions

This report provided recommendations rationalized to existing legislative frameworks and current applied research efforts in different countries in Europe (and the South Korean experience from the 2017 Pohang earthquake). The numerous uncertainties associated with the underground feedback requires the combination of two approaches, (1) the standard TLS protocols used by different countries following existing legislations, and (2) the initiation of a move towards dynamic risk assessment to optimize TLS thresholds which would depend on the local underground feedback and risk thresholds (i.e. ATLS), hence moving away from a fixed, heuristic, magnitude or vibration decision threshold. Method 2 cannot, as of now, supersede the standard method as the only existing test in real operating conditions of the ATLS was done in October 2019 at one site (section 10). More tests will be required before changing the regulations in place. When no legislative framework exists, still a standard TLS should be used but in conjunction with ATLS testing.

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