Petascale Research in Earthquake System Science
or
From a Spiral of Inference to Cell Phone Towers. A Path From Blue Waters to the Real World

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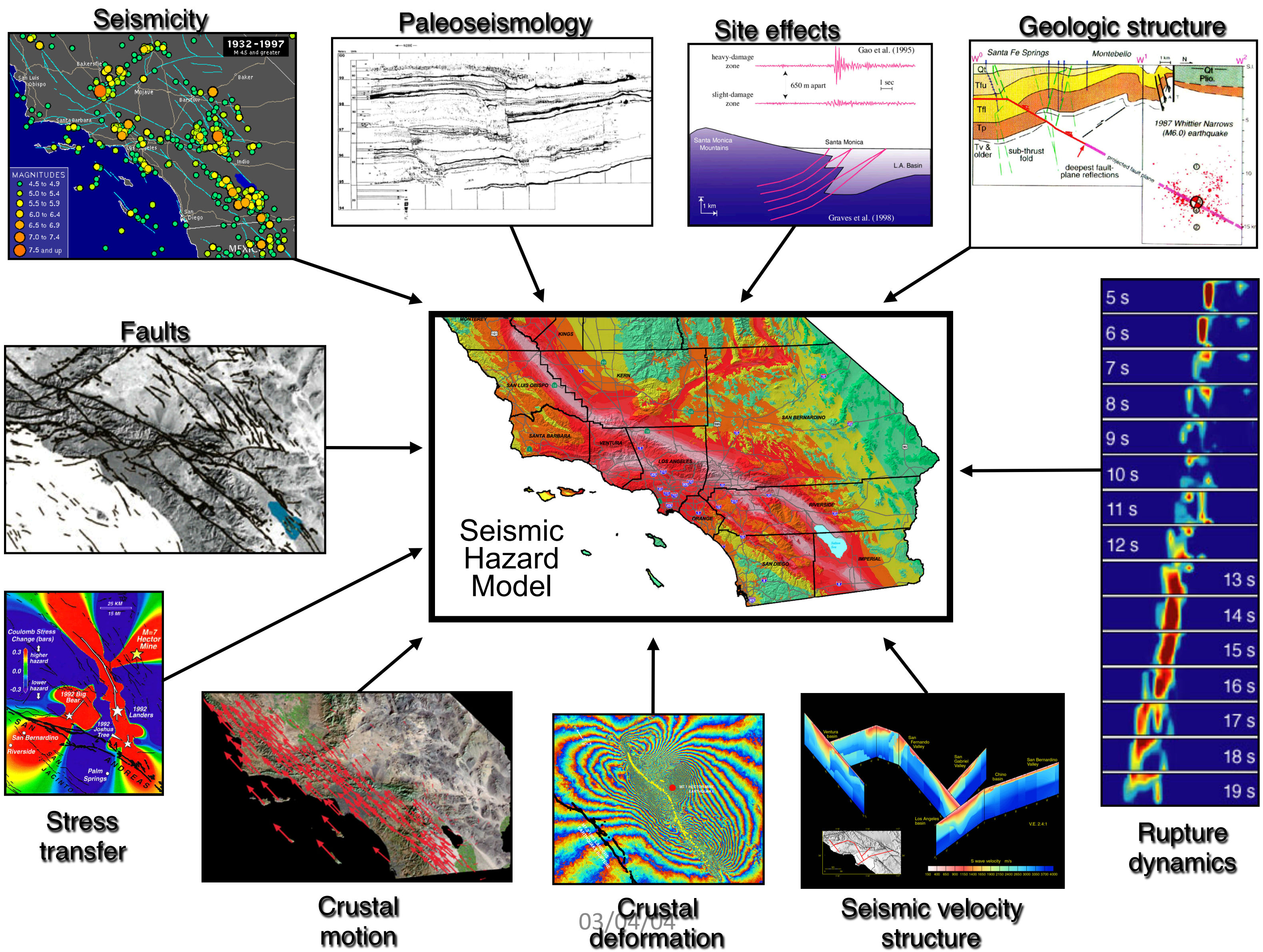
co-PI: Jacobo Bielak Carnegie Mellon University
co-PI: Yifeng Cui San Diego Supercomputer Center
co-PI: Kim Bak Olsen San Diego State University
Presenter: Philip Maechling Southern California Earthquake Center

