SOUTHERN CALIFORNIA EARTHQUAKE CENTER
2014 Annual Report Summary

Title of Project:
ALLCAL – An Earthquake Simulator for UCERF3
Name of PI: Steven N. Ward
Institution: University of California, Santa Cruz

Abstract:

This proposal aims to step up from the existing ALLCAL2 fault system to one that represents the UCERF3 fault system as closely as possible and to compare earthquake simulator output with UCERF3 forecasts. The basic UCERF3 deformation model consists of down dip width, strike, dip, rake, geological slip rate and surface traces of 313 fault sections. As provided, the basic UCERF3 deformation model is not suitable for earthquake simulation. Certain assumptions have to be made to adapt UCERF3 for earthquake simulation. I call my product UCERF3-ES to differentiate the two sets (ES referring to Earthquake Simulator). The current UCERF3-ES for California is quite complex, including 25,586 elements in all. Progress during 2014 includes: (1) A sizable reduction in the outer loop time step and near elimination of multiple nucleations on entry to the inner loop. This reduces the importance of fault section continuity. (2) A new approach to fixing initial section strengths based on Magnitude-Area scaling laws. (3) The first statewide rupture forecast and seismic hazard calculation based on earthquake simulation.

Exemplary Figure:

Figure 5. UCERF3-ES Rupture Forecast. 30 year probability of experiencing a quake M>5.5 (left) and M>6.7 (right) per 0.1 x 0.1 degree cells. This format is identical to the recently released UCERF3 Rupture Forecast. I believe that these are the first rupture forecasts for all of California to derive from an earthquake simulator.

Technical Report: In following pages.

Publication:
(2015) "Seismic Slosh" A YouTube movie https://www.youtube.com/watch?v=-ztj-uw4_uo

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2014 Annual Technical Report
Title of Project: ALLCAL – An Earthquake Simulator for UCERF3
Name of PI: Steven N. Ward **Institution:** University of California, Santa Cruz

I. UCERF3 Fault System Adapted to ALLCAL: UCERF3-ES

Progress on this proposal in 2014 aimed to step up from the existing ALLCAL2 fault system to one that represents the UCERF3 fault system as closely as possible and to compare earthquake simulator output with UCERF3 forecasts.

The basic UCERF3 deformation model consists of down dip width, strike, dip, rake, geological slip rate and surface traces of 313 fault sections. Surface traces consist of two endpoints and perhaps several waypoints between. As provided, the basic UCERF3 deformation model is not suitable for earthquake simulation. Fact is, no unique way exists to adapt UCERF3 for earthquake simulation. Certain assumptions have to be made no matter who makes the leap. I call my product UCERF3-ES to differentiate the two sets (ES referring to Earthquake Simulator).

II. UCERF3-ES. What is involved?

Let me quickly step through my procedures that distinguish the basic UCERF3 deformation model and UCERF3-ES.

IIa. Fault Continuity

The first step in my procedure collects and combines those UCERF3 fault sections that can be reasonably assumed to be continuous. Several UCERF3 section endpoints share exactly the same latitude and longitude so there is little argument that these sections are parts of a continuous fault. Many other UCERF3 sections have endpoints that differ by just 10s or a few 100 meters. For these, I use my judgment to link certain section pairs as continuous. From the original 313 UCERF3 fault sections, I generate 256 continuous faults.

What is the difference if fault sections are called continuous or not? Fault segment continuity or element adjacency come to play in setting initial conditions and in interpreting products. For instance, in Step IIb, fault traces will be smoothed. Continuous sections are smoothed as a single

