Annual Report, 2008

SOUTHERN CALIFORNIA EARTHQUAKE CENTER

Title of Project: Geodetic Inputs to Seismic Hazard Estimation

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I. Geodesy's Roles in California Earthquake Hazard

This project aims to develop fresh approaches and applications of geodetic data in earthquake hazard estimation. In my view, geodetic data plays two roles in quantifying earthquake hazards. The first are *Stand-Alone Approaches* where geodetic interseismic site velocities are first turned into strain rates, then strain rates turned into moment rates, then finally moment rates turned into earthquake rates. (A new *Stand-Alone* Approach developed in 2008 is described below.) The second role includes *Combined Approaches* where geodetic data is merged with fault systems and earthquake simulators to make improved hazard estimates. Elements of *Stand-Alone Approaches* may be included in the *Combined Approaches*, so the methods go hand-in-hand.

II. Geodetic Hazard - Original Stand-Alone Approach-

The original *Stand-Alone Approach* to geodetic earthquake potential has been described by us several times. In 2008, this SCEC-developed approach has been newly applied to Europe. I show these new products in Figures 1 and 2.

(1) Compile interseismic velocities for using available GPS sites (Figure 1, left).

(2) Invert GPS horizontal site velocities into *maximum geodetic strain rate*

$$\dot{\varepsilon}_{max} = \max[|\dot{\lambda}_1|, |\dot{\lambda}_2|] \quad (1)$$

using a variable-sized smoothing window taking care to remove rotations (Figure 1, right). $\dot{\varepsilon}_{max}$ is the largest eigenvalue ($\dot{\lambda}_1$ or $\dot{\lambda}_2$ in absolute value) of the horizontal strain rate tensor.

(3) Translate the maximum geodetic strain rate into *geodetic moment rate density*

$$\dot{M}_{geodetic}(\mathbf{r}) = 2\mu H_s \dot{\varepsilon}_{max} \quad (2)$$

using Kostrov's formula per unit area and maps of seismogenic thickness, H_s.

(4) Finally, moment rate density becomes *earthquake rate density* (or earthquake potential) under the assumption that (2) distributes into earthquake sizes that follow a truncated

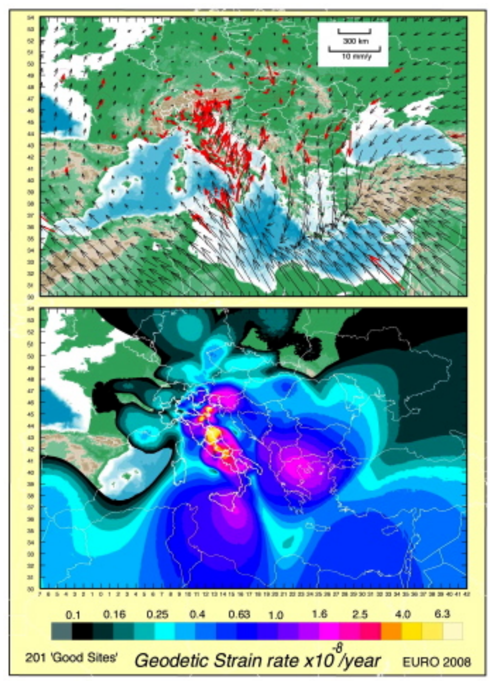

Figure 1. (*Top*) GPS geodetic sites in Europe (red arrows) and interpolated velocity field (dark arrows). (*Bottom*) Original *Stand-Alone* map of strain rate inverted from horizontal site velocities. New for 2008.