Blue Waters All Hands Meeting
May 2015 Meeting

13 May 2015

Seismic Hazard Analysis is a System-Level Problem



Why SCEC Earthquake System Science Research Needs Blue Waters

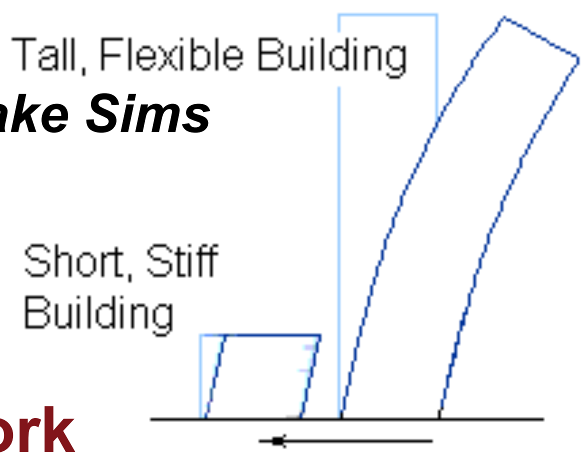
- Research continues to extend geographical range, higher resolution, more time steps
  - Size of “new” problems pushes the computational (CPU, memory, disk) limits of small systems
- Improved inputs include fault models and earth structure models can motivate updating previous results
  - Individual simulations do not “solve” the problem. Re-running completed simulations, with new inputs, often requires increasing the need for computational time
- Need to increase the maximum simulated frequency requires improved physics and improved code performance
  - High-frequency simulations can now be considered with Blue Waters scale systems

Why SCEC Earthquake System Science Research Needs Blue Waters

Correlation between simulation's f_max and the fundamental mode of buildings vibration:

height (in floors) = 10 / frequency (Hz)

- *20 floors ~= 10 / 0.5Hz – Probabilistic CyberShake 14.2*
- *10 floors ~= 10 / 1.0Hz – Probabilistic CyberShake 15.4*
- *5 floors ~= 10 / 2.0Hz*
- *2.5 floors ~= 10 / 4.0Hz – Single Earthquake Sims*
- *1.5 floors ~= 10 / 8.0Hz*
- *1 floor ~= 10 / 10Hz*



- **2x frequency -> 16x computational work**

Why SCEC Earthquake System Science Research Needs Blue Waters

- Earthquake system science computational research uses a broad range of codes and system capabilities (CPU,GPU, Data Intensive, Workflows)
  - Multiple research codes and computing tools and techniques are supported by Blue Waters system

- Scale of simulations have led to multi-month time to solution.
  - Blue Waters helps reduce the “time to solution” for some long duration simulations to manageable levels (months not years).

	Milestone Activities	Problem Size	Code	WCT (Hours) CPU [GPU]	Nodes per Run CPU [GPU]	Repe-titions	Total Node Hrs (million)	Storage (TB)
M1	Dynamic Rupture	4 Hz 350km x 150km x 36km 30 billion elements, 45Ktimesteps	SORD	8.75	4,000	8	0.35	10
M2-1	Validation Simulations	2 Hz; 200m/s 200km x 150km x 50km 2 billion elements, 50K timesteps	Hercules	2.3	750	12	0.02	10
M2-2		4 Hz; 200 m/s 200km x 150km x 50km 16 billion elements,100K timesteps	Hercules	9.3	3,000	6	0.17	10
M3-1	1994 Northridge	8 Hz; 400 m/s 150km x 100km x 30km 450 billion elements, 200K timesteps	AWP-ODC	24.0	6,000	4	0.58	40
M3-2		8 Hz; 400 m/s 150km x 100km x 50km 15 billion elements,100K timesteps	Hercules	8.7	3,000	4	0.10	10
M3-3		8 Hz; 200 m/s 150km x 100km x 50km 90 billion elements,200K timesteps	Hercules	24.0	13,000	2	0.63	20
M4-1	2014 ShakeOut	2 Hz; 500 m/s 600km x 300km x 100km 144 billion elements,160K timesteps	AWP-ODC	14.8	4,000	4	0.24	20
M4-2		4 Hz; 500 m/s 600km x 300km x 87.5km 1.91 trillion elements, 320 timesteps	AWP-ODC GPU	23.5 [13.4]	22,000 [4,000]	3	1.71	170
M4-3		4 Hz; 200 m/s 600km x 300km x 80km 40 billion elements, 200K timesteps	Hercules	23.1	6,000	1	0.14	10
M5	CyberShake	2 Hz; 250 m/s 3 components 83.3 billion elements, 80K timesteps	CyberShake Framework AWP-ODC SGT-GPU	4 [5]	2,250 [4,300]	286	8.72	1,700
						Total	12.66	2,000

