Testing 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
Food for thought...
UCERF3-ETAS (U3ETAS)

**Goal** – a useful model for OEF ("... to help communities prepare..."; Jordan et al., 2014)

“Useful” – means reliability and skill at the larger magnitudes ($M \geq 6.5$ in CA)

*Note* - The relative usefulness of different models will vary with use (e.g., statewide insurance portfolio versus site-specific nuclear power plant)
General Questions

Is passing/winning the current CSEP tests either necessary or sufficient with respect to usefulness?

Are there other tests we should be including that could do better with respect to evaluating usefulness?

If relative usefulness depends on use, shouldn’t we be testing in the context of some specific uses? (we don’t want to waste time splitting hairs)
UCERF3-ETAS Testing Issues

How to deal with thousands of logic-tree branches?

Model produces synthetic catalogs

- (critical for model evaluation/testing)
- How to test these in CSEP?

Forecasts at important magnitudes ($M \geq 6.5$) depend on interplay between elastic rebound and characteristic MFDs

- How to decide between viable elastic rebound implementations?
- How characteristic (in terms of MFD bulge) can faults be?
What is UCERF3-ETAS?
(how does it differ from other models in CSEP)
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
Why? Because aftershocks (triggered events) can be large and damaging…

Landers

Turkey

Darfield → Christchurch

Sumatra
USGS’s Short-Term Earthquake Probability (STEP) Model

Gerstenberger et al. (2005)

Operational aftershock hazard map based on Reasenberg-Jones:

\[
\text{Rate} \mu 10^{-M} \frac{1}{(t + c)^p \cdot r^n}
\]

Gutenberg Richter

Distance Decay
Constraints we might use:

- Generic aftershock statistics
- Sequence-specific aftershock statistics
- Location of recent or ongoing seismicity (e.g., as manifested by coulomb stress changes)
- Proximity to active faults
- Time since last event on those faults
- Long-term MFD on those faults
- Long-term event rates
- Other things…
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
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- Uses **Epidemic Type Aftershock Sequence** model (ETAS; Ogata, 1988) to generate synthetic catalogs of \( M \geq 2.5 \) events

Simulations (synthetic catalogs) are critical for identifying potential problems, such as the need for elastic rebound; also needed to define loss distributions
Epidemic Type Aftershock Sequence (ETAS) Model

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

\[
(t,x) = (t,x) + k\lambda^{(M_i - M_{min})}(t - t_i + c)^p c_s (r + d)^q
\]

\[
i : t_i < t
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n )</td>
<td></td>
<td>0.67</td>
<td>0.45 – 0.75</td>
</tr>
<tr>
<td>( p )</td>
<td></td>
<td>1.07</td>
<td>1.0 – 1.4</td>
</tr>
<tr>
<td>( c )</td>
<td>years</td>
<td>1.78E-05</td>
<td>1.00E-6 – 3.16E-4</td>
</tr>
<tr>
<td>( a )</td>
<td></td>
<td>1.96</td>
<td>&gt;1.8</td>
</tr>
<tr>
<td>( d )</td>
<td>km</td>
<td>0.79</td>
<td>&gt;0.63</td>
</tr>
<tr>
<td>( k )</td>
<td>(years)^(p-1)</td>
<td>2.84E-03</td>
<td>3.79E-4 – 4.97E-3</td>
</tr>
</tbody>
</table>

We use parameters from Hardebeck (2013) for \( M \geq 2.5 \) events in California.
Epidemic Type Aftershock Sequence (ETAS) Model

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

\[ \lambda(t, x) = \lambda_0 \exp \left( M - M_{\min} \right) \left( \frac{t - t_i}{\beta} \right) \left( 1 - \frac{1}{r + d} \right)^q \]

Key Assumption:

Statistics inferred from small earthquakes apply to large (damaging) earthquakes on poorly known, finite faults.
UCERF3-ETAS – in a nutshell:

