The Uniform California Earthquake Rupture Forecast, Version 2 (UCERF 2)

By 2007 Working Group on California Earthquake Probabilities*

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The Uniform California Earthquake Rupture Forecast, Version 2 (UCERF 2)

2007 Working Group on California Earthquake Probabilities (WGCEP) and the USGS National Seismic Hazard Mapping Program (NSHMP)

Executive Summary

California's 35 million people live among some of the most active earthquake faults in the United States. Public safety demands credible assessments of the earthquake hazard to maintain appropriate building codes for safe construction and earthquake insurance for loss protection. Seismic hazard analysis begins with an earthquake rupture forecast—a model of probabilities that earthquakes of specified magnitudes, locations, and faulting types will occur during a specified time interval. This report describes a new earthquake rupture forecast for California developed by the 2007 Working Group on California Earthquake Probabilities (WGCEP 2007).

2007 Working Group on California Earthquake Probabilities

WGCEP 2007 was organized in September, 2005, by the U. S. Geological Survey (USGS), the California Geological Survey (CGS), and the Southern California Earthquake Center (SCEC). It was charged with two tasks: (1) collaborate with the National Seismic Hazard Mapping Program (NSHMP) in producing a revised, *time-independent* forecast for California as input to the 2007 revisions of the national seismic hazard maps, and (2) create a uniform, statewide, *time-dependent* model that, among other purposes, could be used by the California Earthquake Authority (CEA) in setting earthquake insurance rates.

The national seismic hazard maps utilize a time-independent forecast in which the probability of each earthquake rupture is completely independent of the timing of all others. Time-dependent models are based on the concept of stress renewal: the probability of a fault rupture drops immediately after a large earthquake releases tectonic stress on the fault and rises again as the stress is regenerated by continuous tectonic loading. However, observations in California and elsewhere show that the earthquake cycle associated with this elastic rebound theory can be highly irregular, owing, for example, to stress interactions among neighboring faults. We do not understand these interactions well enough to model them explicitly; therefore, variations in the earthquake cycle must be calibrated empirically using historical observations of seismicity and geologic data on the dates and sizes of prehistoric earthquakes (paleoseismology).

Time-dependent earthquake rupture forecasts, in which the probabilities of future events are conditioned on the dates of previous earthquakes, have been the focus of five previous Working Groups on California Earthquake Probabilities (WGCEP 1988, 1990, 1995 & 2003). Each of these working groups has expanded on its predecessors, improving the data and forecasting methodology, and each has drawn on input from broad cross-sections of the earth science community. Building on this experience, we calculate time-dependent probabilities of large earthquakes on major faults (generally those with the highest rates of slip) where the requisite information is available: the expected mean frequency of earthquakes and the elapsed time since the last earthquake. Where such information is lacking, we use time-independent probabilities, which require only an estimate of earthquake frequency.

The WGCEP 2007 study differs from previous WGCEP efforts by:

- reporting earthquake probability for the entire state of California instead of subregions;
- using uniform methodology across all regions;
- using the same earthquake rate model as the 2007 National Seismic Hazard Map Program;
- compiling and using updated, uniform, and publicly accessible statewide data;
- developing new methods to make models more rigorously adherent to observational data, particularly fault slip rates (moment balanced);
- making analysis tools and data available through a readily accessible web-based interface.

In general, we have adopted the results from previous working groups where justified and have updated the model only when compelled to by new information or understanding, or by necessity to conform the analysis to a uniform statewide approach and with the NSHMP assessment.

Review and Consensus-Building Processes

All UCERF 2 model elements and WGCEP 2007 documents were reviewed by an internal Scientific Review Panel (SRP) comprising experts who were not WGCEP 2007 members. The SRP reported to the Management Oversight Committee (MOC), which coordinated the review and oversaw consensus-building processes. External oversight and review was provided by the National Earthquake Prediction Evaluation Council (NEPEC) and the California Earthquake Prediction Evaluation Council (CEPEC), as well as CEA’s Multidisciplinary Research Team. CEPEC and NEPEC tracked model development throughout the WGCEP 2007 process and reviewed the final report.

Advice and comment from the scientific and engineering communities was sought regularly through open meetings and workshops during the several phases of UCERF development. Participants included experts from academia, private and corporate providers of hazard assessments, consulting companies, and government agencies. WGCEP progress was reported at major scientific gatherings such as annual meetings of the American Geophysical Union, the Seismological Society of America, and the Southern California Earthquake Center.

