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Varenna workshop report

Operational earthquake forecasting and decision making

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A workshop on *Operational earthquake forecasting and decision making* was convened in Varenna, Italy, on June 8-11, 2014, under the sponsorship of the EU FP 7 REAKT (Strategies and tools for Real-time EArthquake risK reducTion) project, the Seismic Hazard Center at the Istituto Nazionale di Geofisica e Vulcanologia (INGV), and the Southern California Earthquake Center (SCEC). The main goal was to survey the interdisciplinary issues of operational earthquake forecasting (OEF), including the problems that OEF raises for decision making and risk communication. The workshop was attended by 64 researchers from universities, research centers, and governmental institutions in 11 countries. Participants and the workshop agenda are listed in the appendix.

The workshop comprised six topical sessions structured around three main themes: the science of operational earthquake forecasting, decision making in a low-probability environment, and communicating hazard and risk. Each topic was introduced by a moderator and surveyed by a few invited speakers, who were then empaneled for an open discussion. The presentations were followed by poster sessions. During a wrap-up session on the last day, the reporters for each topical session summarized the main points that they had gleaned from the talks and open discussions. This report attempts to distill this workshop record into a brief overview of the workshop themes and to describe the range of opinions expressed during the discussions.

1. Background

The concept of operational earthquake forecasting was developed by the International Commission on Earthquake Forecasting for Civil Protection (ICEF; Jordan et al. [2011]) in a report requested by the Italian government after L'Aquila earthquake of April 6, 2009 (available at http://www.annalsofgeophysics.eu/index.php/annals/article/view/5350). According to the ICEF definition, OEF comprises procedures for gathering and disseminating authoritative information about the time dependence of seismic hazards to help communities prepare for potentially destructive earthquakes. The ICEF report has stimulated a broad discussion about the development of OEF and its practical utility in managing seismic risk.

The search for "diagnostic precursors" has so far been unsuccessful; no signals have yet been discovered that can reliably predict the location, time, and magnitude of an impending earthquake with high probability. But the ICEF concluded that earthquake clustering models can reliably forecast earthquakes at low probabilities over short time intervals. According to these models, the short-term probabilities of large earthquakes may increase by up to 2-3 orders of magnitude during seismic sequences, though they rarely exceed about few percent per week. Decision making in such a "low-probability environment" is problematic and poorly studied. An even more formidable challenge is how to communicate the hazard information and risk implications to various stakeholders, including the public at large, in a comprehensible and effective way.

2. Science of operational earthquake forecasting

Two sessions on OEF science highlighted the formulation and testing of probabilistic forecasting models based on seismic clustering [e.g., Ogata 1988, Reasenberg and Jones 1989, Michael 2012], and a third surveyed how OEF systems are developing in Italy, New Zealand, and the United States [Marzocchi et al. 2014, Gerstenberger et al. 2014, Field et al. 2015]. A hot topic was the seismicity induced by deep fluid injection, which is rapidly changing the seismicity of the U.S. continental interior [e.g. Ellsworth 2013] and has become a political as well as scientific issue in several countries. Speakers pointed out the difficulty of accommodating the rapid rise of induced seismicity into long-term probabilistic seismic hazard assessments (PSHA) that are the basis for most national seismic hazard maps, and this motivated discussions of how OEF systems could be useful for projecting time-dependent earthquake probabilities in regions experiencing anthropogenic seismicity increases.

Short-term clustering models, such as the short-term earthquake probability (STEP; Gerstenberger et al. [2005]) and epidemic type aftershock sequence (ETAS; Ogata [1988]) models, currently show the highest information gains relative to long-term forecasts, making them the prime candidates for OEF applications. It was reported that various versions of these models are now being continuously evaluated against seismic data in several testing regions around the world by the Collaboratory for the Study of Earthquake Predictability (CSEP). CSEP is an international infrastructure for evaluating earthquake forecasting models through prospective forecasting experiments that are blind, transparent, and reproducible. CSEP testing experiments, which currently involve over 400 variations of statistical forecasting models, are running in California, New Zealand, Italy, Japan, Western Pacific, and at global scale; other testing regions under consideration include Iceland and part of China. CSEP has been enhancing its procedures to provide more robust statistical evaluation of the models and to assess a wider range of model types [e.g. Jordan 2006, Zechar et al. 2010].

