KEM-15 Final report

Risk of Seismicity due to Cooling Effects in Geothermal Systems | Final report

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Scope

One of today's greatest challenges is the energy transition from fossil fuels to low-carbon renewables. Geothermal energy is a local solution for base load heat and electricity supply. As such it has the potential to provide safe and clean energy for the growing urban areas in the Netherlands and worldwide. In the Netherlands, geothermal energy is conventionally extracted from deep sedimentary aquifers that may be intersected by fractures and faults. While permeable fractures and fault zones may serve as fluid pathways, thereby improving fluid production from and injection to a reservoir, they also pose the risk of hosting seismic events caused by geothermal operations. The risk of induced seismicity is a major factor that currently hinders the widespread development of geothermal energy. Injection-induced seismic risk must thus be better understood to develop methods and frameworks to assess and mitigate the risk of larger induced seismic events.

In the Netherlands, geothermal energy is commonly utilized by producing hot fluid from a sedimentary reservoir through a producer, extracting the heat at the surface via a heat exchanger, and re-injecting the cold fluid via an injector (well doublet). This re-injection operation cools down the reservoir, which triggers a variety of coupled thermo-hydro-mechanical processes leading to changes in the effective normal stress and shear stress acting on a fault. Given that the Dutch subsurface is commonly intersected by normal faults, these stress changes induced by existing and planned geothermal systems may then result in sudden slip of nearby faults, which could potentially be associated with seismic release of the stored energy.

It is therefore required to improve the understanding of the thermo-hydro-mechanical effects due to cold water injection in geothermal systems. Of particular interest is the influence of operational parameters such as injection temperature, injection pressure/rate, injected volume and distance to faults and the influence of geological boundary conditions such as rock properties, fault properties and the in-situ and dynamic stress field on induced seismicity. This will allow to develop better guidelines and tools for safe exploration, development and operation of geothermal systems in The Netherlands.

The mission of the team is to help developing better tools to estimate the increase of the seismic hazard produced by conventional and enhanced geothermal projects. Up to now, in some geothermal projects, questions related to risk of people, buildings and infrastructure and the discussions about causality of damage of (residential) buildings have been one of the key questions for the acceptance of the projects. KEM-15 intends to provide more reliable estimations of seismic hazard increase produced by geothermal operations. This information could be useful for public communication and public acceptance purposes.

In this final project report the results of the KEM-15 study are summarized and organized in the work packages according to the project proposal. Individual deliverables and reports are assembled as appendices. First, a review of processes governing induced seismicity in geothermal and other operations is provided from the laboratory perspective together with a review of the geology of the Netherlands (**WP1, Appendix 1, 2 and 3**). Based on this information, generic (**WP2**) and specific (**WP3**) modelling scenarios were setup (**Appendix 4**). Three different modelling approaches were used to assess induced seismic hazard: slip tendency analysis (**Appendix 5, 6, 10 and 11**), rate and state friction theory (**Appendix 6, 7 and 10**) and a Coulomb stress change model (**Appendix 8, 9, 10 and 11**). The Coulomb stress change model is a new model that was developed within the frame of KEM-15. The slip tendency and Coulomb stress change models were verified by history matching injection operations at the Groß Schönebeck Enhanced Geothermal System site. The rate and state friction model was verified by history matching a laboratory experiment. Modelling approaches and results are summarized in **WP2** and **WP3**. A translation of the Coulomb stress change model results to site-specific seismic intensities and the ranking of the investigated parameters were performed in **WP4** and **WP5 (Appendix 12)**. This final project report is an update of the 2nd interim report from September 2021.

