UCERF3-ETAS
Including Spatiotemporal Clustering for a California Operational Earthquake Forecast (OEF)

By the ongoing Working Group on California Earthquake Probabilities (WGCEP)


OEF additions: M. Blanpied, J. Hardebeck, L. Jones, W. Marzocchi, K. Porter, D. Trugman, M. Werner, N. van der Elst
Working Groups on California Earthquake Probabilities (WGCEPs)

The most official time-dependent earthquake forecasts for California

A better and more useful approximation
UCERF2 Issues:

1) Assumes segmentation

2) Excludes multi-fault ruptures

3) Over-predicts M ~6.7 events

4) Elastic rebound not self-consistent

5) Lacks spatiotemporal clustering

UCERF3 Solutions:

New method supported by physics-based simulators

ETAS Operational Eqk Forecasting
UCERF3 Publication Status

UCERF3-TI (Time-Independent Model):

- Main report and 20 Appendices in USGS OFR 2013-1165 (also CGS Special Report 228)
- Main report & Appendix N also in BSSA (2014, vol. 104, no. 3)

UCERF3-TD (Long-Term Time Dependent Model)

- Main report & two methodology papers published in BSSA (April, 2015)
- USGS Fact sheet too

UCERF3-ETAS (Spatiotemporal Clustering Model for OEF)

- Under development

http://pubs.usgs.gov/of/2013/1165
UCERF3 Publication Status

**UCERF3-TI (Time-Independent Model):**

- Main report and 20 Appendices in USGS OFR 2013-1165 (also CGS Special Report 228)
- Main report & Appendix N also in *BSSA* (2014, vol. 104, no. 3)

**UCERF3-TD (Long-Term Time Dependent Model)**

- Main report & two methodology papers published in *BSSA* (*April, 2015*)
- USGS Fact sheet too

**UCERF3-ETAS (Spatiotemporal Clustering Model for OEF)**

- Under development

http://pubs.usgs.gov/of/2013/1165
Theory & Observations suggested ruptures can jump between faults within ~5km (e.g., Harris & Day, 1993; Wesnousky, 2006; respectively)

Segment-busting earthquakes:
- 2002 M 7.9 Denali
- 1992 M 7.3 Landers
- 1999 M 7.2 Hector Mine
- 2010 M 7.2 El Mayor–Cucapah
- 2011 M 9.0 Tohoku, Japan

You can move from any point on the green fault cluster to any other point without jumping more than 5 km
Data Fits (better than UCERF2):

**Region MFDs**

**Slip Rates:**

**Paleo Event Rates:**
Data Fits (better than UCERF2):

Region MFDs

<table>
<thead>
<tr>
<th>Latitude (degrees)</th>
<th>Slip Rate (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>33.5</td>
</tr>
<tr>
<td>6</td>
<td>34.0</td>
</tr>
<tr>
<td>7</td>
<td>34.5</td>
</tr>
<tr>
<td>8</td>
<td>35.0</td>
</tr>
<tr>
<td>9</td>
<td>35.5</td>
</tr>
<tr>
<td>10</td>
<td>36.0</td>
</tr>
<tr>
<td>11</td>
<td>36.5</td>
</tr>
<tr>
<td>12</td>
<td>37.0</td>
</tr>
<tr>
<td>13</td>
<td>37.5</td>
</tr>
<tr>
<td>14</td>
<td>38.0</td>
</tr>
<tr>
<td>15</td>
<td>38.5</td>
</tr>
<tr>
<td>16</td>
<td>39.0</td>
</tr>
<tr>
<td>17</td>
<td>39.5</td>
</tr>
<tr>
<td>18</td>
<td>40.0</td>
</tr>
</tbody>
</table>

UCERF3-TI:

- Relaxes segmentation assumptions
- Incorporates multi-fault ruptures
- Fits a broader range of data better
- Samples a wider range of epistemic uncertainties
- Is relatively simple, reproducible, and extensible
- Enables hypothesis testing (e.g., GR vs. Characteristic faults)

It’s still a limited approximation of the system, however.
UCERF3 Publication Status

UCERF3-TI (Time-Independent Model):

• Main report and 20 Appendices in USGS OFR 2013-1165
  (also CGS Special Report 228)

• Main report & Appendix N also in BSSA (2014, vol. 104, no. 3)

UCERF3-TD (Long-Term Time Dependent Model)

• Main report & two methodology papers published in BSSA (2015)

• USGS Fact sheet too

UCERF3-ETAS (Spatiotemporal Clustering Model for OEF)

• Under development
Reid’s (1911) Elastic-Rebound Theory:

Rupture probabilities drop on a fault after experiencing a large rupture and build back up with time as tectonic stresses re-accumulate

The basis of all previous WGCEP models:

Problem – WGCEP 2003/2007 algorithm is biased and not self-consistent for un-segmented models
UCERF2 Methodology (from WGCEP 03):