Model developers emphasized the role of CSEP testing in validating models, or model combinations, for the practical purposes of OEF. CSEP experiments are also aimed at addressing important scientific questions, for example testing the hypotheses that clustering is self-similar from small to large earthquakes. The null hypothesis is that earthquakes do not encode any information about the magnitude of the future events; the alternative hypothesis is that the preparatory phase of a large shock is somehow different, implying more predictability. The limitations of CSEP were also discussed, particularly regarding the infrequency of large earthquakes, which limits the power of the prospective tests for that class of events. It was generally agreed that, in order to get better statistics at higher magnitudes, prospective testing in the existing natural laboratories should be augmented with experiments in new natural laboratories and the testing of worldwide forecasts, as well as through well-structured retrospective testing. It was reported that both activities are under active development at the CSEP testing centers.

The clustering models involve generic statistics that do not explain the distinctive features observed in specific seismic sequences. Some participants argued that such deficiencies rendered the models inadequate for operational purposes. Others disagreed, noting that, though the models are uncertain and cannot explain everything, their forecasting performance has been validated by prospective testing in the CSEP natural laboratories, and they should therefore be useful within their stated limitations and epistemic uncertainties.

All participants agreed that the skill of existing short-term forecasting methods is very modest. It is rare for the weekly probability of large shocks to reach 1% (usually after another large shock). Researchers are exploring how to increase forecasting skill by incorporating other types information into the forecasting models, including constraints on stress changes and rupture nucleation processes, as well as non-seismic precursory activity.

Potential improvements may also come from the explicit incorporation of fault-based rupture models, such as the short-term extensions of the Third Uniform California Earthquake Rupture Forecast (UCERF3), which is being developed by the Working Group on California Earthquake Probabilities [Field et al. 2015]. Knowledge of the fault geometries and slip rates better defines the distribution of the large ruptures that could be triggered during seismic sequences, and it allows the concept of elastic rebound and stress relaxation to be incorporated into the clustering models.

A major topic in the workshop discussions was the need for consistency among forecasting methods across a full range of forecasting time scales. New Zealand researchers reported that, in the Canterbury region, earthquake forecasting is now being done using hybrid models that incorporate the short-term STEP model, the long-term PSHA model, and a medium-term model called EEPAS (Every Earthquake a Precursor According to Scale), developed in New Zealand [Rhoades and Gerstenberger 2009].

There was much interest in the lessons learned from recent Canterbury sequence, which began with the 2010 Darfield earthquake and has since provided a data-rich environment for evaluating OEF practice and its impact on society. The New Zealanders provided interesting perspectives on the important question of how expert opinion should be used in combination with earthquake clustering models. In recent practice, experts have defined a set of plausible scenarios that span the possibilities for the evolution of the seismic sequence, attaching to each scenario a probability that is consistent with the probability given by the earthquake clustering models [Gerstenberger et al. 2014].

Representatives from other advisory groups described different approaches. In Italy, for example, the

Grand Risk Commission (GRC) relies on expert opinion about the peculiarities of each seismic sequence rather than short-term forecasting models, which results in qualitative rather than quantitative assessments of the sequence's possible evolution. In United States, the California Earthquake Prediction Evaluation Council and the National Earthquake Prediction Evaluation Council have not yet structured their procedures to release homogeneous information consistently during seismic sequences, although the U.S. Geological Survey has been routinely, automatically producing generic assessments of aftershock probabilities after every M≥3.5 in California for almost 20 years. Presently, USGS is working to expand the approach nationwide and to more rigorously handle situations where a straight Omori-Gutenberg-Richter probability assessment may not be the best representation of the hazard, and considering approaches for continuous production of probabilities.

There was a consensus among the participants that expert opinion should be included in OEF, but some disagreement on how to integrate it with quantitative models. Most modelers in the audience favored the quantitative formulation of expert opinion; for example, through well-structured expert elicitations. Some stressed the importance of casting all OEF information in the form of probabilities, both aleatory and epistemic, to allow an adequate separation between science of hazard assessment and the more socially complex process required to formulate an appropriate spectrum of risk-mitigation options.

