Immediate aftershock forecasting after a strong earthquake: Towards real-time aftershock forecasting

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@SCEC/CSEP workshop
Outline

- Aftershock forecasting, and its problems
- Forecasting from the incomplete data
- Forecasting experiment
Forecasting aftershocks after the main shock

- Immediate forecast of aftershock is strongly required.
- We need to tailor a forecast model to each aftershock sequence.

![Graph showing cumulative number of aftershocks over time for various earthquakes.]

- 2004 Chuetsu (M6.8)
- 2007 Chuetsu-Oki (M6.8)
Forecasting from an early aftershock data is difficult

The data in the early period is highly deficient.

1995 Hyogo-Ken-Nambu earthquake of M 7.3

Time from the main shock [day]
Outline

- Aftershock forecasting, and its problems
- Forecasting from the incomplete data
- Forecasting experiment
Schematic illustration of our procedure

Underlying Eqs: detected EQs. + missing EQs.

- Underlying EQs.
- Missing
- Detected EQs.

Statistical Modeling

Aftershock Model

\[ \lambda(t, M) \]

Omori-Utsu law
Gutenberg-Richter law

Fitting
Schematic illustration of our procedure

Underlying Eqs: detected EQs. + missing EQs.

Statistical Modeling

\[ \lambda(t, M) \]

Underlying Aftershock Model

Omori-Utsu law

Gutenberg-Richter law

Detection Rate

\[ \Phi(t, M) \]

Prior for parameters

Estimate

Fitting

Detected Aftershock Model

Detected EQs.

(Underlying)

(Unknown)

Missing

(Data)
Estimating the detection rate

**Magnitude dependence of the detection rate**

\[
\Phi(M | \mu, \sigma) = \int_{-\infty}^{M} \frac{1}{\sqrt{2\pi}\sigma^2} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \, dx
\]

\(\mu\): the magnitude with 50 % detection rate

**Observed magnitude distribution:**

(G-R law) × (Detection Rate function)


**Time dependence of the detection rate**

- Assume the parameter \(\mu\) is a function of the time.
- Estimate \(\mu(\tau)\) using Bayesian smoothing method

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Forecast experiment (1)

The aftershocks of the 2011 Tohoku-oki earthquake of M9.0
The NEIC PDE Catalog
Forecasting experiment (1)

The aftershocks of the 2011 Tohoku-oki earthquake of M9.0
The NEIC PDE Catalog (provided by USGS)

Learning period | Forecast period |
--- | --- |
0 – 3 [hour] | 3 – 6 [hour] |
0 – 6 [hour] | 6 – 12 [hour] |
0 – 12 [hour] | 12 – 24 [hour] |
0 – 24 [hour] | 24 – 48 [hour] |
Estimating the detection rate function

$\mu(\tau)$: 50 % detection magnitude
**Forecast experiment with the 2011 Tohoku sequence**

<table>
<thead>
<tr>
<th>Learning period</th>
<th>0 - 1 day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forecasting period</td>
<td>1 - 31 day</td>
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</tbody>
</table>

Omi et al., Scientific Reports (2013)

**Aftershock frequency [1/Day]**

- **Our model**
- **Conventional model**

<table>
<thead>
<tr>
<th>M&gt;5.0</th>
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<tbody>
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<td>Time from the main shock [Day]</td>
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</table>

<table>
<thead>
<tr>
<th>M&gt;6.0</th>
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<td>Time from the main shock [Day]</td>
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Immediate forecast with the 2011 Tohoku sequence

Omi et al., Scientific Reports (2013)

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<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Learning period</td>
<td>0 - 3 h</td>
<td>0 - 6 h</td>
<td>0 - 12 h</td>
<td>0 - 24 h</td>
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<td>3 - 6 h</td>
<td>6 - 12 h</td>
<td>12 - 24 h</td>
<td>24 - 48 h</td>
</tr>
</tbody>
</table>

Bar: 95% interval
Forecast experiment with real-time data

- Analyzing the real-time data from the Hi-net catalog that lists automatically determined events.
- The aftershocks of the M6.3 earthquake on Feb. 25, 2013 in Nikko, Japan.

The Hi-net catalog (available in real-time)

The JMA catalog (available after 1-2 days)
Forecasting experiment with real-time data

- The M6.3 earthquake on Feb. 25, 2013 in Nikko, Japan
- Forecasting is prepared based on Hi-net catalog, and compared with JMA catalog

- Hi-net catalog (Real-time data)
- JMA catalog (Revised Catalog)

Omi et al., Scientific Reports (2013)
Towards Real-time aftershock forecasting

**Quality of the Real-time data**

- More data, better forecast. (although the detection of aftershocks is not a task of priority after a large earthquake)

- In Japan, the Hi-net seems to reasonably detect earthquakes in real-time owing to the dense seismic network, enabling us to make an unbiased forecast.

**Forecasting method**

- Can deal with the incomplete early aftershock data.

- Can assess the uncertainty of the forecast. (See my poster!!)
Conclusion

- We proposed a method for estimating the underlying aftershock model from the incomplete data of early aftershocks.

- Our method well forecasts the aftershock activity from the incomplete data available a few hours after a main shock.

- Our method is also effective for the real-time data.
References

T. Omi, Y. Ogata, Y. Hirata & K. Aihara,
“Forecasting large aftershocks within one day after the main shock”
Scientific Reports (2013).
Thank you !!!
State-Space model formulation

State

\[ \mu_{i+1} = \mu_i - 1 + (\mu_i - 1 - \mu_i - 2) + \delta_i \]

Observation

\[ M_i = \mu_i + \epsilon_i^{\beta, \sigma} \]

\( \delta_i \) : Gaussian noise, \( \epsilon_i^{\beta, \sigma} \) : non-Gaussian noise
Objective Bayesian Estimation

Estimate $\mu = \{\mu_1, \mu_2, \ldots, \mu_N\}$, $\beta$, and $\sigma$ from $M = \{M_1, M_2, \ldots, M_N\}$

Likelihood:
$$P_{\beta,\sigma}(M|\mu) = \prod_{i=1}^{N} \beta e^{-\beta(M_i - \mu_i) - \frac{\beta^2 \sigma^2}{2}} \phi(M_i|\mu_i, \sigma)$$

Prior:
$$P_V(\mu) = \frac{1}{\sqrt{2\pi V}} e^{-\frac{(\mu_i + 2\mu_{i+1} + \mu_i)^2}{2V}}$$

Bayesian Estimation: Find $\mu$ that maximizes the posterior pdf,

$$P_{\beta,\sigma,V}(\mu|M) \propto P_{\beta,\sigma}(M|\mu)P_V(\mu)$$

Parameter Estimation (EM method):

Find $\beta$, $\sigma$ and $V$ that maximizes the posterior pdf,

$$P(\beta, \sigma, V|M) \propto P_{\beta,\sigma,V}(M)P(\beta, \sigma, V)$$