- For every observed and simulated M≥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
UCERF3-ETAS examples (1-year simulations):

Northridge

Landers

Spontaneous
1\textsuperscript{st} generation
2\textsuperscript{nd} generation
3\textsuperscript{rd} generation
...
Example 1-year simulations for M7 Mojave SAF event (Tom Jordan’s “nightmare”):

Typical sequence

Hellish sequence
Based on 10,000 simulations:

Average Temporal Decay:
Based on 10,000 simulations:

**Average Distance Decay:**

![Graph showing average distance decay](image)
Based on 10,000 simulations:

**M≥2.5 Nucleation Rates:**

![Map of Southern California showing nucleation rates](image)

- **Primary Only**
- **All Descendants**

Log10(Mojave M7 Full TD M≥2.5 Nucleation Rate)
Based on 10,000 simulations:

Supra-seismogenic on-fault ruptures – Nucleation (all descendants):
Based on 10,000 simulations:

Supra-seismogenic on-fault ruptures – Participation (all descendants):
Based on 10,000 simulations:

Magnitude-Frequency Distribution (all descendants)
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 (even if GR imposed)

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 (even if GR imposed)

Related question:

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

**Possible Rupture**
Probability greater than zero 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 (even if GR imposed)

Related question: 

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

![Diagram showing San Andreas Fault with red and blue areas]

- **Possible Rupture**
  - Probability greater than zero 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) Characteristically 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.

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

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 tune, let alone test these models at the magnitudes we care about for hazard and loss?
Based on 10,000, 1-year simulations:

**M 5.5** event on Mojave SAF (all descendants):
Based on 10,000, 1-year simulations:

**M 5.5** event on Mojave SAF (all descendants):

This can be “fixed” by adjusting the GR correction (or by applying some kind of elastic rebound)

But how do we know what to tune the model to?
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
General Questions

Is passing/winning the current CSEP tests either necessary or sufficient with respect to usefulness?

Are there other tests we should be including that could do better with respect to usefulness?

If relative usefulness depends on use, shouldn’t we be testing in the context of some specific uses? (we don’t want to waste time splitting hairs)

For UCERF3-ETAS, it’s necessary but not sufficient
General Questions

Is passing/winning the current CSEP tests either necessary or sufficient with respect to usefulness?

Are there other tests we should be including that could do better with respect to usefulness?

If relative usefulness depends on use, shouldn't we be testing in the context of some specific uses? (we don't want to waste time splitting hairs)

Important events ($M \geq 6.5$) have finite surfaces; how to test these in terms of spatial distribution?

Have models simulate catalogs with finite ruptures?
General Questions

Is passing/winning the current CSEP tests either necessary or sufficient with respect to usefulness?

Are there other tests we should be including that could do better with respect to usefulness?

If relative usefulness depends on use, shouldn’t we be testing in the context of some specific uses? (we don’t want to waste time splitting hairs)
USGS Powell Center Meetings on OEF

1. Potential Uses of OEF (March 16-19, 2015)
2. Best Science for OEF (Oct 19-22, 2015)
3. Operationalization Challenges for OEF (future?)
4. OEF Testing and Verification (future?)

Possible early adopters:

- CEPEC/CalOES
- CEA (insurance)
- PG&E (e.g., nuclear facilities)

Formalize CSEP tests for these uses?

Formalize CSEP tests for these uses?

Formalize CSEP tests for these uses? (maybe we’ll find that point-process models (e.g., STEP) are good enough?)
UCERF3-ETAS Testing Issues

How to deal with thousands of logic-tree branches?

Model produces synthetic catalogs

- (critical for model evaluation/testing)
- How to test these in CSEP?