WP1: Review of induced seismicity (Deliverable 1)

In WP1, first relevant scientific publications were collected, screened, commented and shared between project participants. The collected literature was made available to all project participants. Based on this literature, two induced seismicity review studies were performed that form *Deliverable 1*:

- Report: "Key parameters affecting induced seismicity in geothermal reservoirs across scale (lab, mine, field)" (Hofmann, H., Ji, Y., Cacace, M., Zang, A., Zimmermann, G., Shapiro, S.) - **Appendix 1**

- Publication: Ji, Y., Hofmann, H., Duan, K., Zang, A. (2022). Laboratory experiments on fault behaviour towards better understanding of injection-induced seismicity in geoenergy systems. Earth-Science Reviews 226:103916. https://doi.org/10.1016/j.earscirev.2021.103916 - **Appendix 2**

In **Appendix 1** the influence of operational parameters such as injection temperature, injection pressure, injection rate, injected volume and distance to faults and the influence of geological boundary conditions such as rock properties, fault properties and the in-situ and dynamic stress field on induced seismicity is reviewed. The effect of temperature is of importance, as cascade utilization of geothermal resources becomes more important to increase geothermal energy efficiency, and this results in lower re-injection temperatures. This literature study includes a summary of relevant physical processes, modelling approaches, and a review of selected laboratory and mine scale experiments as well as field scale examples of injection-induced seismicity in geothermal reservoirs. We differentiate between mechanical, hydraulic and thermal processes, highlight relevant coupled processes, and explicitly describe the influence of geological parameters, operational parameters and the effect of temperature on injection-induced seismicity. Based on this we discuss different seismic risk mitigation measures for geothermal operations.

In **Appendix 2** we present a state-of-the-art review on injection-induced seismicity from the laboratory perspective. Understanding the fault behaviour is key to successful management and mitigation of injection-induced seismic risks. As a fundamental approach, laboratory experiments have been extensively conducted to assist constraining the processes that lead to and sustain various injection-induced fault slip modes. Laboratory studies are required to understand fault mechanics during fluid injection by identifying key parameters and processes under controlled conditions. On the other hand, laboratory testing has limitations, which are the finite sample size and boundary conditions. In this review, the basics of fault behaviour, including fault strength and instability, are first briefly summarized, followed by the stability analysis arising from the current theoretical framework. After the description of common laboratory methods and auxiliary techniques, we comprehensively review the effects of fault properties, stress state, temperature, fluid physics, fluid chemistry and injection protocol on fault behaviour, with focus on the implications for injection-induced seismicity. The review shows that the previous work on displacement-driven rock friction and fault slip modes partially unravel the mystery of injection-induced fault behaviour, and recent experimental studies on the injection-driven response of critically stressed faults provide complementary insights. Overall, laboratory experiments have substantially advanced our understanding of injection-induced seismicity, which has been successfully used to interpret many field observations. However, there are still outstanding questions in this area, which could be addressed by future experimental studies, such as the feasibility of seismic-informed adaptive injection strategy for mitigating seismic risks, cold fluid injection into critically stressed faults under hydrothermal conditions, and fault friction evolution during cyclic injection spanning from undrained to drained conditions.

The second part of WP1 comprises a report on the Dutch geology relevant to geothermal operations:

- Report: “Geological review study” (Baudouy, L., Duvail, C., Whitney, B.) – **Appendix 3**

This report forms the base to setup the generic and specific modelling scenarios for WP2 and WP3:

- Report: ”Modelling Scenarios for KEM-15” (Hofmann, H., Zimmermann, G., Zang, A., Shapiro, S.) – **Appendix 4**

The three typically exploited geothermal reservoirs in the Netherlands described in this study and chosen for the modelling study are:

1) Delft Sandstone
2) Slochteren Sandstone
3) Dinantian Limestone

While the Delft Sandstone and Slochteren Sandstone reservoirs represent matrix-dominated systems with high porosity and permeability, the Dinantian Limestone represents a fracture-dominated system which may be exploited by drilling into fault zones or developing Enhanced Geothermal Systems (EGS). We consider both scenarios in our models.

WP2: Generic modelling study of induced seismicity (Deliverable 2)

Generic modelling scenarios comprise a sensitivity analysis of relevant parameters for the Slochteren Sandstone formation. This formation was chosen as it is the most heavily exploited geothermal reservoir in the Netherlands. A summary of all model parameters including base case, minimum and maximum values as well as a description of all modelling scenarios is provided in **Appendix 4** (and the respective thesis and publications - **Appendix 5, 6 and 9**).

All numerical modelling studies were performed with the flexible parallel implicit finite element code GOLEM, which is based on the Multiphysics modelling framework MOOSE. GOLEM is an open source software developed at GFZ Potsdam and available for download (https://www.gfz-potsdam.de/en/software/moose-modelling-application-golem).

