Analysis of complex seismicity pattern generated by fluid diffusion and aftershock triggering

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Abstract: *According to the well-known Coulomb failure criterion, the variation of both, stress and pore pressure, can result in earthquake rupture. Aftershock sequences characterized by the Omori law are often assumed to be the consequence of mainshock induced stress changes, whereas earthquake swarms are supposed to be triggered by fluid intrusions. In practice, both types of seismicity are often not clearly distinguishable that might result from an interplay of stress triggering and fluid flows in the earthquake generation process. We show that the statistical modeling of earthquake clustering by means of the Epidemic Type Aftershock (ETAS) model and simple pore pressure diffusion models can be an appropriate tool to extract the primary fluid signal from such complex seismicity patterns. This is demonstrated for two examples of natural swarm activity observed in Central Europe.*

1. Introduction

Stress triggering has been identified as an important mechanism for earthquake generation. This mechanism is based on a well-known criterion for earthquake occurrence, the Coulomb failure criterion, $CFS \equiv \tau - \mu(\sigma - P) \geq 0$, stating that a positive Coulomb failure stress (CFS) could promote failures. Here, τ defines the shear and σ the normal stress on the failure plane (positive for compression), μ is the coefficient of friction, and P is the pore pressure which reduces the effective normal stress. Thus earthquakes can be triggered by stress changes as well as due to pore pressure changes.

Aftershock activity which is usually associated with the stress changes of mainshocks generally decays according to the modified Omori law, $\lambda(t) = K(c+t)^{-p}$, where K, c and p are constants, and t is the elapsed time since the main event (Utsu et al. 1995). The Epidemic Type Aftershock Sequences (ETAS) model is a stochastic point process incorporating the empirically observed characteristics of stress triggered activity, where each earthquake has some magnitude-dependent ability to trigger its own Omori law type aftershocks (Ogata 1988). In particular, the rate of aftershocks induced by an earthquake that occurred at time t_i with magnitude M_i is given by

$$\lambda_i(t) = \frac{K}{(c + t - t_i)^p} \cdot e^{\alpha(M_i - M_{min})} \tag{1}$$

for time $t > t_i$, where α is a constant and M_{min} is the lowest magnitude cut of the catalog. The total occurrence rate,

$$\lambda(t) = \lambda_0(t) + \sum_{\{i:t_i<t\}} \lambda_i(t) \quad , \tag{2}$$

is sum of the rate of all preceding earthquakes and the background rate $\lambda_0(t)$ which refers to activity which is not triggered by precursory earthquakes, or in other words, which is not a part of an aftershock sequence. At tectonic plate boundaries, the background activity is usually assumed to result from tectonic plate motion and can be approximated by a constant. On the other hand, in intraplate regions, $\lambda_0(t)$ is likely to be related to time-dependent processes such as pore pressure changes. According to the theory of poroelasticity (Biot 1962), the evolution of pore pressure in a source free homogeneous half-space due to irrotational flow can be described by the diffusion equation

$$\frac{\delta}{\delta t}P = D\frac{\delta^2}{\delta x^2}P \ , \tag{3}$$

where D is the hydraulic diffusivity (Wang 2000).
In this study, we investigate two examples of natural swarm activity in Central Europe: (i) Vogtland/NW-Bohemia, where activity seems to result from a deep unknown fluid source; and (ii) Reichenhall region, where earthquakes seem to be related to observed rain events. We show for both cases that the statistical modeling of the earthquake activity is able to extract the underlying fluid signal.

2. Vogtland Earthquake Swarms

The Vogtland region is well known for the episodic occurrence of earthquake swarms. The most recent and best documented strong earthquake swarm occurred between August and December 2000 and consisted of approximately 5000 earthquakes with local magnitudes exceeding the magnitude of completeness (m_c=0.2). The results presented here are an overview of previous investigations (Hainzl & Fischer 2002, Hainzl & Ogata, 2005).

Method and Results

At first, we fit the ETAS model to the whole activity assuming a constant forcing rate λ_0. The five parameters (λ_0, K_0, α, c, p) of the ETAS model are estimated by the maximum likelihood method. To explore this non-stationary behavior, then the ETAS model is fitted in a moving time window.
We find that the ETAS model fits the earthquake sequence very well. The great majority of earthquakes in this *swarm* is found to belong to self-triggered activity, in particular to embedded aftershock sequences. All estimated parameters are in agreement with values for tectonic earthquake activity except the α-value (α=0.7) which is similar to previous findings for other earthquake swarm activity, but lower than typical values found for non-swarm activity ($\alpha\approx 2$). Although the background forcing is found to trigger only a small fraction of earthquakes, our analysis in moving time windows reveals a large systematic variation of the external forcing strength $\lambda_0(t)$. The earthquake swarm seems to be initiated by a strong fluid impulse which decreases within the first 10 days. Our results are in good agreement with with the identified phases of diffusion-like hypocenter migration (Parotidis et al. 2003). The efficiency of the deconvolution procedure has also been proved by an analogous analysis of simulated earthquake activity, which is forced by pore pressure diffusion and incorporates stress field changes in a 3-dimensional elastic half-space (Hainzl 2004, Hainzl & Ogata 2005).

3. Bad Reichenhall Earthquake Swarms

Reports of felt earthquakes in the area of the Staufen Massif near Bad Reichenhall, SE Germany, range back several hundred years reaching maximum intensities of I_0 = V on the macroseismic scale (Kraft et al. 2005). The underlying mechanism is not fully resolved so far. We analyze data of a network recently installed by the University of Munich and the Geological Survey of the Bavarian State. The data set consists of 1171 earthquakes recorded in the year 2002. The seismicity is characterized by two swarm type phases in March and August, the later occurred after intense rainfall which led to severe flooding in Central Europe.

Method and Results

We test the hypothesis proposed by Kraft et al. (2005) that rainfall triggered the earthquake via the mechanism of pore pressure diffusion. According to the Coulomb failure criterion, earthquakes can be triggered in the absence of stress changes only if the pore pressure increases. Our statistical earthquake model has therefore the intensity function

$$\lambda_0(z,t) = \lambda_{00} + c\ \dot{p}(z,t) \qquad \text{if} \quad \dot{p}(z.t) > 0; \quad \text{else} \qquad \lambda_0(z,t) = \lambda_{00} \tag{4}$$

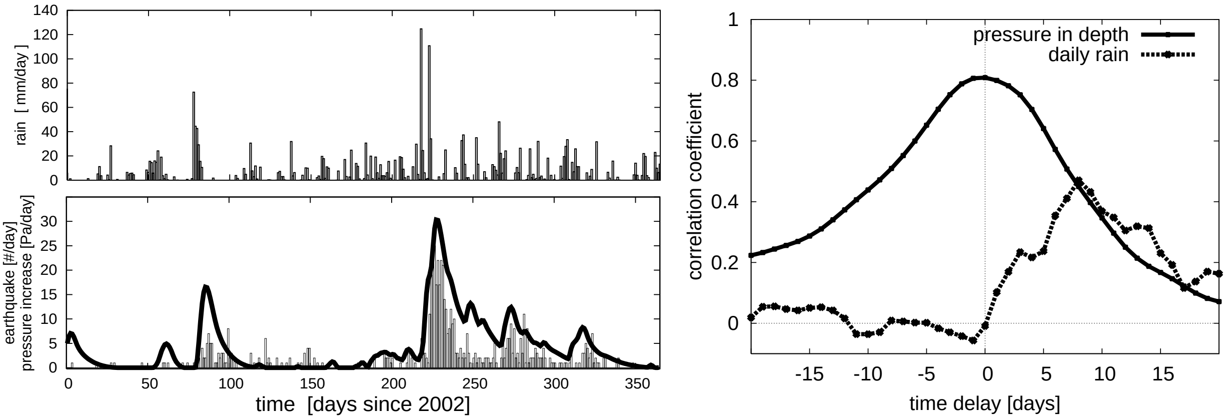

Figure 1: Left: The rain rate (top) and the seismic rate (bottom) observed in the region of Reichenhall, SE Germany. The bold line indicates the mean pressure change in the depth resulting from linear diffusion of the rain water. Right: The linear correlation coefficient between the daily rain amount (dashed line), respectively the mean daily pressure increase in depth (solid line), and the daily number of earthquakes as a function of the time shift.

where c and λ_{00} are constants. The latter describes the part of the forcing rate which cannot be related to pore pressure changes. The pressure changes in depth z are calculated from the pressure changes at the surface $P_0(t)$ due to the rainfall by means of the Greensfunction G of the diffusion equation

$$\begin{aligned} \dot{p}(z,t) &= \frac{d}{dt}\int_{-\infty}^{t} G(z,t-\tau)P_0(\tau)d\tau \\ \text{with} \qquad G(z,t-\tau) &= \frac{H(t-\tau)}{\sqrt{4\pi D(t-\tau)}}\exp\left(-\frac{z^2}{4D(t-\tau)}\right) \end{aligned} \tag{5}$$

where H is the Heaviside function. In our case, $P_0(t)$ is the average of the four meteorologic stations in this region. The estimation of the three parameters (λ_{00}, c, D) is carried out by the maximum likelihood method. To avoid complications near the surface, we focus on earthquakes in the depth interval 1-4 km.

The maximization of the likelihood function yields the hydraulic diffusivity D=0.3 m^2/s. This value for the diffusivity corresponds well to results obtained from fluid pressure experiments at boreholes. With the estimated diffusivity, we are now able to calculate the effect of the time-dependent surface rain on the pore pressure in depth. The figure shows the calculated mean pressure increase in the depth interval 1-4km as a function of time. This curve is compared with the observed daily number of earthquakes. Both curves are closely related. We calculate the linear correlation coefficient between both curves as well as between the time series of the daily earthquake number and the daily rain amount. While the seismicity is not correlated with the rain data with zero time delay, it shows significant correlation if the seismicity is shifted 8 days back (R_{max}=0.5). On the other hand, the pore pressure change in depth is strongly correlated without delay time with a maximum correlation coefficient which almost doubles that of the rain data (R_{max}=0.8).

4. Discussion

The study of natural swarm activity occurred in Vogtland region indicates that aftershock sequences are embedded and can even dominate swarm activity (Hainzl & Ogata 2005). In this case, the ETAS model can explain most of the activity and the fluid signal is almost burried. However, the fluid signal can be reconstructed by means of the time-dependence of the background forcing rate. In the Mt. Hochstaufen region, aftershock activity make up only a minor fraction of the activity and the shape of the extracted background rate is almost only the shape of the smoothed activity. In this case, however, we have additional information about the potential fluid source and can directly test the pore pressure diffusion model.

5. Conclusions

In natural seismicity, aftershocks are often embedded even in swarm-like activity. The ETAS modeling is an effective method to deal with aftershocks. To deal with swarm-like seismicity, the hypothesis of a constant background activity has to weakened because fluid flows, silent earthquakes and other mechanisms enhance or reduce the earthquake probability. In cases where we have no knowledge about the source of earthquake generation, the statistical modeling can reveal the time-dependence of the mechanism. This is the case for the swarm activity in Vogtland. The revealed signature is found to be in good agreement with the signal of fluid diffusion from a high pressure source. In cases where we have some information about the potential source function, we can go one step further and replace the back ground forcing by a functional form. This is done in the case of the Bad Reichenhall swarm activity where we test the triggering mechanism of pore pressure diffusion due to rainfall. The resulting high correlation between model and observation suggests that rain water diffusion is really the responsible mechanism in this case.

6. References

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