

# *The Potential Uses of Operational Earthquake Forecasting*

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## ABSTRACT

This article reports on a workshop held to explore the potential uses of operational earthquake forecasting (OEF). We discuss the current status of OEF in the United States and elsewhere, the types of products that could be generated, the various potential users and uses of OEF, and the need for carefully crafted communication protocols. Although operationalization challenges remain, there was clear consensus among the stakeholders at the workshop that OEF could be useful.

## INTRODUCTION

Operational earthquake forecasting (OEF) involves the dissemination of authoritative information about time-dependent earthquake probabilities over time scales of hours to decades, with the goal of informing the decisions that people and organizations make to mitigate seismic risk (Jordan and Jones, 2010; Jordan *et al.*, 2011; Marzocchi, Jordan, and Woo, 2015). In other words, OEF provides real-time forecasts to help communities prepare for earthquakes. The usefulness of OEF has been questioned in the literature (Peresan *et al.*, 2012; Wang and Rogers, 2014), with a rebuttal provided by Jordan *et al.* (2014). This article contributes to that discussion by summarizing the findings of a two-day workshop held March 2015 at the United States Geological Survey (USGS) Powell Center in Fort Collins, Colorado. The gathering involved discussions among a variety of potential users and model developers (see Acknowledgments) in an effort to identify potential uses of OEF and to examine lessons learned from recent earthquakes and best practices regarding effective communication. Although the goal of the Powell Center project is to deploy at least a prototype OEF system for California, the discussions and developments are more widely applicable, including to areas of induced seismicity (e.g., Ellsworth, 2013; Petersen *et al.*, 2015).

## CURRENT STATUS OF OEF

The USGS initiated OEF efforts in the 1980s, with foreshock alerts as part of the Parkfield Earthquake Prediction Experiment (Bakun *et al.*, 1987; Parkfield Working Group, 1993), two earthquake advisories issued in conjunction with the State of California prior to the Loma Prieta earthquake (U.S. Geo-

logical Survey Staff, 1990), and aftershock and foreshock alerts based on the Reasenberg and Jones (1989) model, which estimates earthquake probabilities based on empirical Omori-Utsu and Gutenberg-Richter statistics. The Reasenberg and Jones model has been used to generate automated alerts following moderate earthquakes in California and for advisories issued by an *ad hoc* process after the 2010 Haiti earthquake, the 2010 Maule, Chile, earthquake, the 2010 El Mayor-Cucapah, Mexico, earthquake, the 2011 Mineral Springs, Virginia, earthquake, and the 2015 Gorkha, Nepal, earthquake. The short-term earthquake probability (STEP) model of Gerstenberger *et al.* (2005) added spatial information and hazard to the Reasenberg and Jones model; the USGS produced STEP forecasts for California for several years but discontinued these postings in 2010 due to maintenance issues. Improving OEF capabilities is an identified strategic goal of the USGS (Holmes *et al.*, 2012; pp. 32) with two current foci. The first effort is automating the Reasenberg and Jones process for regions outside of California. The second effort involves combining the epidemic type aftershock sequence (ETAS) model (Ogata, 1988), which takes into account secondary aftershock sequences, with long-term earthquake probabilities. Combining short- and long-term forecasts was first done with the foreshock model of Agnew and Jones (1991), but that model was limited to forecasting only the largest events (see Michael, 2012, for a general discussion). The new approach, discussed below, aims to provide consistent forecasts over the full range of magnitudes and over a wide range of time scales. These efforts have been endorsed by the National Earthquake Prediction Evaluation Council (NEPEC), which advises the USGS on earthquake prediction research priorities (see Data and Resources).

Workshop attendees also reported on recent experiences and current capabilities of OEF in Italy (Marzocchi *et al.*, 2014), developed following the 2009 L'Aquila earthquake, and in New Zealand, deployed during the 2010–2011 Canterbury sequence (Gerstenberger *et al.*, 2014). The Italian system forecasts both event probabilities and ground-motion hazard for various time intervals, based on an ensemble of two ETAS models and a version of the STEP model. This OEF is continuously delivered by Istituto Nazionale di Geofisica e Vulcanologia (INGV) to the Department of Civil Protection, and they are presently working with communication experts on how to shape effective public messages. OEF is also regularly

**Table 1**  
**Potential Products that Could Be Produced Either Directly by an Operational Earthquake Forecast System or by Further Processing in Downstream Risk Calculations**