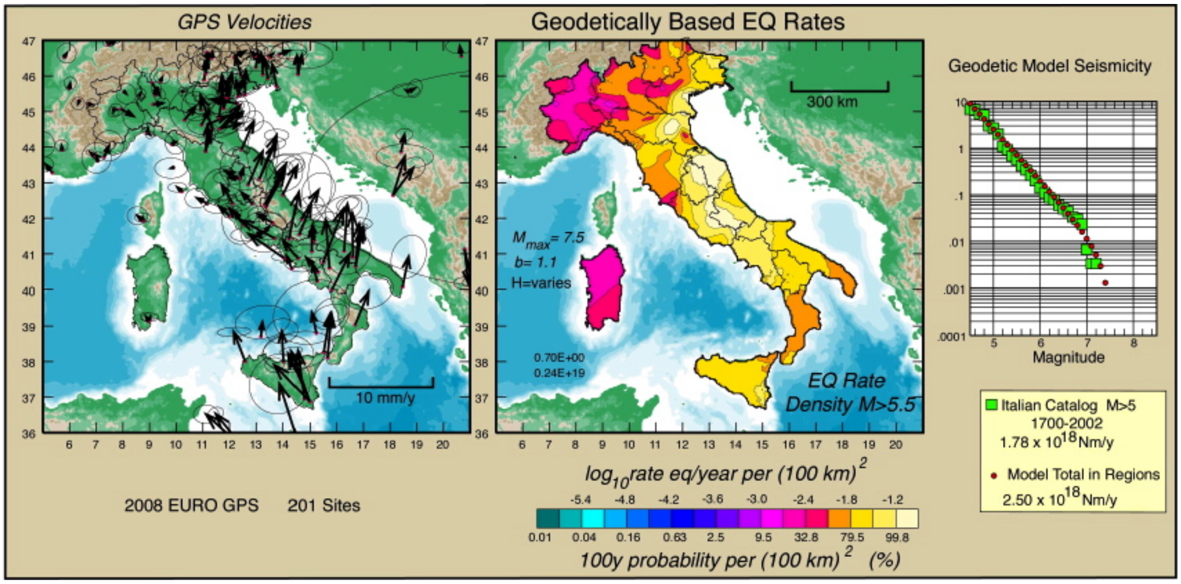

Figure 2. Original *Stand-alone* geodetic earthquake potential models for $M_{>}$=5. assuming b=-1.1 and M_{max}=7.5 (*right*) derived from the European GPS data set (*left*). New for 2008.

Gutenberg-Richter distribution of given b-value and M_{max}.

Figure 2 (*center*) maps geodetic earthquake potential as $\log_{10}$ rate of events per year M>5 predicted in 100 km by 100 km boxes around each location. Grid-based earthquake potential maps like these represent a general means to formulate earthquake hazard. Figure 2 (far right) plots the total rate of Italian seismicity predicted from the geodetic models (red lines) and compares them with observed seismicity (green squares). In *Stand-Alone* earthquake potential models, geodetic moment rate is conserved rather than earthquake rates, so the selection of M_{max} plays strongly into earthquake rates. If M_{max}=7.5, the earthquake rates predicted by geodesy fit the observed rates over the entire magnitude range.

II. Geodetic Hazard - New Stand-Alone Approach.

As a bridge to a *Combined Approach*, a new geodetic *Stand-Alone Approach* was developed this year. The new approach for California runs as follows:

(1) Compile interseismic GPS velocities.

(2) Augment these with virtual GPS sites offshore that are assumed to move at Pacific Plate velocity (Figure 3a).

(3) Take a "scoop" of Planet Earth containing California and tile the floor and walls of the scoop with dislocations (Figure 3b).

(4) Adjust the direction and strength of the slip on the dislocation tiles $\mathbf{u}_{\mathbf{tiles}}$ to adequately reproduce the measured GPS velocities at the surface sites $\mathbf{v}_{gps}$ by solving

$$\mathbf{v}_{gps} = \mathbf{V}\mathbf{u}_{tiles}^{geod} \quad (4)$$

where V_{ij} is the *i*-th component of one of the gps site velocities due to the *j*-th unit slip component on one of the tiles. These motions (Figure 3c) form the geodetic interseismic velocity field.

