Annual Report, 2005
SOUTHERN CALIFORNIA EARTHQUAKE CENTER

Title of Project:
Collaborative Research: Paleoseismic Constraints on Earthquake Simulation Models of Southern California:

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I. Southern California Earthquake Simulator - Physics Based.

In 2005, we continued to develop a physics based earthquake simulator that produces spontaneous, dynamic rupture on geographically correct and complex system of interacting faults. While the simulator admits several compromises, it has been designed to reproduce and incorporate behaviors that geologists measure such as slip rate, slip per event and recurrence interval. The prototype serves as tangible evidence that realistic earthquake simulations can be constructed even now. The primary product of earthquake simulators is a long series of earthquakes. This simulator generates dynamic ruptures from magnitude 8+ down to about magnitude 3, so a 2000 year run produces ~10,000 events spread from Mexico to Parkfield, and from San Clemente Island to Nevada. Figure 1 shows a few frames of a recent run. We encourage readers to view the movie at:

http://es.ucsc.edu/~ward/simulation9_pga.mov

Our simulations provide all details of every rupture. Computed surface offsets along strike are especially telling because the purest paleoseismic

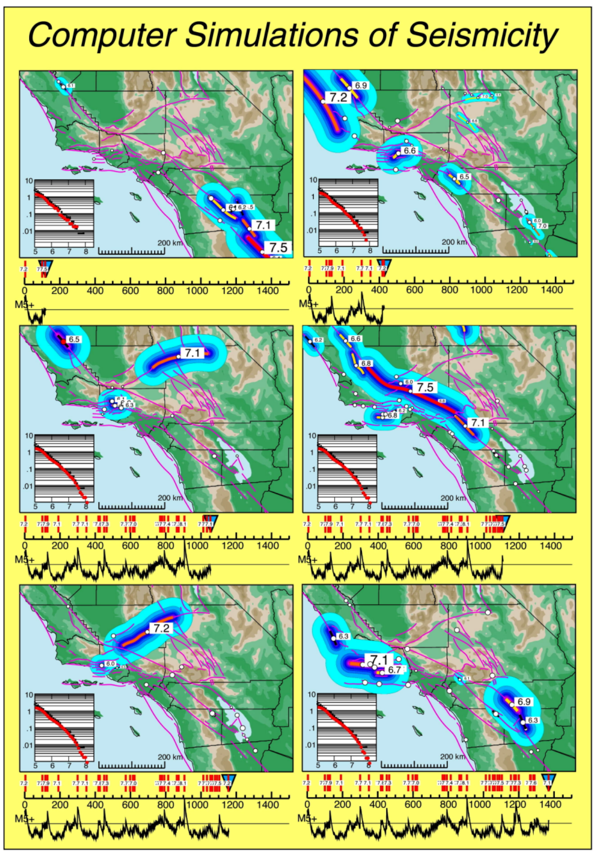

Figure 1.

Figure 1. Six frames of animation from a recent run of the earthquake simulator. The animation shows a 1500 year earthquake sequence. The movie plots all earthquakes M>5. For events M>6, PGA is contoured around the rupture and a magnitude number is shown. To the left is a graph of the cumulative number of M5+ quakes (red dots) overlaid on the actual rates (black dots) from 1850-2002. The simulator now involves a wide enough selection of faults such that bulk seismicity is Gutenberg-Richter like, with a b value near 0.9. Along the bottom is a sliding time indicator that deposits red bars at the occurrence of M>7 events. The residual "bar code" pattern gives some feeling for the periodicity or aperiodicity of major quakes. The jagged line along the bottom is the 25 year average rate of M5+ events.

data are earthquake dates and earthquake slip measured at a point -- the paleoseismic site. Geologists can locate their site on these maps and compare predicted slip per event and its variation directly. Over long periods, the slip for all quakes always sums to the specified slip rate of the fault. The agreement of the predicted long-term seismic offset with measured geologic slip rate is a fundamental feature of this simulator. We tune the simulator by adjusting fault strengths such that computed earthquake recurrence intervals versus magnitude roughly correspond to observed intervals to the extent that paleoseismologists know them as cataloged in the SERT below.