Product/Metric	Description
Magnitude probability distribution	The likelihood of having earthquakes of different magnitudes in a given area and for a specified time span
Spatial distribution of triggering	Specifying where triggered events are most likely to occur
Fault triggering probabilities	A prioritized list of faults that could nucleate or participate in large triggered events, accounting for any elastic-rebound effects
Full earthquake rupture forecast (ERF)	Specifying the likelihood of all possible events (at some discretization level) for a given time span
Stochastic event sets	Synthetic catalogs of triggered events as implied by an ERF
Hazard estimates	The probability of exceeding hazard-related intensity measures (e.g., PGA, PGV, PGD, SA, MMI) as a function of time and space*
Sequence duration	Time needed for some measure (e.g., earthquake rate) to drop back to some level
Scenario earthquakes	Representative examples of earthquakes that could be triggered
Ground deformation probabilities	Forecast of future fault offsets (e.g., due to creep) and/or other types of ground deformation
Landslide probabilities	The likelihood of triggering landslides
Liquefaction probabilities	The likelihood of triggering liquefaction
<b>Hazard-Risk Separation Interface</b>	
Population and/or infrastructure exposed	The number of people, houses, commercial properties, schools, hospitals, etc. with a certain likelihood of experiencing certain shaking or other hazard thresholds
Deaths/injuries/hospitalizations	Risk estimates with respect to human physical health and survival
Damage level and collapse probability	Loss and collapse estimates with respect to built infrastructure
Downtime	Likelihood and length of disruption to business, power, water, waste disposal, telecommunication, and communication systems
Inspection priority or concern level	A customized and prioritized list of assets that may require attention (e.g., as provided by the ShakeCast system)
Each product will constitute an estimate in that uncertainties will need to be quantified.	
*PGA, peak ground acceleration; PGV, peak ground velocity; PGD, peak ground displacement; SA, Spectral acceleration; MMI, modified Mercalli intensity.	

delivered to the Commissione Nazionale per la Prevenzione e Previsione dei Grandi Rischi (the Grand Risk Commission), which provides the Italian government with expert advice about natural hazards and their associated risks. INGV is also collaborating with a consortium of seismic engineering departments in Italy, to move from OEF to operational earthquake loss forecasting, which produces loss metrics, such as the expected number of collapsed buildings, displaced residents, injuries, and fatalities (Iervolino *et al.*, 2015).

OEF in New Zealand has been developed for end users ranging from the public to government decision makers. The system combines short-term, medium-term, and long-term models to forecast both event probabilities and ground-motion hazard for time frames of 1 day to 50 years. This hybrid model has been used to inform rebuilding decisions in Christchurch, which was severely damaged during the Darfield aftershock sequence in 2011 and subsequently has upgraded its building design standards. For more recent events, aftershock scenario earthquakes also have been provided to help end users interpret the forecasts (e.g., GNS Science, 2014).

A few key points were emphasized repeatedly during the introductory presentations. First, long-term forecasts, which are applicable from decades to centuries, represent our first line of defense for mitigating earthquake risk, primarily by informing building codes. Also, Omori–Utsu-based statistical clustering models have demonstrable reliability and skill with respect to short-term triggering and therefore provide a rational basis for short-term OEFs. However, the primary challenge to usefulness is that triggering models usually estimate a low probability for damaging earthquakes (Jordan *et al.*, 2011). Probability gains may be as great as factors of 1000, but the overall likelihood of triggering damaging events will typically be less than a few percent. The exceptions are during aftershock sequences of very large ( $M > 7$ ) earthquakes, when this probability can climb above 10%. Such low-to-moderate probabilities will constitute useful information if the potential consequences of large triggered events are high (e.g., Marzocchi *et al.*, 2015). That said, about half of all large damaging earthquakes lack any detectable foreshocks, meaning they will occur without potential warning (e.g., Agnew and Jones, 1991). OEF can also produce high-probability forecasts for

smaller aftershocks that are felt but cause little damage; understanding that such events are to be expected can be reassuring in the aftermath of a large earthquake (Wein and Becker, 2013). As stated by Saathoff and Everly (2002, p. 249), “better than any medication we know, [reliable] information treats anxiety in a crisis.”