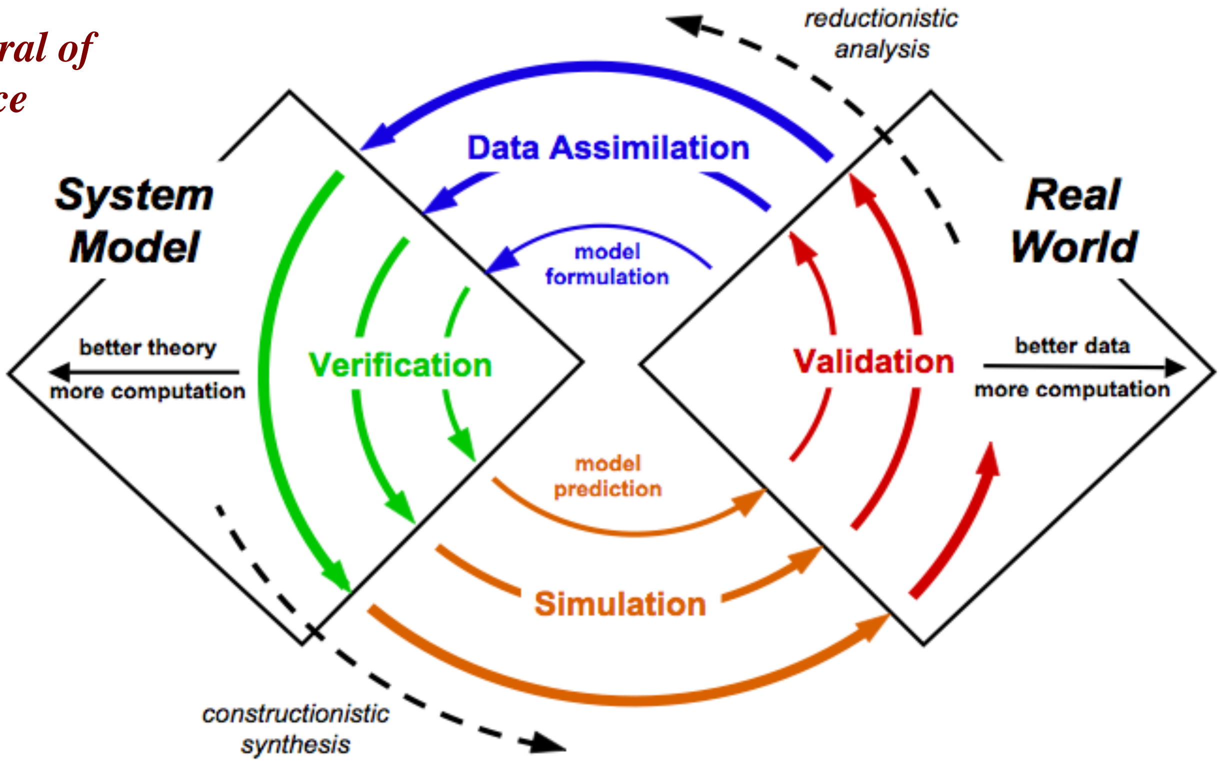
Blue Waters Reduces Computational Time to Solution

CyberShake Application Metrics (Hours):	PSHA	2008 (Mercury, normalized)	2009 (Ranger, normalized)	2013 (Blue Waters/ Stampede)	2014 (Blue Waters)
Application Core Hours:	0.69	19,448,000 (CPU)	16,130,400 (CPU)	12,200,000 (CPU)	10,032,704 (CPU+GPU)
Application Makespan:	98 seconds	70,165	6,191	1,467	342
Makespan (Days)		2,923	257	61	14.2

SCEC needs reflect the broader HPC requirements of geosystem science…

- **Geosystem science requires an iterative, computationally intense process of model formulation and verification, simulation-based predictions, validation against observations, and data assimilation to improve the model**

Inference Spiral of System Science



- **As models become more complex and new data bring in more information, geosystem science requires ever increasing computational resources**

Blue Waters Results May 2014 - May2015

1. Integrate new Physics into ground motion simulations
   – Kim Olsen, William Savran, Kyle Withers, Zheqiang Shi, Jacobo Bielak, Ricardo Taborda, Naeem Khoshnevis, Dorian Restrepo

