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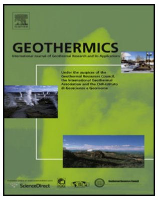

Induced seismicity risk analysis of the 2006 Basel, Switzerland, Enhanced Geothermal System project: Influence of uncertainties on risk mitigation

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ABSTRACT

We present a probabilistic seismic risk analysis of the 2006 Basel Enhanced Geothermal System (EGS) experiment. We combine induced seismicity time-dependent hazard with the RISK-UE macroseismic method and propose a logic tree approach to capture epistemic uncertainties. We find that the expected losses vary over several orders of magnitude for the tested parameters. It indicates that the previous Basel EGS seismic risk study (SERIANEX), which did not include epistemic uncertainties, led to subjective estimates. We address the issue of decision-making under uncertainty by discussing the role of model ambiguity in a simple traffic light system for EGS seismic risk mitigation.

1. Introduction

The Deep Heat Mining Project (Häring et al., 2008) to exploit the geothermal potential of the crystalline rocks below the city of Basel, Switzerland, was abandoned in 2009 due to unacceptable risk associated to increased seismic activity during and following hydraulic stimulation (Baisch et al., 2009). The largest induced earthquake ($m_L = 3.4$; $M_w = 3.2$, 8 December 2006) was widely felt by the local population and provoked slight non-structural damage to buildings, estimated to several millions Swiss Francs (CHF) (e.g., Baisch et al., 2009; Giardini, 2009; Kraft et al., 2009). Baisch et al. (2009) (hereafter also referred to as SERIANEX study – a non peer-reviewed report) concluded that "*the Basel site might not be favourable for developing an Enhanced Geothermal System (EGS)*" due to a high population density and high tectonic activity rate. A high density of population is however sought after since it is more profitable if customers are close to the energy source (for heating, in addition to electricity production).

The purpose of an EGS is to produce geothermal energy on a commercial scale in environments where the connection from the well to the reservoir, or the hydraulic conductivity of the reservoir itself, is limited. It thus requires to enhance the productivity of the existing reservoir, i.e. the connected network of cracks through which fluids can circulate. This is achieved by injecting fluid under high-pressure into a borehole (e.g., Smith, 1983; Brown et al., 2012). Although considered as an attractive environment-friendly energy source, applications are currently limited due to induced seismicity (e.g., Majer et al., 2007; Giardini, 2009). The termination of the Basel EGS project is one of the best examples of the issues faced with induced seismicity. We should also mention the case of the EGS project of Soultz-sous-Forêts, France (e.g., Charléty et al., 2007), where earthquakes of magnitude $M < 3$ prompted concerns by the local population. No structural damage was caused by these events but a number of residents did put in claims to insurance companies, which were turned down after close examination (Majer et al., 2007).

As noted by Bommer et al. (2006), innovative risk reduction strategies are possible in the scope of induced seismicity since one can manage the risk through control of the hazard, in contrast with standard seismic risk mitigation where only an intervention on vulnerability and/or exposure is feasible. Traffic-light systems have been proposed to determine when the risk associated to induced seismicity reaches an unacceptable level and thus when the EGS operations must be modified or stopped (e.g., Bommer et al., 2006; Häring et al., 2008; Giardini, 2009; Convertito et al., 2012). However, we see three main issues, which may hamper the application of a traffic-light system: (1) the "induced seismicity hazard mitigation paradox", which is that the largest induced event commonly

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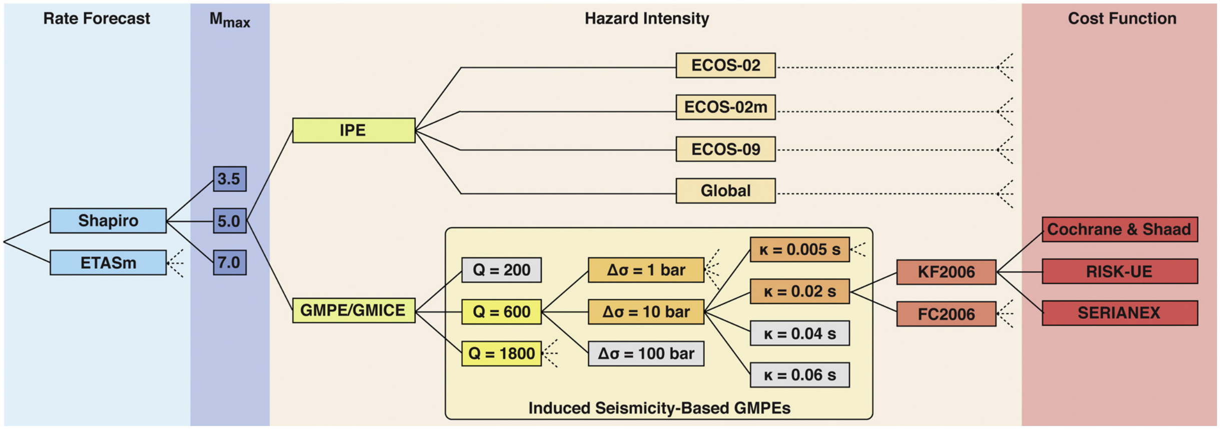