II. Paleoseismic Constraints -The SERT

This year we [Lisa Grant, Tom Rockwell] continued to assemble a data product called the *Simplified Earthquake Recurrence Table.* The SERT represents a simplified working consensus on recurrence interval versus magnitude for the faults of Southern California for comparison with earthquake simulators. The SERT data constrain earthquake simulators in two ways: 1) through input of measured *slip rates,* and 2) by comparison of computed *recurrence interval* and *slip per event* with actual field measurements. The current SERT has recurrence estimates for 59 of 101 faults (Table 1). A crucial aspect of the SERT is "Recurrence of What? A recurrence interval itself is of no use unless it is referred to a given size quake. The SERT attempts to list recurrence interval in years for any of M6+, M6.5+, M7+ and M7.5+ earthquakes breaking various faults and fault segments. True, such an effort can be uncertain business given what little we know about many of the faults, but the SERT is precisely what is needed to calibrate/validate physical earthquake simulators.

SERT2005.11

Fault	M6+	M6.5+	M7+	M7.5+	Slip Rate
A7 SAF-Creeping					0
A8 SAF-Parkfield	<	25			34
A9 SAF-Cholame	<	<	230		34
A10 SAF-Carrizo	<	<	160	250	34
A11 SAF-Mojave	<	<	105		30
A12 SAF-San Bernar	<	<	144		24
A13 SAF-Coachella	<	<	220	360	18
A14 Brawley	200	<			5
A15N Imperial-N	<	130			20
A15C Imperial-C	<	<	240		20
A15S Imperial-S	<	130			20
SJ8 San Bernardino	<	<	200		15
SJ9 San Jacinto	<	<			15
SJ10 Anza	<	<	250		15
SJ11 Coyote Cr	<	80			5
SJ12 Borrego	<	80			4
SJ13 Superstion Mt.	<	<	300		5

SJ14 Superstion Hll	<	150			4
SJ15 Elmore Ranch	150				1
EL15 Whittier	<	<	1750		2.5
EL16 Glen Ivy	<	175			5
EL17 Temecula	<	<	500		5
EL18 Julian	<	<	<	2500	3
EL19 Coyote Mt.	<	<	900		3
EL20 Laguna Salada	<	<	2000		3.5
EL21 Earthqk Valley	<	<	3000		2
LA01 Santa Monica	<	7000			1
LA04 Sierra Mad-cn	<	1000			3
LA05 Sierra Mad-Sfd	1000				2
LA06 Verdugo	<	1000			0.7
LA07 Clamshell	2000				0.5
LA08 Cucamonga	<	650			5
LA09 Hollywood	<	<	10000		1
LA10 Raymond	<	4500			0.5
LA12 Palos Verdes	<	<	1500		3
LA13 Newport Ing	<	<	2000		1
LA14 B Compton	<	2500			0.1
SB04 Arroyo-MRidge	<	<	8000		0.4
SB09 San Cayetano	<	450			6
SD01 Nwprt Ing-off	<	<	2000		1.2
SD02 Rose Cny-off	<	<	2500		1.5
SE01 Garlock W	<	<	<	750	6
SE02 Garlock E	<	<	<	500	7
SE03 Blackwater	<	<	5000		0.6
SE05 Helendale	<	<	3300		0.6
SE06 Lockhart			4000		0.6
SE08 Bullion-Mesq	<	<	3300		0.6
SE09 Johnson Vly-N	<	<	5000		0.6
SE10 Landers	<	<	6000		0.6
SE11 Emerson-CpMt	<	<	5000		0.6
SE12 Pinto Mtn	<	<	3300		2
SN15 Death Vlly-N	<	<	2000		5
SN16 Owens Vlly	<	<	2000		1.5
SN21 Death Vlly-Grb	<	<	<	2000	2
SN22 Death Vlly-S	<	<	1000		2
CI01 Santa Rosa Isl	<	<	8000		1
CI02 Santa Cruz Isl	<	<	4000		1
CI03 Anacapa-Dume	<	<	2000		3
CI06 Malibu Coast	7500				0.3
BB02 Pleito	500				1.4

Table 1. Current Simplified Earthquake Recurrence Table (SERT).