Model Framework

We have built on previous WGCEP and NSHMP efforts to quantify regional earthquake probabilities in California, using the best available science to develop a new framework for a Uniform California Earthquake Rupture Forecast (UCERF). The UCERF framework comprises a sequence of four model types: a *fault model* that gives the physical geometry of the larger, known faults; a *deformation model* that gives slip rates and aseismicity factors to each fault section; an *earthquake rate model* that gives the long-term rate of all earthquakes of magnitude five or greater ($M \geq 5$) throughout the region; and a *probability model* that gives a probability of occurrence for each earthquake during a specified (future) time interval. This report presents the latest versions of each of these models, including the statewide time-independent earthquake rate model incorporated into the 2007 revisions to the national seismic hazard map (ERM 2.3) and the time-dependent earthquake probability model derived from ERM 2.3 (UCERF 2). The results are intended for use in forecasting the intensity of ground shaking throughout California.

The model incorporates both aleatory uncertainties (arising from natural variability) and epistemic uncertainties (resulting from lack of knowledge). The latter were included by constructing a logic tree with branches representing viable alternative hypotheses. We restricted our consideration to data and methods that have been published, or accepted for publication, in peer-reviewed scientific journals or as U.S. Geological Survey Open File Reports. If relevant published models differed significantly, we applied logic-tree weighting to represent the alternatives. Generally, two alternatives were given equal weight in the absence of any clear evidence to favor one over the other. When there was evidence to favor a given branch, the assignment of relative weights was made though a consensus-building process, which we describe for each case.

Earthquake Rate Model

The WGCEP 2007 earthquake rate model features a new fault geometry with more accurate values of dip and seismogenic depth, and new compilations of fault slip rates and paleoseismic events. The final version, ERM 2.3, includes two alternative fault models for southern California thrust-fault geometry and three alternatives representing the uncertain slip distribution between the southern San Andreas and San Jacinto faults. A significant logic-tree branching involves the choice of the magnitude-area relationship, which is used to translate from fault slip rates to earthquake rates; the global database of rupture areas and magnitude determinations has significant spread, leaving room for alternative interpretations.

Another important model branching incorporates alternative representations of the earthquake rates on major faults. We compiled an *a priori* earthquake rate model derived by a community consensus of paleoseismic and other geologic observations. We also calculated a moment-balanced version of the model, which modifies the earthquake rate to match the observed long-term slip-rate data; the resulting rates were constrained to fall within the ranges derived from paleoseismic observations. These two models balance a consensus of geologic and seismologic expert opinion with strict adherence to specific observational data.

We tested ERM 2.3 in three different ways: by comparing the predicted magnitude-frequency distributions of earthquakes with a unified historic and instrumental earthquake catalog for California and surrounding regions, by comparing integrating measures of deformation across the plate-boundary zone with the plate rate, and by comparing the distribution of source types in the model with historical data. A major issue was overprediction of the rate of $M \geq 6.5$ earthquakes, known informally as “the bulge”, a problem common to previous WGCEP and NSHMP studies. ERM 2.3 predicts an annual rate for $M \geq 6.5$ earthquakes of 0.32 events/yr, which exceeds the historically observed rate of 0.24 events/yr by about a third, though it lies within the

95% confidence bounds on the observed rate (0.13-0.35 events/yr). In comparison, the NSHMP 2002 model for California exceeded the observed rate by a factor of two.

Time-Dependent Earthquake Probability Model

We tightly coordinated the development of the earthquake rate models for California with NSHMP, so that both the 2007 revisions of the national seismic hazard maps and UCERF 2 are based on ERM 2.3. Constructing an earthquake rupture forecast from ERM 2.3 required a probability model that specifies how events are distributed in time, and here we departed from the NSHMP 2007 conventions by considering, along with a time-independent (Poisson) forecast, time-dependent forecasts that use stress-renewal assumptions to condition the event probabilities for the most active faults on the date of their last major rupture.

Our choice of UCERF 2 model branches was based on a careful review of all available probability models. A particularly influential branching is the “empirical” probability model, which includes a geographically variable estimate of California earthquake rate changes observed during the last 150 years. We lack consensus on the underlying physics that causes broad earthquake rate changes, though there is much promising research involving fault interactions. Rather than applying complex physical models to adjust probability, WGCEP 2007 relies on the simpler empirically-based correction.

An important seismic hazard for California is the Cascadia subduction zone, which extends