While using the same underlying coupled thermo-hydro-mechanical processes, three complementary approaches were used to assess the induced seismic hazard:

1) slip tendency (ST) analysis (**Appendix 5, 6, 10 and 11**)
2) rate and state friction (RSF) theory (**Appendix 6, 7 and 10**)
3) a Coulomb failure stress change (CFS) model (**Appendix 8, 9, 10 and 11**).

The slip tendency analysis was performed in the framework of a Master thesis, which was updated and submitted to the Netherlands Journal of Geosciences:

- Master thesis: "Coupled thermo-hydro-mechanical simulation of geothermal reservoirs to assess the reactivation potential of faults" (Bakul Mathur, Technical University Braunschweig, September 2021) – **Appendix 5**
- Manuscript submitted to NJG: "Thermo-hydro-mechanical simulation of cooling-induced fault reactivation in Dutch geothermal reservoirs" (Bakul Mathur, Hannes Hofmann, Mauro Cacace, Gergö Hutka, Arno Zang) – **Appendix 6**

Here, the underlying physics, the numerical model setup and the modelling results are provided. This includes a base case model for the Slochteren formation (Rotliegend), a sensitivity analysis of the most important model parameters and the specific models of the Slochteren, Delft and Dinantian formations. The model was calibrated in a previous study on the Enhanced Geothermal System site Groß Schönebeck, where a slip tendency analysis for long-term cold-water injection was performed in a Rotliegend reservoir in the North German Basin.

The rate and state friction model was implemented in GOLEM in the frame of the KEM-15 project. A laboratory fault activation experiment was used for model validation and analysis of the fault slip behaviour. The modelling approach, calibration results and fault slip analysis are provided in a submitted manuscript, which is under review at the time of preparing this report:

- Publication: Hutka, G.A., Cacace, M., Hofmann, H., Zang, A., Wang, L., Ji, Y. (2023). Numerical investigation of the effect of fluid pressurization rate on laboratory-scale injection-induced fault slip. Scientific Reports 13:4437. https://doi.org/10.1038/s41598-023-30866-8 **Appendix 7**

The field scale RSF model was not used in the generic modelling study (sensitivity analysis), but only for the specific base case Slochteren model (**Appendix 6 and 10**).

The theory of the Coulomb failure stress (CFS) change model used in this study was developed in the framework of the KEM-15 project. The theory has been implemented in GOLEM and validated against the Groß Schönebeck field case:

- Publication: Cacace, M., Hofmann, H., Shapiro, S. (2022). Projecting seismicity induced by complex alterations of underground stresses with applications to geothermal systems. Scientific Reports 11:23560. https://doi.org/10.1038/s41598-021-02857-0 - **Appendix 8**

The CFS model was used in the generic modelling scenarios (sensitivity analysis for Slochteren Sandstone; WP2):

- Manuscript submitted to NJG "Investigating seismicity rates with Coulomb failure stress models caused by pore pressure and thermal stress from operating a geothermal well doublet in a generic subsurface fault and layer structure of the Netherlands" (Gergö Hutka, Mauro Cacace, Hannes Hofmann, Bakul Mathur, Arno Zang) – **Appendix 9**

and in the specific modelling scenarios (Slochteren, Delft, Dinantian; WP3; **Appendix 10 and 11**). The results of the base case Slochteren Sandstone CFS model were used as input for the seismic intensity calculations (WP3; **Appendix 12**).

WP3: Forward modelling scenarios representative for the Dutch subsurface (Deliverable 3)

While the sensitivity analysis was performed only with the Slochteren Sandstone model, the specific modelling scenarios were setup for the three most relevant geothermal formations in the Netherlands as described in WP1 (Delft Sandstone, Slochteren Sandstone, Dinantian Limestone).

Since for no Dutch site sufficient data was available to setup a site-specific model, we developed the following specific modelling scenarios based on our literature review (WP1, **Appendix A4**): Slochteren base case model, deep low porosity Slochteren model, shallow high porosity Slochteren model, fault offset Slochteren model, Delft base case model with different re-injection temperatures of 15°C and 45°C, Delft base case model with a well-to-fault distance of 500m, Dinantian base case fault model, Dinantian fault damage zone model, Dinantian EGS models with 250 m and 500 m distance to the fault.