Decisions to undertake mitigation actions based on OEF information depend on the balance between costs and benefits, which are specific to the risk at hand. Because these decisions are contingent on a host of economic, political, and psychological considerations that lie beyond the science of hazard analysis, scientific information about future earthquake activity should be developed independent of any specific risk assessment or mitigation effort. Moreover, all validated OEF information should be made available to all potential users in a timely manner (although perhaps tailored for different user groups). These principles of hazard-risk separation and transparency imply that seismologists should provide potential end users with complete, probabilistic forecasts, including the epistemic uncertainties (Jordan *et al.*, 2014). Ideally, OEF systems should be policy neutral; that is, they should not involve decisions to withhold information until some activity or probability threshold is exceeded (as in a deterministic prediction), or until a “significant” mainshock has occurred, because doing so would not only imply that we know how to define these things for all potential users, but would also effectively put scientists in the inappropriate role of making policy decisions.

Recent events have underscored the public’s hunger for OEF information during active earthquake sequences, with expectations rising with the proliferation of social networking. It is well known that information vacuums invite unfounded predictions and misinformation (e.g., Mileti and Peek, 2000), such as the rumors on Twitter that “experts are holding back on a prediction to avoid panic” within hours of the 2010 El Mayor–Cucapah earthquake (Jordan and Jones, 2010). The level of certainty provided by amateur predictors can also be particularly attractive and therefore distracting (e.g., Marzocchi, 2012).

The infamous L’Aquila trial, in which seven Italian officials were charged with involuntary manslaughter, was at least partly a consequence of miscommunications about earthquake risk by the Italian Department of Civil Protection. That agency convened its Grand Risk Commission before the L’Aquila earthquake to address ill-founded earthquake predictions that were worrying the public during the active seismic sequence preceding the L’Aquila mainshock, but it lacked the operational capabilities to accurately assess and report the evolving seismic hazard (Marzocchi, 2012). The best solution in such predicaments is to have an OEF system that produces authoritative, scientific information (Jordan *et al.*, 2011; Jordan, 2013).

## OEF PRODUCTS

Table 1 lists a variety of information that could be estimated for either naturally triggered or human-induced earthquakes. These range from relatively simple earthquake-probability statements to loss estimates. The most complete forecast information from

an OEF standpoint would be a suite of earthquake rupture forecasts (ERFs), each giving the probability of every possible event (at some approximation level) for a given time span, with the alternative ERFs in the suite representing epistemic uncertainties.

The workshop reviewed progress on the OEF model being developed for California, in which an ETAS-based spatiotemporal clustering component is being added to the Third Uniform California Earthquake Rupture Forecast (UCERF3; Field *et al.*, 2014, 2015); this combined model is referred to as UCERF3-ETAS. The main goals for this earthquake rupture forecast (ERF) are to (1) relax segmentation assumptions and include multifault ruptures; (2) include both elastic rebound and spatiotemporal clustering together, as is apparently needed to get realistic behavior (Field, 2012); and (3) support the generation of synthetic earthquake catalogs (stochastic event sets) for improved model testing and to enable full probability distributions to be quantified for hazard and loss metrics (rather than providing just mean estimates).

We also reviewed a variety of USGS real-time products that may be relevant to OEF. For example, the Prompt Assessment of Global Earthquakes for Response (PAGER) system (Wald *et al.*, 2010) provides fatality and economic-consequence estimates following significant earthquakes worldwide, and the ShakeCast system (Wald *et al.*, 2008) sends automatic notifications to registered users indicating the level of shaking and likely impacts given the location and fragility of their particular facilities. Should these capabilities be extended to forecast equivalent losses due to possibly triggered events? Such calculations would be nontrivial because, rather than considering just the single event that has occurred, one must integrate losses over every earthquake in every possible sequence of events that could follow, at least in some approximate way.

The calculations can be made more efficient by precomputing losses for all possible events defined by the forecast model, as was demonstrated at the workshop using the UCERF3-ETAS prototype. Loss estimates for model-derived aftershock sequences will be more uncertain than those for the actual earthquakes monitored by PAGER, because the latter usually have well-estimated magnitudes and often observed ground-motion constraints. Presentations were given on the range of current loss-modeling capabilities within the USGS and on factors that might need to be considered in such calculations (such as mainshock damage increasing structural fragility or changes in replacement costs due to increased demand for building materials following a damaging event). The utility of operational earthquake loss forecasting is expected to be highest for applications in which the risk tolerance is smallest, as in the case of critical facilities. When the probabilities are low and the uncertainties are large, it may be more appropriate to focus on simpler loss metrics, such as the number of people exposed to different hazard levels.