Forecasts at important magnitudes \((M \geq 6.5)\) depend on interplay between elastic rebound and characteristic MFDs

- How to decide between viable elastic rebound implementations?
- How characteristic (in terms of MFD bulge) can faults be?
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):
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2) For a given ETAS simulation, we sum losses for all events that occurred in the synthetic catalog to get a loss estimate.
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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.
Not just mean expected loss

Gains depend on forecast duration

For single-family dwellings, but full inventory can also be used

Fatalities also available

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$

Loss (Billion $)
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**
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**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)

You can move from any point on the green fault cluster to any other point without jumping more than 5 km

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
### Grand Inversion Equations

<table>
<thead>
<tr>
<th>Equation set</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ \sum_{i=1}^{k} D_{fr} v_e = 0 ]</td>
<td>Slip Rate Balancing: ( v_e ) is the subsection slip rate (from a deformation model) and ( D_{fr} ) is the slip on the ( s )th subsection in the ( i )th event, averaged over multiple occurrences of the rupture and as measured at mid-seismogenic depth.</td>
</tr>
<tr>
<td>[ \sum_{i=1}^{k} \sum_{r=1}^{n} G_{fr} P_{r}^{\text{paleo}} f_r = \mu_r^{\text{paleo}} ]</td>
<td>Paleoseismic Event Rate Matching: ( \mu_r^{\text{paleo}} ) is a paleoseismically inferred event rate estimate, ( G_{fr} ) specifies whether the ( r )th rupture utilizes the ( s )th subsection (0 or 1), and ( P_{r}^{\text{paleo}} ) is the probability that the ( r )th rupture would be seen in a paleoseismic trench.</td>
</tr>
<tr>
<td>[ R_s = \frac{R_{s-1}^{m} + R_{s+1}^{m}}{2} ]</td>
<td>Fault Section Smoothness Constraint: This enables forcing the nucleation rate, ( R_s ), in the ( m )th magnitude bin to vary smoothly along a fault section, where the ( s-1 ) and ( s+1 ) subsections are adjacent to the ( s )th subsection.</td>
</tr>
<tr>
<td>[ \lambda_r f_r = 0 ]</td>
<td>Improbability Constraint: This allows us to force relatively improbable events to have a lower rate (for example, based on multi-fault rupture likelihoods). A higher value of ( \lambda ) results in more smoothing, and can lower rates further.</td>
</tr>
<tr>
<td>[ f_r = f_r^{a-priori} ]</td>
<td>A Priori Constraint: This constrains the rates of particular ruptures to target values, either on an individual basis (for example, make Parkfield occur every ( \approx 25 ) years) or for a complete rupture set (for example, as close as possible to those in UCERF3).</td>
</tr>
<tr>
<td>[ \sum_{i=1}^{k} M_{fr} v_e = R_s^{m} ]</td>
<td>Regional MFD Constraint: This enables forcing a geographic region, ( s ), to have a specified magnitude-frequency distribution (MFD), such as Gutenberg-Richter. ( R_s^{m} ) represents the nucleation rate for the ( m )th magnitude bin in the ( s )th region. Matrix ( M_{fr} ) contains the product of whether the ( r )th rupture falls in the ( m )th magnitude bin (0 or 1) multiplied by the fraction of that rupture that nucleates in the ( s )th region.</td>
</tr>
<tr>
<td>[ \sum_{i=1}^{k} M_{fr} P_{r}^{\text{a-priori}} f_r = R_s^{m} ]</td>
<td>Fault Section MFD Constraint: This enables forcing subsections to have specific nucleation MFDs. ( R_s^{m} ) is the nucleation rate for the ( m )th magnitude bin on the ( s )th subsection. Matrix ( M_{fr} ) contains the product of whether the ( r )th rupture falls in the ( m )th magnitude bin (0 or 1) multiplied by the fraction of that rupture that nucleates on the ( s )th subsection.</td>
</tr>
</tbody>
</table>

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### UCERF3 Logic-tree Branches (for long-term model)

