KEM Research review, evaluation and interpretation

TITLE: *Seismic Risk due to Cooling Effects in Geothermal Systems (KEM-15)*

KEM Quality review

The aim of this project was to investigate the risk of induced seismicity due to the injection of cold fluid into a relatively warmer rock, as would be done during geothermal energy production from a typical "doublet" configuration. The scientific team that was assembled to conduct this project consisted of some of the world leaders in the hydromechanics of geothermal energy production, induced seismicity, and closely related areas of geomechanics.

The project began with a review of processes governing induced seismicity in geothermal and other sub-surface operations, along with a review of the geology of the Netherlands. The results of these components of the project were then summarized in several reports.

In the next phase of the project, several generic and specific modelling scenarios were set up, based on geological conditions at some potential geothermal sites in the Netherlands. Three reservoirs were considered: Delft Sandstone, Slochteren Sandstone, and Dinantian Limestone. The main focus was to investigate the possibility of slip along pre-existing normal faults, due to cold-water injection. These scenarios are summarized in Appendix 4.

Three different modelling approaches were used to assess induced seismic hazard: slip tendency analysis, rate and state friction theory, and a newly developed Coulomb stress change model. The slip tendency and Coulomb stress change models were verified by history-matching the injection operations at the Groß Schönebeck EGS site, whereas the rate and state friction model was verified by history matching a laboratory experiment. The numerical modelling studies were conducted using the GOLEM open source software that has been developed at GFZ Potsdam.

Overall, the amount of work performed in this project is quite large. Much of the work seems to be of high quality. However, the results of the project have been reported in a manner that is very confusing for the reader. The submitted documents contain a large number of appendices that have different formats; some are in the form of project reports, whereas others are in the form of manuscripts that look like drafts of journal articles. Moreover, several papers published by the KEM-15 researchers were submitted as part of the reporting for KEM-15, but most of these papers describe research that was performed for projects other than KEM-15. It would have been preferable for the project to be reported in one unified project report document.

Unless the notation is misinterpreted, the treatment of the thermal expansion coefficients of a fluid-saturated rock seems to be incorrect. The drained thermal expansion coefficient of a porous rock is unaffected by the pore fluid, and is exactly equal to the thermal expansion coefficient of the solid (mineral) phase. The undrained thermal expansion coefficient of a porous rock must depend on the Skempton coefficient. The equations on pages 8 and 9 of Appendix 4 are incorrect. Please see p. 202 of *Fundamentals of Rock Mechanics*, Jaeger *et al.* (2007). However, since the simulated results are probably only meaningful in a qualitative sense, it is difficult to tell if any errors in the numerical values of the thermal expansion coefficients have substantially contaminated the conclusions.

The results of the project include a seismic hazard analysis (Appendix A12). Although the analysis has been conducted in a professional manner, trying to follow international standard approaches to probabilistic seismic hazard analysis some issues have arisen from the review that could have required more careful address. A non-exhaustive list is given below.

- An admittedly time variant issue such as geothermal-activity-induced seismicity has been treated via a classical tectonic approach in which the process of occurrence of earthquakes is time-invariant.
- The minimum magnitude for tectonic and geothermal sources appears to be different (M2 vs M4), which is inconsistent. The minimum magnitude in hazard analysis is the minimum magnitude of engineering interest; as such, it can't be arbitrarily different for different seismic sources. Having equal minimum magnitude for tectonic and geothermal sources could possibly revert part of the conclusions on the effect on the seismic hazard of the geothermal sources.
- The hazard analysis is carried out in terms of PGA, which is known to be more affected by the minimum magnitude than spectral ordinates at longer period, which in turn are more relevant for risk assessment of common structures (buildings) and infrastructure. This could also lead to change part of the conclusions on the effect of geothermal activities on seismic hazard.
- The hazard analysis apparently does not contemplate the issue of triggered seismicity, neglecting the possibility that geothermal and tectonic sources models considered in the analysis interact. If interaction is possible, the conclusions of the study could change.
- To consider Vs = 200 m/s as a 'standard rock' seems to be erroneous.
- The integration over distance up to 300 km apparently calls to include the induced seismicity of the Groningen field due to gas extraction (including abandonment), that also appears to be neglected.

