Appendix O—Gridded Seismicity Sources

By Peter M. Powers[1] and Edward H. Field[1]

Introduction

The Uniform California Earthquake Rupture Forecast, Version 3 (UCERF3) is a forecast of earthquakes that fall into three broad categories: big earthquakes on identified major faults ($M \geq 6.5$), smaller earthquakes on or near those same faults ($M \leq 6.5$), and earthquakes of all sizes that are not associated with identified faults. UCERF3 gridded (or background) seismicity sources represent all earthquakes that fall into the latter two categories. These earthquakes do not have a geologic- or seismicity-based finite-source representation in UCERF3. Instead, they are represented as point or planar fault sources at the centers of evenly spaced grid cells that make up the UCERF3 forecast region. Their role is important in that they express future, distributed earthquake occurrences and account for the fact that many large earthquakes do not occur on known, mapped faults.

Background

The 2008 National Seismic Hazard Map Project (NSHMP) gridded seismicity-source model (Petersen and others, 2008; Frankel and others, 1996, 2002), adopted in UCERF2, divides the western United States into discrete regions (fig. O1) and treats each region as an independent set of gridded sources with common parameters (for example, maximum magnitude [M_{max}], strike, *b*-value, and focal mechanism). The regions were identified on the basis of differences in the historical catalog (for example, quality and completeness) and tectonic style. Spatially uniform M_{max} and *b*-values and spatially variable *a*-values, or rates, constrain the magnitude-frequency distribution (MFD) of each source in a region. In regions with little seismicity (a rarity in California), a minimum earthquake rate (or floor) also is applied. Source rates were derived by smoothing the rates of declustered events in each region using an isotropic Gaussian kernel with a 50-km radius. In California, several subregions received special treatment: Mendocino, Imperial, Brawley, and the creeping section of the San Andreas Fault. These regions either had fixed strike sources, M_{max} and *b*-values that differed from the broader regional value, or were smoothed by using an anisotropic kernel. A primary challenge in building a gridded seismicity forecast is to avoid double counting at grid cells that overlap spatially with faults. The 2008 NSHMP addressed this issue by reducing M_{max} of sources within 10 km of near-vertical faults and over more steeply dipping faults.

The focal mechanisms of each source reflect the tectonic style of the parent region, with each source assigned a weighted combination of strike-slip (SS), reverse (R), and normal (N) motion with weights that sum to 1. For example, grid sources spanned by the coastal California catalog have SS weights of 0.5 and R weights of 0.5, whereas sources spanned by the western

[1] U.S. Geological Survey.

U.S. extensional catalog have SS weights of 0.5 and N weights of 0.5. This level of focal-mechanism specificity is accommodated by the ground-motion prediction equations used in the NSHMP, and it ultimately provides a better estimate of hazard. As for implementation, UCERF2 defines sources at the centers of the 7,636 grid cells in the 0.1 by 0.1 degree discretization of California and its buffer zone [the regional earthquake likelihood model (RELM)] test region; Field, 2007). Because catalog smoothing generates overlap between the NSHMP source regions, any UCERF2 grid source is a composite of all coincident NSHMP regional sources that have a non-zero rate.

