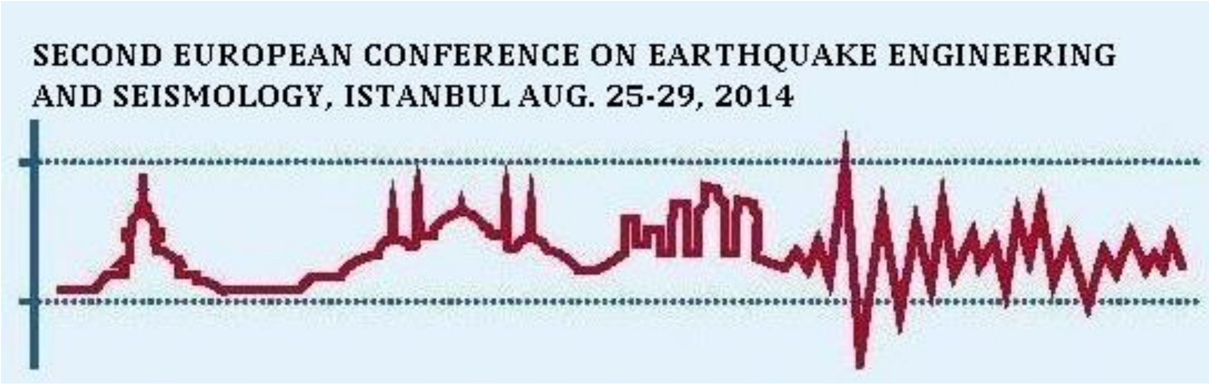

ON THE PSEUDO-PROSPECTIVE STOCHASTIC FORECASTING OF AFTERSHOCKS: THE 2014 KEFALONIA SEQUENCE IN GREECE

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On January 21st, 2014, an earthquake of M_w=6.1 struck the region of Kefalonia Island (Greece), causing severe damage in the area of Paliki peninsula. It was followed by numerous aftershocks, increasing even more the feeling of anxiety and the willingness of people to know more about the ongoing seismic activity in the region. Society and the responsible institutions were all concerned to learn about the seismic process during a seismic crisis. All this requires answers to questions about the time dependence of regional seismic hazards and reveals that we have entered the era of operational earthquake forecasting.

The goal of operational forecasting is to provide the public with authoritative information on seismicity rate changes and mainly, on strong aftershocks probabilities during a sequence. Seismic hazards change dynamically in time, because a strong earthquake suddenly alters the conditions within the fault system that will increase the likeliness of future earthquakes. Statistical and physical models of earthquake interactions (Ogata, 1988; 1998; Gospodinov & Rotondi, 2006) have begun to capture many features of natural seismicity, such as aftershock triggering and clustering. The short-term stochastic models provide the tools to perform a formal assessment of aftershock occurrence probabilities (Karakostas et al., 2014; Jordan et al., 2011). They demonstrate a probability gain in forecasting future earthquakes relative to the long-term time-independent models typically used in seismic hazard analysis.

Aftershocks occurrence probability assessment is based on two power laws that describe the behavior of events in a sequence. The first is the well known Modified Omori Formula (MOF), considering the temporal decay of aftershocks occurrence rate (Omori, 1894) and the second is the one describing the size distribution of earthquakes. For the temporal distribution Ogata (1988) later proposed the epidemic type aftershock sequence (ETAS) model, involving each aftershock in the secondary triggering of events.

As an alternative to MOF and the ETAS Gospodinov and Rotondi (2006) proposed the RETAS model which is based on the assumption that only aftershocks with magnitudes larger than or equal to a threshold M_{tr} can induce secondary seismicity. The conditional intensity function of this model is formulated as

$$\lambda(t|H_t) = \mu + \sum_{\substack{t_i<t \\ M_i \geq M_{tr}}} \frac{K_o\, e^{\alpha(M_i - M_o)}}{(t - t_i + c)^p} \qquad (1)$$

where μ (shocks per day) is the rate of background activity, p and c are free parameters, the coefficient α measures the magnitude efficiency of a shock in generating its aftershock activity and K_0 is a multiplier, common to all aftershocks, which has an impact on the total aftershock productivity. The

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symbol H_t denotes the process history (times and magnitudes in this case). The advantage of using RETAS is that by varying the M_{tr} values between the magnitude of completeness M_0 and the main shock magnitude, we verify all intermediate versions of the RETAS model, including the ETAS and the MOF models as limit cases.

