Overview of Some Operational Earthquake Forecasting (OEF) Capabilities and Products

Edward H. Field (USGS)
&
Kevin Milner, Nicholas van der Elst, Jeanne Hardebeck, Morgan Page, Andy Michael, & Other WGCEP participants

11WCEE, 2018
Operational Earthquake Forecasting (OEF)

• The timely dissemination of authoritative information about potentially damaging earthquakes, including triggered events (Jordan and Jones, 2010; Jordan et al., 2011)

• Falls under the USGS statutory responsibility (Disaster Relief Act of 1974, appendix E)

• There is ongoing debate about whether OEF is useful enough to be worth deploying
Aftershocks (triggered events) can be large and damaging…

J-tree → Landers → Big Bear → Hector Mine in 1990s

Darfield → Christchurch → M7.8 Kaikoura

Italy 1997-2016
Rules of thumb:

1) Every earthquake has a ~6% chance of being followed by something larger in the week that follows (or ~10% over 1-year, or ~15% over 10 years)

2) About half of large events will come with no warning (no foreshocks)

*No operationalization needed here*

*Is more information useful?*
The USGS has been releasing aftershock information since the 1980s...

<table>
<thead>
<tr>
<th>Auto notifications for M≥5 events in California</th>
<th>Occasional ad hoc notifications elsewhere (hand built; slow)</th>
<th>STEP aftershock hazard (2005-2010)</th>
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</thead>
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Issues:

1) Nothing is currently operational (automated) outside California

2) Only basic info provided (expected magnitude frequency distribution (MFD) for aftershocks)

3) Fault information is ignored
Evolving OEF Questions

a) Would more OEF information be useful?

b) What represents best available OEF science?

c) Adequacy Question: Is a candidate model right enough to be useful, and useful enough to be worth operationalizing? (or more right and/or more useful than a previous or simpler one?)

d) How do we assess the value of each OEF product, from each viable model, to each potential user, so as to prioritize which models/products are worth deploying?

USGS Powell Center Meetings on OEF:

1. Potential Uses of OEF (March, 2015)

2. Best Science for OEF (Oct., 2015)


4. Testing simulation- and fault-based forecasts (February, 2018)
Evolving OEF Questions

a) Would more OEF information be useful?

USGS Powell Center
Meetings on OEF:

1. Potential Uses of OEF (March, 2015)
## Table 1. Workshop participants.

<table>
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<th>Name</th>
<th>Affiliation</th>
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<td>PG&amp;E</td>
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<td>Ackerman, Shawna</td>
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Uses/Users Discussed:

• Public preparedness
• Official Advisory Councils
• Emergency Management
  • CalOES
  • School Systems
  • Caltrans
  • Utility Companies
  • Hospitals
• Post-Earthquake Building Inspection/Tagging
• Zoning and Building Codes
• Oil and Natural Gas Regulation
• Insurance Industry and Capital Markets
• Others
**Potential OEF Products**

1) **Magnitude Probability Distribution**
   Probability of one or more events vs magnitude for specified region and timespan.

2) **Magnitude Probability Map**
   Spatial distribution for events exceeding specified magnitude for timespan.

3) **Hazard Curve**
   Probability that an intensity measure type (e.g., MMI, PGA, PGV, etc.) will exceed various values at a specified location and for a specified timespan.

4) **Hazard Map**
   Spatial probability that an intensity measure type (e.g., MMI, PGA, etc.) will exceed a specified value over a specified timespan.

5) **Loss Exceedance Curve**
   Probability that loss will exceed various values over a specified timespan.

6) **Loss Exceedance Map**
   Spatial distribution of loss exceedance probability for a specified value and timespan.

7) **Fault participation probability**
   List or map for a chosen timespan.

8) **Gains for 1-7 above**
   Relative to long-term or pre-event conditions.

9) **Stochastic event sets**
   Synthetic catalogs of events, possibly including finite-rupture surface information.

10) **Example aftershock scenario events**
    Example aftershock scenario events e.g., ShakeMap, PAGER, and/or ShakeCast products for one or more events that might occur.
Evolving OEF Questions

a) Would more OEF information be useful?

USGS Powell Center Meetings on OEF:

1. Potential Uses of OEF (March, 2015)

The Potential Uses of Operational Earthquake Forecasting (SRL, 2016)

by Edward H. Field, Thomas H. Jordan, Lucile M. Jones, Andrew J. Michael, Michael L. Blamped, and Other Workshop Participants

ABSTRACT

This article reports on a workshop held to explore the potential uses of operational earthquake forecasting (OEF). We discuss the current state of OEF in the United States and abroad, the types of products that could be generated, the various potential users of OEF, and the need for careful, well-defined communication strategies. Although operational challenges remain, there was strong consensus among the stakeholders in the workshop that OEF could be useful.

