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Dear Suzette:

This letter is to transmit to you the attached recommendations being made by the National Earthquake Prediction Evaluation Council (NEPEC) concerning USGS activities in the field of Operational Earthquake Forecasting (OEF).

These recommendations are based on NEPEC's extensive consideration of the issues surrounding OEF. This included reading a number of published papers, some supporting and some questioning OEF. We then met at SMU in Dallas on September 2-3, 2015, and heard presentations by several USGS personnel engaged in research related to OEF. At that meeting we decided upon our recommendations and I drafted a version of them to be considered by the NEPEC members. The attached document is a result of rewriting of these recommendations by all of the Council members, but the essence of our recommendations are unchanged from those developed in our publically announced and open September 2-3 meeting.

If you have any comments or questions about our recommendations, or other issues that fall under the purview of the NEPEC, please feel free to contact me directly or through the Earthquake Hazards Program office.

Sincerely,

Terry E. Tullis

Terry E. Tullis, Chair NEPEC
Professor, Emeritus and Research

NEPEC RECOMMENDATIONS TO THE USGS ON OPERATIONAL EARTHQUAKE FORECASTING (OEF)

OVERVIEW

The National Earthquake Prediction Evaluation Council met on September 2-3, 2015 in Dallas, TX and heard numerous presentations on the USGS activities and plans for OEF. The following are our recommendations based on these presentations and on our prior review of the literature on OEF.

OEF activities and plans within the USGS are numerous and fall into three stages: 1) research, 2) testing, and 3) operational. All address large changes in relative probability for earthquakes within a low absolute probability environment.

The activities and plans we have considered are the following:

a) Preparation of annual hazard maps for earthquakes in the United States that are likely caused by anthropogenic injection of fluids into the Earth's crust.
b) Implementation of simple operational short-term earthquake probability forecasts for the entire United States and globally, following earthquakes above a predetermined magnitude, using well-established methods based on the work of *Reasenberg and Jones* [1989].
c) Research into and preliminary testing of short-term earthquake probability forecasts created following earthquakes above a predetermined magnitude in the United States and globally, using well-established methods based on Epidemic Type Aftershock Sequence (ETAS) models.
d) Research into earthquake probability forecasts based on a combination and extension of UCERF3 and ETAS methods.

As discussed in more detail below, NEPEC recommends that items a) and b) on the above list be made operational as soon as possible. Furthermore, NEPEC believes that it is important to emphasize research and testing of item c) and that it be made operational as soon as its readiness is demonstrated to NEPEC and the USGS can devote necessary resources to its implementation. We see considerable potential value in the possible future deployment of item d) into testing and operational stages, but the extensive research needed to determine if this approach is viable in an operational mode will likely take several years.

NEPEC concludes that it is important for the USGS to create an OEF system that delivers earthquake probability forecasts throughout the United States to a wide variety of users in both the public and private sectors, including government officials, emergency managers, emergency planners, first-responders, corporations and the general public. It will be important to first implement operational short-term earthquake forecasting using established and widely used methods, and continue to take a lead role in the development of improved methods for OEF. USGS is the designated federal agency within the National Earthquake Hazards Reduction Program with the responsibility for issuing earthquake advisories. If such authoritative information is not provided in a timely manner by the

USGS, those who need such information will get it from other less reliable and authoritative sources. Regardless of our inability to predict earthquakes with the degree of certainty and accuracy that everyone would wish, the USGS is in the unique position to use the best available science to provide authoritative forecast information, including the associated uncertainties, to those who seek it.

DETAILS

Annual Induced Seismicity Hazard Maps. The dramatic increase in seismicity in the Central and Eastern US (CEUS) in the past few years has caused considerable concern on the part of many about what we might expect in terms of future earthquake occurrence there. Much of this increase in seismicity is due to pumping of fluids down deep disposal wells, although in some locations other activities of the oil and gas industry, including hydraulic fracturing and production, also contribute. This increased activity is generally termed "induced seismicity." Lack of sufficient data, especially concerning focal depths, focal mechanisms and stress drops of the earthquakes, and concerning operational factors such as pumping rates, volumes and pressures at the wells, means that scientists have limited capability to infer the causes of these earthquakes.