Fig. 1. Logic tree representing the different input parameters and models tested. The components of the logic tree are described in detail in Section 2. All paths have equal weights except for the GMPE parameters represented in grey, for which a null weight is fixed based on parameter estimations in Switzerland.

occurs after shut-in (e.g., Majer et al., 2007; Baisch et al., 2010). The hazard increase after shut-in can be explained by a change in the *b*-value, which origin remains to be understood (Barth et al., 2013); (2) biased decision threshold due to some ambiguity on hazard and risk estimates and (3) unexpected operational problems. In the present study, we focus on the second issue, which relates to risk mitigation under uncertainty. Uncertainty assessment is particularly challenging for EGS related induced seismicity, where less than 20 relevant case studies exist to date (Evans et al., 2012).

The aim of the present study is twofold: (1) to provide a seismic risk analysis of the 2006 Basel EGS experiment, including model uncertainty, and (2) to illustrate the implications of risk ambiguity for risk mitigation in a simplified traffic-light system. The proposed approach combines time-dependent induced seismicity hazard assessment (Bachmann et al., 2011; Mena et al., 2013) with the RISK-UE macroseismic approach to damage assessment (Lagomarsino and Giovinazzi, 2006; Baisch et al., 2009). Epistemic uncertainties are systematically captured following a logic tree approach, as used in standard PSHA (Kulkarni et al., 1984) and results compared to the SERIANEX study in which model uncertainties were not considered. To our knowledge, the present study is the first one to consider uncertainties in a systematic way for EGS seismic risk analysis. Results apply to other technologies involving fluid injection into the subsurface, as for example wastewater disposal (e.g., Horton, 2012), carbon capture and sequestration (e.g., Stirling et al., 2012; Zoback and Gorelick, 2012), secondary recovery of oil and gas (water flooding) and the exploitation of unconventional gas reservoirs (shale gas, hydraulic fracturing) (National Research Council, 2012). It is important to state that the analysis presented in the present article should not be considered as a definitive seismic loss assessment of the 2006 Basel EGS project. Use of other models or other methods may yield different outcomes. Results are presented only to illustrate the influence of uncertainties on risk mitigation.

2. Input models

We first present the different input models and related data used in the present study, most of which can be represented in a logic tree structure. Fig. 1 shows the logic tree proposed for the Basel EGS risk analysis, which would also apply to other EGS sites in Switzerland. Other models and model parameters may be required in other tectonic settings. The different levels of the logic tree are described below.

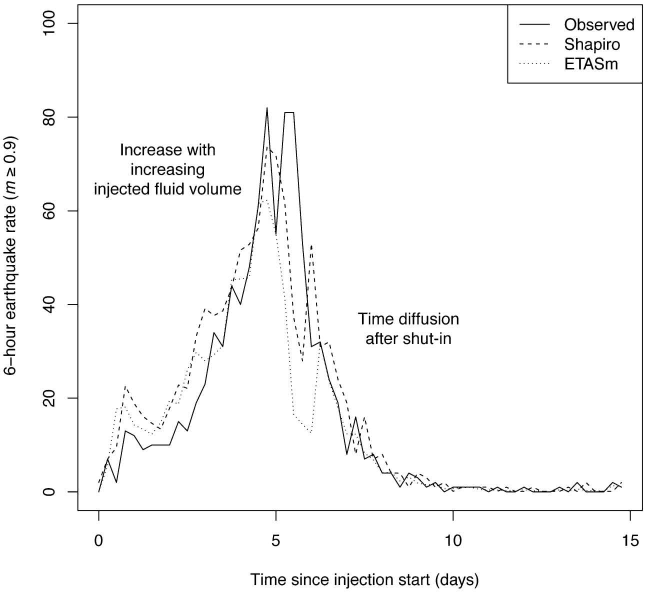

Fig. 2. Basel induced seismicity 6-h rate time series, observed and forecasted. The observed rates and Shapiro and ETAS forecasts are taken from Mena et al. (2013).

2.1. Hazard rate

The probability of occurrence of induced earthquakes is determined from induced seismicity forecast models. We tested the results of two models (Shapiro SR and ETAS E5) computed by Mena et al. (2013), which are based on a 6-h pseudo-prospective approach (Fig. 2). Both models are based on the well-established correlation between induced seismicity activity and fluid injection (Majer et al., 2007 and references therein).

The Shapiro model (e.g., Shapiro et al., 2007; Shapiro and Dinske, 2009; Shapiro et al., 2010) suggests that (1) the number of induced earthquakes increases approximately proportionally to the injected fluid volume and that (2) the diffusion of induced seismicity with time in the post-injection phase can be described by the modified Omori law (Langenbruch and Shapiro, 2010). The original ETAS (Epidemic-Type Aftershock Sequence) model (Ogata, 1988) considers stationary background seismicity and aftershock diffusion based on the modified Omori law. Here, each event (regardless of being a background event or an aftershock) can produce aftershocks. To make the ETAS model applicable to induced seismicity,