INTRODUCTION

Operational earthquake forecasting (OEF) involves the dissemination of authoritative information on near-term earthquake probabilities to various types of decision-makers, with the goal of informing the decisions that people and organizations make to mitigate seismic risk (Baldwin and Jones, 2010; Jordan et al., 2012; Matsuzaka, Jordan, and Wha, 2014). In other words, OEF provides real-time forecasts to help communities prepare for earthquakes. The potential of OEF has been questioned in the literature (Proctor et al., 2012; Wang and Rogers, 2014), with a recent report published by Jordan et al. (2016). This article contributes to that discussion by summarizing the findings of a two-day workshop held in March 2015 at the United States Geologic Survey (USGS) Powell Center in Fort Collins, Colorado. The gathering involved discussions among a variety of potential users and model developers (the acknowledged need for in an effort to make a potential use of OEF recognize) to develop a broad and diverse audience and to gain insights from diverse earthquake hazards and perceptions regarding seismic risk, earthquake hazards and perceptions regarding seismic risk. Although the goal of the Powell Center project was to identify a broader range of stakeholders, the discussions and developments on more widely applicable, including to seeks of small magnitude (e.g., Gomiero, 2012; Pomer et al., 2010).

CURRENT STATUS OF OEF

The USGS initiated OEF efforts in the 1980s, with workshops drawing on the USGS Earthquake Predictive Experience (Sachs et al., 1983; Parkin, Waring, 1985), into earthquake advisories issued in cooperation with the State of California prior to the Loma Prieta earthquake (1989). Geophysical Survey (1990), and afterwards a feedback system based on the Forecast and June (1990) model, which forecasts earthquake probabilities based on empirical estimates of observed and Greenberg, Richter statistics. The Kawcic and Jones models have been used to generate automated near-term following forecasts in California and for faults annexed in California and for faults annexed in California and for faults annexed in California and for faults annexed in California and for faults annexed in California and for faults annexed in California and for faults annexed in California and for faults annexed in California and for faults annexed in California and for faults annexed in California and for faults annexed in California and for faults annexed in California and for faults

Stakeholders and early adopters said yes...
Evolving OEF Questions

a) Would more OEF information be useful?
b) What represents best available OEF science?

Candidate OEF Models:

1) Reasenberg & Jones (1989)
2) STEP (Gerstenberger et al., 2005)
3) ETAS (Ogata, 1988)
4) UCERF3-ETAS (Field et al., 2017)

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Progressively more sophisticated, complicated, and computationally demanding

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Candidate OEF Models

1) Reasenberg & Jones (1989)

Rate of aftershocks with time:

\[ \lambda(t) \propto 10^{(M_{mainshock})} \times (t + c)^{-p} \]
Candidate OEF Models

1) Reasenberg & Jones (1989)

USGS notifications will soon be automatically generated for M≥5 events throughout the US (led by Jeanne Hardebeck and Andy Michael)

Main Limitations:

• No spatial information provided (nor hazard or loss estimates)
• Does not adapt well to large (or larger) aftershocks
• Ignores faults
Candidate OEF Models

1) Reasenberg & Jones (1989)

2) STEP (Gerstenberger et al., 2005)

Not being further developed at the USGS (ETAS deemed preferable for variety of reasons)
Candidate OEF Models

1) Reasenberg & Jones (1989)
2) STEP (Gerstenberger et al., 2005)
3) ETAS (Ogata, 1988)

Epidemic Type Aftershock Sequence

generalization of Reasenberg-Jones:

\[
\lambda(t,x) = \lambda_0 \mu(x) + \sum_{t : t_i < t} k_i \theta(M - M_{min}) (t - t_i + c)^\rho c_s (r + d)^{-q}
\]
Candidate OEF Models

1) Reasenberg & Jones (1989)
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USGS ETAS tool being developed by Nicholas van der Elst using OpenSHA
Candidate OEF Models

1) Reasenberg & Jones (1989)
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USGS ETAS tool being developed by Nicholas van der Elst using OpenSHA

- Provides spatial information & handles large (or larger) aftershocks well
- Includes hazard maps
Candidate OEF Models

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Main Limitation:
• Ignores faults
Candidate OEF Models

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- All imply that the most likely place for the next event is the location of the most recent one (opposite of Reid’s elastic rebound)
- And experts think that fault proximity is important when it comes to triggering large earthquakes...
e.g., the California Earthquake Prediction Evaluation Council issues warnings when small earthquakes are occurring near the San Andreas Fault.
e.g., the California Earthquake Prediction Evaluation Council (CEPEC) issues warnings when small earthquakes are occurring near the San Andreas Fault.
The question: is this M 5 earthquake more likely to trigger something big (e.g., $M \geq 6.7$) than this one?