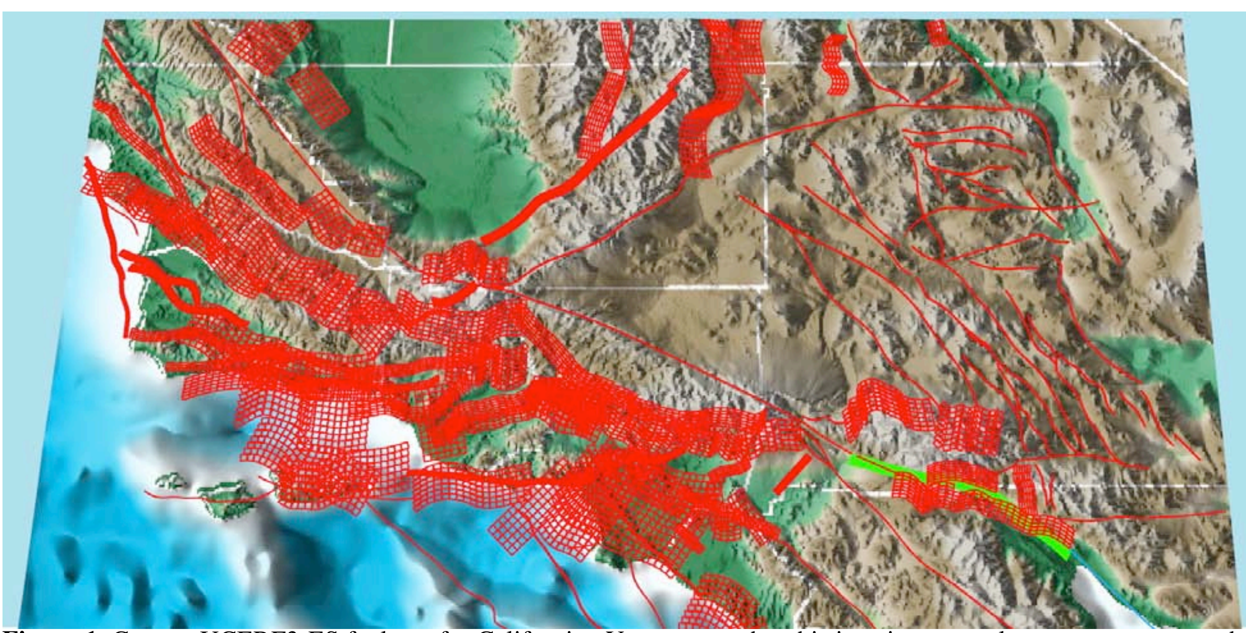

Figure 1. Current UCERF3-ES fault set for California. You can see that this is quite a complex system to run earthquake simulations. There are 25,586 elements in all.

entity whereas discontinuous sections are smoothed piecemeal. Likewise in Step IIf, slip rates will be smoothed and taper to zero at fault ends and bottoms. Continuous faults have fewer ends than stand alone ones. When counting earthquakes and assigning certain features like magnitude, area or length, it is necessary to assemble broken elements into discreet "ruptures" (see simultaneous nucleations, below). Fault segment continuity and element adjacency aid this determination.

IIb. Fault Trace Smoothing
Once the sections are grouped into continuous faults, I fit a smooth curve through the traces, fault by fault. The smooth curves may jump in position and azimuth at gaps between nearby faults, but not between sections of continuous faults.

IIc. Fault Trace Sampling – Along Strike Element Length
Once the fault traces are smoothed, they are sampled at uniform intervals along strike. Each interval will become a fault "element". Fault elements are much smaller than fault sections. The current version of UCERF3-ES employs a 3 km length spacing producing 5286 elements along strike.

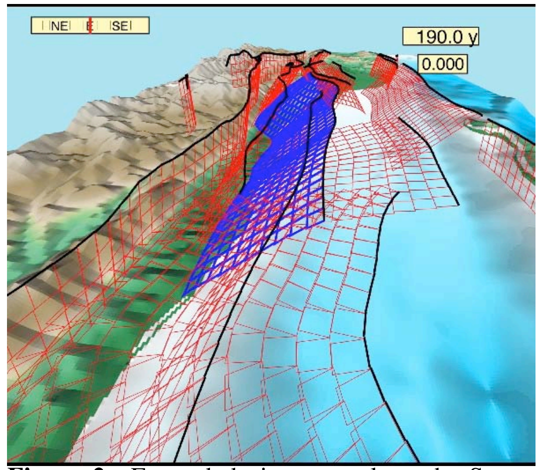

Figure 2. Expanded view east along the Santa Barbara Channel showing details of UCERF3-ES. For very curved faults, mean strike scaling sacrifices element corner continuity to reduce rips, tears and overlaps. The blue elements form the new Ventura-Pitas Point fault that is thought to generate M8 quakes.