Other common themes from these introductory presentations included the difficulty in going from a prototype capability to a fully operational system, the need to identify and support early adopters, the importance of a flexible and iterative development process with appropriate performance feedback loops, and

that success with users will require considerable time and resource commitments. Finally, several participants highlighted the need for carefully crafted and well-timed communication protocols.

## USERS AND USES OF OEF

The workshop identified and discussed the following potential users and uses, and we expect more to emerge as OEF capabilities become available.

### Public Preparedness

Simple low-cost actions that can be taken by the public based on OEF include (1) checking food, water, medical supplies, and cash on hand, and keeping phones charged and gas in the car; (2) reviewing family emergency plans; (3) securing household objects; and (4) perhaps evaluating the overall structural integrity of dwellings. Following the Christchurch earthquake, other relevant decisions concerned whether to relocate to other areas and when to start rebuilding damaged homes (Becker *et al.*, 2015). OEF could also trigger preemptive mitigation efforts such as considering structural retrofits and earthquake insurance options.

Routine OEF would also provide “teachable moments”—opportunities for earthquake preparedness education (Mileti and Peek, 2002). Outweighing concerns that regular messaging will numb the public or the demonstrable cost of false alarms (Simmons and Sutter, 2009), studies have shown that our sense of risk decays over time and that repetition is therefore important for effective messaging (Brickman and Campbell, 1971; Mileti and Darlington, 1995). This need for reinforcement is especially true for the even-lower long-term earthquake probabilities associated with less-active (normal) times. Low risk leads to less personal earthquake experience and a lower sense of threat and vulnerability (e.g., Mileti and Darlington, 1995), making it harder to compete for attention with the other risks people are facing. OEF could also counter the tendency for an affected population to downplay the future aftershock risk based on perceptions that the worst has already occurred (Wein *et al.*, 2015).

Proper messaging is paramount, especially because warnings that lack information about which actions should be taken are ineffective or even counterproductive (Mileti and Sorenson, 1990; Mileti, 1999). Timing of different content is also important. For example, immediately following the Christchurch earthquake, the public showed little capacity to react to aftershock forecasts, because they were busy dealing with the crisis. However, their appetite for quantitative information increased as the incident evolved from the response phase to recovery and preparedness modes (Wein *et al.*, 2015).

The Christchurch and L'Aquila earthquakes exemplified the potential psychological benefits of OEF, especially with respect to reassuring the public that the sequences were not scientifically surprising (e.g., Wein and Becker, 2013). Transparency and full disclosure are also important to empower people, because transparency, trust, and confidence in authorities

are essential for effective risk communication and management (e.g., Siegrist and Zingg, 2014).

Transparency and full disclosure include providing quantitative information, and there is ample evidence that there is a demand for this. For example, after the Christchurch earthquake one resident stated, “My mother-in-law was in the CTV building [which collapsed], and she spent 12 weeks in the hospital. She prefers to see the numbers.” Having more quantitative information allows people to make more nuanced choices based on their own level of risk tolerance, influencing decisions such as minimizing the time spent in vulnerable buildings by sleeping outside, which is common in Italy, or whether to modify travel plans to an area with elevated hazard. For some people, numbers provide comfort even if they are not fully understood, because they indicate that scientists understand what is happening. Going further, a particularly savvy homeowner might even want a loss-exceedance curve for their dwelling to enable a more informed decision between spending money on retrofits versus earthquake insurance.

Some Christchurch residents were stressed by OEF forecasts that extended the time span beyond days and weeks to months and years when they were busy struggling to recover from the earthquake. Furthermore, some people were frustrated by the predominant and continued use of probabilities in aftershock forecasts (Wein *et al.*, 2015). A well-known psychological phenomenon is “probability neglect” (Sunstein, 2003): bad outcomes attract attention and evoke emotional responses, which can result in people ignoring the actual likelihood of the event. People who find processing numerical information challenging are more susceptible to these types of biases (Peters *et al.*, 2006). Nevertheless, probabilistic information appears, on balance, to improve decision making (Joslyn and LeClerc, 2012; Peters *et al.*, 2014), but it is important to communicate early and often and to evaluate message effectiveness, especially with respect to members of the community who may misinterpret, misuse, or even fear the content. We know that people respond positively to consistent, authoritative statements from multiple sources about the specific actions they should take, even when the future is highly uncertain (e.g., Mileti and Darlington, 1995). One approach is to utilize well-established best practices with respect to message design, such as the internalization–distribution–explanation–action (IDEA) model of Sellnow and Sellnow (2013) and Sellnow *et al.* (2015).