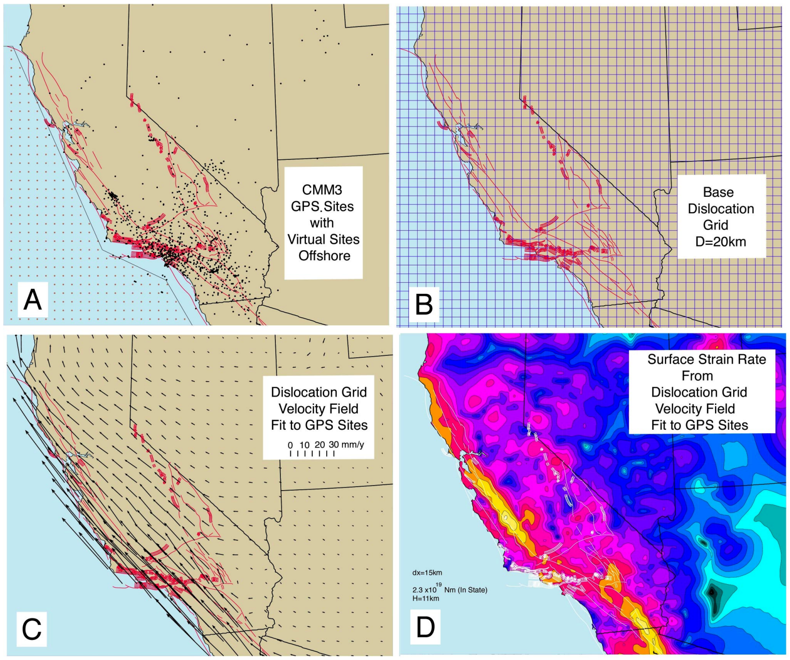

Figure 3. New *Stand-Alone* approach to Geodetic Hazard. (A) Combine observed (onshore) and virtual (offshore) GPS data. (B) Isolate the entire field volume ('scoop') with buried dislocations. (C) Find slips on those dislocation tiles to match the GPS velocities at the given sites. (D) Use the analytical forms for velocity, stress, and strain to estimate geodetic hazards and fault slip rates.

The advantage of the new approach over the original approach is that now, the continuous deformation field within the "scoop" obeys the static equations of elasticity and produces no shear stress at the Earth's surface. Moreover all 3 components of velocity and 6 components of strain and stress are known analytically, not just at the surface, but at all depths within the Earth. The new approach offers huge advantage in that with $\mathbf{u}^{geod}_{tiles}$ known from (4), we can evaluate, geodetically-based 3-D Coulomb stressing rates $\mathbf{\Sigma}_{geod}$ ON SPECIFIC FAULTS AT DEPTH by

$$\Sigma_{geod} = \mathbf{R}_{tiles}\mathbf{u}^{geod}_{tiles} \quad (5)$$

where $(R_{tiles})_{ij}$ is the Coulomb stress rate on *i*-th fault element due to the *j*-th unit slip component on one of the tiles. Equation (5) is crucial in merging geodesy with fault systems and earthquake simulators. Figure 3d shows *maximum geodetic strain rate* (equation 1) obtained from the interseismic velocity field (Figure 3c). The strain rates in Figure 3d can be compared to those in Figure 1 and of course, the new strain rates can be turned into *Stand-Alone* earthquake density maps like Figure 2.

III. Geodetic Hazard - Combined Approach with an Earthquake Simulator

Earthquake simulators like ALLCAL are gaining acceptance as viable methods to estimate earthquake hazards on the fault system of California (Figure 4). The current ALLCAL procedures however, are only interested in earthquakes on the faults, so the off fault deformations are not relevant. The *new ALLCAL procedures* concerns themselves with off fault deformations in a *Combined Approach*. Geodesy has two roles in the *Combined Approach*. Geodesy's first role is to help constrain the slip rate ON THE FAULTS. Geodesy's second role is to constrain the seismic hazard OFF THE FAULTS. Off fault hazard cannot be addressed by the simulator so it needs input from geodesy.