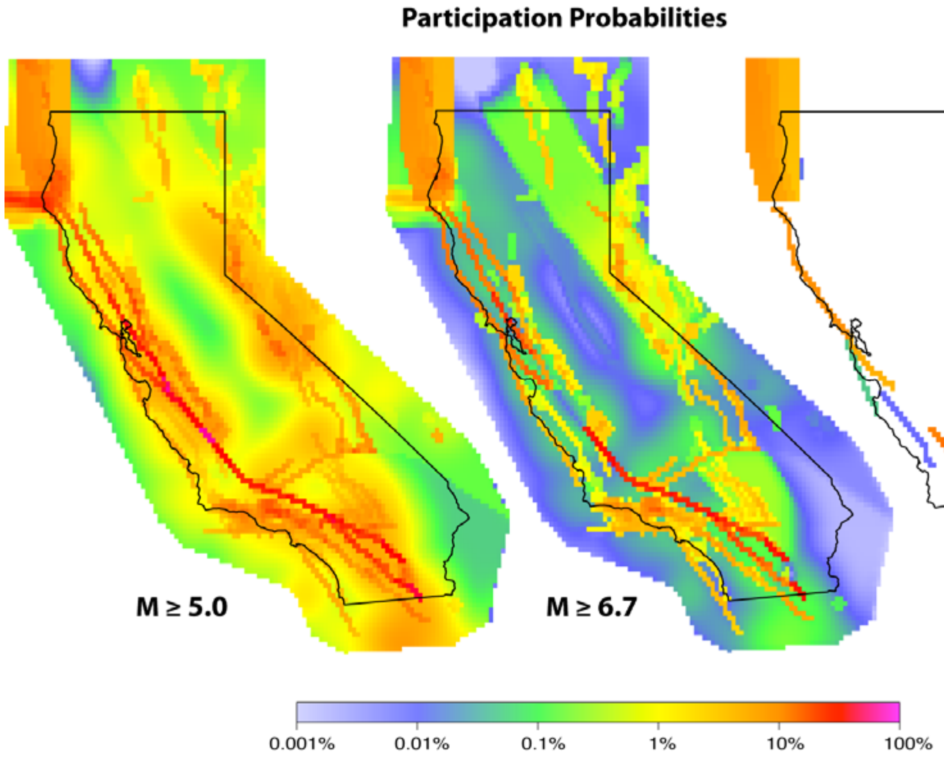

Figure A. Participation probability maps, displaying the mean UCERF 2 probabilities that an individual $0.1^{\circ} \times 0.1^{\circ}$ cell in the statewide grid will be involved in a fault rupture of any source type above the specified magnitude threshold during the next 30 years. The magnitude thresholds shown here are M • 5.0, 6.7, and 7.7. Probability color scale is logarithmic; i.e. each decrement unit represents a 10-fold decrease in probability.

about 1200 km from Vancouver Island in British Columbia to Cape Mendocino in California and is capable of generating an earthquake of M 9 or larger. Because this fault lies mostly outside the state, we treated it as a special case with its own logic tree, which included two rupture scenarios: (1) M 8.8-9.2 events that rupture the entire Cascadia subduction zone every 500 years on average, and (2) M 8.0-8.7 events whose ruptures cover the entire zone over a period of about 500 years. A time-independent model was applied to the M 8.0-8.7 scenario, and a time-dependent model to the M 8.8-9.2 scenario.

In computing event probabilities, the branches were weighted by expert opinion gathered in open workshops. The UCERF 2 model has been implemented in a modular (object-oriented), extensible framework using the OpenSHA platform, so that experiments with alternative branch weights can be easily investigated and future updates can be quickly accommodated as new data and methods emerge. The final UCERF 2 logic tree incorporated 480 branches that received nonzero weight, each of which produces a separate set of probabilities for all earthquakes in California. We take the mean and spread of these results to represent the best estimate of earthquake probability and its sensitivity to parameter uncertainty.

Results of Probability Calculations

According to UCERF 2, a M ≥ 6.7 earthquake is virtually assured in California during the next 30 years (99.7% probability of occurrence). Larger events are less likely: the mean 30-year UCERF 2 estimate gives a 94% chance of a M ≥ 7.0 earthquake, a 46% chance of a M ≥ 7.5 shock, and 4.5% chance of a M ≥ 8.0 event. The UCERF 2 range for these latter probabilities is 85-99%, 29-65%, and 0-11%, respectively. In addition, we estimate a 10% probability of a M ≥ 8.0 earthquake somewhere along the Cascadia subduction zone (perhaps far from California) in the next 30 years. We emphasize that the probabilities calculated for the largest magnitude events should be used with caution, because they depend critically on rupture scenarios that involve fault lengths longer than historically observed ruptures, as well as an extrapolation of scaling relationships, such as the magnitude-area relationships, beyond the limits of the empirical data.

Dividing the state into two approximately equal areas, we find the 30-year probability of a large earthquake to be higher in the southern half: a M ≥ 6.7 earthquake has a 97% chance of occurring in southern California in 30-years, compared to a 93% probability in northern California, and the odds for a M ≥ 7.5 event are doubled (37% vs. 15%). In addition to state-wide and regional estimates, our report gives probabilities for individual faults and fault segments throughout the state, as well as a geographically variable background rate.