Public messaging is most effective when it includes recommended actions (Mileti and Sorenson, 1990; Mileti, 1999). In particular, Christchurch residents reported that, during the crisis of a damaging earthquake, they could not think clearly and needed reminders of what protective actions to take and how to get help (Wein *et al.*, 2015). However, given the hazard-risk separation principle, any actionable recommendations would not come from the scientists operating the OEF system, but from entities that have a statutory responsibility for making such recommendations, such as emergency managers, including the Federal Emergency Management Agency or the California Governor’s Office of Emergency Services (CalOES). To

include such information in the messages issued by the OEF system will require coordination with the emergency managers, such as was done as part of the Parkfield Earthquake Prediction Experiment. Findings from the Canterbury earthquake sequence study of communication confirms this need for coordinated message content and, furthermore, identifies the need to include psychosocial support messaging from social services or welfare agencies (Wein *et al.*, 2015). These coordinated messages can then be broadcast by the news media.

In short, OEF can nudge people toward taking actions that will minimize their risks. A carefully crafted, predefined, and tested communication protocol is vital, because the chaotic aftermath of damaging earthquakes is a particularly bad time to design and deploy new messages.

### OFFICIAL ADVISORY COUNCILS

OEF can provide useful information to entities like the NEPEC, which advises the USGS Director on earthquake threats, and the California Earthquake Prediction Evaluation Council (CEPEC), which similarly advises CalOES. Following major California earthquakes, for example, CEPEC generally, although not consistently, adheres to a notification protocol that has probability-based alert levels. CEPEC currently relies on generic probabilities or *ad hoc* estimates calculated informally, rather than on an automated, customized, and well-tested forecasting system. The evaluation protocols are also time consuming, requiring the scheduling of meetings or teleconferences. Moreover, the use of the alerts also varies. For example, the 2001 M 4.1 Bombay Beach earthquake led to a formal advisory from the state, whereas the 2009 M 4.8 Bombay Beach earthquake did not, in spite of the latter being larger and closer to the San Andreas fault (Jordan and Jones, 2010).

### EMERGENCY MANAGEMENT

Emergency managers exist at various levels of government, from federal to local, as well as within various private organizations. Each level has somewhat different needs for OEF, depending on their response capabilities and requirements. Larger organizations with a greater number of staff or responsibility for critical infrastructure may wish to receive more detailed and more frequent information compared to smaller departments.

In lower-probability environments (e.g., following an M 5 earthquake near the San Andreas fault), emergency management uses of OEF might include reiterating recommended preparedness measures, conducting disaster-response drills, increasing the readiness of emergency equipment and personnel, mitigating nonstructural risks, completing communications checks, and emphasizing earthquake preparedness in media messaging. OEF could also guide other emergency management decisions, such as during the Faenza, Italy, earthquake swarm, where tents were provided to those who did not feel safe in their homes (Jordan *et al.*, 2014).

In higher-probability environments (e.g., following a larger, perhaps damaging earthquake), OEF could also be used as a basis for locating shelters and emergency equipment away

from higher-hazard areas and deciding when risks have decayed enough or sufficient risk-reduction measures have been implemented to initiate search and rescue, building inspection, and demolition activities. For instance, after the 1989 Loma Prieta earthquake, a small earthquake occurred on the Hayward fault near the damaged Cypress freeway. Based on a discussion of aftershock clustering, demolition activities were suspended for several hours and the workers were redeployed to other activities. In more extreme circumstances, OEF could influence decisions regarding cordoned-off areas, the identification of safe zones, state-of-emergency declarations, and evacuation notices. For example, in Christchurch, aftershocks were factored into cordoning decisions, although this could have been managed even better had more information been available (Becker *et al.*, 2015). OEF may be very useful to establish when people can reoccupy buildings after an event. For example, after the first of two 2012 earthquakes in northern Italy, one of the most pressing questions was when people could return to work.

Emergency managers at the workshop emphasized the need for quantitative information and even expressed frustration in getting vague proclamations from scientists over the phone. They also expressed concerns about undertaking costly activities if the hazard probabilities are small or if the confidence in the forecast is low. This justifiable reluctance emphasizes the need for complete, authoritative, reliable, and timely information (although perhaps delivered at varying levels of detail). Because the range of uses of OEF will be broad in terms of technical sophistication, the emergency managers also emphasized that success will require training before, during, and after the launch of any functioning OEF system. A few emergency management needs are elaborated below.