Based on a weight-average of section probability gains

\[ P_{r}^{U2} = f_{r} \sum \frac{(P_{s}^{BPT} M_{o_{s}} / f_{s})}{\sum \dot{M}_{o_{s}}} \approx P_{r}^{Pois} \sum \frac{\dot{M}_{o_{s}} \left( P_{s}^{BPT} / P_{s}^{Pois} \right)}{\sum \dot{M}_{o_{s}}} \]

UCERF3 Methodology:

Based on a weight-average of section recurrence intervals and time-since-last-event

\[ \mu_{r}^{cond} = \frac{\sum \mu_{s} A_{s}}{\sum A_{s}} \]
\[ \eta_{r} = \frac{\sum (T_{s} / \mu_{s}) A_{s}}{\sum A_{s}} \]
\[ P_{r}^{BPT} = P_{r}^{BPT} \left( \eta_{r}, \frac{\Delta T}{\mu_{r}^{cond}}, \alpha \right) \]
\[ P_{r}^{U3} = P_{r}^{BPT} \left[ \frac{\mu_{r}^{cond}}{\mu_{r}} \right] \]
UCERF3 Elastic-Rebound Model:

- Much more self consistent & less biased (although not perfect), as shown by Monte Carlos simulations

- Supports magnitude-dependent aperiodicity

- Accounts for historic open interval (e.g., last event was sometime before ~1875), so time-dependent model now applied to all faults (which is influential)

- Consistent with physics-based simulators (a WGCEP first)

- Model is more testable
Main Result: implied average time-dependent probability gain for $M \geq 6.7$ in next 30 years:
UCERF3 Publication Status

Time-Independent Model (UCERF3-TI):

• Main report and 20 Appendices in USGS OFR 2013-1165
  (also CGS Special Report 228)

• Main report & Appendix N also in BSSA (2014, vol. 104, no. 3)

Long-Term Time Dependent Model
(UCERF3-TD)

• Main report & two methodology papers submitted to BSSA

Spatiotemporal Clustering Model for OEF (UCERF3-ETAS)

• Under development
Why? Because aftershocks (triggered events) can be large and damaging…

Landers

Turkey

Darfield → Christchurch

Sumatra
• Does not assume segmentation or the characteristic earthquake hypothesis (includes multi-fault ruptures)

• Includes both elastic-rebound and spatiotemporal clustering (aftershocks)

• Uses Epidemic Type Aftershock Sequence model (ETAS; Ogata, 1988) to generate synthetic catalogs of $M \geq 2.5$ events
UCERF3-ETAS

- Does not assume segmentation or the characteristic earthquake hypothesis (includes multi-fault ruptures)
- Includes both elastic-rebound and spatiotemporal clustering (aftershocks)
- Uses Epidemic Type Aftershock Sequence model (ETAS; Ogata, 1988) to generate synthetic catalogs of $M \geq 2.5$ events
UCERF3-ETAS

- Does not assume segmentation or the characteristic earthquake hypothesis (includes multi-fault ruptures)
- Includes both elastic-rebound and spatiotemporal clustering (aftershocks)
- Uses Epidemic Type Aftershock Sequence model (ETAS; Ogata, 1988) to generate synthetic catalogs of M≥2.5 events

Simulations (synthetic catalogs) are critical for identifying potential problems, such as the need for elastic rebound.
Epidemic Type Aftershock Sequence (ETAS) Model

An empirically based description of triggering statistics (Ogata, 1998):

\[ \lambda(t,x) = \lambda_0 u(x) + \sum_{i : t_i < t} k i 0^{a(M_i - M_{min})}(t - t_i + c)^{-p} c_s (r + d)^{-q} \]

- Main Shock
- Primary Aftershocks
- Secondary Aftershocks
- Tertiary Aftershocks
Epidemic Type Aftershock Sequence (ETAS) Model

An empirically based description of triggering statistics (Ogata, 1998):

\[
\lambda(t, x) = \lambda_0 \mu(x(t)) + k \cdot 10^{a(M_i - M_{min}) - \alpha(t_i)} \cdot (r + d)^{-q}
\]

Key Assumption:

Statistics inferred from small earthquakes apply to large (damaging) earthquakes on poorly known, finite faults.

Secondary Aftershocks

Tertiary Aftershocks
UCERF3-ETAS – in a nutshell:

- For every observed and simulated $M \geq 2.5$ event, sample a number of triggered events according to ETAS parameters, long-term rates, and elastic-rebound probabilities; also sample spontaneous events if desired.