Important questions remain as to where induced events may occur, their occurrence rates, and how large the earthquakes from induced seismicity can become in any particular area. Concerning where induced events may occur, current research has focused on where they have occurred in the past; models are not yet available to assess whether they might occur in as-yet-undeveloped locations, or in developed locations where future production/injection rates change. Concerning occurrence rates, available evidence suggests that the same type of frequency-magnitude relationship exists for induced seismicity as for natural tectonic earthquakes [*Wells and Coppersmith*, 1994], including having a *b* value close to 1 (although perhaps as large as 1.3 in Oklahoma). Concerning the maximum earthquake size that may occur in any region, it is still unclear whether it is controlled by available fault size, as for tectonic events, or by the total volumes or the rates of injected fluids. The maximum magnitude earthquake that has occurred to date for a given type of operation may not be the largest one that can occur. Looking at the size of the contiguous area occupied by nearby induced events, and using relevant empirical scaling relations [*Stirling and Goded*, 2012; *Wells and Coppersmith*, 1994] to convert that area into an earthquake size, is one approach to providing a preliminary estimate of the maximum earthquake magnitude that could occur in an evolving sequence. This estimate would itself evolve with the observed activity.

Because of the rapidly increasing numbers and locations of apparently induced earthquakes, including damaging earthquakes in a number of states including Oklahoma, making hazard maps for induced earthquakes annually is an important USGS activity that can be expected to garner increasing public attention. Current preliminary maps presented to NEPEC by the USGS give a general idea of the predominant areas of earthquake hazard from induced seismicity, although they have limitations that future research and better availability of industry data could address. The maps tend to be a spatially smoothed representation of past seismicity, which may not be appropriate for regions where earthquakes are associated with a few isolated high-rate wells or very productive fields. At present the maps do not account for the fact that production and injection rates vary significantly over time periods of less than a year to a few years, and there are commonly situations where operators respond to seismicity by changing injection/production rates and practices. Maps based solely on past induced seismicity are in some sense always out-of-date.

Thus it is important to at least consider the potential for induced seismicity due to future anthropogenic activities that have not yet commenced. This includes fluid injection and extraction operations associated with the petroleum industry, as well as carbon sequestration. This is important input information to the engineering community as they consider the implications of induced seismicity for seismic design. Because of the importance of induced seismicity, the preparation of these hazard maps is an activity in which research, testing, and operational forecasting activities need to occur simultaneously. The future implementation of OEF to better handle evolving induced seismicity sequences is an important area for research.

Operationalize Aftershock Forecasting based on Reasenberg and Jones (1989). Following a large earthquake, there is a critical need for authoritative information on what to expect in the way of aftershocks. There are many practical reasons that emergency responders, building inspectors, and others need this information. Also, sociological studies show that it is greatly reassuring for the public to know what to expect and to know that the potentially alarming number, size, and frequency of aftershocks is not unusual and is expected by experts.

For years, the USGS has been making forecasts based on aftershock statistics from *Reasenberg and Jones* (1998), hereinafter referred to as RJ, and making some of them available on the web, although they have not always been prominently and consistently disseminated. The time has come to do this on a routine basis in a more prominent way. NEPEC believes that although such an approach should be replaced by an ETAS approach as quickly as is prudent, it is important to move forecasts into an operational mode without delay using the well-established RJ methodology. There will clearly be some work involved in setting up the apparatus to do this routinely and it will take some staff time to maintain an operational system. The value of having operationalized USGS forecasts is worth the modest effort. Furthermore, when an ETAS approach is deemed ready to replace the RJ-based system, many of the procedures for making forecasts operational developed for RJ can be adopted for the ETAS method.

