UCERF3 IMPLEMENTATION FOR A SITE-SPECIFIC PROBABILISTIC SEISMIC HAZARD ANALYSIS IN SOUTHERN CALIFORNIA

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ABSTRACT

The UCERF3 procedure represents a departure from the traditional approach of developing a seismic source model and then computing probabilities of exceedance, in that it begins with a set of seismic source characterizations with full variability and then performs a state-wide inversion to best fit observed data. This allows the UCERF3 model to incorporate multi-fault rupture scenarios while honoring observed seismicity, paleoseismic, geologic, and geodetic data; however, the computationally intensive inversion is impractical to reproduce and refine for site-specific applications. We present a methodology for implementing the UCERF3 seismic source model for site-specific PSHA. The proposed methodology allows for the incorporation of 1) local faults not included in the more regional UCERF3 model, 2) added epistemic branches in the UCERF3 fault characterizations based on local site-specific data, and 3) incorporation of near-source directivity effects in the PSHA. An application example is presented for a site-specific PSHA for the Sanitation Districts of Los Angeles County in Southern California. Additionally, our methodology has been used and reviewed on recent projects, including the Lawrence Livermore National Laboratory and Sisk Dam in California.

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The UCERF3 procedure represents a departure from the traditional approach of developing a seismic source model and then computing probabilities of exceedance, in that it begins with a set of seismic source characterizations with full variability and then performs a state-wide inversion to best fit observed data. This allows the UCERF3 model to incorporate multi-fault rupture scenarios while honoring observed seismicity, paleoseismic, geologic, and geodetic data; however, the computationally intensive inversion is impractical to reproduce and refine for site-specific applications. We present a methodology for implementing the UCERF3 seismic source model for site-specific PSHA. The proposed methodology allows for the incorporation of 1) local faults not included in the more regional UCERF3 model, 2) added epistemic branches in the UCERF3 fault characterizations based on local site-specific data, and 3) incorporation of near-source directivity effects in the PSHA. An application example is presented for a site-specific PSHA for the Sanitation Districts of Los Angeles County in Southern California. Additionally, our methodology has been used and reviewed on recent projects, including the Lawrence Livermore National Laboratory and Sisk Dam in California.

Introduction

The Uniform California Earthquake Rupture Forecast, Version 3 (UCERF3) time-independent seismic source model [1,2] represents a multi-year collaborative effort within the California scientific community to update the prior time-independent seismic hazard models (UCERF2 [3]).

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on a state-wide basis. Two primary achievements are included in this effort, namely to relax fault segmentation and multi-fault rupture limitations and characterize it in a quantitative way as part of the inversion process, while still honoring existing constraints of historic seismicity, paleoseismic, geologic, and geodetic data. The state-level model is achieved through a computationally intensive inversion approach, where annualized rates of individual ruptures are estimated and adjusted to fit rates and magnitude frequency distributions (MFD) of earthquakes for all on-fault and off-fault ruptures simultaneously, with the goal of best fitting the geodetic and geologic observations. This inversion approach provides aggregated mean MFD for each fault section. In conjunction with the fault geometry, the fault section MFD provides the fully integrated result of the UCERF3 logic tree for each fault section. The mean MFD incorporate all the epistemic and aleatory uncertainties in the UCERF3 model.

One limitation of the UCERF3 model is that it was achieved through a computationally intensive inversion approach, which is impractical to reproduce and refine for site-specific applications. Another limitation is that it was developed at a state-wide level, and as such may not include some less-active, but potentially significant seismic sources in the immediate proximity of a given site. We present a methodology for implementing the UCERF3 seismic source model for site-specific probabilistic seismic hazard analyses (PSHA) [4,5,6] with an example application for a site-specific PSHA for the Sanitation Districts of Los Angeles County in Southern California. Our proposed methodology uses UCERF3 model inputs for fault sources and key inversion outputs for magnitude recurrence. The proposed methodology allows for the incorporation of 1) local faults not included in the more regional UCERF3 model, 2) additional epistemic branches the UCERF3 fault characterizations based on local site-specific data, and 3) incorporation of near-source directivity effects in the PSHA. Our methodology has been used and reviewed on recent projects in Northern and Southern California.

**UCERF3 Overview**

The UCERF3 framework includes logic tree branches to represent epistemic uncertainty for the three major components of the overall seismic source model: 1) fault models, 2) deformation models, and 3) earthquake rate models. Fault models include the spatial geometry of the larger active faults in the region along with its associated epistemic uncertainties. UCERF3 includes two alternative fault models: Fault Model 3.1 (FM3.1) and Fault Model (FM3.2), which represent alternative representations of several fault groups. The deformation models provide estimates of fault slip rates based on historical seismicity, paleoseismicity, geologic, and geodetic data. The earthquake rate models define the long-term rate of all possible earthquake ruptures above a given magnitude threshold considering balance on-fault and off-fault deformation, segmentation, magnitude distributions on faults, and overall moment rate balances. The combination of all these models results in 1,440 different logic tree branches.