The three modelling approaches were compared on Scenario S1 (Slochteren base case model):

- Report "Comparison between slip tendency (ST), rate-and-state friction (RSF) and Coulomb failure stress (CFS) change models" (Hofmann, H., Hutka, G., Mathur, B., Cacace, M., Zang, A., Shapiro, S.) - **Appendix A10**

Additional specific CFS scenarios for Slochteren Sandstone, Delft Sandstone and Dinantian limestone (S33-41) are presented in a separate report:

- Report "Coulomb failure stress models of the Slochteren Sandstone, Delft Sandstone and Dinantian Limestone for KEM-15" (Hofmann, H., Hutka, G., Mathur, B., Cacace, M., Zang, A., Shapiro, S.) - **Appendix A11**

Seismic hazards were calculated for the Slochteren Base Case Scenario for multiple locations in the Netherlands:

- Report: "Seismic Risk due to Cooling Effects in Geothermal Systems: Seismic hazard assessment" (Secanell, R., Duvail, C., Mariniere, J., Labidi, M.) – **Appendix A12**

The seismic hazard assessment (SHA) quantifies how locations further away from the seismic source are less affected by induced seismicity and that the relative increase in seismic hazard is comparably large in areas with low background seismicity and relatively low in areas with high background seismicity. Nevertheless, larger seismic events are more likely to be induced in areas with a large background seismic hazard. Please note that the seismic hazard assessment was performed with the seismic catalogue from intermediate modelling results. However, differences between intermediate results and the final reported ones are insignificant and the input to the SHA is clearly described.

WP4: Ranking of operational parameters for conventional geothermal systems (Deliverable 4)

In WP4 we synthesized the results of the generic modelling study of the Slochteren sandstone and the specific modelling study of the Slochteren sandstone and Delft sandstone to derive a ranking of operational parameters for conventional geothermal systems.

Based on the results of the ST, CFS and RSF models presented above, we derive the following general conclusions:

Local geological conditions have the strongest influence on the risk of cooling-induced seismicity. If the distance between the injection well and a fault is larger than the distance between injection and production well there is likely no elevated risk of cooling-induced seismicity on that fault plane. This is because the cold-water front is growing around the injection well with time until injection is stopped because thermal breakthrough occurs at the production well. However, even direct injection into a fault zone may be safe depending on the local geological conditions (i.e., a fault that is stable also under stress conditions that are changed by geothermal operations).

By adapting operational parameters such as the position of the well in relation to critically stressed faults, the re-injection temperature, and the injection pressure/rate cooling-induced seismicity can significantly be influenced.

The respective parameter ranking with the first parameter showing the largest influence on induced seismic hazard (within the maximum variability expected for each parameter and without considering inter-parameter relationships; note that not all parameters are relevant in all models):

1) **Fault orientation with respect to in-situ stress field: critically oriented faults**

   Faults that are critically oriented with respect to the in-situ stress field require lower stress disturbances by subsurface operations compared with faults that are unfavourably oriented for slip. The size of the fault restricts the maximum slip area and hence the maximum moment magnitude that may be triggered by stress perturbations induced by geothermal operations.

2) **Fault properties: rate and state friction a-b parameter and fault friction coefficient**

   In RSF theory, a positive a-b value indicates velocity-strengthening behaviour, which represents stable fault slip, while a negative a-b value indicates velocity-weakening behaviour, which represents unstable fault slip. A critically stressed fault, which is triggered by stress changes due to geothermal operations may hence slip seismically or aseismically, depending on it’s a-b value. In the Netherlands, current literature indicates primarily positive a-b values that promote stable slip. This parameter is primarily relevant to estimate whether or not a fault may experience accelerated fault slip. However, it is difficult to determine this parameter in-situ.

3) **Well location: Respect distance between injection well and fault**

   The size of a fault limits the maximum moment magnitude it can host. If no fault is present, no felt seismic event may occur in conventional geothermal operations. Therefore, the distance between a geothermal injection well and the nearest fault that may host a felt seismic event is a possible measure to significantly reduce injection-induced seismic risk. However, faults are often targets for geothermal operations due to the locally enhanced fluid and temperature flow, and are often exploited without causing any injection-induced seismicity.

