What’s new and what’s next in aftershock forecasting

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USGS Earthquake Science Center
Who is operational earthquake forecasting for?

- Audience/stakeholders:
  - Public: what to expect/what’s normal?
  - Emergency Response: situational awareness. Aid in rescue decisions
  - FEMA, lifelines: Triage, where to park the trucks, realistic scenarios.
  - Scientists: prospective testing of earthquake models.
Over what time frame is an aftershock forecast useful?
Over what time frame is an aftershock forecast useful?

Forecast for a Magnitude 7 Mainshock

<table>
<thead>
<tr>
<th>Stage</th>
<th>Dominant Time Period (Kobe, Northridge, Christchurch)</th>
<th>Probability of an Aftershock with Magnitude 6 or larger</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Emergency Response</td>
<td>0 to 14 days</td>
<td>61%</td>
</tr>
<tr>
<td>(search and rescue, fire</td>
<td></td>
<td></td>
</tr>
<tr>
<td>fighting, shelters, damage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>assessment)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Restoration</td>
<td>14 days to 1 year</td>
<td>33%</td>
</tr>
<tr>
<td>(restore utilities, debris</td>
<td></td>
<td></td>
</tr>
<tr>
<td>removal, temporary repairs)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Reconstruction</td>
<td>1 to 3 years</td>
<td>11%</td>
</tr>
<tr>
<td>(structures replaced to</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pre-disaster levels)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Betterment</td>
<td>3 to 10 years</td>
<td>11%</td>
</tr>
<tr>
<td>(major projects improve</td>
<td></td>
<td></td>
</tr>
<tr>
<td>community to a new</td>
<td></td>
<td></td>
</tr>
<tr>
<td>standard)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Long-Term</td>
<td>10 to 50 years</td>
<td>13%</td>
</tr>
<tr>
<td>(life with a new normal)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Slide courtesy of Andy Michael
Current state of operational earthquake forecasting at the USGS

- California Generic model only (no automatic tuning)
- Text-based forecast posted as a link somewhere on USGS event page
- Earthquake Science Center has been asked to ‘Operationalize’ (automate) forecasts for M5+ earthquakes in US.

Omori 1900, Utsu et al., 1995

![Graph showing Omori's law](image)

### Sun 24 Aug 2014 03:20:44 AM PDT

**USGS**

6km (4mi) NW of American Canyon, CA

USGS currently issues earthquake advisories for all M≥5 mainshocks in California. Example: Napa Earthquake Sun 24 Aug 2014 4:20 AM PDT

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**Background Information About Aftershocks**

Like most earthquakes, the recent earthquake is expected to be followed by numerous aftershocks. Aftershocks are additional earthquakes that occur after the mainshock and in the same general area. Usually, aftershocks are smaller than the mainshock, but occasionally an aftershock may be strong enough to be felt widely throughout the area and may cause additional damage, particularly to structures already weakened by the mainshock. As a rule of thumb, aftershocks of magnitude 5 and larger are considered potentially damaging.

Aftershocks are most common immediately after the mainshock; their average number per day decrease rapidly as time passes. Aftershocks are most likely to be felt in the first few days after the mainshock, but may be felt weeks, months, or even years afterwards. In general, the larger the mainshock, the larger its aftershocks will be felt.

Aftershocks tend to occur near the mainshock, but the exact geographic pattern of the aftershocks varies from earthquake to earthquake and is not predictable. The larger the mainshock, the larger the area of aftershocks. While there is no "hard" cutoff distance beyond which an earthquake is totally incapable of triggering an aftershock, the vast majority of aftershocks are located close to the mainshock. As a rule of thumb, a magnitude 6 mainshock may have aftershocks up to 10 to 20 miles away, while a magnitude 7 mainshock may have aftershocks as far as 30 to 60 miles away.
R&J is bad for operational earthquake forecasting. Ex: 2015 M7.8 & M7.3 Nepal earthquakes

2015 M7.8 and 7.3 Nepal

- Reasenberg and Jones forecast ‘breaks’ if there is a big aftershock.
- Current solution: ad-hoc “double” forecast (triple, quadruple?)
- Better solution: Epidemic-Type model…
ETAS: Epidemic-type aftershock sequence

- Basic rule of the epidemic model: Every earthquake, including aftershocks, triggers more earthquakes.
- Aftershock sequence is always a sum of contributions.
  - Big aftershocks are like new outbreaks in an epidemic
  - About 50% of aftershocks are secondary

$$r(t, M) = \sum_{t_i < t} 10^{a + \alpha(M_i - M)}(t - t_i + c)^{-p}$$
ETAS localizes hazard in time (and space) compared to R&J