UCERF3 subdivides each fault section (~30-60 km) into subsections with lengths that are about half the seismogenic thickness (5-7 km), resulting in more than 2,600 total subsections for each fault model (FM3.1 and FM3.2). Ruptures are defined as a set of two or more contiguous fault subsections that passed certain criteria (e.g., all fault sections connect within 5 km or less [1]). This allows relaxed segmentation, as ruptures can extend across fault section boundaries. The final set included more than 250,000 and 300,000 ruptures for the FM3.1 and FM3.2,
respectively. For comparison, the total number of ruptures included in UCERF2 was less than 8,000.

Key results of the inversion approach include fault participation rate maps and nucleation and participation MFD. Fault participation rate maps are provided for each fault section and show the rate at which adjacent fault subsections participate in ruptures on the given fault section. Figure 1 shows the fault participation rate map for the Palos Verdes fault. The available nucleation and participation MFD are computed for each subsection and aggregated for each fault section, subregion, or for the entire region. Figure 2 shows the available participation MFD for the Palos Verdes fault.

Figure 1. Fault Participation Rate Map for the Palos Verdes Fault (FM3.1) (based on Field et al. [1]).

These results, along with rupture geometry data, are provided as fault system solutions. Available solutions include branch solutions for individual UCERF3 logic tree branches, branch-averaged solutions representing an approximate mean where individual fault model branches have been reduced to a single mean value, and “true mean” solutions that are similar to the branch-averaged solutions but retain all variability in the fault models.

Some limitations of the UCERF3 framework and results for use in site-specific probabilistic PSHA include:

1. The state-level model is achieved through a computationally intensive inversion approach, which is impractical to reproduce and refine for site-specific applications.

2. An MFD for a given fault section produced by the UCERF3 inversion procedure usually contains ruptures that participate in adjacent fault sections, therefore, most of the MFD cannot be used directly in a site-specific PSHA, as some ruptures would be double-counted.
3. The UCERF3 seismic source model was developed at a state-wide level, and as such, it does not include some less-active, but potentially significant seismic sources in the immediate proximity of a given site, nor does it have a refined level of detail for nearby faults.

![Participation MFD for the Palos Verdes Fault.](image)

**Figure 2.** Participation MFD for the Palos Verdes Fault.

### Application of UCERF3 to Site-Specific PSHA

Our goals for a site-specific implementation include the ability to accurately reproduce the results of UCERF3 down to very low annual probabilities of exceedance (10,000- or 100,000-year return periods), add new or modify existing local faults with associated accommodations for background seismicity, include near-source directivity and hanging wall effects, and have the ability to deaggregate seismic hazard results for magnitude, distance, and epsilon.

Most UCERF3 MFD for fault sections, or even fault subsections, cannot be used directly in site-specific PSHA, because they include multi-fault ruptures which would be double-counted in the PSHA if MFD were used without modification. Consider a scenario where a north-south trending strike slip fault passes near the site (this is termed the Control fault), with two additional north-south trending faults near the ends of the Control fault. The MFD for the Control fault includes magnitudes larger than the Control fault can support on its own, meaning that the Control fault participates in ruptures that pass through, or emanate from, the adjacent faults. For the site-specific PSHA, the rate of these larger magnitude should be retained in the MFD for the Control fault. Since these multi-fault ruptures occur simultaneously on the Control fault and the adjacent fault, the rate of these events must be removed from the MFD for the adjacent faults in order to avoid double counting. Biasi and Anderson [7] present a method to iteratively construct fault subsection MFD so that each rupture is attributed to the fault subsection closest to the site,
while we use fault section MFD, which include the aggregate rates for all subsections. The subsection rates generally have a low gradient from one end of a fault section to the other, and we have found that the impact of using fault section data is generally small, with some exceptions. The methodology outlined below is used to make the necessary adjustments to the fault section MFD.

**Methodology**

Multi-fault rupture scenarios, as illustrated in the fault participation maps (Figure 1), are used to identify Fault Systems, or groups of faults that participate together in larger magnitude, multi-fault ruptures. Fault Systems include a Control fault, which is usually, but not always, the fault closest to the site, and one or more Dependent fault sections. In addition, there are a limited number of Independent faults, or faults that do not participate in any multi-fault ruptures. For most site-specific PSHA applications in California, evaluation of the UCERF3 multi-fault rupture scenarios to identify Control and Dependent faults can be limited to sources within about 100 to 200 km of the site of interest.