2. Extend simulations to Higher Frequencies and Compare Results between equivalent Codes
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3. Ensemble (probabilistic) simulations at higher frequencies
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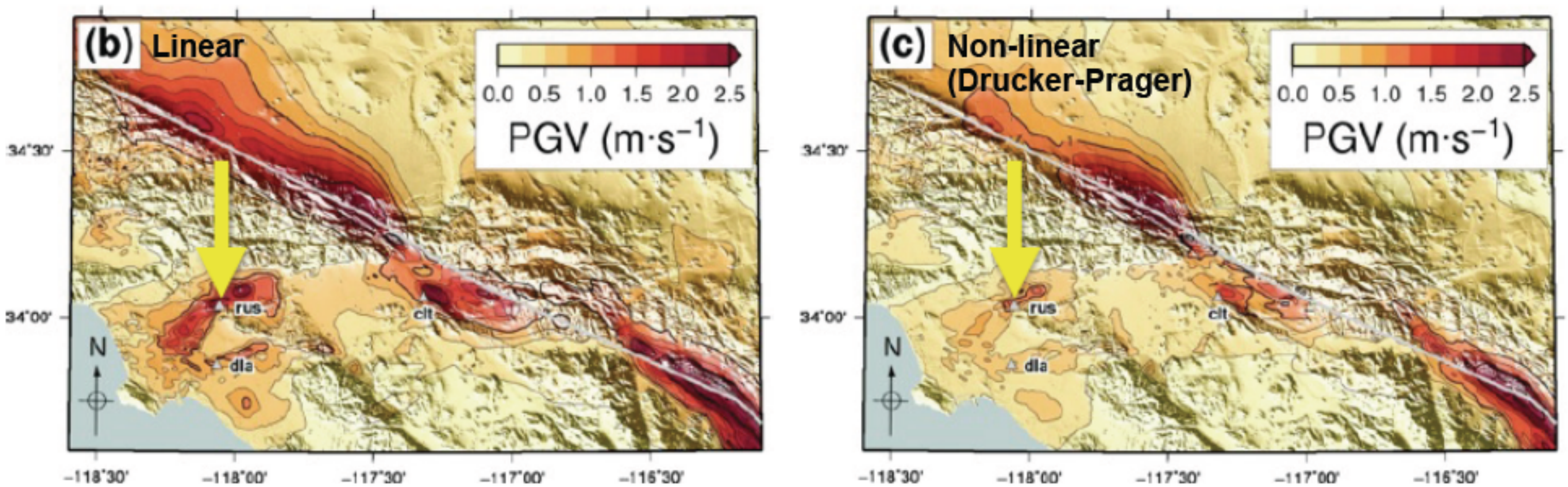
High-F Project



SCEC simulations 2014

physics-based deterministic → CyberShake 0.5 Hz - - - → *empirical stochastic*

High-F modeling must validate new physics

- fault roughness
- near-fault plasticity
- frequency-dependent attenuation
- topography
- small-scale near-surface heterogeneity
- near-surface nonlinearity

5 Hz

SCEC simulations 2018

physics-based deterministic → *physics-based stochastic* - - - → *empirical stochastic*

Discussion About Difference of Slip Velocity Functions

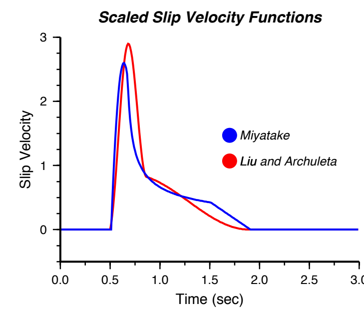
GP Model Recipe (G & P)

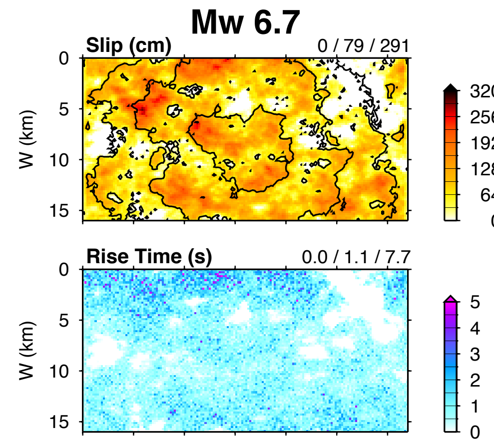
local rise time of the **i** th subfault, τ **i** , which scales with local slip Si:

$\tau_i = 2 \times k \times \mathrm{sqrt}(Si^{1/2})$ z<5km

$\tau_i = k \times \mathrm{sqrt}(Si^{1/2})$ z<8km

$\tau a = al \times 1.6 \times 10^{-9} \times Mo^{1/3}$ average rise time (Somerville et al., 1999)

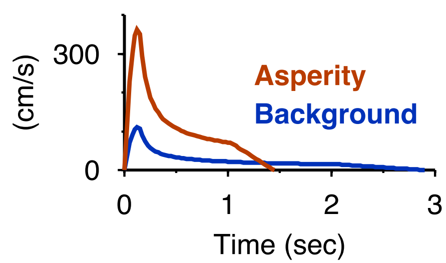




Model A Recipe

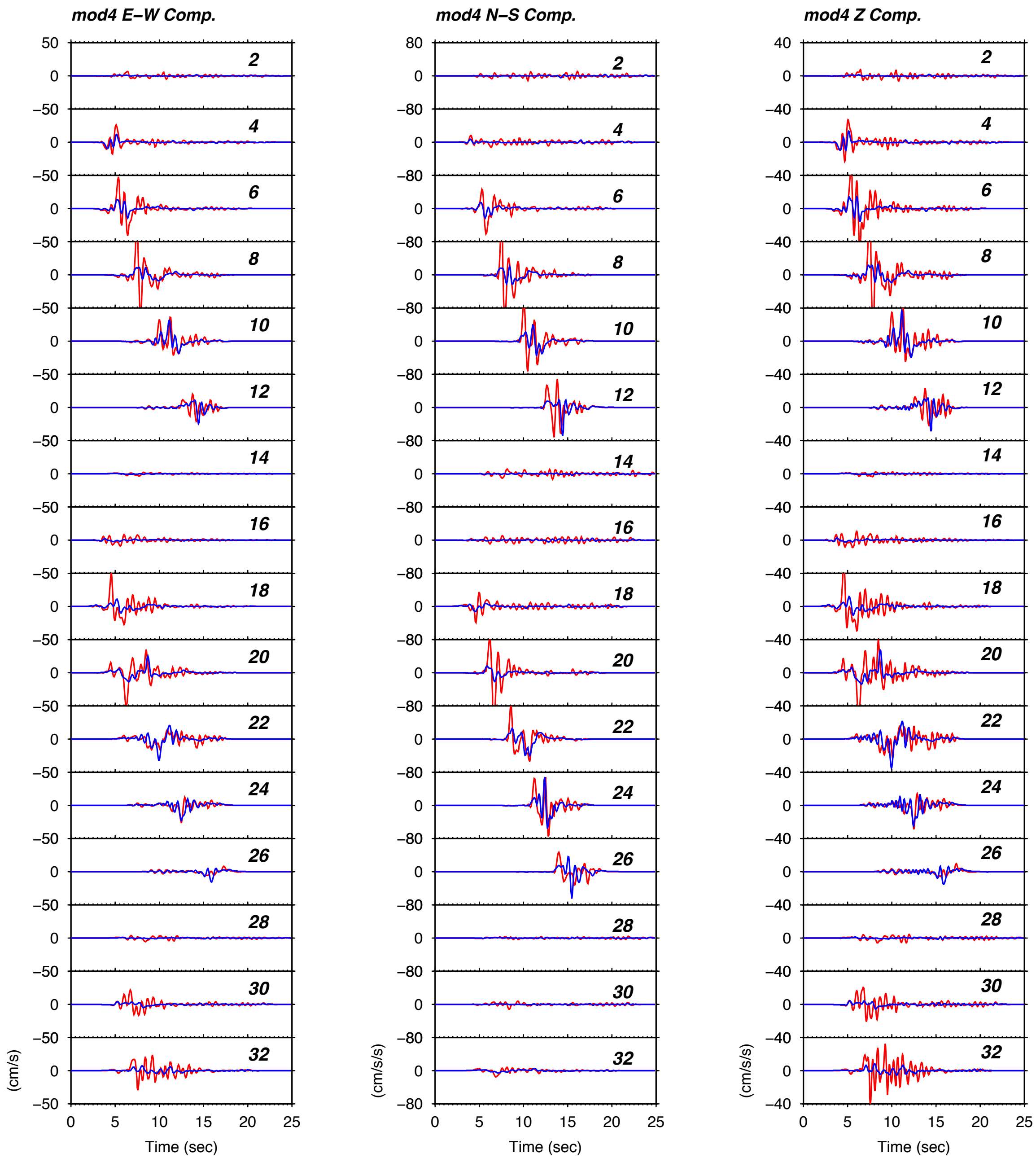
$\tau i = L/Vr/2.$ L asperity area diameter

td=4./fc/pi ??