#### *California Governor's Office of Emergency Services (CalOES)*

The CalOES is responsible for overseeing and coordinating emergency preparedness, response, and recovery within the state, and it is required by statute to provide information on increased earthquake probabilities and suggested mitigation actions. The information on earthquake likelihoods currently comes from CEPEC, as described previously. CalOES advises on recommended protective actions via different products for three audiences: government, media, and the public.

#### *School Systems*

A representative from the Los Angeles Unified School District (LAUSD) identified several possible uses of OEF by educational institutions:

- Push out preparedness messaging to all staff and schools (check emergency supplies, review protocols with staff, update emergency plan, print student rosters, and practice drop-cover-hold-on with students).
- Notify facilities maintenance and operations for critical infrastructure issues, preplanning, and staging of equipment.
- Notify the Office of Environmental Health and Safety, District Nursing, Student Medical Services, and Information Technology.

- Notify the Los Angeles School Police Department; they may go on tactical alert and cancel regular days off and scheduled vacation days.
- Notify transportation (school buses).
- Notify food services (to accelerate food delivery schedule or send extra food).
- Notify Beyond the Bell, so that after-school programs and overnight camps are aware and prepared.
- Cancel travel or field trips to any areas of possible impact.
- Test radio operations at all schools and facilities and that are assigned to vehicles and personnel.
- Activate the Emergency Operations Center at an appropriate tactical level.
- Notify parents to have them review family emergency plans, including reunification locations, update emergency cards, including the names of those authorized to pick up students, and access other information (e.g., the LAUSD emergency plan app for mobile devices).

This list represents a good window into the wide range of concerns and activities that large organizations might need to consider. However, LAUSD is a very large school district, comprising 650,000 kindergarten–twelfth grade students spread over 710 square miles, so some of these uses may not be applicable to smaller educational institutions.

#### *California Department of Transportation (Caltrans)*

The California Department of Transportation (Caltrans) manages more than 50,000 miles of state highways, freeways, and bridges. One of the main concerns regarding earthquakes is the need to keep transportation lines open following a large damaging event so that overall rescue and recovery operations can proceed as smoothly as possible. In general, Caltrans could use OEF as described for emergency managers above but with some transportation-related specifics, such as developing routing maps and defining possible detours for disaster supply chains. They could also conduct ShakeCast-type analyses of their infrastructure given the complete forecast or for some representative scenario earthquakes, which would enable reprioritization to address their more vulnerable structures in both near- and long-term planning.

OEF will be most informative, in terms of exhibiting the highest probability gains, just after a large earthquake has occurred; so it remains to be seen how useful OEF will be to Caltrans when they are busy evaluating damage from a given event. Caltrans currently has predictive models for fire (FireCast) and is developing a system for flooding (FloodCast), so incorporating OEF would fit in well with how they address other perils (and note that the cast in FireCast and FloodCast is short for forecast, whereas that in ShakeCast is short for broadcast). As with the emergency managers discussed above, Caltrans participants also expressed the importance of getting full, quantitative, and robust information from an OEF system, including quantification of uncertainties.

#### *Utility Companies*

OEF could also be of use to electricity providers, water departments, dam operators, waste and sanitation companies, refin-

eries, and communication providers (radio, TV, cable, cellular, and satellite). Power and water/wastewater critical infrastructure affected by the Canterbury earthquake sequence demonstrated the use of OEF in decisions about sizing the response of the labor force, when to repair nonstructural damage, where to lay new transmission and distribution lines, and repair scope and design standards (Becker *et al.*, 2015). Utility representatives attending the workshop described uses for OEF similar to those described above for emergency management. Unique activities identified here include delaying high-risk maintenance activities, such as pulling nuclear rods at a nuclear power plant. Any significant changes in longer-term hazard might also be an important consideration for some utilities, as expressed by a representative from Pacific Gas and Electric. This representative also expressed concern with the threat posed to pipelines and other facilities due to postseismic deformation and/or the triggering of landslides from aftershocks; while quantifying such hazards is theoretically feasible, it is probably beyond the scope of a first-generation OEF system.

#### *Hospitals*

The potential use of OEF in hospitals or other medical facilities is similar to that described for emergency managers. Some domain-specific actions that could be taken include activation of hospital command centers, postponing high-risk outpatient treatment and elective surgery until shaking hazards have adequately subsided, or using demand-surge forecasts to decide whether to recall staff and stage mobile hospital tents and medical supplies for use as triage and treatment areas in case a large triggered event causes an influx of injured victims. Other actions include reevaluating the threat to oxygen, water, and power supplies, the loss of which would significantly reduce the ability of a hospital to provide care and could require activation of plans to relocate essential services or to evacuate.