Experts think so, but we’ve lacked an operationalizable model that can quantify this.
Candidate OEF Models

1) Reasenberg & Jones (1989)
2) STEP (Gerstenberger et al., 2005)
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4) UCERF3-ETAS (Field et al., 2017)

A goal of this model was to include not only fault proximity, but also fault activity rate and elastic-rebound readiness.

These ignore faults
**UCERF3 Goals:** include both *multi-fault ruptures* and *spatiotemporal clustering* (potentially damaging aftershocks), both of which have been ignored in previous forecast models.

---

O’Rourke et al. (2014)
UCERF3-ETAS in a Nutshell

ETAS Model
(Epidemic Type Aftershock Sequence)

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

\[
\lambda(t,x) = \lambda_0(x) + \sum_{i \in \{i : t_i < t\}} k_1 t_i^{\alpha - 1} \exp(-\frac{t_i - c}{\beta}) \cdot c_3(r + d)^{-q}
\]

UCERF3-TD

Main Shock

Primary Aftershocks

Secondary Aftershocks

Tertiary Aftershocks
UCERF3-ETAS in a Nutshell

**Product:** synthetic catalog of events (stochastic event set)

**ETAS Model**
(Epidemic Type Aftershock Sequence)

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

\[
\lambda(t, x) = \lambda_0(x) + \sum_{i : t_i < t} k_1 10^{(M_i - M_c)} (t - t_i + c)^p c_3(r + d)^q
\]

- **Main Shock**
- **Primary Aftershocks**
- **Secondary Aftershocks**
- **Tertiary Aftershocks**
**Product:** synthetic catalog of events (stochastic event set) obtained by doing the following:

- Discretize UCERF3 region into $2 \times 2 \times 2$ km cubes
- For every observed and simulated $M \geq 2.5$ event, we randomly sample a number of triggered events and their origin times (using ETAS parameters)
- For each event, we randomly sample a cube according to the distance decay from parent.
- We then choose a rupture based on the current probability that each can nucleate from within the cube, and considering elastic rebound on faults.
- We also allow spontaneous events to occur, which can also produce aftershocks.

**ETAS Model**
*(Epidemic Type Aftershock Sequence)*

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

$$
\lambda(t, x) = \lambda_{\text{aft}}(x) + \sum_{i} \lambda_i \left( t - t_i + c \right)^p c_3(r + d)^q
$$

- $\lambda_{\text{aft}}(x)$
- $\lambda_i$ triggering rate
- $t_i$ origin time
- $t$ current time
- $c_3(r + d)^q$ decay function

**UCERF3-ETAS in a Nutshell**

- Bookkeeping is somewhat complicated due to need for elastic-rebound updating and numerical efficiency
- Updating with ongoing seismicity will capture, at least partially, any static or dynamic stress triggering effects

- Main Shock
- Primary Aftershocks
- Secondary Aftershocks
- Tertiary Aftershocks

---


*1992 M=7.3 Landers shock promotes the M=6.5 Big Bear shock 3 hours later*
M 6.1 Parkfield Aftershocks
(10 yrs following)

average of 200,000 simulations

Note that the M7.8 1857 Fort Tejon earthquake is believed to have been preceded by an M6.1 Parkfield foreshock (Sieh, 1978; Meltzner and Wald, 1999).
Swarms near Bombay Beach

200,000 UCERF3-ETAS Simulations

Likelihood of something big on nearby SAF

UCERF3-ETAS - 2012 M 4.8 event
UCERF3-ETAS - 2016 Swarm
UCERF3-TD
UCERF3-TI
UCERF3 Summary: we now have a scientifically plausible, operationalizable, end-to-end forecast for California that:

- Relaxes segmentation and includes multi-fault ruptures
- Includes elastic rebound and spatiotemporal clustering
- Generates synthetic catalogs (stochastic event sets)
- Published in BSSA and SRL, and “Turing tests” in BSSA (Page & van der Elst, 2018)
- Within reach: USGS PAGER- and ShakeCast-type products, but giving risk from *triggered* events
**UCERF3 Summary:** we now have a scientifically plausible, operationalizable, end-to-end forecast for California that:

**Scientific Implications:**

Combing spatiotemporal clustering with faults implies a need for both characteristic magnitude-frequency distributions and elastic rebound (longstanding debate settled?)

