Enhanced Geothermal Systems: Mitigating Risk in Urban Areas

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With the global challenge to satisfy an increasing demand for energy while at the same time stabilizing or reducing carbon dioxide (CO₂) concentrations in the atmosphere, geothermal energy from enhanced geothermal systems (EGSs) increasingly is being recognized as an attractive alternative energy source throughout the world. However, the risks associated with the seismicity necessarily induced during the development of an EGS constitute a significant challenge for the widespread implementation of this technology. This article provides a preliminary overview of lessons learned from an attempt to develop an EGS beneath the city of Basel, Switzerland.

Enhanced Geothermal Systems

EGS, also known as the “hot dry rock” or “hot fractured rock” technique, refers to a technology that uses hydraulic stimulation of a hot (T > 100°C) but comparably impermeable (κ < 10⁻¹⁶ square meters) rock mass at depth (Z > 3 kilometers) to create an artificial geothermal reservoir. During hydraulic stimulation, fluids are pumped under high pressure into a target area in which pore pressure increases as the fluid propagates away from the injection well and fracturing of the host rock occurs.

Research studies (see review by Tester et al. [2006]) at various sites around the world have confirmed that seismicity associated with EGSs is dominated by shear failure of favorably oriented natural joints as a response of normal stress reduction due to high-pressure fluid injection. The permeability inside the stimulated rock volume is thought to increase due to a self-propagating effect that inhibits the complete closure of the naturally rough fracture surfaces after they have experienced slip. The ruptures generate elastic waves detectable by sensitive seismic networks. Therefore, seismic monitoring techniques are routinely applied at EGS sites to map the spatial and temporal development of the stimulated volume and to characterize the geothermal reservoir. Once a sufficiently large reservoir (volume > 1 cubic kilometer) has been developed, additional production wells are drilled into the stimulated volume to extract heat from the rock mass by circulating fluids through the enhanced fracture network.

The Basel Deep Heat Mining Project

One of the first purely commercially oriented EGS projects, the Deep Heat Mining project, was initiated in Basel, Switzerland (Figure 1), in 1996 by an industry consortium (GeoPower Basel, or GPB). Basel, the industrial center of Europe’s chemical and pharmaceutical industry, borders France and Germany, and more than 700,000 people live in the trinational agglomeration area.

In October 2006, the injection well that was drilled in an industrial zone in Basel reached its final depth of 5 kilometers in the granitic basement. Beginning on 2 December 2006, water was injected into the well with increasing flow rates [Häring et al., 2008] (Figure 2). Seismicity was monitored by six borehole seismometers near the injection well and by up to 30 seismic surface stations in the Basel area. Because of strongly increased seismic activity, which included a local magnitude (Mₛ) 2.7 event, injection had already been stopped a few hours prior to a Mₛ 3.4 event that occurred on 8 December 2006. This earthquake rattled the local population and received international media attention. Slight nonstructural damage, such as fine cracks in plaster, corresponding to an intensity of V on the European Macroseismic Scale (EMS-98), has been claimed by many homeowners, with a damage sum, already paid by GPB’s insurance, of US$7 million. In addition, one of the directors of the project is facing prosecution before the criminal court of Basel.

About 1 hour after the Mₛ 3.4 event, bleed-off to release pressure was initiated by opening the injection well, and hydrostatic downhole pressure was reached within 4 days. Since then, the seismicity slowly decayed. Three additional earthquakes with Mₛ > 3 were felt 1–2 months after bleed-off. More than 2 years later, sporadic seismicity inside the stimulated rock volume still was being detected by the down-hole instruments.

At present, the EGS project is on hold and awaits the completion of an independent risk analysis study by a consortium of seismologists and engineers, selected by state authorities following an international bid. The study is expected to be completed by the end of 2009, and public authorities will decide then whether the project can continue.

Seismological Aspects of EGS

Although EGS technology has been applied and studied at various sites since the 1970s [e.g., Tester et al., 2006], the physical processes and parameters that control injection-induced seismicity—in terms of earthquake rate, size distribution, and maximum magnitude—are still poorly understood. Consequently, the seismic hazard and risk associated with the creation and operation of EGSs are difficult to estimate.

The well-monitored Basel seismic sequence...
provides an excellent opportunity to advance the understanding of the physics of EGS. The Swiss Seismological Service (SED) is investigating the Basel data set in the framework of the multidisciplinary research project GEOTHERM (http://www.geotherm.ethz.ch) and recently submitted first results for publication [e.g., Deichmann and Ernst, 2009; Deichmann and Giardini, 2009], with additional studies currently being conducted. Two aspects of EGS that are particularly relevant for the assessment of seismic hazard are highlighted below: ground motion scenarios and real-time forecasting of an ongoing earthquake sequence.

To predict the expected peak ground motion and the corresponding intensities from scenario earthquakes, Ripperger et al. [2009] tested existing SED ground motion prediction models [Kästli and Fäh, 2006] against the observations of the largest event of the Basel sequence (Figure 3b). They then estimated potential consequences of even larger earthquakes at the same location. This assessment is based on scaling relations that allow converting measured ground motion to macroseismic intensities as well as on finite difference simulations that incorporate a detailed three-dimensional geological model.

A macroseismic intensity of VIII (EMS-98) is predicted by Ripperger et al. [2009] for a $M_L$ 5.7 scenario earthquake in Basel. The probability of triggering such an event is considered extremely small in the case of the Basel EGS project; however, fluid injections into deep wells have triggered earthquakes of this size elsewhere in the past [Nicholson and Wesson, 1990].

Because there are currently no reliable and well-calibrated physics-based models of seismic hazard due to induced seismicity, Bachmann et al. [2009] have implemented an approach that uses the statistical properties of injection-induced microearthquakes to provide input for developing probabilistic seismic hazard models. Their analysis shows that the postinjection seismicity at Basel can be well modeled by the Omori law for aftershock decay, highlighting that the physical processes during EGS stimulation are statistically not very different from other known seismicity clusters such as aftershock sequences or earthquake swarms. They estimate the background seismicity level for the reservoir volume by downscaling the corresponding source zone of the Swiss hazard model [Giardini et al., 2004], and they predict a continuation of the induced sequence for up to 20 years.

Bachmann et al. [2009] then introduce a new mitigation strategy for larger-magnitude earthquakes, based on the real-time short-term earthquake prediction (STEP) concept adopted in California since 2005 (Gerstenberger et al., [2005]; see also http://earthquake.usgs.gov/eqcenter/step). This new implementation of STEP for the Basel area estimates the occurrence
A second challenge is related to regulatory and insurance aspects: What are the standards in terms of risk studies and seismic monitoring that should be imposed on future projects, keeping in mind that projects need to remain economically viable? A preliminary comparison with past earthquakes of similar magnitude and focal depth in Switzerland, which also considered the locally measured ground motion data, indicates that the damage claims of approximately US$7 million after the $M_7$ 3.4 event in Basel are out of proportion and may be partially unjustified. Although the project promoters and the insurance company gave an independent engineering firm the task of evaluating the individual claims, it appears that the insurance company did not question possibly unjustified claims, and it seems to have been more expedient for the insurance company to pay lump-sum compensations rather than fight such claims. As a consequence, given that the occurrence of stronger events can never be entirely excluded, the Basel case could have a significant impact on the insurance cost of future projects.

The third challenge, and possibly the biggest obstacle for future projects, is related to the communication of risk and its acceptance by society and decision makers. It is clear to many scientists that EGS systems carry a small but non-zero risk—as do most technologies, especially in the energy sector. Dams can break, nuclear power plants may fail, CO$_2$ released from oil and gas contributes to global warming, and EGSs can create damage through induced earthquakes. The open question is whether or not society is able to find ways to balance and accept the risks associated with EGSs.

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