Such aftershock forecasts will be undertaken for mainshocks throughout the United States, although the magnitude threshold will vary with region. For California the threshold is probably M4. For the Pacific NW and the CEUS the magnitude threshold may differ. Such forecasts could also be undertaken on a world-wide basis. For each mainshock, the initial forecast will use values of the RJ parameters a, b, p, and c selected to be appropriate for the location of the mainshock. These parameters should be developed for the entire Earth, different tectonic regimes, and for more specific regions within the U.S. The world-wide triggering magnitude threshold values will typically be considerably larger than for the US and are likely to vary with location. Although it may make sense for world-wide aftershock probabilities to be presented on a USGS website, the degree to which the USGS offers to assist local authorities will depend on what local capabilities exist and whether such assistance is requested by the foreign government or by US agencies with interests in the region.

One of the deficiencies of the RJ method is that it does not specify the geographical extent of an aftershock zone, although that region is obviously in the vicinity of the triggering earthquake. A second deficiency is that the RJ approach fails to account for secondary aftershock sequences following the occurrence of a significant aftershock. The RJ approach requires manual resetting of the starting time and implied area of a decay sequence following a large aftershock, as was illustrated by the laborious efforts of the USGS to forecast aftershock activity following the Nepal earthquake of April 25, 2015. A third deficiency becomes manifest during prolonged swarms (no obvious mainshock). A fourth deficiency is that the performance of the RJ method has never been tested formally, an exercise that may prove difficult due to shifting parameterizations and lack of retrospective documentation. A further requirement for good fits to an aftershock sequence is that the productivity factor a, and perhaps the decay rate constant p, are modified from their initially assumed values using (ideally) a Bayesian approach as the aftershock sequence develops. This is currently best done with human intervention. Note that although the RJ approach is cast in terms of forecasting the statistical properties of aftershocks, in a small percentage of the cases a subsequent earthquake can be larger than the triggering event. Although RJ computes probabilities that the larger event will occur, "second generation" aftershocks triggered by that event are not accounted for in the RJ formulation for the initiating event, but are a natural feature of the ETAS method.

Work toward relatively rapid replacement of the RJ method in OEF by an ETAS method. NEPEC is convinced that some version of an ETAS approach will be an improvement over the RJ method for OEF and that the USGS should continue pursuing, developing, and testing an ETAS method. Before it replaces the RJ method in OEF, NEPEC would like to see the results of testing the method, including the satisfactory performance of well-developed codes to implement it in OEF, and a demonstration that ETAS performs better than the RJ approach. Making ETAS operational may be more challenging than expected, a possibility that strongly contributed to NEPEC’s assessment that OEF should begin with the RJ method and not wait for an ETAS implementation.

Advantages of an ETAS method are that it naturally accounts for some of the problems of the RJ method listed above: It can present the spatial distribution of aftershock probabilities; because it is a cascade approach, it naturally accommodates the occurrence of observed large aftershocks without manual intervention; it is less sensitive to the initial selection of parameter values; and it more easily tunes the parameter values to the particular aftershock sequence as the sequence develops. For all of these reasons, it appears to be a superior approach to use for OEF and hence should replace the RJ method as soon as testing shows it is ready and necessary resources are available for implementation. After both methods are implemented, NEPEC envisions that the results of the ETAS method would provide the public operational forecasts, but comparisons of its performance with that of the RJ method should be undertaken. Such testing might provide useful insight for further refinement of the details of the ETAS method being used.

Long-term value of research into using a combined UCERF3-ETAS approach for OEF. NEPEC was intrigued by the ongoing effort to develop a time-dependent earthquake forecasting capability using a combination and extension of ETAS and the UCERF3 time-independent model. UCERF is the acronym for the Unified California Earthquake Rupture Forecast [*Field et al.,* 2015]. This is a large complex model of the behavior of California[1]s faults and earthquakes funded by the California Earthquake Authority and built by collaborative efforts of the USGS, the California Geological Survey, and the Southern California Earthquake Center. UCERF is a complex model with a large number of parameters, and it is presently far from being ready for use in OEF. Nevertheless, its potential appears high enough that it is valuable to devote some USGS resources to its continued development and testing.