IId. Fault Width Sampling – Down Dip Element Width
The chosen value of down dip width for each element, need not be the same as element length. UCERF3 gives a down dip width for each fault section, say 13 km. The simulator needs an integer number of elements down dip. You can either fix element width to match the section width exactly, or fix element width and select the nearest integer number of elements to match section width as closely as possible. In the current version I use the latter approach and fix element width to 3 km. Fixing element width and element length, establishes the total number of elements. The current UCERF3-ES includes 25,586 elements (Figure 1).

IIe. Down Dip Element Positions - Mean Strike Scaling.
The simulator requires the latitude, longitude and depth of the four corners of every element. Fault Trace Sampling returns only the elements along the surface trace. The basic UCERF3 deformation model gives a constant dip for each fault section. I have developed a method called "mean strike scaling" that distributes elements down dip in such a way as to minimize rips, tears and overlaps. As a price for this improvement, the corners of one element no longer coincide with the corners of "adjacent" elements (see Figure 2). This is not a big problem however, because the simulator evaluates stresses and displacements at the center of each element, not at the edges (See Bad Element Pairs below).

IIf. Slip Rate Smoothing
Earthquake simulators require a geological slip rate per element applied indirectly through 'backslip stressing'. The basic UCERF3 deformation model supplies a geological slip rate constant per fault section. UCERF3-ES smooths these rates both along strike and down dip such that slip tapers to zero at fault bottoms and along strike at the ends of continuous faults.

IIg. Bad Element Pairs. The heart of earthquake simulations is the interaction matrix, R_{ij}. R_{ij} tabulates the Coulomb stress change at the center the i-th element from unit slip on the j-th element. Generally

$$|R_{ii}| > |R_{ij}| \qquad (1)$$

that is, the stress change from unit slip on the element itself (self-stress) should be greater than the stress change from unit slip on any other element (interaction stress). This is usually so, however in complex fault systems like Figure 2, the edge of one fault element may fall near the center of another. Stress changes near element edges can violate (1) and lead to instabilities in the inversion for slip. After generating R_{ij}, I zero any R_{ij} if (1) is not satisfied.

IIh. Assigning Strength/Tuning

Earthquake simulators track stresses on the fault elements resulting from the sum of tectonic loading, self-stress and interaction stress. When stress exceeds "strength" earthquakes happen. Thus, the "strength" of each element has to be specified. Assigning strength appears like a "black box" to those unfamiliar with simulators, so it is worth reviewing the current process. Initially, the 313 sections are assigned strength based on scaling relations. Given the section area, first a characteristic magnitude, then a characteristic uniform slip can fixed from a magnitude versus area scaling relation. The simulator knows how to calculate a uniform stress drop over the whole section needed to generate the given characteristic slip at the section center. That stress drop value is the starting value for segment strength.