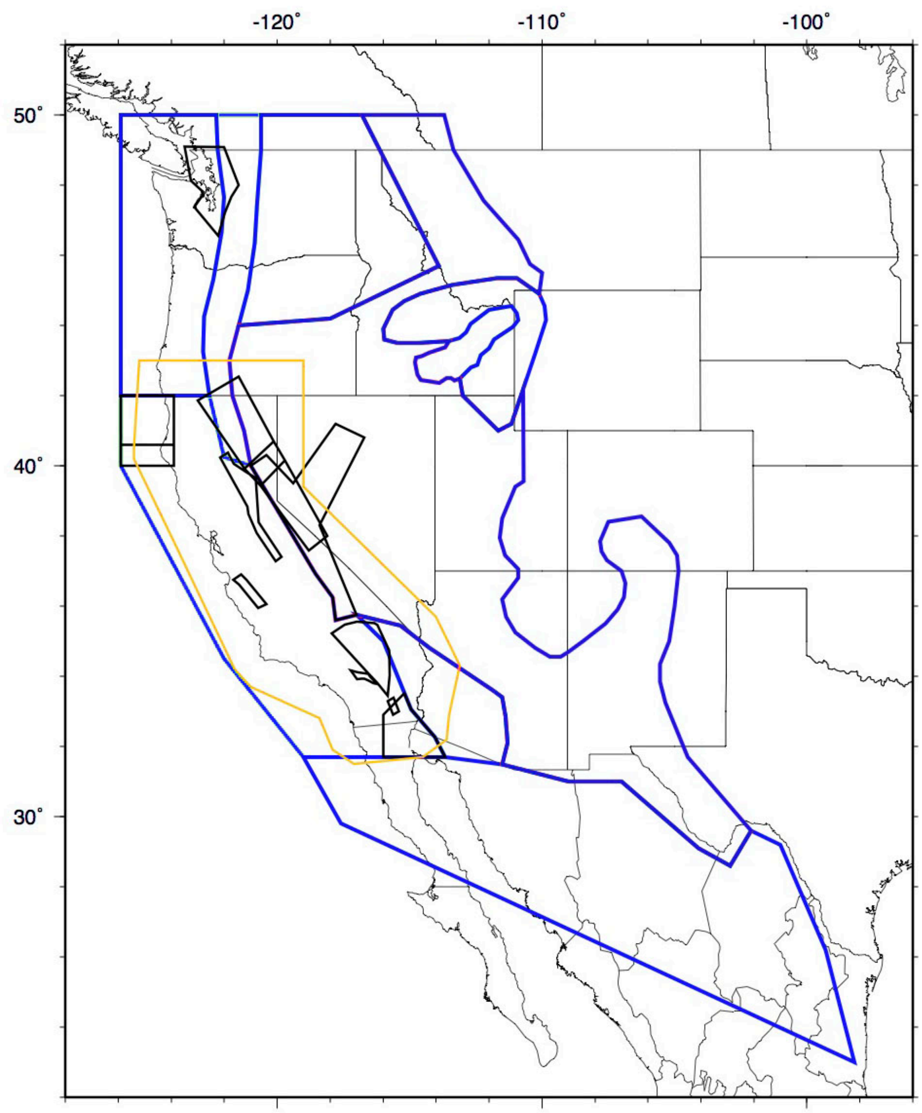

Figure O1. Map of the 2008 National Seismic Hazard Map Project polygons used to define the boundaries of grid source regions (shown in blue; special seismicity zones are shown in black). These regions were used to subdivide the declustered historical seismicity catalog prior to smoothing and the calculation of gridded-source rates. The yellow line marks the boundary of the Regional Earthquake Likelihood Model testing region, the area spanned by the Uniform California Earthquake Rupture Forecast, versions 2 and 3.

Gridded-Source Model

UCERF3 is fundamentally different than UCERF2. With the introduction of the Grand Inversion and fault-system-wide solutions, there are regional constraints on the rate of off-fault (or background) earthquakes that are uniquely balanced with on-fault rates for each solution (appendix N, this report). Moreover, the addition of new faults to the model has alleviated the need for "special" seismicity zones. The foregoing describes how a gridded seismicity-source model is constructed for any Grand Inversion solution and branch of the UCERF3 logic tree. Every Grand Inversion solution provides the necessary data to build a gridded seismicity-source model. Grand Inversion realizations are constrained by a total, regional MFD, which the inversion partitions among (1) large, on-fault (supra-seismogenic) events, (2) small, near-fault (subseismogenic) events, and (3) truly off-fault (unassociated) events. The sum of the latter two events is the total, regional MFD of gridded seismicity sources. How the various MFDs are constructed depends on the constraints supplied by a particular logic-tree branch (for example, the choice of a characteristic or Gutenberg-Richter regional MFD constraint, the chosen gridded seismicity maximum magnitude, or the chosen spatial probability density function [PDF] of seismicity, and so on.). As with UCERF2, UCERF3 gridded seismicity sources are centered in non-overlapping 0.1 by 0.1 degree cells that span the RELM testing region.

Distributing the inversion-supplied subseismogenic and unassociated MFDs is a multistep process that hinges on bookkeeping the spatial relationships between fault-section polygons and grid cells. It should be noted that these same bookkeeping tools are required during the inversion setup process. Fault-section polygon definitions are described below, followed by the bookkeeping process and the definition of MFDs for gridded sources.