Winding the Machine. One issue in all earthquake simulators is: How does one "wind-up" an earthquake machine in a self-consistent, physically plausible manner such that the faults keep

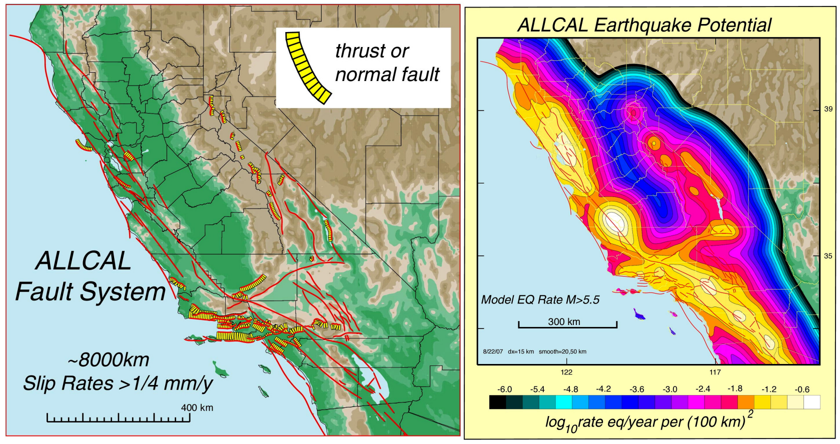

Figure 4. Earthquake potential (right) derived directly from the ALLCAL earthquake simulator (*left*). In the simulator, earthquakes occur only on the specified faults. Earthquake hazard and potential have been windowed off fault. Instead, geodetic information be used to fill in off fault hazard.

pace with their estimated geological speed? The *current ALLCAL procedures* for fixing the driving stresses first moves all *j* fault elements forward by their stated geological slip rate u_j; then it computes the induced Coulomb stress rate Σ_i on the *i*-th fault element from self-slip ($R_{ii}u_I$) and slip on all other elements ($R_{ij}u_j$) by

$$\Sigma_{geol} = -\mathbf{R}\mathbf{u}_{geol} \quad (6)$$

An applied interseismic stressing rate $\mathbf{\Sigma}_{geol}$ enables each fault element to move at its geological rate (averaged over time) and lets the machine keep making earthquakes. Equation (6) is called the backslip method and it assumes that long term slip rates are well known from geology -- a sizable assumption for some faults.

As I see it, Role 1 for geodesy in a *Combined Approach* lay in joint inversions of geodetic site velocities together with geologically constrained fault stressing rates ($\mathbf{\Sigma}_{geol}$) such that both geodesy and geology have a say in fixing fault slip rates. As discussed in Section II, new methods make it possible to compute a geodetically-based Coulomb stressing rate $\mathbf{\Sigma}_{geod}$ at depth on all of ALLCAL's fault elements through equation (5). Thus, a purely geodetically-based estimate of the slip rate <u>on all the system faults</u> is found immediately from

$$-\mathbf{R}^{-1}\Sigma_{geod} = -\mathbf{R}^{-1}\mathbf{R}_{tiles}\mathbf{u}_{tiles}^{geod} = \mathbf{u}_{geod} \quad (7)$$

In words, $\mathbf{u}_{\mathrm{geod}}$ is that set of slip rates that removes the Coulomb stress generated by the interseismic geodetic velocity on all of the system faults. Unlike fault-by-fault inversions for geodetic slip rates, all fault interactions are included in (7). Figure 5 plots driving stress rates $\mathbf{\Sigma}_{\mathrm{geol}}$ and $\mathbf{\Sigma}_{\mathrm{geod}}$ (*top*) and fault slip rates $\mathbf{u}_{\mathrm{geod}}$ and $\mathbf{u}_{\mathrm{geol}}$ (*bottom*) for 8000km of ALLCAL's faults. There are many differences in geological $\mathbf{u}_{\mathrm{geod}}$ and geodetic $\mathbf{u}_{\mathrm{geol}}$ slip rates that are worthy of discussion in their own right, but the goal is not to determine whether geological or geodetic slip rates are better, but rather formulate a joint inversion for the driving deformations $\mathbf{u}_{tiles}^{joint}$

$$\begin{bmatrix} \mathbf{V} \\ -\mathbf{R}^{-1}\mathbf{R}_{tiles} \end{bmatrix} \mathbf{u}_{tiles}^{joint} = \begin{bmatrix} \mathbf{v}_{gps} \\ \mathbf{u}_{geol} \end{bmatrix} \quad (8)$$

such that both GPS velocities $\mathbf{v}_{\mathrm{gps}}$ and geological fault slip rate information $\mathbf{u}_{\mathrm{geol}}$ are adequately represented. I think that it is remarkable that information as distinct as GPS site velocities and geological fault slip rates can be quantitatively joined, through physical models, into a single equation (8).

