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Large magnitude events during injections in geothermal reservoirs and hydraulic energy: A heuristic approach

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ABSTRACT

The occurrence of induced seismicity during reservoir stimulation requires robust real-time monitoring and forecasting methods for risk mitigation. We propose to derive an estimation of M_{max} (here defined as the largest single seismic event occurring during or after reservoir stimulation) using hydraulic energy as a proxy to forecast the total induced seismic moment and to model the transient evolution of the seismic moment distribution (based on the Gutenberg–Richter relation). The study is applied to the vast dataset assembled at the European pilot research project at Soultz-sous-Forêts (Alsace, France), where four major hydraulic stimulations were conducted at 5 km depth. Although the model could reproduce the transient evolution trend of M_{max} for every dataset, detailed results show different agreement with the observations from well to well. This might reveal the importance of mechanical and geological conditions that may show strong local variations in the same EGS.

1. Introduction

Induced seismicity is a crucial issue for Enhanced Geothermal Systems (EGS) development. Large magnitude events (in the following defined as events showing a moment magnitude larger than 2) can occur during the stimulation phase of the reservoir or during the operational (circulation) phase. Such events were observed in many EGS: in Soultz-sous-Forêts, France (Gérard et al., 2006; Charlety et al., 2007; Dorbath et al., 2009), in Basel, Switzerland (Häring et al., 2008), or in Cooper Basin, Australia (Baisch et al., 2006a,b) for example. In the following, we will focus on seismic events observed during the reservoir development only, i.e. during stimulation phases (during and after injection) conducted by high pressure injections of water or brine. We restrict our analysis to the stimulation phase as it is generally associated with high seismicity rates, which helps to reduce the statistical uncertainty, e.g. compared to the lower seismic activity during long-term production. Our study is based on monitoring data acquired during the stimulation of the 5 km deep boreholes of the EGS of Soultz-sous-Forêts (France).

Seismicity prediction in geothermal reservoirs using several methods has been developed for years (Baujard, 2003; Kohl and Mégel, 2007). Reservoir models are based on the numerical simulation of physical processes occurring during injection or circulation. Flow in porous and fractured media, mechanical coupling and thermal transport are the most important ones. Examples of such models are FRACTure (Kohl and Hopkirk, 1995), Tough2 (Rutqvist, 2011), or FRACAS (Bruel, 2005). Seismic events magnitudes were successfully simulated using e.g. rate- and state-dependent friction models (McClure and Horne, 2011), block-slider mechanisms (Baisch et al., 2010), discrete particle models (Yoon et al., 2014) or by combining probabilistic approach and empirical observation (Bachmann et al., 2011; Shapiro et al., 2007; Shapiro and Dinske, 2009). Goertz-Allmann and Wiemer (2013) present a model that may explain the observed variation of *b*-value. It has been showed that cyclic pressurizations of a geothermal reservoir could enhance permeability and reduces induced seismicity (Zang et al., 2013).

Our work aims at developing a heuristic model that can give indications on the largest magnitude event M_{max} that could be induced during a given pumping sequence in a reservoir. To that purpose, we propose to correlate the hydraulic energy provided to the reservoir by fluid injection and the seismic moment released by induced seismicity, and to use this correlation to derive a prediction of M_{max}, using a real-time Gutenberg–Richter relation computation. Such methods were already applied, as one can find in the literature examples of comparison of the pumped energy, or of the injected

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volume with the highest magnitude event obtained or with the total seismic moment (see for example McGarr, 1976, 2014; Baisch et al., 2009). Here, we propose to go one step further and to use a simple relation between the hydraulic energy and the total induced seismic moment in order to predict M_{max} evolution during reservoir stimulations resolved by time bins.

2. Physical background

The hydraulic energy applied to a reservoir can be estimated through the integration of pumping power over time or through the integration of the pressure distribution in the reservoir over its volume. The pumped hydraulic energy can be computed with:

$$E_{h,pumped} = \int Q\Delta P\, dt, \tag{1}$$

with $E_{h,\ pumped}$ [J] being the pumped hydraulic energy, Q [m^3/s] the flowrate, ΔP [Pa] the overpressure and t [s] the injection time.

The integration of the overpressure distribution over the reservoir volume also represents a quantity of energy. The advantage of this estimation of energy is that, on the contrary to the pumping energy (which is zero if computed in a time interval after shut-in), there is still some "residual energy" after shutting in the well. This energy will be called in the following "reservoir hydraulic energy" and can be computed with the following relation:

$$E_{h,res} = \int\int\int \Delta P\, dV, \tag{2}$$

with $E_{h,\ res}$ [J] being the hydraulic reservoir energy, ΔP [Pa] the overpressure and V [m^3] the reservoir (rock and fluid) volume. The seismic moment is obtained by:

$$M_0 = \mu \cdot S \cdot d \tag{3}$$

with M_0 [Nm] being the seismic moment, μ [Pa] the shear modulus, S [m^2] the surface of rupture and d [m] the displacement. The moment magnitude of the events is computed using the following relation (Hanks and Kanamori, 1979):

$$M_w = \frac{2}{3}\log(M_0) - 6.07. \tag{4}$$

With M_w [−] being the moment magnitude and M_0 [Nm] the seismic moment.

3. Dataset

Our work is based on the unique data set acquired from the three deep boreholes of the European research pilot-EGS site at Soultz-sous-Forêts, France (Dorbath et al., 2009). The following data will be used:

- GPK2 stimulation, starting 30.06.2000. Approx. 23′400 m^3 of water were injected during 6 days. A total number of 6′947 seismic events were recorded and located by a surface network. The highest magnitude recorded was 2.6.
- GPK3 stimulation, starting 27.05.2003. Approx. 37′500 m^3 were injected during 11 days. A total number of 7′175 events were recorded. Only 2′253 events were located. The highest magnitude recorded was 2.9.
- GPK4 first stimulation, starting 13.09.2004. Approx. 9′300 m^3 were injected during 3.5 days. A total of 1′182 events were recorded. Only 794 events were located. The highest magnitude recorded was 2.3.
- GPK4 second stimulation, starting 09.02.2005. Approx. 12′500 m^3 were injected during 4 days. A total of 1′246 events were recorded. Only 764 events were located. The highest magnitude recorded was 2.7.

These data were acquired using the surface network of EOST ("Ecole et Observatoire des Sciences de la Terre" – University of Strasbourg). It consisted of 14 temporary stations in 2000, and was upgraded through the installation of nine permanent stations in 2003. For the stimulations in 2004 and 2005 the permanent network was enhanced by a temporary network of only six temporary stations (Dorbath et al., 2009). It must be underlined that the catalogues for GPK4 might be incomplete.

The injection scheme considered for each stimulation sequence as well as the time-distance representation for the localized events are represented in Fig. 1 for the stimulation of GPK2, in Fig. 2 for GPK3, in Figs. 3 and 4 for the stimulations of GPK4.

For each injection sequence, an event rate has been calculated for the largest magnitude events (in number of events of magnitude higher than 1, 1.5 and 2 using 12 h intervals). The ratio of the number of events of magnitude greater than 1 over the total event number was also computed. It can be observed that the ratio has a tendency to increase after the shut-in of the well, so the proportion of larger events increases. Similar observations have been made by Schindler et al. (2008), who found that the mean amplitudes recorded at the seismic stations increased significantly after shut-in. Furthermore, there are numerous examples where the largest event induced by hydraulic stimulation was observed after shut-in (Baisch et al., 2006a,b, 2009; Häring et al., 2008). It was also shown, that the b-value tends to decrease after shut-in (Bachmann et al., 2012), which results in a larger proportion of large magnitude events.

The total energy pumped into the system during the pumping sequence and the total seismic moment have been calculated for each stimulation (see Table 1 and Fig. 5). The total seismic moment is the sum of the seismic moments of all events. Deriving a universal relation between the total seismic moment and the pumped energy is not possible using simple physical considerations. Nevertheless, as it seems that the total seismic moment increases with the pumped energy, an empirical linear relation will be assumed in the following between hydraulic energy and total seismic moment released, as follows:

$$M_0 = c \cdot E_h \tag{5}$$

With M_0 [Nm] the seismic moment, E_h [J] the hydraulic energy, and c a constant.

4. Methodology

The proposed methodology aims at predicting the total seismic moment that will be released at time $t+\Delta t$, using a comparison between the hydraulic energy injected into the system and the total seismic moment released at time t. The general methodology can be summarized by the following steps:

- *Step 1*: at time t, computation of the ratio R of total seismic moment recorded $M_{0,t}$ [Nm] and the hydraulic energy injected $E_{h,t}$ [J]:

$$R = \frac{M_{0,t}}{E_{h,t}} \tag{6}$$

- *Step 2*: at time t, the b-value is computed, following the Gutenberg–Richter relation (Gutenberg and Richter, 1944). The value of the seismic moment obtained for $N=1$ and $N=10$ is computed, where N is the events number of a given magnitude.
- *Step 3*: at time $t+\Delta t$, the total predicted seismic moment is computed after:

$$M_{0,t+\Delta t} = R \cdot E_{h,t+\Delta t} \tag{7}$$

$M_{0,t+\Delta t}$ [Nm] and $E_{h,t+\Delta t}$ [J] being the total seismic moment predicted and the hydraulic energy injected or present in the