R&J averages over secondary triggering

ETAS has rate spikes at large aftershocks

Forecast start

A

Differential Time (days)

0 10 20 30

Cumulative Aftershock Count

0 20 40 60 80 100 120 140 160 180 200

Probability

0 0.05 0.1

Final Aftershock Count

0 20 40 60 80 100 120 140 160 180 200

RJ89 (Poisson distribution)

Observed distribution

USGS science for a changing world
No magnitude forecasting in sight (aside from G-R)

Helmstetter and Sornette, 2003

“mainshock” magnitude is independent of foreshock numbers

Aftershocks follow G-R, with no distinction between aftershocks/foreshocks

Earthquakes probably don’t know how big they’re going to get until they get there

Forecasts must always include caveats about low probability high-impact events.
Global forecasts: regionalized generic models

- Typical largest aftershock
- Subduction zones
- Active continent
- Stable continent
- Deep subduction
- Mid-ocean ridges
Bayesian model updating for sequence-specific forecasts

2010 El Mayor-Cucapah

Cumulative number of aftershocks above M3.7

Data

Sequence-specific

Model

time = 1 day

$\alpha_{ms}$

Sequence-specific

$a$

Sequence-specific

$p$

Sequence-specific

$log-c$

Sequence-specific

Generic

Generic

Generic

Generic
What’s next: Beyond parametric models

Parametric Forecast: Advantages
- Model can be trained on relatively few data once the statistical laws are devised.
- The statistical laws themselves are fascinating.

Disadvantages
- Parametric models can be “over-tuned.” (though using a prior helps tremendously)
  - Aleatory variability has to be assumed modeled.
  - Some percentage of sequences just don’t fit the idealized model
Alternative: Similarity-based forecasting

Construct forecast from previous similar sequences.

- Almost model free: just define similarity.

Advantages: no surprises. Forecast distribution is distribution of real sequences.

Disadvantages: lots of data needed to sample complete distribution.
Similarity-based forecasting

Example: M7 earthquake with 6 M5+ aftershocks in the first day

- Similarity defined from event count.
- Forecast distribution is non-Poissonian:
  - Poisson forecast: 0-8 aftershocks
  - Similarity forecast: 0-23 aftershocks (no surprises)
- In practice, combine strengths through ensemble modeling.
- Other possibilities for defining similarity
Epidemic-type forecasts can zero in on aftershock hot-spots.

2015 M7.8 and 7.3 Nepal
Epidemic-type forecasts can zero in on aftershock hot-spots.

- The aftershock hazard map evolves with time...
Epidemic-type forecasts can zero in on aftershock hot-spots.

- Large aftershocks change the hazard landscape…
Epidemic-type forecasts can zero in on aftershock hot-spots.

- Aftershock hazard continues to be elevated…
Moving from spatial rate to spatial hazard

- GMPEs and local topographic slope as proxy for $V_s30$ for site amplification (probabilistic ShakeMap)

Without site effects

With site effects
What’s in the pipeline at the USGS?

- Automatic epidemic-type forecasts for M5+ in the United States.
- A summary ‘pin’ on the USGS event page.
- Scenarios, Magnitude-probability tables.
- Spatial forecasts?
- Depends on user interest and programmatic support…

<table>
<thead>
<tr>
<th>Forecast Interval</th>
<th>Magnitude</th>
<th>Number</th>
<th>Number Range</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Day</td>
<td>M ≥ 3</td>
<td>5</td>
<td>0 - 25</td>
<td>12%</td>
</tr>
<tr>
<td></td>
<td>M ≥ 6</td>
<td>0</td>
<td>0*</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td></td>
<td>M ≥ 7</td>
<td>0</td>
<td>0*</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td></td>
<td>M ≥ 8</td>
<td>0</td>
<td>0*</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td></td>
<td>M ≥ 9</td>
<td>0</td>
<td>0*</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>1 Week</td>
<td>M ≥ 3</td>
<td>8</td>
<td>0 - 35</td>
<td>55%</td>
</tr>
<tr>
<td></td>
<td>M ≥ 6</td>
<td>0</td>
<td>0 - 1</td>
<td>&lt;1%</td>
</tr>
<tr>
<td></td>
<td>M ≥ 7</td>
<td>0</td>
<td>0*</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td></td>
<td>M ≥ 8</td>
<td>0</td>
<td>0*</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td></td>
<td>M ≥ 9</td>
<td>0</td>
<td>0*</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>1 Month</td>
<td>M ≥ 3</td>
<td>13</td>
<td>1 - 55</td>
<td>98%</td>
</tr>
<tr>
<td></td>
<td>M ≥ 6</td>
<td>0</td>
<td>0 - 1</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>M ≥ 7</td>
<td>0</td>
<td>0 - 1</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td></td>
<td>M ≥ 8</td>
<td>0</td>
<td>0*</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td></td>
<td>M ≥ 9</td>
<td>0</td>
<td>0*</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>1 Year</td>
<td>M ≥ 3</td>
<td>54</td>
<td>4 - 250</td>
<td>&gt;99%</td>
</tr>
<tr>
<td></td>
<td>M ≥ 6</td>
<td>0</td>
<td>0 - 1</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>M ≥ 7</td>
<td>0</td>
<td>0 - 1</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>M ≥ 8</td>
<td>0</td>
<td>0 - 1</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td></td>
<td>M ≥ 9</td>
<td>0</td>
<td>0*</td>
<td>&lt;0.1%</td>
</tr>
</tbody>
</table>