Note: The parameters used in computing the slip function presented here may need to be verified using NIED's report.

Simulated Accelerograms for Model 1 and G&P



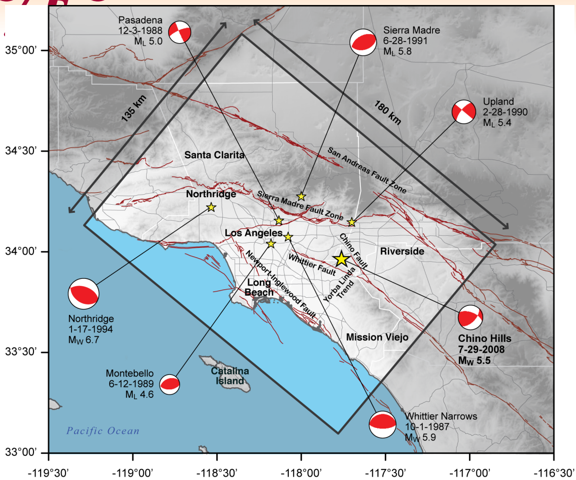
1D Multilayers Velocity Model

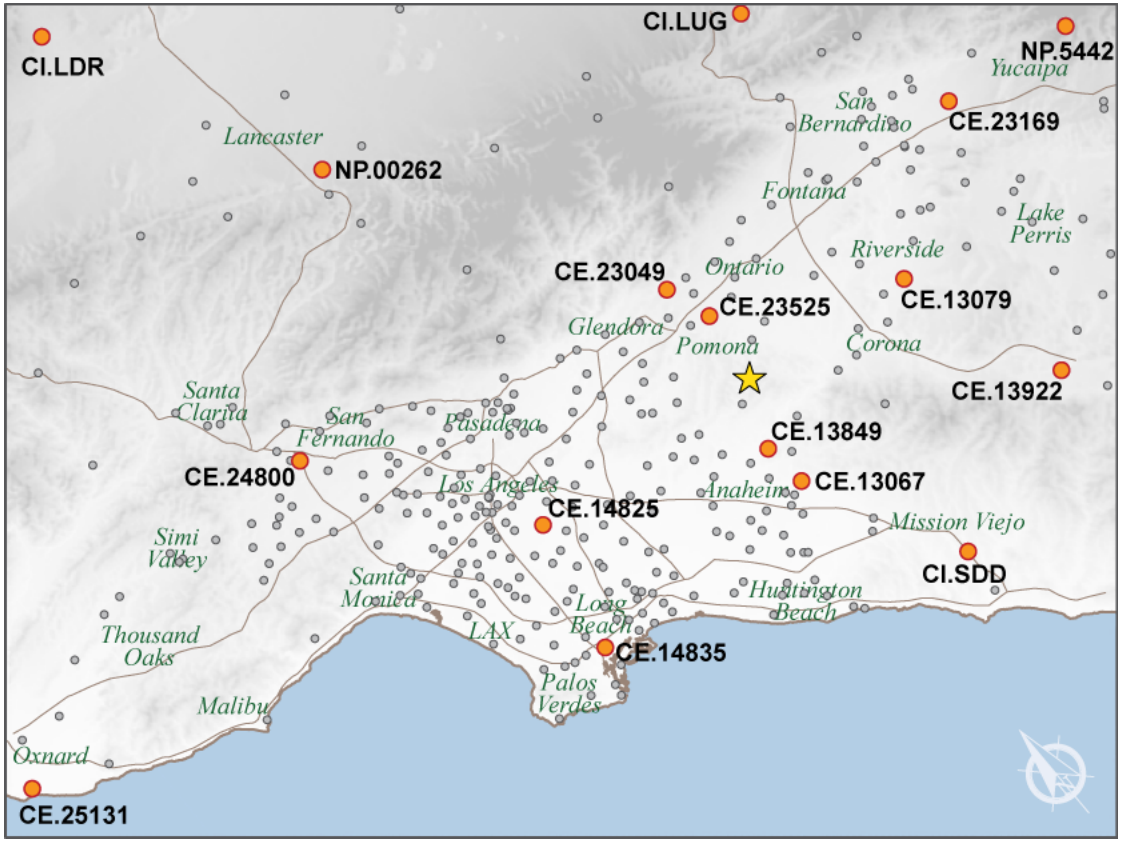
Fmax = 2 Hz

G&P Red traces

Model 1 Blue traces

The 2008 chino hills earthquake and region of interest





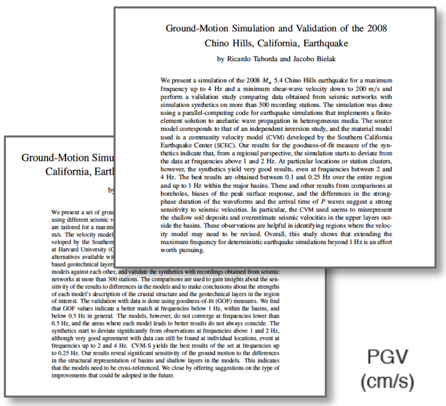
- Largest earthquake in the L.A. region since the 1994 Northridge earthquake.
- Combination of thrust and strike-slip faulting between the Whittier and Chino faults.