Fault-Section Polygons

As defined in the UCERF3 report, a fault-section is a proxy for all earthquakes that nucleate inside the corresponding fault-section polygon. Fault-section polygons are subdivisions of the polygons defined for an entire fault-zone. Fault-zone polygons, as used in UCERF3, are the combination (or union) of three independently defined polygons (shown in figure O2B): the geologically defined polygon for the fault; the surface projection of the fault, if dipping; and a buffer on either side of the fault trace. The geologic polygon (fig. O2A) is derived from a UCERF3 fault model, and it generally extends to 1 km on either side of the fault trace unless it has been expanded to encompass a broader zone of mapped surface deformation (see appendix A, this report, for more details). The width of the buffer polygon on either side of a fault trace scales linearly from 0 km at 50˚ dip to 12 km at 90˚ dip (fig. O2C). Vertical faults therefore have a broad zone of influence that scales down as dip decreases and the area of the surface-projection polygon increases. Figure O2B shows how the three polygons are combined. Once the polygons are defined for each fault in a fault model, they are sliced at inversion-supplied section boundaries (fig. O2B) in the average dip direction for the fault to yield individual fault-section polygons. Although this approach is by no means perfect, it maintains consistency with the 2008 NSHMP approach of assigning a comparable zone of influence (~12 km) to each fault to avoid double counting.