1) Randomly choose a cube where a primary event nucleates

2) Randomly choose a rupture given the relative nucleation rate of those within the cube

Bookkeeping is somewhat complicated due to need for elastic-rebound updating
Main Scientific Issues:

1) Including both spatiotemporal clustering and finite-fault ruptures implies a requirement for elastic rebound

2) Characteristic magnitude-frequency distributions (Non GR) may or may not be a problem; elastic-rebound seems to solve this for all but the most extreme cases

3) Important issue is how to apply tight spatial clustering statistics (e.g., >90% aftershocks within a few km of main shock) to faults that are not that well known (spatially)

4) How can we test these models at the magnitudes we care about for hazard and loss?
Main Scientific Issues:

1) Including both spatiotemporal clustering and finite-fault ruptures implies a requirement for elastic rebound

Otherwise ~85% of triggered large events would re-rupture the same fault (Field, 2012, SSA), which we don’t see in nature

Leaving it out also produces doomsday sequences, and screws up Båth's Law.
Main Scientific Issues:

1) Including both spatiotemporal clustering and finite-fault ruptures implies a requirement for elastic rebound

Related question: Just ruptured
   no chance of doing so again soon according to UCERF3-TD

Can the red rupture be triggered (nucleate) from the blue area that just ruptured?
Main Scientific Issues:

1) Including both spatiotemporal clustering and finite-fault ruptures implies a requirement for elastic rebound

Related question: **Just ruptured**

no chance of doing so again soon according to UCERF3-TD

Can the red rupture be triggered (nucleate) from the blue area that just ruptured?

Saying yes leads to over-triggering of fault-based ruptures due to the many aftershocks within the blue area
Main Scientific Issues:

1) Including both spatiotemporal clustering and finite-fault ruptures implies a requirement for elastic rebound

2) Characteristic magnitude-frequency distributions (Non GR) may or may not be a problem; elastic-rebound seems to solve this for all but the most extreme cases

We have a correction if needed, but we are still exploring if and when this is necessary
Main Scientific Issues:

1) Including both spatiotemporal clustering and finite-fault ruptures implies a requirement for elastic rebound

2) Characteristic magnitude-frequency distributions (Non GR) may or may not be a problem; elastic-rebound seems to solve this for all but the most extreme cases

3) Important issue is how to apply tight spatial clustering statistics (e.g., >90% aftershocks within a few km of main shock) to faults that are not that well known (spatially)

We also continue to explore this question
Main Scientific Issues:

1) Including both spatiotemporal clustering and finite-fault ruptures implies a requirement for elastic rebound.

2) Characteristic magnitude-frequency distributions (non-GR) may or may not be a problem; elastic-rebound seems to solve this for all but the most extreme cases.

3) Important issue is how to apply tight spatial clustering statistics (e.g., >90% aftershocks within a few km of main shock) to faults that are not that well known (spatially).

4) How can we test these models at the magnitudes we care about for hazard and loss?

UCERF3-ETAS provides forecasts that pass a laugh test, but are they reliable/useful?

This question/problem will plague any model that attempts to forecast larger damaging earthquakes because we lack adequate observations; are we therefore stuck with expert judgment for some time to come?
Also Note:

UCERF3-ETAS has assumptions, approximations, and corrections ("all models wrong, some are useful")

Every component will get a thorough vetting as we operationalize over the next year or two

CSEP tests – necessary (but not sufficient)
Toward operational loss modeling...
Example 1-year simulations for M7 Mojave SAF event (Tom Jordan’s “nightmare”):

Typical sequence

Hellish sequence

No Main Shock
1) Pre-compute economic losses and fatalities for every UCERF3 rupture (~500,000) using an OpenSHA implementation of the HAZUS-MH methodology (Porter et al., 2012, SRL):
1) Pre-compute economic losses and fatalities for every UCERF3 rupture (~500,000) using an *OpenSHA* implementation of the HAZUS-MH methodology (Porter et al., 2012, *SRL*):

2) For a given ETAS simulation, we sum losses for all events that occurred in the synthetic catalog to get a loss estimate.
1) Pre-compute economic losses and fatalities for every UCERF3 rupture (~500,000) using an *OpenSHA* implementation of the HAZUS-MH methodology (Porter et al., 2012, *SRL*):

2) For a given ETAS simulation, we sum losses for all events that occurred in the synthetic catalog to get a loss estimate.

3) Repeat to obtain N different simulated catalogs
1) Pre-compute economic losses and fatalities for every UCERF3 rupture (~500,000) using an *OpenSHA* implementation of the HAZUS-MH methodology (Porter et al., 2012, *SRL*):

2) For a given ETAS simulation, we sum losses for all events that occurred in the synthetic catalog to get a loss estimate.

3) Repeat to obtain N different simulated catalogs

4) Make a histogram of the N loss values, giving a probability distribution of possible losses.
1-year Losses
From Triggered (& Spontaneous) Earthquakes

Following M7 Mojave SAF Main Shock; mean = 8.3 B$
No Main Shock; mean = 1.6 B$

* These curves do not include losses from the main shock, which is 5.9 B$

Not just mean expected loss
Gains depend on forecast duration
For single-family dwellings, but full inventory can also be used
Fatalities also available
**USGS OEF Goal (?)**: PAGER-type loss estimates from possibly triggered events?
Conclusion: we now have an operationalizable, end-to-end system to forecast losses in California that:

- Relaxes segmentation and includes multi-fault ruptures
- Includes elastic rebound and spatiotemporal clustering
- Generates synthetic catalogs (stochastic event sets)
- Includes very efficient loss calculations