4) **Background seismicity: Seismogenic index**

   A larger seismogenic index shifts the expected natural and induced seismic events towards larger magnitudes. In the Netherlands, the seismogenic index is rather low due to the limited natural seismicity observed. This parameter is especially relevant for the case where faults are unknown. However, it can only be sufficiently well constrained based on historic data. Since the Seismogenic index is also a combined result of the properties described below, it dictates the result of Seismogenic index models, such as the CFS model developed and applied in this study.

5) **Rock properties: Elastic rock properties, thermal expansion coefficient and permeability**

   Stiff, low permeability rocks with high thermal expansion coefficient have a higher seismic risk compared with soft, high permeability rocks with low thermal expansion coefficient.

6) **Operational parameters: Injection rate/pressure and temperature**

   Pressure-induced effective stress changes happen relatively early in a geothermal well doublet. In the considered cases a new pressure equilibrium was reached after a few weeks to months since the same amount of fluid was injected as produced. Instead, the cold-water front continues to grow until injection is stopped. Besides a careful choice of the well location, adjusting the operational parameters of a geothermal project can significantly reduce the seismic risk.

7) **Fluid properties**

   The influence of fluid viscosity and density on induced seismicity is relatively minor.

The quantitative description of the influence of the individual parameters in the ST and CFS models can be found in the respective appendices.

WP5: Ranking of operational parameters for enhanced geothermal systems (Deliverable 5)

In WP5 we use the results of the specific modelling study of the Dinantian limestone models to draw conclusions on the impact of selected parameters (injection temperature and distance to fault) on the potential seismic hazard.

Compared with conventional geothermal systems, high pressures during stimulation treatments need to be additionally taken into account. However, engineering measures such as well location, number of stimulation stages, well spacing and operational parameters can also control the seismic hazard to some degree. Contained multi-stage systems with some respect distance to critically stressed fault zones pose a significantly lower seismic risk compared with stimulating large fault zones. Overall, we consider the ranking for EGS and conventional systems as the same.

WP6: Recommendations (Deliverable 6)

Here we present a combined recommendation of the data and studies required prior to the start of a geothermal project to improve the safety of the planned operations. Based on the results of the KEM-15 project presented above, we derived the following recommendations:

1) An a-priori site-specific seismic risk assessment should be performed for each geothermal project to evaluate the natural seismic hazard and the potential for induced seismicity.

2) If locally the seismic risk is elevated a detailed numerical modelling study of the planned operations should be performed a priori to determine well locations and operational parameters. The models presented here (or similar reservoir models) can be a basis for this. The risk of cooling-induced seismicity on unknown faults can be estimated based on the natural seismicity in an area and injection test data using the Coulomb failure stress approach. The likelihood of cooling-induced slip of known faults can be estimated based on slip tendency analysis. The dynamic slip behaviour of such faults can be analysed using a rate and state friction model.

3) During operation a local seismic monitoring network is required to monitor whether and how induced seismicity evolves in near real-time.

4) Decrease of injection rate/pressure (or stop of injection or even start of production) and increase of re-injection temperature are the most efficient methods to mitigate a further increase of induced seismicity once a pre-defined maximum magnitude event, maximum peak-ground acceleration or other criteria is observed. Monitoring of the change in seismic response to these actions will verify the efficiency of these methods. Such a traffic light system is the main seismic risk mitigation measure. Updated risk assessments can be used to decide whether and under which conditions to re-start operations.

The fact that no induced seismicity is observed in any conventional matrix-type geothermal project in the Netherlands and the results of the KEM-15 study suggest that the induced seismic hazard by geothermal operations in these kinds of systems (e.g., Slochteren Sandstone, Delft Sandstone) is relatively low. The modelling result suggest that even elevated seismic risks are manageable to some degree with sufficient risk assessment, monitoring and mitigation measures. New greenfield developments using new methods (e.g., EGS) in less known geological settings or in settings with previous induced seismicity (e.g., Dinantian limestone) requires a more in-depth analysis compared with the well-known and safely operated conventional geothermal reservoirs in the Netherlands.