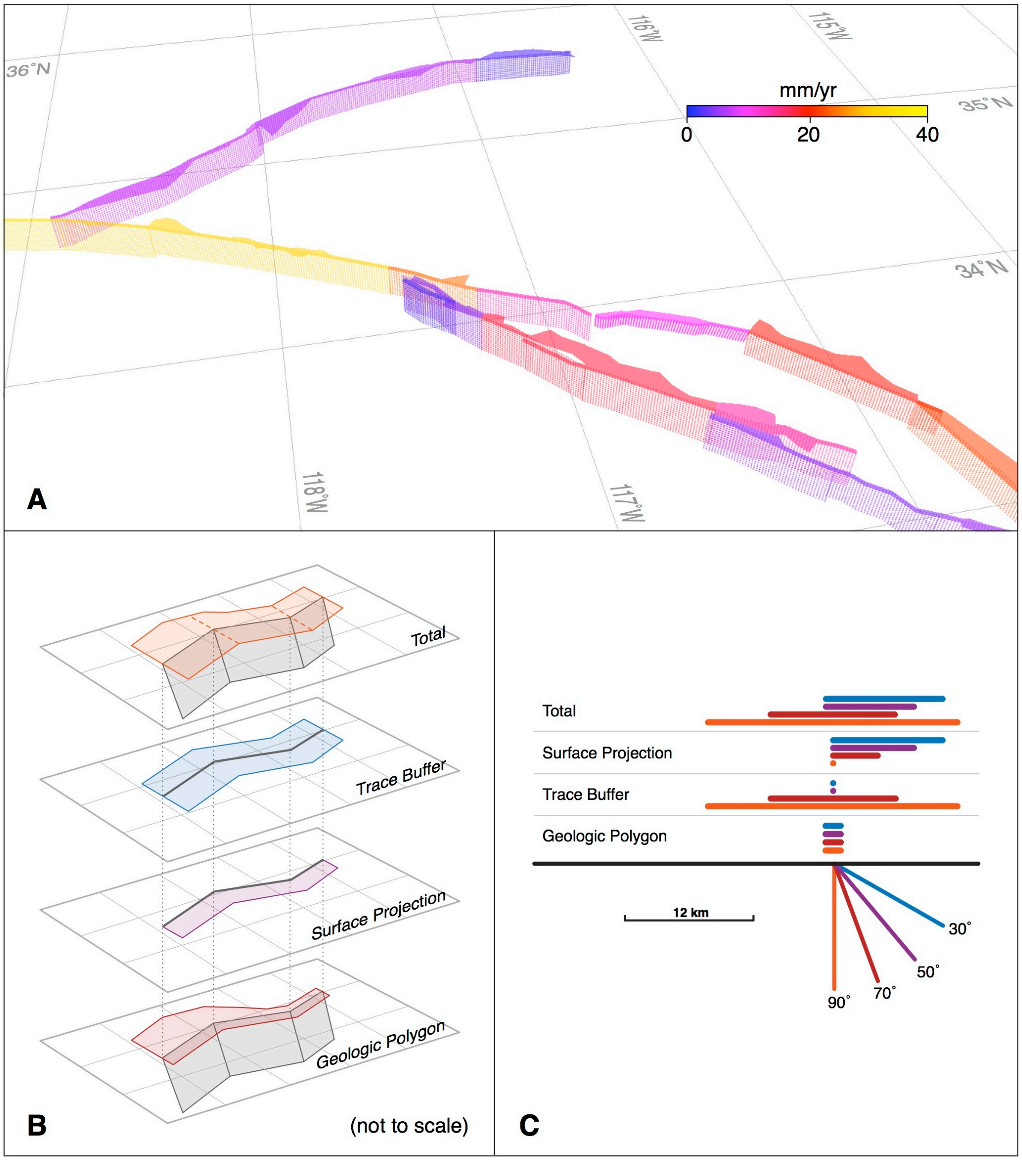

Figure O2. The definition and creation of fault-zone polygons. A, Perspective view of the Garlock, southern San Andreas, and San Jacinto Fault systems, color coded by slip rate. Down-dip projections of the faults are stippled, and the geologically defined surface polygons are solid. Note that the geologic polygons typically extend to 1 km on either side of the fault traces, but in many places are broader to accommodate additional mapped surface features. B, Schematic diagram of the combination (or union) of geologic, surface-projection, and trace-buffer polygons to form the "total" polygon used in Uniform California Earthquake Rupture Forecast, Version 3 (UCERF3). The example fault dips at ~70˚, so the buffer polygon would extend to 6 km on either side of the fault trace. The dashed orange lines in the "total" polygon mark the subdivisions used to define polygons for the individual fault sections. C, Cross-sectional view of a fault showing how dip variations influence the widths of the trace buffer, the surface projection, and ultimately, the "total" fault polygon as used in UCERF3.

Bookkeeping

To facilitate the distribution of earthquake rates among faults and gridded seismicity sources, we implemented tools to compute the mapping between grid cells and fault-section polygons. That is, given an inversion solution, we need to know which cells a fault-section polygon intersects and in what proportion. Conversely, we need to know which fault-section polygons each cell intersects and in what proportion. The latter mapping is used only in pre-inversion setup.

The nomenclature used to describe these mappings is as follows. We index grid cells in i and fault sections in k and denote the fraction of a fault-section polygon in a cell as $p_{k\to i}$ and the fraction of a cell in a fault-section polygon as $p_{i\to k}$. In other words, given the area of intersection of a fault-section polygon and grid cell, $p_{k\to i}$ is that area divided by the total area of the fault-section polygon, and $p_{i\to k}$ is that area divided by the total area of the grid cell. The latter fractions, $p_{i\to k}$, are used only during the preinversion setup of some logic-tree branches to apportion grid-cell seismicity rates (derived from various models of smoothed seismicity) onto individual fault sections. In this case, those cells that are intersected by multiple, overlapping fault section polygons are problematic in that the sum of all $p_{i\to k}$ for a given ith cell may be greater than 1. To address this, $p_{i\to k}$ values are scaled to sum to the total fraction of the cell intersected by (or occupied by) fault-sections. For example, in the case where half a cell is spanned by a single fault section, $p_{i\to k}$ is 0.5. If, however, three overlapping sections individually span 60, 40, and 20 percent of a cell, and in aggregate the sections cover 60 percent of a cell, then $p_{i\to k}$ is scaled to 0.3, 0.2, and 0.1, respectively. As part of this bookkeeping, we also compute the total fraction of each cell that is occupied by fault sections, p_i.