#### **Postearthquake Building Inspection and Tagging**

Reentry of buildings is highly desirable after an earthquake, especially if they are one's home or place of work. However, doing so can be dangerous, especially if there has been structural damage and/or there is a significant probability of damaging aftershocks. Consequently, government officials, or engineers deputized by those officials, evaluate questionable structures and generally apply a color-coded tag: red if unsafe, yellow if fit for restricted use, and green if the building's seismic safety has not been significantly compromised.

The evaluator often uses procedures documented in ATC-20-1 (Applied Technology Council, 2005) to determine if damaged, or potentially damaged, buildings are safe for continued use. Buildings are tagged unsafe if earthquake damage has caused the structural system to lose capacity and make the building much more likely to collapse in an aftershock. In addition to prioritizing building evaluations to minimize the risk to inspectors, OEF could also be used to apply time-varying inspection results, where a building tagged as red might evolve into yellow as the hazard subsides. Proposed procedures for this have already been published (Yeo and Cornell, 2008; Luco

*et al.*, 2011), and implementing such a capability has been identified as a priority by the Applied Technology Council (Gallagher *et al.*, 1999).

### **Zoning and Building Codes**

The Christchurch earthquake is the best example of how OEF can influence longer-term zoning, relocation, and building-code decisions. The New Zealand OEF model, which produces forecasts with time spans from one year to decades, was part of a suite of information used in defining zones for land retirement (no rebuilding) in liquefaction- and rock-fall-susceptible areas of Christchurch. The same OEF model with a 50 yr time span was used to revise the building design guidelines for the Canterbury region (Gerstenberger *et al.*, 2014; Becker *et al.*, 2015).

### **Oil and Natural Gas Regulation**

Although induced seismicity was not the main focus of our meeting, an obvious potential use of OEF is in the regulation of oil and gas industry activities, especially in regard to the seismic hazards induced by wastewater injection. For example, one such regulatory body, the Texas Railroad Commission, recently proposed rules that would allow them to modify, suspend, or terminate a permit “if injection is likely to be or determined to be causing seismic activity.” Clearly having an authoritative source of seismicity information would benefit such activities. Moreover, having an objective model that can define the relative likelihood that an event was induced versus natural would presumably be informative in any damage-liability litigation.

Regulatory actions are typically taken when an earthquake is detected within some distance of an active well. However, it is not the earthquake itself that causes concern, but the possibility of deaths and/or economic losses from a possibly triggered larger event. OEF could therefore provide the basis for more advanced loss modeling, whereby regulators might weigh probabilistic losses against the economic consequences of halting operations.

### **Insurance Industry and Capital Markets**

One perhaps underappreciated use of OEF involves the insurance industry and capital markets. Most people know about earthquake insurance and although OEF would seem like a rational basis for modifying premiums (because savvy consumers could game the system annually), the regulatory process for changing rates charged to consumers typically takes years, making yearly rate adjustments impractical at this time. Another product is reinsurance, which enables an insurance company to pass some of their risk along to another insurance entity, increasing the likelihood of remaining solvent should a large event occur. Companies have more flexibility with respect to changing their reinsurance levels than with changing rates charged to customers, so it is here that OEF could be more useful.

For example, consider a statewide earthquake insurance provider holding \$5 billion in capital (from selling premiums), plus another \$5 billion in reinsurance, implying a total claim-paying capacity of \$10 billion. In terms of remaining financially solvent, the company is at risk if one or more earthquakes cause a

total payout that exceeds this \$10 billion capacity. Suppose the company has a risk tolerance of 1 chance in 500 per year, meaning anything greater than a 0.2% chance of exceeding the payout capacity in any given year is unacceptable. Modeling losses using a long-term earthquake forecast such as UCERF3 could imply that they are within their risk tolerance. However, OEF-based losses following an **M** 5.5 event near the San Andreas fault may very well push the probability of exceeding \$10 billion well above 0.2% over the next year, at which time the company might want to purchase more reinsurance (and the companies providing the latter would want to adjust their premiums as well).