Role 2 for geodesy in a *Combined Approach*. What we are doing now is to use the simulator to estimate earthquake hazard ON the faults and geodetic strains to estimate hazard OFF the faults. As discussed in Section II, *Stand-Alone* Approaches take the interseismic strain field, then finds moments, then earthquake potential and hazard. Simple enough, but we can not just add the *Stand-Alone* geodetic earthquake potential (Figure 2) to the ALLCAL earthquake potential (Figure 4b) for two reasons:

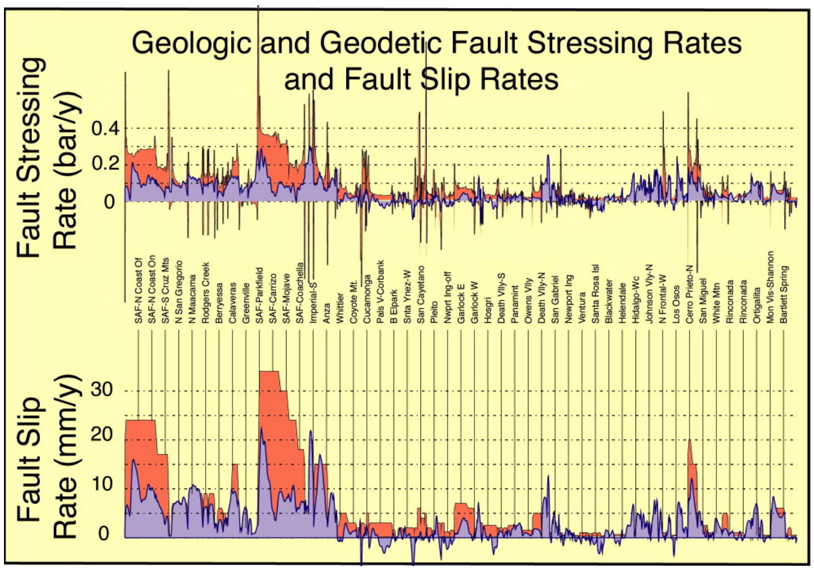

Figure 5. Fault stressing rate (*top*) and long term slip rates (*bottom*) determined by geology (red) and geodesy (purple). Comparing $\mathbf{u}_{geod}$ and $\mathbf{u}_{geol}$ speaks to the discussion question posed at the 2008 SCEC Meeting, *"Are geologic/geodetic rate discrepancies important for earthquake forcasting?"* New for 2008.

(1) The patterns of interseismic strains in *Stand-Alone* Approaches are temporary and will be shed back onto faults during quakes;

(2) You would be "double counting" earthquake potential in that quakes produced from strains shed back onto faults are already included in the simulator. What we want to find and add to the simulator are the "residual" or "geologic" strains and their earthquake potential off the faults. Coseismic + Interseismic = Geologic has been a basic concept in the interpretation of the earthquake cycle since Lawson's time. In 'vertical cut-in-halfspace' models of the 1960's and 1970's the combination of Coseismic +Interseismic left nothing but a step offset in displacement at the cut. In the 2-D concept, no geologic or residual strains accumulate in the Earth through an earthquake cycle. In complex 3-D fault systems this is not so. The geologic deformation field does have step offsets at faults, but also significant residual strains off fault. These Geologic strains are presumably released on faults not included in the simulator. So, for geodesy's Role 2 in a *Combined Approach* we construct a Geologic deformation field by summing Coseismic and Interseimic fields, compute earthquake potential/hazard; then and ADD this to the earthquake potential/hazard calculated on the faults by the simulator. Now we still must be careful not to double count strains. Because the Geologic deformation field is discontinuous across faults, it will generate large strains there. Earthquake potential from near-fault strain is already included in ALLCAL, so after calculating earthquake potential from the Geological strains we "window-out" any potential atop the faults. The window-out would be one minus the window-in used to smooth the ALLCAL earthquake potential off the faults.