The UCERF3 MFD for Control faults and Independent faults are used without modification. The MFD for Dependent faults are reduced by removing the rate of larger magnitude earthquakes that occur on the Control fault. Some Dependent fault sections may participate in ruptures in more than one Fault System and may need their MFD reduced more than once, and in some cases, a Control fault may have a reduced MFD because it is also a Dependent fault in a Fault System closer to the site.

Dependent fault MFD reductions are constrained by both the participation rate of the Dependent fault in the Control fault ruptures and by an independently calculated distance- and rupture area-dependent measure of magnitude. The independent magnitude measure for a Dependent fault, Mtd, is the magnitude calculated using UCERF3 magnitude-rupture area relations given an estimate of the fault area between the Control and Dependent faults. Mtd is an analog of the minimum magnitude at which the Dependent fault can participate in ruptures on the Control fault.

The MFD reduction algorithm subtracts rates from the Dependent fault from the largest magnitude (less than or equal to maximum magnitude on the Control fault) towards smaller magnitudes, until the total rate reduction matches the participation rate of the Dependent fault in Control fault ruptures. The magnitude at which the rate reduction matches the participation rate is termed Mtc. If the Mtc magnitude is consistent with the Mtd magnitude, this provides some validation for the reduction method.

For sites where there is a need to consider additional faults not included as UCERF3 fault models, proxy MFD are developed from other UCERF3 sources with similar epistemic fault model attributes of rate and style. The proxy MFD is scaled by the ratio of the seismic moment rate of the added fault and the proxy fault. Scaled MFD may be truncated, if appropriate, based on its judged potential for participation in multi-fault ruptures with adjacent faults.

At other sites, it may be desirable to consider additional or alternative epistemic branches
of the UCERF3 fault models that reflect local site-specific adjustments to geometries, rates, or style of faulting based on new or local site-specific data. These types of alternatives can be readily incorporated through similar modifications to the MFD and Background grid inputs.

The maximum magnitude (Mmax) is reduced for any Background grid points affected by the added or modified fault geometry, within fault buffers consistent with UCERF3 procedures [1], as larger Background earthquakes should be associated with the added or modified fault sources. The minimum magnitude of overlying fault buffers is used to truncate UCERF3 [1,2] Background grid MFD and cap UCERF2 [3] Background gridded maximum magnitude values.

The proposed methodology have been validated by comparing its results with the 2014 U.S. Geological Survey (USGS) National Seismic Hazard Mapping Project (NSHMP) [8] as presented in Altekruse et al. [5].

Limitations and Advantages

This methodology aggregates subsection participation rates for full fault section MFD, and in certain scenarios, this can under- or over-estimate hazard near the ends of the fault. This approach does not retain information about exactly where individual UCERF3 ruptures begin and end, but operating on fault sections may compensate for some of this loss of detail in how the resulting MFD can be used. The resulting adjusted fault section MFD can be applied to classic fault source geometries, so each rupture can be distributed along a single fault section. Though ruptures don’t cross fault section boundaries, hanging wall and directivity effects are generally still accurately modeled.

Application to a Site in Southern California

The Sanitation Districts of Los Angeles County are planning to add a third effluent outfall tunnel to the two existing tunnels transporting effluent from their Joint Water Pollution Control Plant (JWPCP) to the existing ocean outfalls. The JWPCP Effluent Outfall Tunnel is located within a seismically active geologic area of Southern California. In support of the tunnel design, a site-specific PSHA was conducted to develop seismic design recommendations for the project.

The UCERF3 source model was utilized to characterize most of the seismic sources incorporated for the PSHA, and provides a comprehensive database for regional seismic hazard assessments. However, several of the UCERF3 seismic sources within about 40 km of the project site were modified to more accurately depict the available mapping information, as well as to better constrain the closest approach of the surface trace to the project site. A brief description of some of these seismic sources and its implementation in the PSHA is presented below.

- **Palos Verdes fault.** The proposed tunnel alignment crosses the active Palos Verdes fault, and consequently, this fault represents the main seismic hazard contributor to the project facilities. In the UCERF3 fault characterization, the geometry of the Palos Verdes fault is simplified and depicted in the subsurface with a vertical dip along the entire length. For the PSHA, the UCERF3 fault geometry model of this fault was updated and refined based on local data to provide site-specific constraints for the Palos Verdes fault near the project.
facilities. However, the UCERF3 MFD was retained as the basis to define rates of earthquake occurrence on the Palos Verdes fault overall, and was applied to the updated geometry. A detailed description of the Palos Verdes fault is presented in Hogan et al. [9].

- **Cabrillo fault.** The proposed tunnel alignment also crosses the less active Cabrillo fault. The Cabrillo fault is not included in the UCERF3 source model, but it was added to the site-specific source model due to the proximity of this fault to the facilities and because of evidence suggesting late Quaternary and possible Holocene activity. The earthquake occurrence behavior of the Cabrillo fault is defined by a MFD derived from the UCERF3 Palos Verdes fault MFD, but scaled by the relative moment rate of the fault scenarios.