- No significant damages, no fatalities.
- Excellent opportunity for testing assumptions and methodologies.
- Recorded in over 450 strong motion station from different seismic networks. 336 surface stations within simulation domain.

Recent work using different velocity models

case study: 2008 Chino Hills earthquake

Taborda and Bielak (2013)
BSSA, 103(1): 131–156

Taborda and Bielak (2014)
BSSA, 104(4): in press



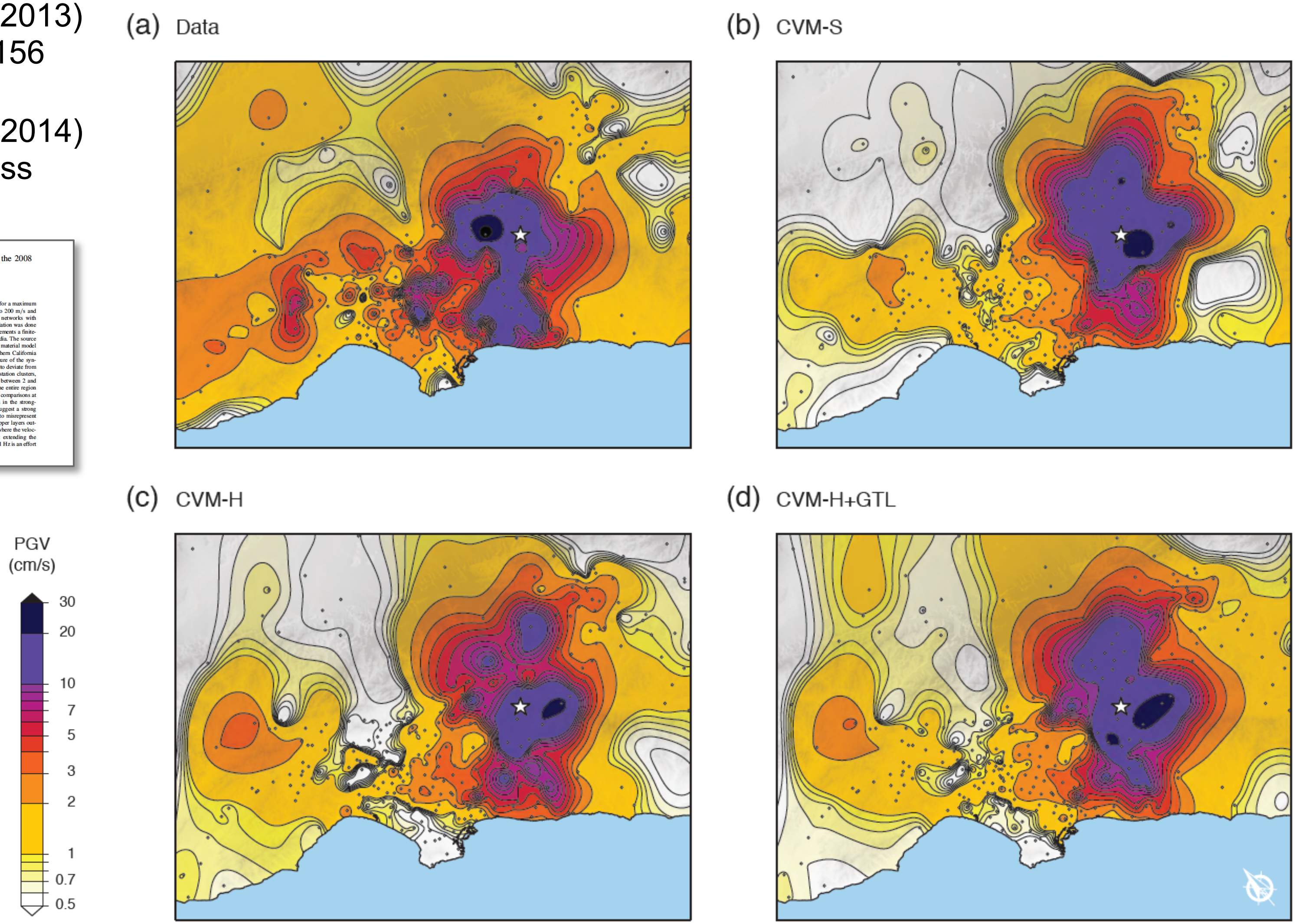
Ground-Motion Simulation and Validation of the 2008 Chino Hills, California, Earthquake