The UCERF 2 earthquake rupture forecast can be visualized by mapping the mean probability that an element of area on a statewide grid will include a fault rupture of any source type above a specified magnitude threshold during the next 30 years. Figure A presents these “participation probability” maps for three magnitude thresholds. For events with M ≥ 5.0, the areas where the participation probabilities exceed 1% (yellow or warmer in color) include over half the state, reflecting the widespread distribution of California seismicity, much of which is represented in the model as “background.” At M ≥ 6.7, this same probability level is confined to the major faults, and at M ≥ 7.7, it is generally restricted to the longer strike-slip strands of the San Andreas fault system.

Table A. 30-year probability of M • 6.7 events on the Type-A faults, rounded to the nearest percent.

Fault	WGCEP (2007) Mean [Min-Max]	WGCEP (2003) Mean [2.5% and 97.5%]	WGCEP (1995) Mean
S. San Andreas	59% [22-94]		53%
Hayward-Rodgers Creek	31% [12-67]	27% [10-58]	
San Jacinto	31% [14-54]		61%
N. San Andreas	21% [6-39]	23% [3-52]	
Elsinore	11% [5-25]		24%
Calaveras	7% [1-22]	11% [3-27]	
Garlock	6% [3-12]		

Table A summarizes the mean probabilities for $M \geq 6.7$ events on the principal strike-slip faults of California, which accommodate most of the motion between the North America and Pacific plates, and it compares our results with those of WGCEP 1995 for southern California and WGCEP 2003 for the Bay Area.

The most dangerous fault is the southern part of the San Andreas, which has a 59% probability of generating a $M \geq 6.7$ earthquake in the next 30 years. This compares with 21% for the northern San Andreas fault.

We have enough data to calculate time-dependent earthquake probability on the principal strike-slip faults in Table A. These faults exist within a web of faults with lower slip rates that we know less about, which are consequently treated as time-independent sources. In southern California, the contribution to overall regional probability from these lower slip-rate faults, which include the reverse faults of the Transverse Ranges, exceeds that of the principal strike-slip faults.

Reliability of Results

The larger the area considered and the longer the time considered generally makes a probability calculation more reliable. Thus the statewide 30-year probability values are more reliable estimates than those for individual faults. However, even the most reliable of our calculations are subject to considerable sensitivity to parameters. For example, across the 480 branches of the logic tree we find a minimum 30-year probability of 29% for a $M \geq 7.5$ earthquake, and a maximum of 65%. Calculations are quite sensitive to parameter choices on individual faults; while the mean calculated probability on the southern San Andreas fault is 59%, we find that the value could reasonably be anywhere between 22% and 94% (see Table A).

There are known limitations with the WGCEP 2007 model, which are discussed in detail in the main report. More research time will bring improvements in key topical areas. For example, new earthquake faults will continue to be discovered. Improvements in our methods for determining maximum magnitudes associated with poorly understood faults are needed. A related major research challenge involves improving our ability to forecast more complex earthquake ruptures that include fault jumps, branching, and segment-breaking ruptures.

Comparisons with Previous Studies

The 30-year probability of a $M \geq 6.7$ earthquake striking the San Francisco Bay Area is 63% for UCERF 2, which is indistinguishable from the 62% value reported by WGCEP 2003 (see Table A). Moreover, the extrema calculated from all of the UCERF 2 branches [0.41-0.84] approximate the 95% confidence interval of WGCEP 2003 results for the aggregate Bay Area probabilities [0.38-0.85]. This agreement indicates that we succeeded in capturing the most important epistemic uncertainties (in part because we were guided by the comprehensive uncertainty analysis of the WGCEP 2003 report).

As shown in the table, there are differences between WGCEP 2007 and WGCEP 2003 calculations for individual fault probabilities in the Bay Area. However, none exceed the uncertainty ranges reported by either working group. The differences resulted primarily from inclusion of paleoseismic observations in UCERF 2 and the restricted inventory of probability models that could be used for our statewide analysis.

The differences in the mean 30-year probabilities for $M \geq 6.7$ events between the 1995 and 2007 studies are more significant. The most important arise from new paleoseismic data and analysis, new geodetic data, and an earthquake rate model that allows a greater variety of rupture sizes on faults. One important change is to the San Jacinto fault, where the probability has been halved from 61%, reported by WGCEP 1995, to 31% [14%-54%] calculated by WGCEP 2007 (see table). Similarly, Elsinore fault probability is halved from 24% to 11% [5%-25%] because of the increased array of possible earthquake magnitudes allowed in the model.

Recommendations

The comprehensive nature of the UCERF 2 analysis has identified many opportunities for future model improvements, and we outline in the report specific recommendations for further research. Examples include the relaxation of fault segmentation and the inclusion of fault-to-fault ruptures, which may be in part responsible for the "bulge" problem; the inclusion of earthquake triggering and clustering, as manifested in aftershock sequences; and improved magnitude-area relationships.