*Earthquake possible but with low probability
In the meantime… Aftershock Forecasting software.

Funded by US-AID OFDA, available soon as an OpenSHA app www.opensha.org/apps
An earthquake of magnitude M7.2 occurred 1.0 day ago 12km SW of Delta, B.C., MX. More earthquakes than usual will continue to occur in the area, decreasing in frequency over the following year or longer. During the next week there are likely to be 160 - 650 aftershocks large enough to be felt locally, and there is a 25 - 30% chance of at least one damaging M8 (or larger) aftershock. The earthquake rate may be re-invigorated in response to large aftershocks, should they occur.

**Anticipated aftershock activity**

Forecast start date: 5 Apr 2010, 22:40:42 UTC

<table>
<thead>
<tr>
<th>Probability of at least one aftershock larger than:</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
<th>M6</th>
<th>M7</th>
<th>M8</th>
<th>M9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Week</td>
<td>54%</td>
<td>87%</td>
<td>94%</td>
<td>94%</td>
<td>94%</td>
<td>94%</td>
<td>94%</td>
</tr>
<tr>
<td>Month</td>
<td>94%</td>
<td>94%</td>
<td>94%</td>
<td>94%</td>
<td>94%</td>
<td>94%</td>
<td>94%</td>
</tr>
<tr>
<td>Year</td>
<td>94%</td>
<td>94%</td>
<td>94%</td>
<td>94%</td>
<td>94%</td>
<td>94%</td>
<td>94%</td>
</tr>
</tbody>
</table>

**Key to colors**

- **Peak MMI**
  - MMI I: Very light
  - MMI II: Light
  - MMI III: Moderate
  - MMI IV: Strong
  - MMI V: Very strong
  - MMI VI: Severe
  - MMI VII: Violent
  - MMI VIII: Very violent

- **Potential Damage**
  - Very light
  - Light
  - Moderate
  - Strong
  - Very strong

This forecast will be updated as new information becomes available.
The next step: Beyond point-process forecasting: Combining the epidemic model with a fault network.

Field et al., 2018

(a) With faults
(b) Without faults

UCERF3-ETAS

$M=6.1$

Parkfield

Log$_{10}$(Expected Num $M>2.5$)

USGS

science for a changing world
Are characteristic faults more susceptible to triggering?

- Characteristic fault: High geologic slip rate compared to instrumentally observed activity (“Sleeping giant”).
- Assumed to make up the activity deficit in large ‘characteristic’ earthquakes
- Translates to: higher probability that any given event on that fault is a foreshock.

Bombay beach swarm (9/26/16)
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- Assumed to make up the activity deficit in large ‘characteristic’ earthquakes
- Translates to: higher probability that any given event on that fault is a foreshock.

![Map of Characteristic Faults and Bombay Beach Swarm](image)
Does fault proximity affect productivity?

- Proximity to faults does not appear to affect aftershock productivity or foreshock rates
- Proximity to faults does not even affect the b-value/MFD
- Either:
  - the near-fault effect is only evident at the largest magnitudes
  - or there’s no such thing as an ‘off-fault’ earthquake.
Conclusion

• Coming soon: automatic Epidemic-type aftershock forecasts for all M5+ earthquakes in the US.

• Map products in development. Looking to identify potential users and build programmatic (and programming) support.

• Continuing research into the effect of faults on the forecast model.

• Standalone software for generating maps and advisories available soon as an openSHA app.