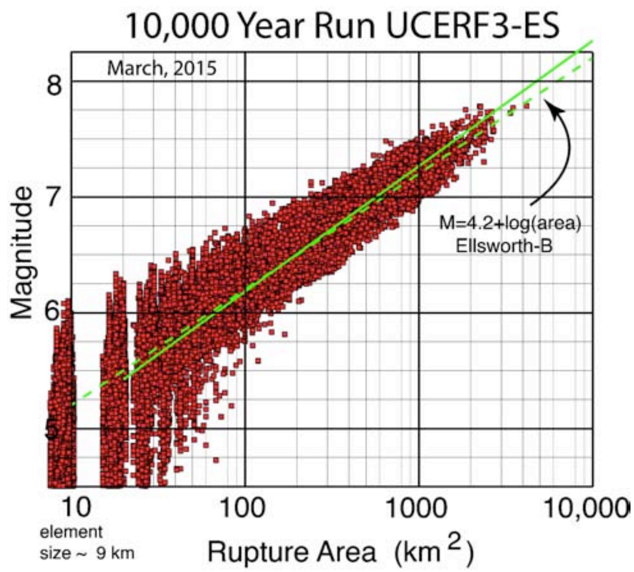

Figure 3. UCERF3-ES Earthquake Scaling Behavior. Dashed green line is Ellsworth-B. Solid green line is linear fit to all synthetic quakes A>20 km^2.

Now, by and large, this strength value is too small because the vast majority of earthquakes in the simulator are not complete stress drop events. Incomplete stress drops happen for two reasons-- (1) Typically fault sections do not fill completely with stress prior to failure. Most often, small parts of the section reach failure prior to others. These patches nucleate "early" rupture. (2) The velocity dependent friction law in ALLCAL allows for healing during rupture. If strength is regained for parts of broken faults during rupture, those parts can be re-loaded, reducing the total stress lost. The outshot of incomplete stress drop is that you first calculate characteristic magnitude by the scaling law and then "add some". I add 0.1 to 0.3 magnitude unit, possibly depending on section area. Figure 3 shows Magnitude versus Area for a recent run of UCERF-ES. The fit (solid green line) is nearly identical to Ellsworth-B (dashed green line), but of course I adjusted the "add some" value to make it so.

Further tuning involves running the simulator for ~10,000 years, tabulating observed versus calculated recurrence intervals for those faults where recurrence information exists, and making small "add some" adjustments. I see no need to go deeply into this aspect of tuning here.

III. UCERF3-ES 2014 Results

The UCERF-ES simulator generates dynamic ruptures from magnitude 8+ down to about magnitude 3, so a 10,000 year run produces perhaps 1,000,000 events. Please view a recent (March, 2015) 1000 year snip at: http://es.ucsc.edu/~ward/UCERF3-1000y.mov . Every one of the thousands of flashes in this movie is an expanding 3-D dynamic rupture. Another movie "flies over" California quakes: http://es.ucsc.edu/~ward/ucerf3-es-map-flyover.mov . The latter movie highlights the complexity of the fault system as well as improvements in graphic style. I put a lot of stock in graphic presentations of science.

Lately, I have been publishing short YouTube science movies of various simulations (http://www.youtube.com/user/ingomar200). The latest earthquake-related movie (March, 2015) is called "Seismic Slosh" see… https://www.youtube.com/watch?v=-ztj-uw4_uo Construction of these movies aligns perfectly with SCEC's mission to broaden the scope of Education and Outreach.

Time Stepping/ Simultaneous Nucleations and Triggered Events.

The "outer loop" of earthquake simulators steps interseismic time interval dt and searches for newly broken elements. If there are any, the simulator jumps to a more detailed "inner loop" to play out the coseismic rupture. To avoid nucleating widely separate parts of the fault system and having to untangle multiple ruptures, it is best that dt be taken very small so that no more than one nucleation occurs per step dt. If there are no elements close to failure from the previous step, a small dt works fine because nothing is slipping and no CPU is spent running the clock forward another dt. On the other hand, if any fault elements constantly remain near failure, a lot of CPU is wasted in generating tiny "creep-like quakes". Earlier versions of ALLCAL left many elements near failure so the interseismic dt had to be several weeks to keep a 10,000 year run manageable in duration. This was a problem because a large dt produced many simultaneous nucleations in passing to the inner loop. Improvements in 2014 however, eliminated most elements that had been 'hanging out' near failure. The interseismic time step dt is now reduced from a couple weeks to about four hours without increase in CPU. Simultaneous, widely-spaced, nucleations are nearly eliminated at this smaller dt, but there are still un resolved issues. Even with a single nucleation on entry to the inner loop, additional nucleations can occur as co-seismic slip plays out. These "triggered events" are induced by co-seismic stress changes. Some triggered events are isolated patches of slip separated by either unbroken elements of the same fault or by gaps between different faults or fault sections. Triggered events cause issue not in the calculation, but in the tabulation. Specifically, should isolated triggered events be considered separate quakes or should they somehow be grouped with their parent? This question remains unresolved. Figure 4 shows earthquake rate versus magnitude for a single 10,000 UCERF3-ES run. The red dots count all isolated triggered events as separate. The blue dots do not count triggered events at all. Co-seismically triggered events contribute nearly 20% of the total moment so ignoring them is not an option, but how to count them? Certainly some isolated ruptures (those that jump fault gaps, for example) ought to be grouped into single event while other isolated ruptures (those quite distant, for example), should be counted separately. The difficulty in identifying continuous faults (Step IIa above) and continuous ruptures is lessened in using a small dt but the issue still remains. Lumping all elements triggered co-seismically into one quake is one option, but not a satisfying one. Possibly further "tweaks" to ALLCAL's friction law may mitigate this problem.