3. Decision making in a low-probability environment

OEF provides probabilistic forecasting information, but the formulation of mitigation options requires that the earthquake hazard, as described in terms of faulting, shaking, and secondary effects such as ground failures, be translated into seismic risk, as measured in dollars, casualties, and social functionality. The engineering and policy approaches to this risk-analysis problem were the topic of the fourth session, and related decision-making issues were addressed by several speakers in the fifth and sixths sessions.

It was noted that the term "low-probability" associated with the hazard is an incomplete description of OEF problem, because the consequences for some stakeholders (e.g., critical facility operators) may be much higher than for ordinary citizens. The higher risk levels perceived by such stakeholders will more frequently warrant mitigation actions. Usually, but not always, a cost-benefit analysis will dictate actions that are relatively low in cost, commensurate with the low probabilities. Earthquake engineers emphasized the quantification of risk through well-defined loss metrics normalized to quiescent reference conditions, such as the expected damage rates to structural models or expected fatality rates, and they illustrated plausible metrics with examples from structural engineering [Iervolino et al. 2015].

There was a substantial agreement among the attendees to separate the formulation of scientific information about hazard from the risk assessments that inform decision making. According to the ICEF, the OEF role is to deliver robust, authoritative hazard information, usually cast in terms of probability. This information has to be translated into risk, i.e. into different kinds of expected losses. Risk assessment is the natural framework in which to formulate mitigation options and to choose the proper actions according to a rationale cost-benefit analysis. Although widely accepted in principle, the precise nature of this hazard/risk separation, as well as the means to achieve it, was debated by the participants, mostly around the question of whether scientists should act as decision makers in evaluating and prioritizing the mitigation options.

One clear example discussed at the meeting is the policy of releasing OEF information only during aftershock sequences [e.g. Wang and Rogers 2014, Jordan et al. 2014]. Most participants agreed that OEF probabilities during vigorous aftershock sequences should be made publically available. After large earthquakes, the probabilities are higher and, according to advocates of the "aftershocks-only" policy, more easily comprehended by the public. Others argued that such a policy violates the hazard-risk separation principle, because it puts OEF in an inappropriate decision-making role; namely, of judging at which probability levels the users of OEF should be informed. Moreover, it violates the transparency principle, also articulated by the ICEF, which states that authoritative scientific information about future earthquake activity should not be withheld from the public.

Those issues aside, it was widely agreed that the utility of forecasting is strongly correlated with the amplitude of the probabilities. Higher probabilities can be more easily used by the decision makers to establish a set of mandatory mitigation actions based on a quantitative rational framework based on cost-benefit analysis. The practical use of forecasts with high-hazard probability rates of less than, say, 5% per week to mitigate the risk is much less clear, and the attending issues have not been yet been sufficiently explored.

Some attendees argued that current short-term forecasting methods are effectively useless for practical purposes, owing to the high false alarm rates implied by the low-probability rates - the "crying-wolf" problem [Wang and Rogers 2014]. Others countered that even small probabilities can be helpful in nudging people towards beneficial self-protection actions that are consistent with their own aversion to risk [Thaler and Sunstein 2009, Jordan et al. 2014]. Some might choose to minimize their time in seismically unsafe buildings, for example. Once citizens are correctly informed about the earthquake threat and possible actions to mitigate their personal risks, they can act as rational decision makers for their own families and communities. It was noted that nudging citizens towards rational actions through the release of authoritative information is commonly employed to defend against many other low-probability hazards, such as terrorism threats and the spread of communicable diseases.

The recent Canterbury seismic sequence in New Zealand has provided an excellent testbed for the use of OEF in decision making on an urban scale. It was reported how quantitative OEF information was delivered, interpreted, and applied to risk mitigation during this sequence, and how the OEF system set up by New Zealand seismologists continues to guide the reconstruction of Christchurch, which was badly damaged by the Darfield aftershocks of 2011 [Wein and Becker 2013, Gerstenberger et al. 2014].

OEF systems will have to service a wide variety of information requirements, most obviously those of the general public and responsible governmental agencies, but also those of other stakeholders, such as those who manage critical infrastructures and insurance / re-insurance companies. The various needs and levels of risk aversions among the many stakeholder groups imply that OEF systems will have to provide scientific information in different formats across a range of forecasting intervals. One notable problem is maintaining the consistency of short-term OEF forecasts with the long-term hazards quantified in PSHA.