A more subtle use of OEF might be in defining and understanding insurance policy deductibles. For example, one California insurance provider considers all earthquakes within a 15-day window as a seismic event for the purpose of handling deductibles. Consider the case in which a mainshock has produced damage that exceeds the deductible, which is typically 15%–20% of the home’s replacement cost. The 15-day rule means that losses incurred from a damaging aftershock on day 14 would be covered in full, but those from an event on day 16 would only be covered by the amount exceeding the deductible. This is not to imply that such rules lack rationality, but that OEF-based loss modeling could be useful in exploring whether there are any unintended consequences or whether there may be more optimal ways of handling triggered events. Another use of OEF, as exemplified after the Christchurch earthquake, is to help decide when insurance-supported repairs and reconstruction can begin, given the possibility of triggered events.

Catastrophe bonds (“cat bonds”) are another financial instrument available for managing risk. They are a type of insurance-linked security made available through capital markets. Their purpose is similar to reinsurance except that the risk is passed along to other types of investors, typically those looking to diversify their portfolios because natural disasters are less correlated with other financial market trends. Cat bonds were first created and used following Hurricane Andrew in 1992 and the 1994 Northridge earthquake. The market has since grown significantly. For example, more than \$300 million in earthquake cat bonds were issued in the first quarter of 2015 alone, implying an annual value of \$1.2 billion.

These markets are a prime potential user of OEF, because they literally place large financial bets on whether or not certain regions will be struck by earthquakes. Commercial loss-modeling companies would likely remain the primary interface between an OEF system and such markets, either by providing actual loss estimates, or by providing clients with access to loss-modeling software. Our workshop included several representatives from this industry. They expressed enthusiasm about the OEF possibilities but also emphasized the need for reliable, authoritative, consistent, timely, and well-tested information, especially given the potentially litigious marketplace. They also need complete earthquake rupture forecasts, including uncertainties, in a well-defined and usable format. With such needs, these entities would be one group of power users of an OEF system, with the ultimate goal being to help maximize the resilience of individuals, financial institutions, and perhaps most importantly, cities and communities.

## Other Potential Users and Uses

Other potential user groups were discussed at the workshop, including banks, energy distributors (gas stations), grocery stores, home supply centers, and financial futures markets. The primary use identified here amounts to ensuring that goods and services can be provided following any triggered earthquakes. For example, a bank might choose to restock their ATMs sooner than otherwise planned. Other potential consumers include: any OEF-information remarketers; nongovernmental organizations concerned with the public welfare, such as the American Red Cross and GeoHazards International; social service providers; and scientific organizations, such as the USGS. One scientific application of OEF is the conditioning of earthquake early-warning systems to expect future earthquakes in regions of increased seismic activity.

## DISCUSSION AND CONCLUSIONS

The range of past OEF uses and new applications discussed at the workshop and outlined in this report shows that OEF has many potential applications, even considering the challenges of establishing an effective system for all potential users. As noted in the context of Caltrans, OEF is going to be most informative in terms of higher probability gains following larger damaging events, and it is not yet clear how to best dovetail OEF information with postearthquake information and activities. We certainly do not want OEF to be a distraction from any disaster-response measures, nor a source of confusion in what may already be a high-anxiety environment. That caveat noted, attendees at the workshop concluded that OEF has clear potential value, especially with respect to reminding the public to be ready, helping emergency managers and operators of critical infrastructure to prepare, and informing financial risk-management entities.

The proper role of OEF is to inform, but not prescribe, the response to changing seismic hazards and risk, and to serve a broad range of user types. Decisions about mitigation actions need to be made by proper authorities, such as emergency managers, and psychosocial support needs to be administered by appropriate organizations. In terms of enabling users to make informed decisions quickly in crisis situations, especially with respect to more technical content, training needs to start well before any actionable earthquake. This and the other guidelines for effective communication discussed here are also addressed in further detail by [Perry et al. \(2015\)](#).

With the potential uses of OEF hereby identified, subsequent workshops will address the appropriate scientific models, operationalization challenges (including real-time access to high-performance computing), model verification and validation, and the effectiveness of OEF communications and products.

## DATA AND RESOURCES

Railroad Commission of Texas Mission Statement is available at <http://www.rrc.state.tx.us> (last accessed April 2015). Information regarding the Catastrophe bonds (“cat bonds”) are available

at <http://www.artemis.bm> (last accessed April 2015). National Earthquake Prediction Evaluation Council (NEPEC) reports is available at [http://earthquake.usgs.gov/aboutus/nepec/reports/NEPEC\\_advice\\_OEF\\_Dec2015.pdf](http://earthquake.usgs.gov/aboutus/nepec/reports/NEPEC_advice_OEF_Dec2015.pdf) (last accessed January 2016). ☒

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