**Practical Implications:**

Deploying UCERF3-ETAS as an Operational Earthquake Forecasting (OEF) system will take considerable time, effort, and resources
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a) Would more OEF information be useful?
b) What represents best available OEF science?

Candidate OEF Models:

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All models are wrong
(they embody assumptions, approximations, and uncertainties)
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c) Adequacy Question: Is a candidate model right enough to be useful, and useful enough to be worth operationalizing? (or more right and/or more useful than a previous or simpler one?)

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Is the inclusion of faults (UCERF3-ETAS) really worth the computational effort?

Current Challenge: the answer depends on what hazard or risk metric one cares about, which varies widely among potential users
Lots of Different Uses

Lots of Different Products

Candidate OEF Models:
1) Reasenberg & Jones (1989)
2) STEP (Gerstenberger et al., 2005)
3) ETAS (Ogata, 1988)
4) UCERF3-ETAS (Field et al., 2017)

Reasenberg-Jones might be adequate for one use (e.g., public messaging) but not for another (e.g., insurance loss forecasts)
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4. Testing simulation- and fault-based forecasts (February, 2018)

i.e., we need to add model valuation to our verification and validation protocol
Examples of Various OEF Products from the HayWired Planning Scenario, Including One Very Quick (and Not-So-Dirty) Hazard-Map Option

(SRL; pre-pub on line)
**Potential OEF Products**

1) Magnitude Probability Distribution
2) Magnitude Probability Map
3) Hazard Curve
4) Hazard Map
5) Loss Exceedance Curve
6) Loss Exceedance Map
7) Fault participation probability
8) Gains for 1-7 above
9) Stochastic event sets
10) Example aftershock scenario events
Candidate OEF Models

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All candidate OEF models essentially assume that large-event likelihood, and therefore risk, correlates with small-event rates (big events start out small)
All candidate OEF models essentially assume that large-event likelihood, and therefore risk, correlates with small-event rates (big events start out small)
M 7.1 HayWired Scenario

U3-ETAS (1 Week following)
“Gain”
current rate/risk versus long-term average rate/risk

M 7.1 HayWired Scenario

M 7.1 HayWired Aftershocks in SF Box

\[ \text{Rate} = (t+0.065)^{-0.942} \]

Log\(_{10}\) Days

M≥2.5 Rate Density (per day)

10^5

10^4

10^3

10^2

10^1

10^0

10^{-1}

10^{-2}

10^{-3}

10^{-4}

10^{-5}

1\,\text{min} \quad 1\,\text{hr} \quad 1\,\text{day} \quad 1\,\text{mo} \quad 1\,\text{yr} \quad 10\,\text{yr}
M 7.1 HayWired Scenario

~70% occur after the first day,
~57% occur after the first week,
~45% occur after the first month,
~23% occur after the first year.
“Gain”
current rate/risk versus long-term average rate/risk
Question for users: What timeframes are you interested in, what gains would you find actionable, and how valuable would the info be?

“Gain”
current rate/risk versus long-term average rate/risk
M 7.1 HayWired Scenario (1 Week following)

Expected Number of Triggered M≥2.5

U3-ETAS

U3-ETAS Gain

Relative to long-term rate
M 7.1 HayWired Scenario (1 Week following)

Expected Number of Triggered M≥2.5

U3-ETAS

No-Faults ETAS
M 7.1 HayWired Scenario  (1 Week following)

Expected Number of Triggered M≥2.5

U3-ETAS

Ratio

U3-ETAS vs No-Faults ETAS
M 7.1 HayWired Scenario (1 Week following)

Fault Participation, M≥6.7
M 7.1 HayWired Scenario (1 Week following)
Probability of Exceeding MMI 4 (light shaking)
M 7.1 HayWired Scenario (1 Week following)

Probability of Exceeding MMI 4 (light shaking)

U3-ETAS

No-Faults ETAS
M 7.1 HayWired Scenario  (1 Week following)
Probability of Exceeding MMI 4 (light shaking)
M 7.1 HayWired Scenario (1 Week following)
Probability of Exceeding MMI 6 (strong shaking)
M 7.1 HayWired Scenario (1 Week following)

Probability of Exceeding MMI 6 (strong shaking)
M 7.1 HayWired Scenario  (1 Week following)

Probability of Exceeding MMI 6 (strong shaking)
M 7.1 HayWired Scenario (1 Week following)

Probability of Exceeding MMI 8 (severe shaking)
M 7.1 HayWired Scenario (1 Week following)

Probability of Exceeding MMI 8 (severe shaking)
M 7.1 HayWired Scenario (1 Week following)

Probability of Exceeding MMI 8 (severe shaking)
M 7.1 HayWired Scenario (1 Week following)

What’s the chance that these shaking levels will be exceeded by aftershocks in the following week?

Rule-of-thumb hint: there is a ~6% chance of triggering something larger
M 7.1 HayWired Scenario (1 Week following)

MMI with 6% chance of being exceeded

HayWired ShakeMap (for main shock)

Mean Expected MMI

U3-ETAS

MMI with 6% POE
M 7.1 HayWired Scenario (1 Week following)

Probability of Exceeding Main Shock MMI

HayWired ShakeMap
(for main shock)

Mean Expected MMI

U3-ETAS

Within 500 km

Probability of Exceeding Main Shock MMI
M 7.1 HayWired Scenario (1 Week following)

Upshot: the ShakeMap for a main shock also represents the ground motion that has a ~6% chance of being exceeded in the next week or 10% in the next year or 15% in the next 10 years (adjusted by any sequence specific variability)
Lots of Different Uses

Lots of Different Products

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A Prototype Operational Earthquake Loss Model for California Based on UCERF3-ETAS – A First Look at Valuation

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We present a prototype operational loss model for California based on UCERF3-ETAS, which represents the first earthquake forecast to relax fault segmentation assumptions and to include multi-fault ruptures, elastic-rebound, and spatiotemporal clustering, all of which seem important for generating realistic and useful aftershock statistics. UCERF3-ETAS is nevertheless an approximation of the system, however, so usefulness will vary and potential value needs to be ascertained in the context of each application. We examine this question with respect to statewide loss estimates, exemplifying how risk can be elevated by orders of magnitude due to triggered events following various scenario earthquakes. Two important considerations are the probability gains, relative to loss likelihoods in the absence of main shocks, and the rapid decay of gains with time. We hope this paper inspires similar analyses with respect to other risk metrics to help determine whether operationalization of UCERF3-ETAS would be worth the considerable resources required.
Operational Earthquake Loss Modeling

1-year statewide losses following an $M$ 7.1 Hayward main shock

$\sim 14\%$ chance of $\geq$ $50$B (from $\sim 2\%$)

1yr Probability Gain = $\sim 7$
Operational Earthquake Loss Modeling

1-year statewide losses following an $M$ 7.1 Hayward main shock

Gain decay with time

Is this useful?
Examples of Various OEF Products from the HayWired Planning Scenario, Including One Very Quick (and Not-So-Dirty) Hazard-Map Option

(SRL; pre-pub on line)

Key Points:

• Probability Gains (relative to long-term hazard/risk) should be relevant to decision making
• Including faults is important if large events drive the hazard or risk
• Mainshock ShakeMaps are a quick (and not so dirty) estimate of the ground motion that has a ~6% chance of being exceeded in the week that follows
Lots of Different Uses

Lots of Different Products

Candidate OEF Models:

1) Reasenberg & Jones (1989)
2) STEP (Gerstenberger et al., 2005)
3) ETAS (Ogata, 1988)
4) UCERF3-ETAS (Field et al., 2017)
Evolving OEF Questions

a) Would more OEF information be useful?

b) What represents best available OEF science?

c) Adequacy Question: Is a candidate model right enough to be useful, and useful enough to be worth operationalizing? (or more right and/or more useful than a previous or simpler one?)

d) How do we assess the value of each OEF product, from each viable model, to each potential user, so as to prioritize which models/products are worth deploying?

We are doing our best to answer this by publishing fleshed-out examples.

But usefulness and value can really only be quantified by users

USGS Powell Center Meetings on OEF:

1. Potential Uses of OEF (March, 2015)

2. Best Science for OEF (Oct., 2015)


4. Testing simulation- and fault-based forecasts (February, 2018)
Questions for potential users:

1) What hazard or risk metric you are concerned about?

2) What gains (increase relative to long-term hazard or risk) would you find actionable?

3) What timeframes are you interested in (given temporal decay and latency)?

4) What is the value of this information to you and/or your clients?