We applied the RETAS model to analyze data samples from the 2014 Kefalonia sequence. We located earthquakes using waveform data from stations of the Hellenic Unified Seismological Network (HUSN). To improve the accuracy of the aftershock focal coordinates, data were relocated, providing the possibility to better identify aftershocks for further analysis. Trying to perform the study as in a real prospective case, all data samples were compiled at the end of each subsequent day - January 26th, 27th, etc. We then accomplished the following procedure: a) we determined the magnitude of completeness M_0 for the first day data sample; b) a RETAS model analysis was performed, identifying the best fit model for these data; c) one day probability for at least one aftershock with M5.0-M7.0 was estimated on the basis of the best fit model; all previous steps were repeated for the data samples of the subsequent days (see the results in Table 1 and in Fig.1)

Table 1 Results from the RETAS analysis performed for the data samples of the 2014 Kefalonia sequence at the end of each subsequent day (b-value is a recurrence law parameter and p-values are the ones from formula (1)). Last column presents the estimated one-day probabilities for aftershock occurrence (at least one shock in the range Mw5.0-Mw7.0)

Forecast date	b-value p-value	Number of aftershocks N Magnitude of completeness M_0	Best fit model	Time after main shock [days]	One-day aftershock occurrence probability (Mw5.0-Mw7.0)
Jan 27 2104	b=0.684 p=3	N=47; M_0=3.4	MOF M_{tr}=6.1	0.409	0.999
Jan 28 42104	b=0.86 p=0.514	N=123; M_0=3.2	MOF M_{tr}=6.1	1.419	0.798
Jan 29 2014	b=0.828 p=0.5527	N=190; M_0=3.1	MOF M_{tr}=6.1	2.417	0.747
Jan 30 2014	b=0.865 p=1.171	N=212; M_0=3.1	MOF M_{tr}=6.1	3.404	0.482
Jan 31 2014	b=0.881 p=1.386	N=231; M_0=3.1	MOF M_{tr}=6.1	4.388	0.339
Feb 1 2014	b=0.759 p=1.497	N=371; M_0=2.8	RETAS M_{tr}=4.3	5.404	0.465
Feb 2 2014	b=0.781 p=1.153	N=409; M0=2.8	RETAS M_{tr}=3.1	6.398	0.409
Feb 3 2014	b=0.798 p=1.173	N=427; M_0=2.8	RETAS M_{tr}=3.1	7.413	0.285
Feb 4 2014	b=0.784 p=1.182	N=499; M_0=2.8	RETAS M_{tr}=3.1	8.418	0.510
Feb 5 2014	b=0.796 p=1.175	N=531; M_0=2.8	RETAS M_{tr}=3.1	9.414	0.447
Feb 6 2014	b=0. 802 p=1.287	N=555; M_0=2.8	RETAS M_{tr}=2.9	10.389	0.371

We named the probability forecasting pseudo-prospective, because, although we tried to be as near as possible to a real prospective case, we did have more time to make our data more complete, perform relocation etc., something, which could hardly be done in a real crisis, especially for the first or second days of the sequence. The results are presented in Table 1 and the evolution of probability values with time is plotted on Fig.1. The following specific features can be unclosed by the performed stochastic modeling and occurrence probability estimation:

- At the beginning of the sequence (first five days) the best fit model is MOF which seems predictable as the main shock should govern the process at first. The p-values for the second and third days are quite low, which points to a very slowly decaying aftershock rate.
- Then, the clustering type changes to RETAS (M_{tr}=4.3, M_{tr}=3.1, M_{tr}=2.9), which reveals that randomness in clustering has increased.

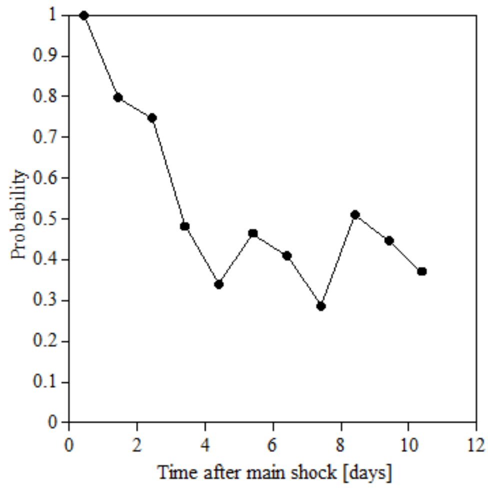

Fig.1 Estimated one-day occurrence probability evolution for at least one aftershock within the magnitude range (Mw5.0-Mw7.0). Each probability is estimated on data up to the end of the considered subsequent day

- The probability values at the beginning (first day) are very high. Although it is expected that the main shock would trigger the highest secondary rate (and occurrence probability consequently), we think that these values are also artificially increased due to the high magnitude of completeness M_o (it is included in the estimation algorithm) and low b-value of the recurrence law (see Table 1).
- On the whole probability values decrease, but occasionally go up and down, depending on events' number and magnitudes for the previous day. This signifies the complexity of this sequence when compared, for example, to the 2013 North Aegean (Greece) seismic sequence (Karakostas et al. 2014), where probabilities decrease smoothly in time. The Mw6.0 second main shock definitely influenced the seismicity rate and probability value increase (see Table 1 and Fig.1)

The results from this attempt to forecast aftershock occurrence probabilities prospectively reveal that the RETAS model is applicable to model stochastically aftershock temporal decay for the Kefalonia sequence and to capture changes in the clustering pattern during its temporal evolution. The model offers the tools to estimate strong aftershock probabilities, but the probability values, especially for the first one or two days, should be treated with caution because they are sensitive on data completeness, which is a problem for the beginning of most aftershock sequences.

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