III. Earthquake Simulation Hazard Models

In 2005 we supplied earthquake potential models for RELM based on SERT/computer simulations of seismicity [Ward, S. N., 2005. Methods for evaluating earthquake potential and likelihood in and around California, *Seismological Research Letters, Submitted*. SCEC# 939]

<u>*Technical description.*</u>

*(*1) Run a several thousand year simulation of earthquakes on the fault system using known fault slip rates with guidance provided by recurrence and slip-per-event information given in the SERT.
(2) Smooth the computed rupture catalog into *synthetic earthquake rate density* maps taking into consideration the finite extent of ruptures as

$$\dot{\rho}(\mathbf{r}_{\mathrm{i}}) = T_{cat}^{-1} \sum_j \sum_{k=1,k_j} \frac{\exp(-[|\mathbf{r}_{\mathrm{i}} - \mathbf{r}_{\mathrm{k}}|/\Delta]^2)}{\pi k_{\mathrm{j}} \Delta^2} \quad (1)$$

In (1) the first term sums over all j ruptures greater than given magnitude, M. The second sum is over all k_{j} fault elements that ruptured in the j-th event.

In synthetic earthquake potential models, geological moment rate is loosely conserved not earthquake rates. Note that because the earthquake simulation model and the geological model employ the same sets of faults and slip rates, they have identical moment rate density distribution along the faults. The primary difference in the models is how the moment rate partitions into earthquakes. In the geological models, the partitioning was prescribed artificially using a Gutenberg-Richter relation. In computer simulations the magnitude distribution of seismicity falls out automatically from the physics of the fault system. Current models have a sufficiently rich set of fault behaviors to produce a near power law distribution of quakes (Figure 2d). Comparisons between predicted and observed bulk seismicity speak favorably toward the model's effectiveness.

<u>*Advantages:*</u> (1) Earthquake potential falls near known faults. (2) Partition of moment rate into earthquake rate is determined from physical laws – i.e. b-value and M_{max} not fixed a-priori (3) Potential to supply time-dependent statistics.

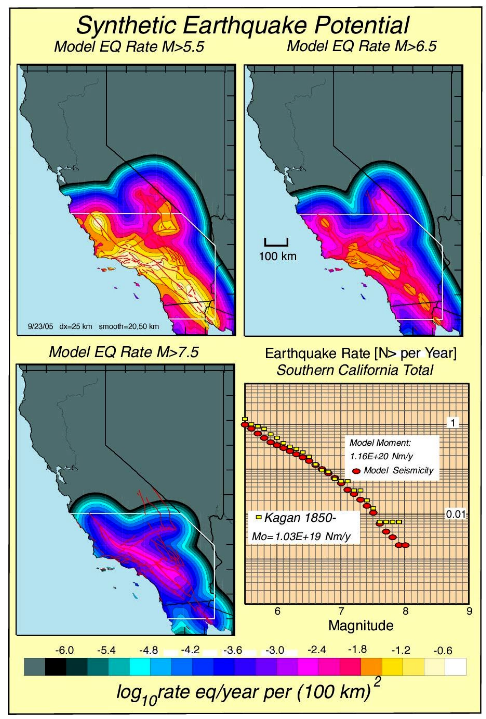

Figure 2. Synthetic earthquake potential models for $M_{>}$=5.5, 6.5 and 7.5. Over long intervals, the simulation should reproduce geological fault slip rates and geological moment rates. Unlike the geological models, synthetic seismicity models do not employ a Gutenberg-Richter relation. Thus, large earthquakes do not fall in proportion to small ones. The simulation fits the historical earthquake rates quite well (*lower right*).