#### Fault Models:
- FM3.1 (0.5)
- FM3.2 (0.5)

#### Deformation Models:
- Geologic (0.3)
- AveBlockMod (0.1)
- NeoKinema (0.3)
- Zeng (0.3)

#### Earthquake Rate Models:
- Scaling Relationships
  - Shaw09mod for both
  - EllsworthB for both
  - HanksBakun08 for both
  - EllsworthB w/ SpatLength
  - Shaw09mod w/ Const Stress Drop

- Slip Along Rupture (Dsr)
  - Sin2 \( \theta \) (0.5)
  - (0.5)
  - (0.5)
  - (0.5)

- Total M \( \geq 5 \) Event Rate (yr \(^{-1}\))
  - 6.5 (0.1)
  - 7.9 (0.6)
  - 9.6 (0.3)

- Inversion Model
  - Characteristic UCERF2 Constrained (1.0)
  - Characteristic Unconstrained (0.0)
  - Gutenberg-Richter Constrained (0.0)
  - Gutenberg-Richter Unconstrained (0.0)

- M \( \text{off-fault} \)
  - 7.3 (0.1)
  - 7.6 (0.8)
  - 7.9 (0.1)

- Off-Fault Spatial Seis PDF (aka SpatialPDF)
  - UCERF2 Smoothed Seis (0.5)
  - UCERF3 Smoothed Seis (0.5)

- Fault Moment Rate Fix
  - Apply Implied Coupling Coefficient (0.0)
  - Relax MFD Constraint (0.0)
  - Apply Both Options (0.0)
  - Do Nothing (1.0)

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1440 Branches
Data Fits (better than UCERF2):

Region MFDs

**Slip Rates:**

- UCERF3
- UCERF2

**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., faults cannot be GR)

*It’s still a limited approximation of the system, however.*
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**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

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

UCERF3 Methodology:

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

\[
\mu_{r}^{\text{cond}} = \frac{\sum \mu_{s} A_{s}}{\sum A_{s}} \quad \eta_{r} = \frac{\sum (T_{s} / \mu_{s}) A_{s}}{\sum A_{s}}
\]

\[
P_{r}^{U3} = P_{r}^{BPT} \left[ \frac{\mu_{r}^{\text{cond}}}{\mu_{r}} \right]
\]

\[
P_{r}^{BPT} = P_{r}^{BPT} \left( \eta_{r}, \frac{\Delta T}{\mu_{r}^{\text{cond}}}, \alpha \right)
\]
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-base simulators (a WGCEP first)

• Model is more testable
Now up to 5720 Branches

### UCERF3 Logic-tree Branches

**Fault Models:**
- FM3.1 (0.5)
- FM3.2 (0.5)

**Deformation Models:**
- Geologic (0.3)
- AveBlockMod (0.1)
- NeoKineMod (0.3)
- Zeng (0.3)

**Earthquake Rate Models:**

#### Scaling Relationships

- Shaw09mod for both
  - (Shaw, 2009b, 2009c) (0.20)
- Ellsworth for both
  - Ellsworth (WGC-02) (0.20)
- HanksBakun08 for both
  - (Hanks & Bakun, 2008) (0.20)

#### Slip Along Rupture (Dsr)

- Tapered
  - (Sak2005) (0.5)
- Boxcar (0.5)
- Slip-Rate proportional (0.0)

#### Total M≥5 Event Rate (yr⁻¹)

- 6.5 (0.1)
- 7.9 (0.6)
- 9.6 (0.3)

#### $M_{\text{off-fault}}$

- 7.3 (0.1)
- 7.6 (0.8)
- 7.9 (0.1)

#### Off-Fault Spatial Seis PDF (aka SpatialPDF)

- UCERF2 Smoothed Seis (0.5)
- UCERF3 Smoothed Seis (0.5)
- Deformation Model Based (0.0)

**Earthquake Probability Models:**

- Low Aperiodicity (0.1)
- Mid Aperiodicity (0.4)
- High Aperiodicity (0.3)
- Poisson (0.2)
Main Result: implied average time-dependent probability gain for $M \geq 6.7$ in next 30 years: