Operational Earthquake Forecasting
- Implementing a Real-Time System for California -

(CA OEF Implementation)

A collaboration between the United States Geological Survey (USGS) and the Southern California Earthquake Center (SCEC), with significant support for meetings from the USGS Powell Center (PIs on the latter are Edward Field* and Thomas Jordan)

Project Summary

It is well known that every earthquake can spawn others (e.g., as aftershocks), and that such triggered events can be large and damaging, as recently demonstrated by L’Aquila, Italy and Christchurch, New Zealand earthquakes. In spite of being an explicit USGS strategic-action priority (http://pubs.usgs.gov/of/2012/1088; page 32), the USGS currently lacks an automated system with which to forecast such events and official protocols for disseminating the potential implications. This capability, known as Operational Earthquake Forecasting (OEF), could provide valuable situational awareness to emergency managers, the public, and other entities interested in preparing for potentially damaging earthquakes.

By leveraging various resources, including support for meetings from the USGS Powell Center, the goal of this project is to deployment an actual OEF system for California, together with a set of peer-reviewed papers describing each aspect of the problem. Given that California embodies some of the most vexing challenges with respect to OEF, our efforts should also greatly facilitate deployments elsewhere.

Project Details

The USGS currently has a real-time, web-based system to estimates fatalities and economic consequences following significant earthquakes worldwide (Figure 1), but no such system to forecast potential losses from earthquakes triggered by these events (e.g., aftershocks). Achieving the latter goal is nontrivial because, rather than considering the single event that just happened, one must integrate over every earthquake in every possible sequence of events that could follow, at least in an approximate way.

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Figure 1. Example of a USGS Prompt Assessment of Global Earthquakes for Response (PAGER) alert, which estimates fatalities and economic losses following significant earthquakes worldwide (Wald et al., 2010; http://earthquake.usgs.gov/earthquakes/pager/). An ultimate goal of Operational Earthquake Forecasting (OEF) is to make equivalent “forecast” reports for potentially triggered earthquakes.

That aftershocks can be more damaging than a main shock was emphasized in the 2010 Canterbury, New Zealand sequence, where the magnitude $(M)$ 7.1 Darfield earthquake was followed by an $M$ 6.2 aftershock that killed more than 180 people in Christchurch (Kaiser et al., 2012). Likewise, the 2009 L’Aquila Italy event exemplified not only the influence of earthquake triggering, but also the importance of information dissemination, as six Italian professionals were convicted of involuntary manslaughter for spreading “inaccurate, incomplete, and contradictory” statements prior to the main shock (e.g., Marzocchi, 2012).
The 2010 Haiti earthquake in Figure 1 also emphasized the need for a well-vetted, automated forecasting system, as the USGS received numerous requests for such information following the event. An official statement was eventually released (available here), but it was 11 days after the main shock, and based on ad hoc calculations made by scientists who had to set aside other work.

A positive outcome of the L’Aquila earthquake was the Italian government’s convening of an International Commission on Earthquake Forecasting (ICEF; Jordan et al., 2011). This group was charged with assessing the scientific knowledge of earthquake predictability, and providing guidelines for OEF implementation. An added benefit of their report (Jordan et al., 2011) was the disambiguation of terms used in the literature and the introduction of several useful concepts.

For example, they coined the term Operational Earthquake Forecasting (OEF), and defined it by two key activities:

1) A continual updating of authoritative information about the future occurrence of potentially damaging earthquakes (including aftershocks)

2) The officially sanctioned dissemination of this information to enhance earthquake preparedness in threatened communities.

The ICEF also define the worthiness of candidate algorithms by their “Operational Fitness”, which is evaluated in terms of:

- **Quality**: Representing both the Reliability of the algorithm (it agrees with observations) and Skill (out-performs simpler models)

- **Consistency**: Assumptions apply over different space, time, and magnitude scales

- **Value**: Benefits outweigh potential costs of taking algorithm-based actions

The ICEF included a review of prediction algorithms, defined as giving a yes or no answer to the possibility of an impending event (based usually on diagnostic precursors such as radon concentrations), and concluded that none has yet demonstrated operational fitness. Probabilistic forecasts, which give a likelihood of occurrence between 0 and 1 rather than a binary yes/no answer, therefore represent the most promising approach.

*Long-term* earthquake forecasts, which apply to durations exceeding several years, have been developed by the USGS (http://earthquake.usgs.gov/hazards/) and by the various Working Groups on California Earthquake Probabilities (WGCEP 1988, 1990, 1995, 2003, 2007). These models represent our first line of defense in mitigating earthquake losses, as they presently form the basis of building codes and other risk-reduction measures.

The question is whether we can do better with respect to *shorter-term* forecasts, which apply to time horizons of several years or less. We clearly see spatiotemporal clustering of earthquakes over such time scales in the form of aftershocks (which represent all types of triggered events...
here). Statistical descriptions of such clustering explain many features of observed seismicity, and can therefore be used, with assumptions, to forecasts how probabilities will evolve over time.

For example, we observe that ~5% of all earthquakes are followed by a larger event, meaning triggered earthquakes can be larger than that doing the triggering. Thus, anytime we have a moderate-sized event, the likelihood of something larger (and potentially damaging) increases by a factor of ~100 compared to the previous state, which would seem to represent an actionable “probability gain”. However, the total likelihood of the triggered event is still low (e.g., a few percent), which can lead to considerable confusion when conveying such information. In fact, this is precisely the predicament Italian officials found themselves in before the L’Aquila earthquake; they were essentially lured into gambling on a prediction (in terms of providing a yes or no answer), rather than giving a more appropriately nuanced answer. To complicate matters, approximately half of all large damaging earthquakes are not preceded by smaller events, and would therefore come with no obvious warning.

Therefore, while it is clear that shorter-term forecasts have potential reliability and skill, especially in anticipating aftershocks following significant events, a remaining question is how to provide value to decision-makers in this high-gain, but low-overall-probability environment.

At the same time, public expectations of real-time information are rising, especially given the proliferation of social networking. Information vacuums invite informal predictions and misinformation. For example, rumors that “experts are holding back on a prediction to avoid panic” were trending on Twitter within hours after the 2010 El Mayor–Cucapah earthquake (Jordan and Jones, 2010). The best defense against such predicaments is to base OEF on objective, open, authoritative, scientific, timely, reviewed, and well-tested information.

More sophisticated users, such as those in the earthquake-insurance industry and catastrophic-bond markets, are much less susceptible to such psychological vagaries, and could clearly benefit from shorter-term forecasts. For example, the occurrence of a nearby event might persuade some savvy homeowners to finally take out a 1-year earthquake-insurance policy, so the market should adjust prices accordingly, or insurance providers might want to hedge against potential payouts by increasing their level of reinsurance.

So where does the USGS stand with respect to OEF, especially given the statutory responsibility to provide such information if possible? Some limited forms of OEF have been practiced at the USGS since the early 1990s. For example, the USGS currently issues aftershock probability notifications within tens of minutes following earthquakes in California. If the magnitude exceeds 3.5, the USGS also sends an automated email advisory to the California Emergency Management Agency (CalEMA), and others, conveying the probability of an $M \geq 5$ aftershock and the number of $M \geq 3$ events expected in the next week.

These products have been formally reviewed and approved by the National Earthquake Prediction Evaluation Council (NEPEC), which was established to advise the USGS director on earthquake-related threats. The USGS is occasionally asked for further information, as in the Haiti example above, but such information is always generated *ad hoc*. Furthermore, these
notifications do not embody information on the risks to populated areas, nor whether the event has occurred near a fault capable of producing large earthquakes.

A limited form of OEF has also been conducted by the California Earthquake Prediction Evaluation Council (CEPEC), which advises CalEMA and the state governor. Following major earthquakes, CEPEC generally (though not consistently) adheres to a notification protocol that has probability-based alert levels. However, CEPEC currently relies on generic probabilities or ad hoc estimates calculated informally, and they are in great need of probabilities based on an operationally qualified, regularly updated forecasting system. The evaluation protocols are also unwieldy, requiring the scheduling of meetings or telecons, which lead to delayed and inconsistent alert actions. Moreover, how the alerts are used can also be quite variable.

An important OEF milestone was the development of the Short-Term Earthquake Probability model (STEP; Gerstenberger et al., 2005), which provided real-time, web-based updates of aftershock hazard in California using empirical clustering statistic. The USGS system was online between 2005 and 2010, but then taken down due to software maintenance issues. There was also growing concern with model consistency. For example, STEP lacks elastic-rebound, where probabilities are thought to drop on a fault after experiencing a large event, and to grow with time as tectonic stresses rebuild. This omission makes STEP fundamentally inconsistent with the more widely used WGCEP models referenced above, and there is evidence that it also leads to implausible triggering statistics for large earthquakes (Field, 2012).

These issues with STEP have been addressed in version 3 of the Uniform Earthquake Rupture Forecast (UCERF3), being developed by the 2014 WGCEP. The time-independent version of the model (Field et al., 2014a) has already been used in the 2014 USGS national seismic hazard maps (Petersen et al., 2014), and a long-term, time-dependent model based on elastic-rebound has also been produced (Field et al., 2014b). Most notably, a shorter-term, spatiotemporal-clustering component has also been implemented, which utilizes all observed $M \geq 2.5$ events when updating shorter-term forecasts. UCERF3 is therefore ready for ‘road testing’ in an OEF system, and the fact that it is implemented with stable object-oriented software (www.OpenSHA.org, Field et al., 2003) will facilitate deployment and maintenance.

Given that OEF is listed as a USGS strategic-action priority (http://pubs.usgs.gov/of/2012/1088; page 32), together with proposals for deploying a prototype system going back to 2011 (Jordan and Jones, 2010), it is somewhat of an institutional embarrassment that we are not further along. This is only exacerbated by the fact that both Italy and New Zealand are now well ahead of us (Marzocchi et al, 2014 and Gerstenberger et al., 2014, respectively), and while this is mainly due to mandates following their recent, damaging earthquakes, we too will be scrambling if we do not get an OEF system deployed before the next big earthquake.

A significant impediment to deployment is the need for communication among a broad range of disciplines (Table 1), especially when only ad hoc funding sources are currently available to support meetings. This is why the set of USGS Powell Center workshops described below will be an important catalyst for deploying an OEF system in California. Achieving our goals will require not only initiating communication among different USGS groups (Table 2), but also leveraging other presently committed resources (Table 3).
While our focus is on California, the issues, challenges, and computer-code requirements are suitably general to be relevant elsewhere. In fact, our project will constitute an important demonstration of feasibility, providing a foundation for not only deployments elsewhere, but also in justifying more permanent resources and for maintaining the interdisciplinary dialog spawned by the project.

Table 1. The disciplines and stakeholders involved in OEF.

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<thead>
<tr>
<th>Earthquake Scientists</th>
<th>Earthquake Engineers</th>
<th>IT Architects</th>
<th>Computer Programmers</th>
<th>Network Seismologists</th>
<th>Hazard &amp; Loss Modeling Experts</th>
<th>Emergency Planning Officials</th>
<th>First Responders</th>
<th>Commercial Risk Modelers</th>
<th>Risk Communication Experts</th>
<th>Social Scientists</th>
<th>General Public Representatives</th>
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Table 2. Groups within the USGS that will be involved in this project (more info on each can be obtained by Googling the acronym).

|----------------------------------------|----------------------------------------------|-----------------------------------|---------------------------------------------------|-------------------------------------------------|-----------------------------------------------|---------------------------------|---------------------------------|---------------------------------|----------------------------------|

Table 3. Presently committed resources that will be leveraged in this project (in addition to the Powell Center meetings).

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<th>A Mendenhall Postdoc to work on OEF has been offered and accepted by Nicholas van der Elst, starting in early 2015.</th>
<th>SCEC will provide software-development support and access to high-performance computing.</th>
<th>SCEC also maintains the Collaboratory for the Study or Earthquake Predictability (CSEP; <a href="http://www.cseptesting.org">http://www.cseptesting.org</a>), which constitutes the primary facility for objectively testing the reliability and skill of different forecast algorithms, including the different flavors of UCERF3 that will be considered in this project.</th>
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Workshops

With support from the USGS Powell Center, we plan to have four 4-day workshops aimed at addressing various challenges associated with deploying an end-to-end OEF system in California, with the goal of having a solid prototype (at least) in place by the end of the project.

The topics and questions to be addressed at each workshop are listed in Table 4. Although the exact format of each remains to be determined, the first two are anticipated to go as follows: the first one or two days of the workshop will involve a larger group to survey the broader issues and options (e.g., for long-term planning), and the final days of the workshop will be reserved for a smaller group that will make final decisions and orchestrate the actual implementation.

Table 4. The topic of proposed workshop, together with a sampling of questions to be addressed at each.

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<th>Workshop Topic</th>
<th>Questions to be Addressed (partial list)</th>
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| 1) Potential Uses of OEF | a) What is the complete range of potential uses of OEF (e.g., from the general public, to emergency managers, to private loss-modeling companies), and how should these be prioritized given resource limitations?  
b) How can we maximize the value of products in a high-gain, low-probability environment?  
c) How do we educate the public, reporters, and other users on the meaning of probability, or any other metric we utilize, and how should we communicate associated uncertainties?  
d) How do we define trigger thresholds with respect to product dissemination, and how should these vary among users (or within different levels of government)?  
e) How do we evaluate costs and benefits, and how can lives and historical landmarks be factored into this?  
f) How can the value of products take into account information available to decision makers in the absence of OEF information?  
g) How do we account for known and unknown epistemic uncertainties in OEF?  
h) What are the psychological benefits (or costs) associated with real-time alerts (e.g., in filling information voids, influencing preparedness, or credibility risks in terms of perceived over- or under-reactions by experts)?  
i) What lessons can be learned from communication experts and the social sciences?  
j) Is the PAGER methodology appropriate for real-time loss forecasts in California? The HAZUS methodology?  
k) What types of assets should we be computing losses for?  
l) What exposure and vulnerability models are most appropriate for these assets?  
m) What types of aleatory and epistemic uncertainties can and should be considered (e.g., spatial correlation of ground motions)?  
n) Can we get a consensus loss distribution for every earthquake rupture in UCERF3? |
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<td>o)</td>
<td>Can we pre-compute losses for each UCERF3 rupture?</td>
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<td>p)</td>
<td>How do we provide commercial loss-modeling companies (e.g., RMS, EQECAT, and AIR) access to our OEF, especially when they have their own in house codes?</td>
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<td>q)</td>
<td>How can we ensure consistency between our results and those coming from the proprietary codes of commercial loss modelers?</td>
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<td>r)</td>
<td>What are the political sensitivities associated with making OEF-based statements for other countries (very important, but perhaps beyond the scope of these meetings).</td>
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<td>2) Viable Scientific Models for OEF</td>
<td>a) How do we merge finite-fault/geologic models with the point process clustering models from statistical seismology?</td>
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<td>b) Is elastic rebound required, and if so, how is it best applied, and what are the consequences of leaving it out?</td>
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<td>c) Do characteristic magnitude-frequency distributions cause problems for clustering models, and how should we deal with them?</td>
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<td>d) Are spatiotemporal clustering statistics variable in time, space, and/or magnitude, and if so, what value is added in accounting for this?</td>
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<td>e) Do/should long-term simulations of events reproduce the long-term rates assumed <em>a priori</em> in the model?</td>
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<td>f) Are Coulomb-based components currently feasible, and could they add value?</td>
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<td>g) Are physics-based earthquake simulators appropriate for inferring spatiotemporal clustering behavior?</td>
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<td>h) What are the consequences of the various approximations required by model (e.g., spatial and temporal discretization)?</td>
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<td>i) What is the difference between a multi-fault rupture and a separate event that is triggered quickly, and is this distinction important for OEF?</td>
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<td>j) How can/should we treat earthquake swarms?</td>
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<td>k) Are transient deformations potentially informative?</td>
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<td>l) Are our models applicable to fluid-injection induced seismicity?</td>
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<td>3) Operationalization Challenges</td>
<td>a) How do we access network seismicity information in real-time (interoperability protocols)?</td>
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<td>b) How are magnitude and locations uncertainties represented, including any temporal variations, and are they reliable?</td>
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<td>c) Are network data versioned and archived, so that one can reproduce an earthquake catalog as it existed in a previous calculation (e.g., before magnitudes were revised based on more information)?</td>
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<td>d) How can we represent the likelihood that some ( M \geq 2.5 ) events are going undetected, as a function of time, space, and magnitude? This will be especially relevant during active aftershocks sequences, which is also when OEF will have greatest value?</td>
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<td>e) How can we get finite-fault rupture models in real-time?</td>
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<td>f) For applying elastic rebound, how do we associate an observed large event with a rupture in the model?</td>
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<td>g) Are high-performance computing resources needed for an operational system (e.g., to obtain multiple Monte Carlo realizations)?</td>
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| **4) Model Verification & Validation** | a) How do we enable and support both retrospective tests and continuous prospective testing?  
|   | b) Do we need event-triggered testing algorithms?  
|   | c) How do we evaluate whether products are communicating the intended information?  
|   | d) Is reliability with respect to forecasting small earthquakes a necessary or sufficient condition with respect to forecasting large ones?  
|   | e) Do models based on sequence-specific or spatially dependent parameters outperform those based on generic statistics?  
|   | f) Are CSEP seismicity-rate tests indicative of predictability with respect to hazard and loss-related metrics?  
|   | g) Are there other testing approaches that can and should be pursued?  
|   | h) What elements of the models remain untestable (from a practical perspective)?  
|   | i) How are epistemic uncertainties best handled in the testing framework?  
|   | j) Can an inferior model (in terms of reliability and skill) actually provide greater value?  
|   | k) How do the models perform with respect to swarms and aftershock sequences in volcanic regions?  
|   | l) How do real-time model uncertainties influence test results?  
|   | m) What is the formal evaluation process for proposed algorithms?  
|   | n) How would CEPEC and NEPEC be involved, and how would they relate to each other?  

h) How and where should the system be deployed in order to minimize maintenance headaches and costs?  
i) What is the best way to do loss calculations in a real-time system (e.g., how should we link existing codes)?
References


