Induced Seismicity—A Challenge for Geothermal Project Development in Germany

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ABSTRACT

During the last years, exploitation of hydro-geothermal energy has attracted increasing attention in Germany. In several cases, felt earthquake activity occurred in the vicinity of geothermal sites after the systems went into operation. Although the observed earthquakes exhibited small magnitudes only, some of them were felt by the local population. No significant material damage was reported, however major concerns exist in the public regarding the safety of geothermal power production. The public perception of the seismic risk as well as the lack of regulative standards impedes the development of geothermal projects in Germany. Several hydrothermal projects are currently put on hold due to seismic risk concerns, and a quantitative assessment of the seismic risk has become mandatory. The basis for a seismic risk analysis is a detailed understanding of the physical processes associated with induced seismicity. This allows numerical simulations of reservoir operations and their impact on seismic risk. In combination with reaction plans (traffic light system), where hydraulic operations are modified or even stopped when induced earthquakes become to strong, the seismic risk can be controlled and minimized.

1. Introduction

Germany has almost no conventional geothermal resources, and hydrothermal projects became economically viable only after the introduction of the Renewable Energies Law (EEG). For geothermal, it was first introduced in the year 2000, with revisions and ameliorations in 2004 and 2009. Several hydrothermal projects have been established since then, mainly in the southern part of Germany.

The occurrence of earthquakes in the vicinity of geothermal sites has brought the issue of the seismic risk associated with geothermal systems into focus. After a geothermal project in Basel (Switzerland) was suspended following an ML3.4 earthquake [1], the public perception of geothermal technologies has become more critical. In 2009, two earthquakes with ML=2.7 and ML=2.4 occurred close to a geothermal site at Landau/Pfalz (Germany), a small city with 43,000 inhabitants. Although no significant material damage occurred, these earthquakes were clearly felt by the local population at Landau. A causal relation between the earthquakes and the geothermal system was neither confirmed nor denied by the operating company of the plant. Immediately after the earthquakes occurred, federal authorities established a scientific expert panel for investigating the cause of the earthquakes. However, at the time of writing, no official statement has been published by the expert group yet. As a result, the local population becomes more and more concerned that in the case of a larger earthquake, material damage might not be covered by the insurance of the operating company. Although Germany has a long tradition of developing "green energy", the public perception of geothermal projects becomes increasingly negative.

Several hydrothermal projects are currently put on hold due to seismic risk concerns, thus turning seismic risk into an economic risk for project developers. Also with regard to liability insurances required for the operation of a geothermal system, a quantitative assessment of the seismic risk prior to project development has become mandatory.

2. Earthquake Mechanisms

The phenomenon of seismicity induced by fluid injection has been known for decades and is described in various articles (see [2] for a summary). Several models have been proposed to explain the physical processes causing induced seismicity. Some of them are based on the concept of hydraulic fracture opening when in-situ fluid pressures exceed the least principal stress. Others assume that the increase of fluid pressure along pre-existing fractures reduces the effective normal stress on the fractures, therefore initiating the release of tectonic stresses [3]. Experiments under controlled conditions at the KTB (Germany) deep drilling well revealed that the latter concept is capable of explaining the characteristic features of seismicity induced by fluid injection below the jacking pressure [2]. Similar stress conditions frequently exist during the stimulation of geothermal reservoirs (Enhanced Geothermal Systems, EGS). Since natural rock-permeability rarely meets the conditions required for geothermal power production, the EGS concept implies the creation of an artificial subsurface heat exchanger by enhancing the rock permeability in a spatially confined region (Figure 1). This reservoir stimulation is achieved by injecting large volumes of fluid into the host rock under high pressures. The associated permeability increase can be explained by the "self-propping" effect of fractures on which shear displacement has occurred (e.g. [4]). After shearing, a portion of the stresses acting on the fracture has been released. Thereafter, the fracture remains stable as long as the hydraulic pressure is not further increased [2]. If, at a later stage, hydraulic pressures exceed previous peak pressures, the same fracture may shear again [2].

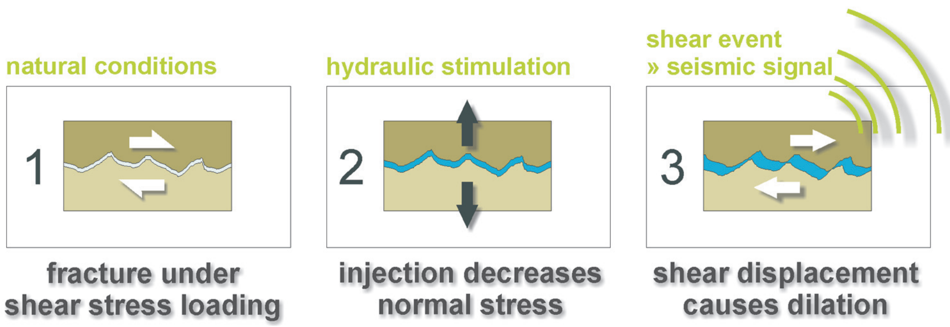

Figure 1. Mechanisms of induced earthquakes. Natural fractures in the subsurface are tectonically stressed (left). Elevated fluid pressures decrease the effective normal stress acting on the fracture (middle) until shearing occurs when the frictional strength of the fracture is exceeded (right).

Earthquakes caused by fluid overpressures are frequently called "induced earthquakes". This type of seismic events occurs during the creation of an EGS reservoir, but occasionally also during operation of geothermal systems (EGS and hydrothermal systems). Figure 2 shows the spatio-temporal evolution of hydraulic overpressures during circulation in a geothermal system. After one year, stationary conditions have not been reached and the sphere of influence of the hydraulic overpressures further increases. Induced earthquakes occur when critically stressed natural fractures (according to Figure 1) exist in a region where the fluid pressure is increasing.

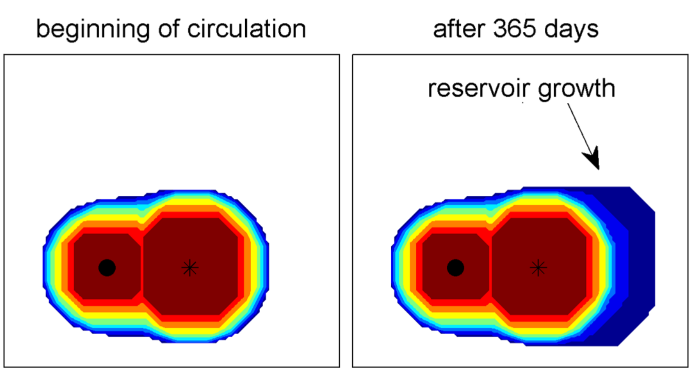

Figure 2. Numerical simulation of hydraulic overpressure and associated reservoir growth during the operation of a geothermal system. Colour encoding denotes permeability increase caused by induced earthquakes (see [5] for details of the numerical simulations). The system is operated in a mass-balanced mode, circulating 50 l/s between a production (circle) and an injection well (star). The region exposed to hydraulic overpressure grows with time (right). This effect becomes more significant with poorer hydraulic connectivity in between the two wells.

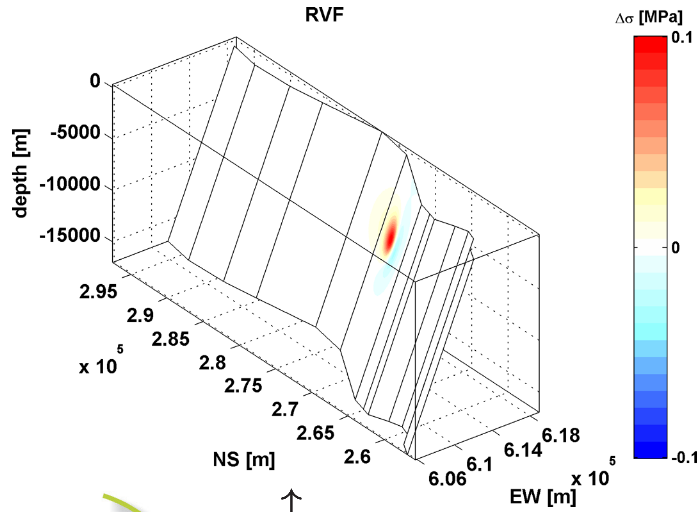

Figure 3. Modelled Coulomb-stress changes on a natural fault close to the Basel (Switzerland) EGS reservoir. Stress changes are due to the thermal contraction of the reservoir and are shown after 25 years of operation. Red colours denote an increase, blue colours a decrease of the seismic risk. The risk of triggering a larger magnitude earthquake by the geothermal plant is insignificant. Figure taken from [1].

During the operation of a geothermal system, also another type of seismic activity may be caused. Reservoir cooling by heat extraction causes stress changes in the subsurface due to the thermal contraction of the rock formation. These changes may promote failure on natural fault zones in the vicinity of the reservoir. The phenomenon of such "triggered earthquakes" was investigated in a seismic risk analysis conducted for the Basel (Switzerland) EGS project [1]. The most relevant parameter here is the Coulomb-stress which is directly related to the seismic risk. For all natural fault zones in the vicinity of the Basel reservoir, Coulomb-stress changes related to the geothermal system are relatively small and their impact on the seismic risk is negligible [1] (Figure 3).

3. Seismic Risk Assessment

Based on the physical models described in the previous section, the development and operation of geothermal systems can be numerically simulated [5]. A limiting factor is the lack of information regarding geological and hydrological parameters prior to drilling. Additionally, the local stress field frequently remains unknown even after the first well(s) are drilled. Therefore, numerical simulations of the geothermal system can usually not be calibrated during the planning phase of a geothermal project. In Germany, however, regulative authorities require a seismic risk assessment already at an early stage of the project. To overcome the uncertainty regarding subsurface parameters, worst case scenarios are considered. Within their uncertainty range, parameters are assumed in a way that the seismic risk resulting from numerical simulations is maximized. Consequently, the seismic risk tends to be considerably overestimated and the resulting seismic risk may not be acceptable from a legal point of view.

However, the numerical simulations not only provide maximum earthquake magnitudes under worst-case conditions, but also the evolution of the seismicity with time until a maximum earthquake magnitude occurs. During hydraulic stimulations in EGS projects, maximum magnitudes are usually reached within days (Figure 4). In other cases, the increase of earthquake magnitudes during injection experiments, e.g. waste water disposal, was much slower, and maximum magnitudes sometimes only occurred after several years [6]. The rate at which earthquake magnitudes increase strongly depends on the geological conditions and the hydraulic operations.

From the numerical simulations, the time after which an earthquake with an unacceptable magnitude occurs is estimated for the worst case scenario. Based on this minimum response time, a reaction scheme – traffic light system [7] – can be defined. As part of the reaction scheme, hydraulic operations may need to be modified or even stopped. This approach provides a basis for initiating a project under the current difficult political and public perception, since the seismic risk becomes "manageable" in a sense that a predefined maximum magnitude will not be exceeded.

An important aspect when designing traffic light threshold values is the phenomenon of post-injection seismicity. Frequently, the largest magnitude earthquake occurs after hydraulic operations

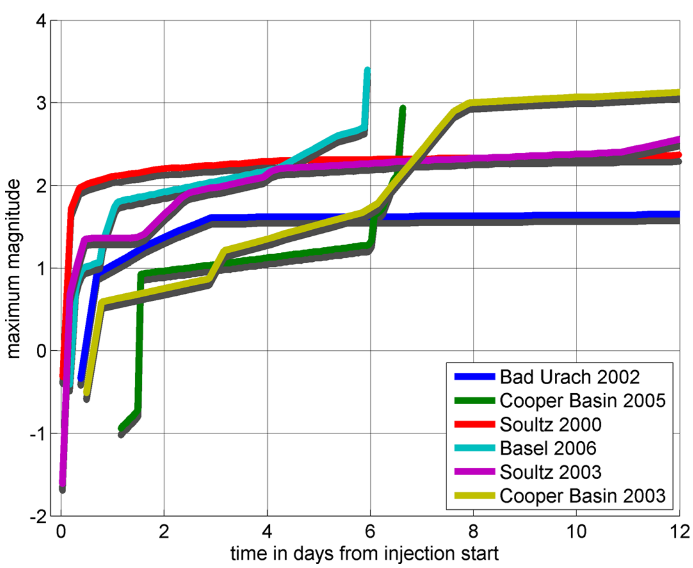

Figure 4. Temporal evolution of earthquake magnitudes that occurred during the stimulation of different geothermal reservoirs. Figure taken from [1].

have already been terminated [1], [5]. This effect can be explained by ongoing pressure diffusion at the reservoir boundaries where stationary conditions have previously not been reached [8]. Assuming worst case conditions, the post-injection magnitude increase can be simulated and magnitude threshold values can be modified accordingly.

4. Conclusions

In the current study, we present approaches how we addressed the issue of seismic risk in several studies recently performed for German hydrothermal projects. Our approaches are based on a physical model of the induced seismicity in combination with numerical reservoir models. By simulating the spatio-temporal evolution of subsurface hydraulic overpressure as well as perturbations of the natural stress conditions related to reservoir cooling, we obtain estimates for the strength (magnitude) of seismic events induced by operating a geothermal system. Due to the lacking knowledge of subsurface parameters, a worst-case scenario technique is applied and the seismic risk is simulated for worst-case conditions. Reaction plans (traffic light systems) specifically designed for worst-case conditions make the seismic risk controllable and manageable, since magnitudes can be kept below predefined threshold values.

5. References

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