Grid-source Magnitude Frequency Distributions

The total MFD of the source centered on each grid cell in the model is:

$$G_{\mathrm{T}}^{i}(m) = G_{\mathrm{S}}^{i}(m) + G_{\mathrm{U}}^{i}(m),$$

where $G_{\mathrm{S}}^{i}(m)$ and $G_{\mathrm{U}}^{i}(m)$ are the MFD of any subseismogenic ruptures and the MFD of unassociated events, for the ith grid cell, respectively. $G_{\mathrm{S}}^{i}(m)$ is computed as the sum of the subseismogenic MFD contributions of all fault-sections that intersect a cell:

$$G_{\mathrm{S}}^{i}(m) = \sum_{k\cap i} p_{k\to i} F_{\mathrm{S}}^{k}(m).$$

Here, the summation implied by $k \cap i$ is over all k fault-sections that intersect the ith grid cell; $p_{k\to i}$ is the fraction of each fault section in the cell, as previously defined; and $F_{S}^{k}(m)$ is the MFD of subseismogenic ruptures associated with the kth fault-section. $G_{\mathrm{U}}^{i}(m)$ is computed as the inversion-supplied total off-fault MFD, $T(m)$, scaled by the corresponding value for a cell from a spatial PDF of seismicity:

$$G_{U}^{i}(m) = \hat{P}_i T(m),$$

where $\hat{P}_i$ is a renormalized spatial PDF of seismicity. Although an inversion solution supplies the spatial PDF of seismicity used during setup, we do not want to apportion seismicity where it is already being accounted for by subseismogenic events associated with fault-sections (that is, $G_{\mathrm{S}}^{i}(m)$). This would amount to double counting. We, therefore, rescale the inversion-supplied spatial PDF of seismicity, P_i, to exclude the areas of each cell that are intersected by fault-section polygons:

$$\hat{P}_i = P_i(1 - p_i) / \sum P_i(1 - p_i).$$

Focal Mechanisms

UCERF3 gridded-seismicity sources currently adopt the UCERF2 and 2008 NSHMP method of assigning focal mechanisms to sources on a per region basis. Although there are data available in the form of much-improved focal-mechanism catalogs for California (Wang and others, 2009), and documentation describing possible implementations (Hiemer and others, 2013; Kagan and Jackson, 1994), the complexities associated with assigning uncertainties to focal-mechanism data (Kagan, 2007) preclude their inclusion in UCERF3 at this time.

References

Field, E.H., 2007, Overview of the working group for the development of regional earthquake likelihood models: Seismological Research Letters, v. 78, no. 1, p. 7–16.

Frankel, A.D., Mueller, C.S., Barnhard, T., Perkins, D.M., Leyendecker, E.V., Dickman, N., Hanson, S., and Hopper, M., 1996, National seismic-hazard maps—Documentation June 1996: U.S. Geological Survey Open-File Report 96–532, 71 p.

Frankel, A.D., Petersen, M.D., Mueller, C.S., Haller, K.M., Wheeler, R.L., Leyendecker, E.V., Wesson, R.L., Harmsen, S.C., Cramer, C.H., Perkins, D.M., and Rukstales, K.S., 2002, Documentation for the 2002 update of the national seismic hazard maps: U.S. Geological Survey Open-File Report, 02–420, 33 p.

Hiemer, S., Jackson, D.D., Wang, Q., Kagan, Y.Y., Woessner, J., Zechar, J.D., and Wiemer, S., 2013, A stochastic forecast of California earthquakes based on fault slip and smoothed seismicity: Bulletin of the Seismological Society of America, v. 103, p. 799–810.

Kagan, Y.Y., 2007, Simplified algorithms for calculating double-couple rotation: Geophysical Journal International, v. 171, p. 411–418.

Kagan, Y.Y., and Jackson, D.D., 1994, Long-term probabilistic forecasting of earthquakes: Journal of Geophysical Research, v. 99, no. B7, p. 13685–13700.

Petersen, M.D., Frankel, A.D., Harmsen, S.C., Mueller, C.S., Haller, K.M., Wheeler, R.L., Wesson, R.L., Zeng, Y., Boyd, O.S., Perkins, D.M., Luco, N., Field, E.H., Wills, C.J., and Rukstales, K.S., 2008, Documentation for the 2008 update of the United States national seismic hazard maps: U.S. Geological Survey Open-File Report 2008–1128, 61 p.

Wang, Q., Jackson, D.D., and Kagan, Y.Y., 2009, California earthquakes, 1800–2007—A unified catalog with moment magnitudes, uncertainties, and focal mechanisms: Seismological Research Letters, v. 80, no. 3, p. 446–457.