<u>*Drawbacks:*</u> (1) Geologists will never be able to specify every fault location, slip rate and recurrence interval. (2) Time consuming to compute. (3) Does not necessarily reproduce historical earthquake rates. (4) Earthquake simulators have many parameters like fault strength and friction laws. (5) Some scientists question the worth of earthquake simulation.

IV. Shaking Hazard Calculation.

With maps of earthquake potential, together with an attenuation relation, the calculation of time independent shaking hazard is straightforward. For grid-based rate density estimates (Figure 2) earthquakes may be considered as point sources occurring at the stated rates and magnitudes at the grid co-ordinates. The mean rate of exceedence of shaking measure A_{crit} at any location $\mathbf{r}$ is found by summing over grid points

$$\dot{N}(A_{crit},\mathbf{r}) = dA\sum_j \dot{\rho}(\mathbf{r}_j)P_j(A_{crit},\mathbf{r}) \quad (2)$$

In (2), $\dot{\rho}(\mathbf{r}_j)$ is the rate density of events at the j-th grid point greater than some magnitude as read from the earthquake potential map. $P_j(A_{crit},\mathbf{r})$ is the probability that those events generate a shaking measure greater than A_{crit} at $\mathbf{r}$, and dA is the area represented by each grid point. Alternatively for rupture-based approaches, the mean rate of exceedence of shaking measure A_{crit} at $\mathbf{r}$ can be estimated by summing over ruptures

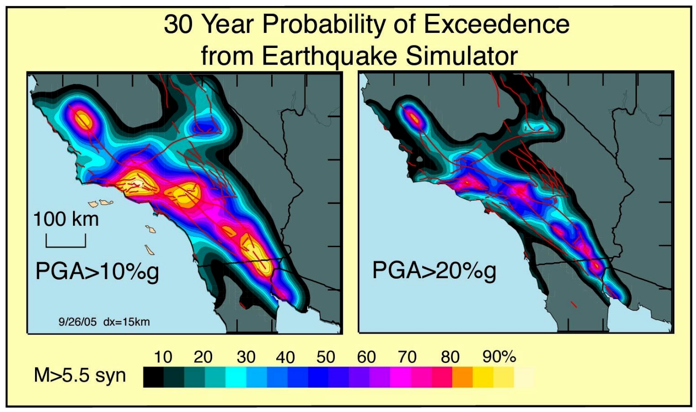

Figure 3. Earthquake hazard map derived directly from the physical earthquake simulator.

$$\dot{N}(A_{crit},\mathbf{r}) = T_{cat}^{-1}\sum_j P_j(A_{crit},\mathbf{r}) \quad (3)$$

where $P_j(A_{crit},\mathbf{r})$ is the probability that the j-th rupture in the catalog generates a shaking measure greater than A_{crit} at $\mathbf{r}$. Poissonian hazard maps for any time interval fall immediately from (2). Figure 3 plots 30-year likelihood of exceeding PGA 10% g and 20% g as predicted directly from the computer simulation in Figure 1. We argue that hazard estimates by earthquake simulation are, even now, as defensible as those generated by any other technique.

Vision for the Future: In prospect, we see SERT-guided computer simulations opening avenues to time dependent hazard estimates or even operational earthquake forecasts. With the simulator's ability to produce earthquake catalogs of virtually unlimited duration, any number of conditionally dependent probabilities lay exposed for query. For instance, "Map the probability of all events greater than magnitude 6 that follow within ten years of a M7.5 San Andreas Fault event at Coachella". "Under the San Gabriel Mountains, how likely is it that a M6 quake precedes a M7 quake by less than six months?"