KEM Evaluation of the results

The output of this project consisted of recommendations and guidelines regarding operational parameters for safe cold-water injection into geothermal reservoirs. Key parameters were investigated within their expected maximum variability and ranked as listed below with respect to their influence on induced seismic hazard:

(1) The orientation of existing faults with respect to the *in situ* stress field is a key parameter, as some faults may already be close to their critical state.

(2) Whether or not a fault will slip in an unstable manner is controlled by the sign of the *a-b* fault constitutive parameter, where negative *a-b* values indicate a propensity for unstable slip. Unfortunately, there is no easy way to estimate the value of this parameter for a given subsurface fault.

(3) Another key parameter is the distance between the injection well and a given fault. Roughly speaking, if the distance between the injection well and the fault is greater than the distance between the injection and production wells, there is unlikely to be a risk of cooling-induced seismicity on that fault.

(4) The risk of induced seismicity is greater in locations that have higher rates of natural seismic activity, as quantified by the seismogenic index. Fortunately, the seismogenic index is low throughout the Netherlands.

(5) The risk of induced seismicity also depends on the properties of local matrix rock. The risk is greater for rocks that are stiffer, less permeable, and which have higher thermal expansion coefficients; seismic risk is reduced for softer, more permeable rocks with low thermal expansion coefficients.

(6) Stress changes leading to seismic hazard are related to injection rate and pressure and the temperature of the injected fluid. By reducing injection pressure and rate and increasing the re-injection temperature, seismicity can be reduced.

(7) Finally, the influence of (injection) fluid properties such as density and viscosity on seismic risk is minor.

Overall, it can be concluded that the researchers have addressed the goals of this project in a thorough manner, using appropriate tools, and have interpreted their results so as to reach useful conclusions and recommendations.

As it regards a hazard analysis due to geothermal activities, given the issues summarized above, the conclusions should be considered with caution, and possibly require further analyses to be consolidated-

KEM interpretation of the outcome

The project has led to the following recommendations, which are supported by the data and the modelling studies:

1. Given the variability of subsurface rock and fault properties and *in situ* stresses, it is necessary to conduct an *a priori* site-specific seismic risk assessment for each proposed geothermal project, to evaluate the natural seismic hazard and the potential for induced seismicity.

2. If the potential location is found to have an elevated risk of induced seismicity, then more detailed modelling, perhaps using the methods employed in this study, should be carried out.

3. Once geothermal energy production has commenced in a given field, a local seismic monitoring network should be set up to monitor any induced seismicity that may occur.

4. If a seismic event (or peak ground acceleration, *etc*.) is observed that exceeds a pre-determined threshold (*i.e*., a “traffic light system”), injection rates can be decreased (or production rates increased), and the temperature of the injected fluid can be increased, in order to mitigate further induced seismicity. The success of these mitigation methods can be assessed by monitoring the induced seismic activity.

The conclusion of this project can be interpreted as follows: if the given recommendations are followed, it is likely that geothermal energy production in the Netherlands can continue, and be expanded, with very low risk of large seismic events being induced. Nevertheless, the comments given on the seismic hazard analysis should also be considered.

Closure text for the website

The aims of this project were to investigate the possibility of the injection of cold fluid into an underground geothermal energy reservoir to create seismic slip on pre-existing faults, and to produce recommendations to mitigate this risk. Based on several different methods of mathematically modelling the process of fault slip, this project has produced several recommendations to mitigate this risk. Potential sites should be characterized before any development, to estimate the propensity for induced seismicity. If a site exhibits a potential risk, more detailed modelling can be done to further define the hazard and possibly rule out that site. Once energy production has started, real-time seismic monitoring should be conducted. If seismic activity us observed that exceeds some pre-defined threshold, injection rate and/or pressure can be decreased, or the temperature of the injected fluid can be increased. The project concludes that if these policies are followed, it is likely that geothermal energy production in the Netherlands can continue to be carried out. However, the remarks given on the hazard analysis part should always be considered.