To avoid confusion during seismic crises, it was recommended that the probability thresholds for significant risk-reduction actions be described in protocols prepared in advance of a crisis through negotiations among scientists, risk analysts, political decision-makers, experts in communication, and interested stakeholders. These protocols should describe the way in which the authoritative scientific information is to be delivered and how high-priority risk mitigation actions are to be implemented.

4. Communicating hazard and risk

The discussions of how OEF information should be communicated to decision makers, including the public at large, dominated the fifth and sixth topical sessions. The social scientists attending the workshop outlined some general findings from their research on risk communication. Humans have the ability to perceive and balance a large number of risks regularly encountered in the natural environment, including high risks at low levels of probability. However, when new information about low-probability, high-consequence events is received, people tend to dichotomize their response: they are either concerned and motivated to act, or they are unconcerned and don't. Studies of this threshold-type response has led to some general guidelines for risk messaging [e.g., Wood et al. 2012, and references therein]:

(i) Communication about specific risks should be layered, with basic information broadcast in high-level messages and more detailed information, including hazard and risk probabilities, made easily available to those who seek it.

(ii) High-level messages should contain authoritative information about the hazard, identify the sources of the information, and be explicit in recommending specific actions to reduce the risk.

(iii) Messaging is most effective when consistent information comes from multiple sources.

(iv) The public should be educated about hazards and risks through a continual dialog with scientists and decision makers and within their own communities.

Considerable debate was centered on how to communicate increases in earthquake hazard and risk when the absolute probability of high hazard remains low. Some geoscientists expressed particular concern over the widespread public illiteracy about probability, which may limit the ability of non-scientists, including decision makers, to comprehend the meaning of the aleatory variability and epistemic uncertainty intrinsic to earthquake forecasting. Techniques for improving public preparedness through OEF have not yet received sufficient attention, although relevant research was conducted in California during the Parkfield prediction experiment and following the 1989 Loma Prieta earthquake [Mileti and DeRouen 1995].

Studies were reviewed that show the ability of even primitive societies to comprehend probability-based statements of risk, as long as the statements are properly formulated and clearly communicated [Fontanari et al. 2014]. It was emphasized that communication can build trust in authoritative information over time, and that honesty about uncertainty can enhance credibility.

Experts in risk communication argued that, when faced with confusing and possibly hazardous situations, people respond positively to authoritative statements from official sources about the actions they should take, even when the future is highly uncertain; properly delivered, authoritative information about impending threats has rarely, if ever, caused panic among an informed populace [e.g. Clarke 2002].

These considerations underline the need for transparency and continuity in broadcasting authoritative scientific information about the time-dependence of earthquake hazards. Several participants noted that the timely communication of authoritative forecasts can benefit the public by filling information vacuums that set the stage for amateur earthquake predictions and misinformation. Seismic crises can also be teachable moments, when people abandon their usual apathy about earthquake preparedness. Timely OEF communication can thus be very effective in teaching people how to reduce seismic risk both in the short and in the long-term.

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Appendix A: Workshop agenda

Session 1: The problem of earthquake forecasting

- The problem of earthquake forecasting (T. Jordan)

- Earthquake forecasting when the background rate is non-stationary: The case of the U. S. midcontinent (B. Ellsworth)

- Forecasting induced seismicity: State of the art and future directions (S. Wiemer)

- Panel discussion (moderator: I. Main; reporter: M. Page)

Session 2: Testing short-term earthquake forecasting models

- The collaboratory for the study of earthquake predictability (D. Schorlemmer)

- The two-way street between next-day seismicity forecasts and operational earthquake forecasting (J. Zechar)

- CSEP developments in support of operational earthquake forecasting: a future perspective (D. Rhoades)

- Panel discussion (moderator: N. Hirata; reporter: M. Werner)

Session 3: Operational earthquake forecasting

- Operational earthquake forecasting in Italy (W. Marzocchi)

- Operational earthquake forecasting in the United States (N. Field)

- Recent experiences in OEF in New Zealand: the good and the bad (M. Gerstenberger)

- Panel discussion (moderator: R. Stein; reporter: M. Blanpied)

Session 4: From short-term hazard to risk

- Operational earthquake loss forecasting: framework and proof of concept (I. Iervolino)

- Evaluating risk and providing advise for low probability-high impact events in the presence of large uncertainties: the experience of the Italian High Risk Commission, 2011-2013 (D. Giardini)