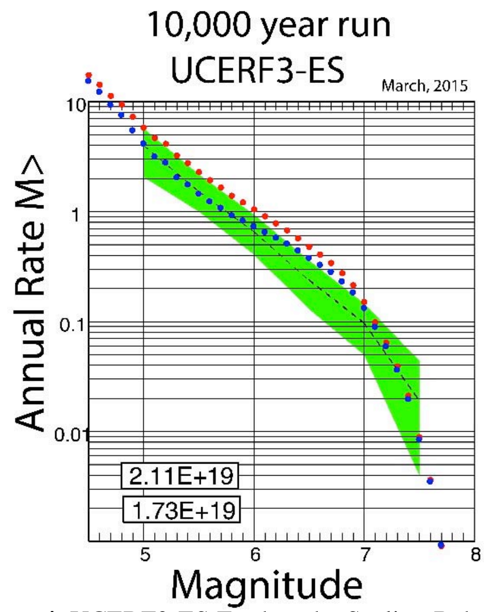

Figure 4. UCERF3-ES Earthquake Scaling Behavior. Red dots include all isolated, triggered events. Blue dots exclude them.

Earthquake Potential Maps.

New results for 2014 include UCERF3-ES earthquake potential maps. UCERF calls these "Rupture Forecasts" and they are the main product of that group. In Figure 5, I plot UCERF3-ES rupture forecast in the same format as the newly released UCERF3 maps; namely, the 30 year probability of experiencing a M<5.5 (left) and M>6.7 (right) quake averaged over 0.1 by 0.1 degree cells. In the future, these maps could be compared quantitatively with UCERF3 to see

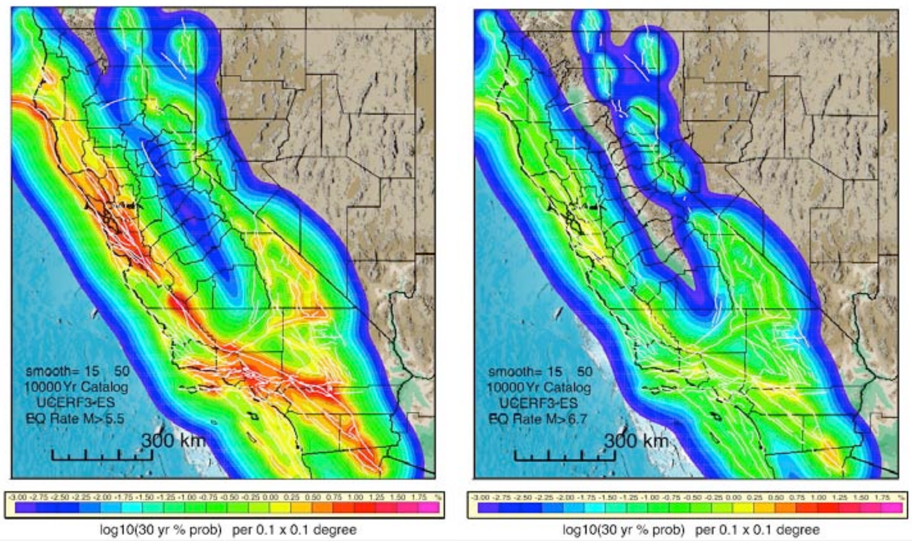

Figure 5. UCERF3-ES Rupture Forecast. 30 year probability of experiencing a quake M>5.5 (left) and M>6.7 (right) per 0.1 x 0.1 degree cells. This format is identical to the recently released UCERF3 Rupture Forecast.