- **Compton fault.** For the site-specific seismic source model application of the Compton fault, in addition to the UCERF3 source characterization, an alternative characterization based on Brankman [10] was also included. In the alternative model, the geometry of the Compton structure is based on a more detailed mapping by Brankman [10] to provide better site-specific resolution of this fault relative to the project facilities. The rate characterization for both alternatives uses the MFD from the UCERF3 model.

As an example of the methodology described in the previous section, selected components of the Palos Verdes fault system will be discussed. Figure 3 shows a map of the surface traces of the faults in the Palos Verdes FM3.1 fault system. The red dot is the target site. The Palos Verdes fault, being closest to the site, is the control fault. The MFD for the adjacent faults include multi-fault rupture rates also included in the Palos Verdes fault MFD, by the UCERF3 fault linkage rules. The participation rates of adjacent faults in ruptures on the Palos Verdes fault are shown in Figure 1. Four faults in the Palos Verdes fault are considered in this example.

![Figure 3. Map of the Surface Traces of the FM3.1 Palos Verdes Fault System.](image)

Figure 2 shows the MFD for the Palos Verdes fault. In this application example, the UCERF3 MFD (supra-seismogenic) (blue line) is used. The other lines in this figure indicate the
UCERF2 MFD (red line), and UCERF3 MFD (sub-seismogenic) (green line). Sub-seismogenic seismicity is derived from seismicity in the vicinity of the fault, and is treated separately in UCERF3 as gridded seismicity. On Figure 2, the thicker lines are the means, and the thinner lines indicate minimum and maximum among all logic tree branches.

Because the Palos Verdes fault passes within a few kilometers of the site, its MFD could be used without modification, as it accounts for all multi-fault ruptures on this fault that will affect the site. However, the rates of multi-fault ruptures it shares with adjacent faults need to be reduced on adjacent participating faults in order to avoid double counting, and to correctly define the distances of earthquakes on the adjacent faults. Multi-fault ruptures that did not involve the Palos Verdes fault will remain on adjacent faults, as long as they are not reduced by other Control faults.

Figure 4 shows the reduced MFD for selected faults in the Palos Verdes fault system based on UCERF3 FM3.1, after applying the methodology described above. Because reductions on a group of adjacent faults are conducted simultaneously, different fault models (i.e., FM3.1 and FM3.2) will produce different MFD on adjacent, participating faults. This is the reason that a fault may have different reduced MFD for FM3.1 and FM3.2 when there is only one original MFD.

Figure 4. Reduced MFD for four faults in the Palos Verdes fault system: a) San Pedro Basin; b) San Pedro Escarpment; c) Redondo Canyon; and d) Malibu Coast faults.
Figure 4 shows the rate reductions for four selected faults in the Palos Verdes FM3.1 fault system. The San Pedro Basin MFD (Figure 4a) is reduced at larger magnitudes, and all events greater than magnitude 7.6 are removed because they are accounted for on the Palos Verdes fault. The San Pedro Escarpment MFD (Figure 4b) has all events between magnitude 7.7 and 7.8 removed (the red line is horizontal here), but retains events of magnitude 7.9 and greater because these are larger than any events that occur on the Palos Verdes fault. Similarly, the Redondo Canyon MFD (Figure 4c) has all ruptures removed from magnitude 7.3 to 7.8, and retains magnitude 7.9 events. The Malibu Coast MFD reductions are too small to discern in Figure 4d because it has a low rate of participation in ruptures on the Palos Verdes fault (Figures 1 and 3).

Conclusions

A methodology for implementing the UCERF3 seismic hazard model for site-specific PSHA has been presented. The proposed methodology allows for the incorporation of 1) local faults not included in the more regional UCERF3 model, 2) additional or refined epistemic branches in the UCERF3 fault characterizations based on site-specific data, and 3) incorporation of near-source directivity effects in the PSHA. The resulting MFD can be applied to individual faults using classical PSHA methodology, which allows for a computationally efficient calculation by including only the seismic sources that may potentially affect a given site (e.g., seismic sources within 100 km), as opposed to the entire state-wide source model.

An application example is presented for a site-specific PSHA for the Sanitation Districts of Los Angeles County in Southern California. In this site-specific study, the UCERF3 characterization of a nearby faults was updated based on local information and additional logic tree branches were considered to include alternative models. Additionally, local faults not included in the UCERF3 source model were considered in the site-specific PSHA. The methodology proposed herein has also been used and reviewed on recent projects, including the Lawrence Livermore National Laboratory [11] and Sisk Dam in California.

References