- Current practice in the United States, and plans for improved dynamic earthquake likelihood forecasting (M. Blanpied)

- Panel discussion (moderator: M. Dolce; reporter: M. Gerstenberger)

Session 5: Decision-making process and risk communication in a low-probability forecasting environment (I)

- Participatory decision making under uncertainty (G. Woo)

- The structure and content of effective risk messages communicated to the public (D. Mileti)

- Managing seismic sequences in Italy: civil protection current practice and questions for the future (M. Dolce)

- Panel discussion (moderator: W. Marzocchi; reporter: T. Sellnow)

Session 6: Decision-making process and risk communication in a low-probability forecasting environment (II)

- Case histories of communicating uncertain earthquake hazard and loss estimates (D. Wald)

- Risk communication strategies when you understand that your audience is about as smart as you are (T. Patt)

- Strategies for communicating science-based messages in times of uncertainty (T. Sellnow)

- Panel discussion (moderator: D. Mileti; Reporter: G. Woo)

Session 7: Summary of the meeting

- Reports on the topic sessions (M. Page, M. Werner, M. Blanpied, M. Gerstenberger, T. Sellnow, G. Woo)

- Wrap-up discussion

Posters sessions:

- A short-term earthquake forecasting experiment in Japan (N. Hirata)

- Operational short-term earthquake forecasting in Japan (K. Doi)

- CORSSA: community online resource for statistical seismicity analysis (J. D. Zechar)

- Evaluating earthquake predictions by using the gambling score (J. Zhuang, J. D. Zechar, C. Jiang)

- Effect of data quality on a hybrid Coulomb/STEP model for earthquake forecasting (S. Steacy)

- Practice and enlightenment of earthquake prediction in China (Xiadong Zhang)

- An operational earthquake forecasting system in metropolitan area around Beijing, China (Yongxian Zhang)

- Short-term forecasting and preparation of earthquakes (D. Albarello)

- Preparing for an operational earthquake forecast experiment in Iceland (F. Panzera)

- Improving earthquake and aftershock risk communication: lessons from the Canterbury earthquakes, New Zealand (S. Potter)

- The effect of including aftershocks in probabilistic seismic hazard assessment modelling: A case study for Wellington (A. Christophersen)

Appendix B: Workshop participants

ALBARELLO, Dario
AMATO, Alessandro
BLANPIED, Mike
CASAROTTI, Emanuele
CATTANEO, Marco
CHIARABBA, Claudio
CHIARALUCE, Lauro
CHRISTOPHERSEN, Annemarie
COMUNELLO, Francesca
CONSOLE, Rodolfo
CRISCUOLO, Annamaria
D'AMICO, Vera
DEICHMANN Nicholas
DI BUCCI, Daniela
DOI, Keiji
DOLCE, Mauro
ELLSWORTH, Bill
FAENZA, Licia
FALCONE, Giuseppe
FIELD, Ned
GARCIA Alexander
GASPARINI, Paolo
GERSTENBERGER, Matt
GIARDINI, Domenico
HERRMANN, Marcus
HIRATA, Naoshi
IERVOLINO, Iunio
JORDAN, Thomas
LE GUENAN, Thomas
LUSSIGNOLI, Orsola
MAIN, Ian
MALAFRONTE, Lucia
MARZOCCHI, Warner
MELETTI, Carlo
MILETI, Dennis
MONELLI, Damiano
MURRU, Maura
NAYLOR, Mark
PAGE, Morgan
PANZERA, Francesco
PATT, Anthony
POWER, Christopher
RHOADES, David
ROSELLI, Pamela
ROSI, Mauro
ROSSI FILANGIERI, Alfonso
SABETTA, Fabio
SCHORLEMMER, Danijel
SEGOU, Margarita
SEIF, Stefanie
SELLNOW, Deanna
SELLNOW, Timothy
SHAPIRA, Avi
STEACY, Sandy
STEIN, Ross
TARONI, Matteo
VOGFJORD, Kristin
WALD, David
WALTER, Andre
WENZEL, Friedemann
WERNER, Maximilian
WIEMER, Stefan
WOO, Gordon
ZECHAR, Jeremy
ZHANG, Xiaodong
ZHANG, Yongxian
ZHUANG, Jiancang
ZUCCARO, Giulio