The UCERF3-ETAS method consists of applying the influence of an earthquake above some threshold magnitude to the background state of a fault system given by a time-independent model. In the case of California, that time-independent model is UCERF3. Given the existence of UCERF3, California is the logical test-bed for the initial exploration of this approach to earthquake forecasting, but in principle the same approach can be applied to other regions. The underlying model, namely UCERF3, provides an environment onto which the perturbation from the triggering earthquake is overlain. Depending on the location of the triggering earthquake, and what might be termed the readiness of the surroundings to participate in an earthquake, the triggering earthquake may cause little effect or a large effect. Given such a complex time-independent underlying fault model, many possible branches of response to the triggering earthquake may exist. By computing a very large number of these branches and suitably averaging their behavior, a probabilistic forecast of triggered earthquake behavior in all parts of the system can be made. What intrigues NEPEC about this approach is that it takes into account the large amount of information about a fault system in areas where it is available. Where less is known, such as in the Pacific NW, the intermountain west, and the CEUS, the range of possible responses will be less rich, but whatever is known could be merged with the effects of the triggering earthquake, thereby providing potentially useful information about increased short-term hazard.

CEPEC is currently faced with making decisions about whether any modest-sized earthquakes located close to faults that are perceived to be overdue for a large earthquake might be foreshocks for some major damaging event. Examples include an earthquake swarm in March 2009, including an M4.8 event, at Bombay Beach on the Salton Sea at the southern end of the San Andreas Fault and the recent August 17, 2015 M4.0 earthquake along the Hayward Fault. In the future, NEPEC might be faced with a similar decision regarding predictions that arise due to evolving seismicity. At present, these councils are only able to make statements concerning probabilities of subsequent large earthquakes based on expert opinion. Assigning probabilities and uncertainties to these evaluations is extremely difficult. NEPEC would greatly appreciate having an operational system based on more quantitative and objective methods such as one combining UCERF3 and ETAS (subject of research at the USGS). Such an approach clearly needs more testing and evaluation before it can be considered for moving into an operational mode. However, if that or some similar system could be demonstrated to have practical value, NEPEC would likely endorse it enthusiastically.

We note that testing such a system for the infrequent large earthquakes that are of the greatest concern is a significant challenge. To do this based on observations in a limited geographic region such as California would likely take several hundred years. Devising tests based on observed seismicity on a world-wide basis might allow valuable testing in a much shorter time period. If such a system were to be implemented within a few years this would have to be done without adequate testing. It will likely fall to NEPEC to decide whether such a system should be made operational without rigorous testing.

CONCLUSION

The USGS is progressing on Operational Earthquake Forecasting in a number of ways, which we have grouped into four categories. NEPEC feels that two of these are ready for implementation in OEF: the creation of annual hazard maps based on induced earthquake activity, and the routine public issuance of aftershock-based earthquake probabilities using the *Reasenberg and Jones* [1989] methodology. Both of these should be implemented in OEF as soon as possible for the entire nation. Work on a third activity that is currently in the research and testing phase, the issuance of ETAS-based aftershock probabilities, should be pursued with as much effort and haste as is feasible. NEPEC looks forward to seeing results of such testing and to being in a position to recommend that this method replace the *Reasenberg and Jones* [1989] approach in OEF. Finally, NEPEC is intrigued by the possibility that the combined UCERF3-ETAS approach currently in the research stage by the USGS might eventually provide the basis for better estimates of earthquake probabilities than can be provided by a basic ETAS model. Research and testing on this at the USGS should continue as resources allow. As a longer term goal, NEPEC endorses continued research into time-dependent fault loading, including slow slip events and visco-elastic flow, which may improve our understanding of the seismic cycle and contribute to improved OEF beyond what is possible with seismicity-based approaches alone.

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