where similarities and differences arise. I believe that the panels of Figure 5 are the first rupture forecasts for all of California to derive from an earthquake simulator.

Unlike UCERF3, UCERF3-ES includes no 'background' or off-fault seismicity, so turning fault-based forecasts to grid-based forecasts requires smoothing. The maps in Figure 5 smooth on-fault seismicity over 15 km and 50 km windows weighted 80% and 20% respectively. Naturally if smoothing is reduced, the faults get redder at the expense of bluing nearby locations. Even with background seismicity, UCERF3 also smooths on-fault seismicity to adjacent grid points so it too has equivalent tradeoffs.

Earthquake Hazard Maps.

In 2014 we have taken a step beyond Rupture Forecasts, to Hazard Forecasts themselves. Hazard forecasts are beyond UCERF purview, but there is nothing keeping us from jumping in. Figure 6 shows the 30 year probability of exceeding 10% g PGA based on 10,000 year earthquake simulator output of UCERF3-ES. The shaking attenuation relation (Joyner-Boore) replaces the smoothing step above to transform a fault-based forecast to a grid-based one.

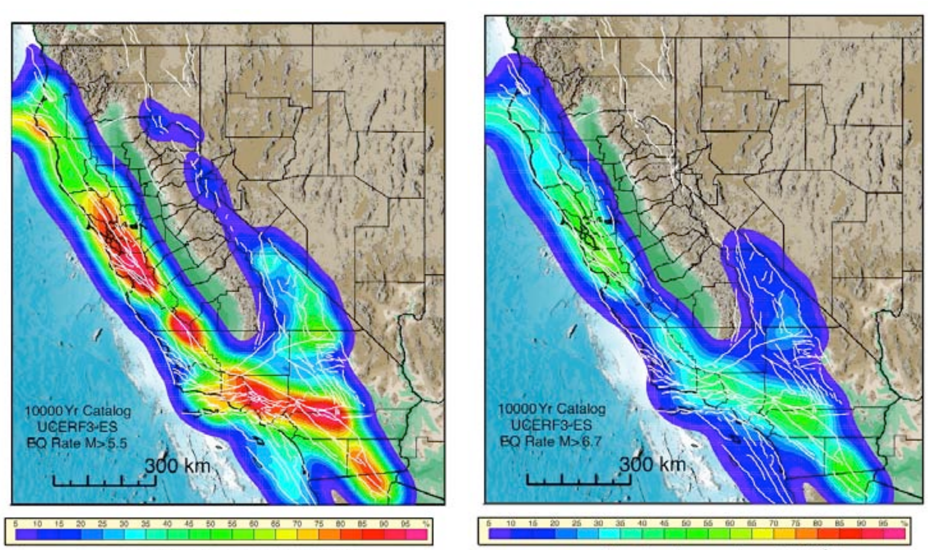

Figure 6. UCERF3-ES Hazard Forecast. These maps show the probability of exceeding 10% g acceleration in 30 years for M>5.5 (left) and M>6.7 (right). To my knowledge these are the first hazard maps for all of California based on earthquake simulators.

IV. Project Vision

The primary objective of this research is to continue to generate and tune versions of UCERF3-ES and evaluate its outputs. I hope that the existence of a credible simulator generating earthquakes on a UCERF3 fault system will build acceptance for, and lay groundwork to, an expanded role for simulators in UCERF4 as called for in SCEC's 2015 RFP.