We state that the mechanism of fluid-injection-induced seismicity, in particular during and after the shut-in of geothermal wells and related thermo-hydro-mechanical effects are still not fully understood. Therefore, current modelling approaches will bear the risk to be unable to investigate the impact of relevant but unknown physical interrelations not implemented in the codes used in this study.

Research questions and answers

In the framework of KEM-15 five research questions were asked. Below, the answers to these questions are summarized. They are based on the numerical modelling studies performed in this project.

R1: For which generic scenarios are there elevated risks of fault instability?

In our models we find elevated risks of fault instability if a large fault is critically stressed and velocity-weakening, close to the injection well, background seismicity is high, rock is stiff and has high thermal expansion coefficient, the difference between reservoir and injection temperature is high and injection is performed over long time with high pressures.

R2: Under what parameters are faults, within reach of the thermal front radiating from the injection well?

If the well-fault-distance is less than the injection-production well distance and the geothermal system is operated until the time of thermal breakthrough a fault is within reach of the thermal front.

R3: What is the influence of fault permeability in relation to the reservoir permeability on the size of the fault plane that is cooled down due to the injection of cold water?

A higher fault (damage zone) permeability (compared to the reservoir permeability) increases the size of the cooled down fault patch and decreases the size of the cooled down reservoir volume. If fluid flow across the fault is possible the thermal effect on the fault is significantly higher due to convective heat transfer compared to impermeable faults with only conductive heat transfer across the fault.

R4: How does the stress tensor change on various spots of a fault plane through time with the development of a cooled patch?

The slip tendency increases with increased pressure and reduced temperature due to a decrease in effective normal stress (major) and an increase in shear stress (minor). Pressure effects are short-term (early), cooling-effects long-term (late). Fluid pressure (fluid-injection induced) can only influence normal stress. Temperature changes and resulting thermal stress changes can influence normal and shear stress along a fault plane.

R5: What is the magnitude of seismic events that can be expected due to combined thermal cooling effects?

Based on the experience with currently running Dutch geothermal projects and in line with the CFS model results, the moment magnitude of seismic events induced by geothermal operations is expected to be below 2 (depending on Seismogenic Index used in the model and on stress field and fault properties). By definition fault size determines the maximum moment magnitude of an earthquake theoretically expected to occur on a particular fault. Compared with natural factors such as fault properties and background seismicity and engineering factors such as the distance of the injection well to a major fault, temperature effects are of minor importance. In tendency, reduction of re-injection temperature increases the expected maximum moment magnitude.

Appendices

A1 **Report "Key parameters affecting induced seismicity in geothermal reservoirs across scale" (Deliverable 1a)**

A2 **Publication "Laboratory experiments on fault behaviour towards better understanding of injection-induced seismicity in geothermal systems" (Deliverable 1b)**

A3 **Report "Geological review study (Deliverable 1c)**

A4 **Report "Modelling scenarios for KEM-15" (Deliverable 1d)**

A5 **Master thesis "Coupled thermo-hydro-mechanical simulation of geothermal reservoirs to assess the reactivation potential of faults" (Deliverable 2a)**

A6 **Manuscript submitted to NJG "Thermo-hydro-mechanical simulation of cooling-induced fault reactivation in Dutch geothermal reservoirs" (Deliverable 2b)**

A7 **Publication "Numerical investigation of the effect of fluid pressurization rate on laboratory-scale injection-induced fault slip" (Deliverable 2c)**

A8 **Publication "Projecting seismicity induced by complex alterations of underground stresses with applications to geothermal systems" (Deliverable 2d)**

A9 **Manuscript submitted to NJG "Investigating seismicity rates with Coulomb failure stress models caused by pore pressure and thermal stress from operating a geothermal well doublet in a generic subsurface fault and layer structure of the Netherlands" (Deliverable 2e)**

A10 **Report "Comparison between slip tendency (ST), rate-and-state friction (RSF) and Coulomb failure stress (CFS) change models" (Deliverable 3a)**

A11 **Report "Coulomb failure stress models of the Slochteren Sandstone, Delft Sandstone and Dinantian Limestone for KEM-15" (Deliverable 3b)**

A12 **Report "Seismic hazard assessment" (Deliverable 3c)**