by Ricardo Taborda and Jacobo Bielak

We present a simulation of the 2008 M_w 5.4 Chino Hills earthquake for a maximum frequency up to 4 Hz and a minimum shear-wave velocity down to 200 m/s and perform a validation study comparing data obtained from seismic networks with simulation synthetics on more than 300 recording stations. The simulation was done using a parallel-computing code for earthquake simulations that implements a finite-element solution to anelastic wave propagation in heterogeneous media. The source model corresponds to that of an independent inversion study, and the material model used is a community velocity model (CVM) developed by the Southern California Earthquake Center (SCEC). Our results for the goodness-of-fit measure of the synthetics indicate that, from a regional perspective, the simulation starts to deviate from the data at frequencies above 1 and 2 Hz. At particular locations or station clusters, however, the synthetics yield very good results, even at frequencies between 2 and 4 Hz. The best results are obtained between 0.1 and 0.25 Hz over the entire region and up to 1 Hz within the major basins. These and other results from comparisons at boreholes, biases of the peak surface response, and the differences in the strong-phase duration of the waveforms and the arrival time of P waves suggest a strong sensitivity to seismic velocities. In particular, the CVM used seems to misrepresent the shallow soil deposits and overestimate seismic velocities in the upper layers outside the basins. These observations are helpful in identifying regions where the velocity model may need to be revised. Overall, this study shows that extending the maximum frequency for deterministic earthquake simulations beyond 1 Hz is an effort worth pursuing.

Ground-Motion Simu[...] California, Eart[...]

We present a set of grou[...] using different seismic v[...] are tailored for a maxim[...] m/s. The velocity model[...] veloped by the Southern[...] at Harvard University (C[...] alternatives available wi[...] based geotechnical layers[...] models against each other, and validate the synthetics with recordings obtained from seismic networks at more than 300 stations. The comparisons are used to gain insights about the sensitivity of the results to differences in the models and to make conclusions about the strengths of each model's description of the crustal structure and the geotechnical layers in the region of interest. The validation with data is done using goodness-of-fit (GOF) measures. We find that GOF values indicate a better match at frequencies below 1 Hz, within the basins, and below 0.5 Hz in general. The models, however, do not converge at frequencies lower than 0.5 Hz, and the areas where each model leads to better results do not always coincide. The synthetics start to deviate significantly from observations at frequencies above 1 and 2 Hz, although very good agreement with data can still be found at individual locations, event at frequencies up to 2 and 4 Hz. CVM-S yields the best results of the set at frequencies up to 0.25 Hz. Our results reveal significant sensitivity of the ground motion to the differences in the structural representation of basins and shallow layers in the models. This indicates that the models need to be cross-referenced. We close by offering suggestions on the type of improvements that could be adopted in the future.



Blue Waters Results May 2014 - May2015

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Single Earthquake Simulations Lead Improvements

- Individual earthquake simulations are used as the codes are improved and are validated to run with improved physics and at higher frequencies.
- Probabilistic simulations require 100,000s of individual earthquake simulations.
- Physics and code improvements developed for individual earthquake simulations are integrated into probabilistic ensemble calculations, as soon as is practical.
- Currently, individual earthquake simulations (4Hz), probabilistic ensemble (1Hz)

AWP-ODC (FD) Blue Waters 4Hz Simulation

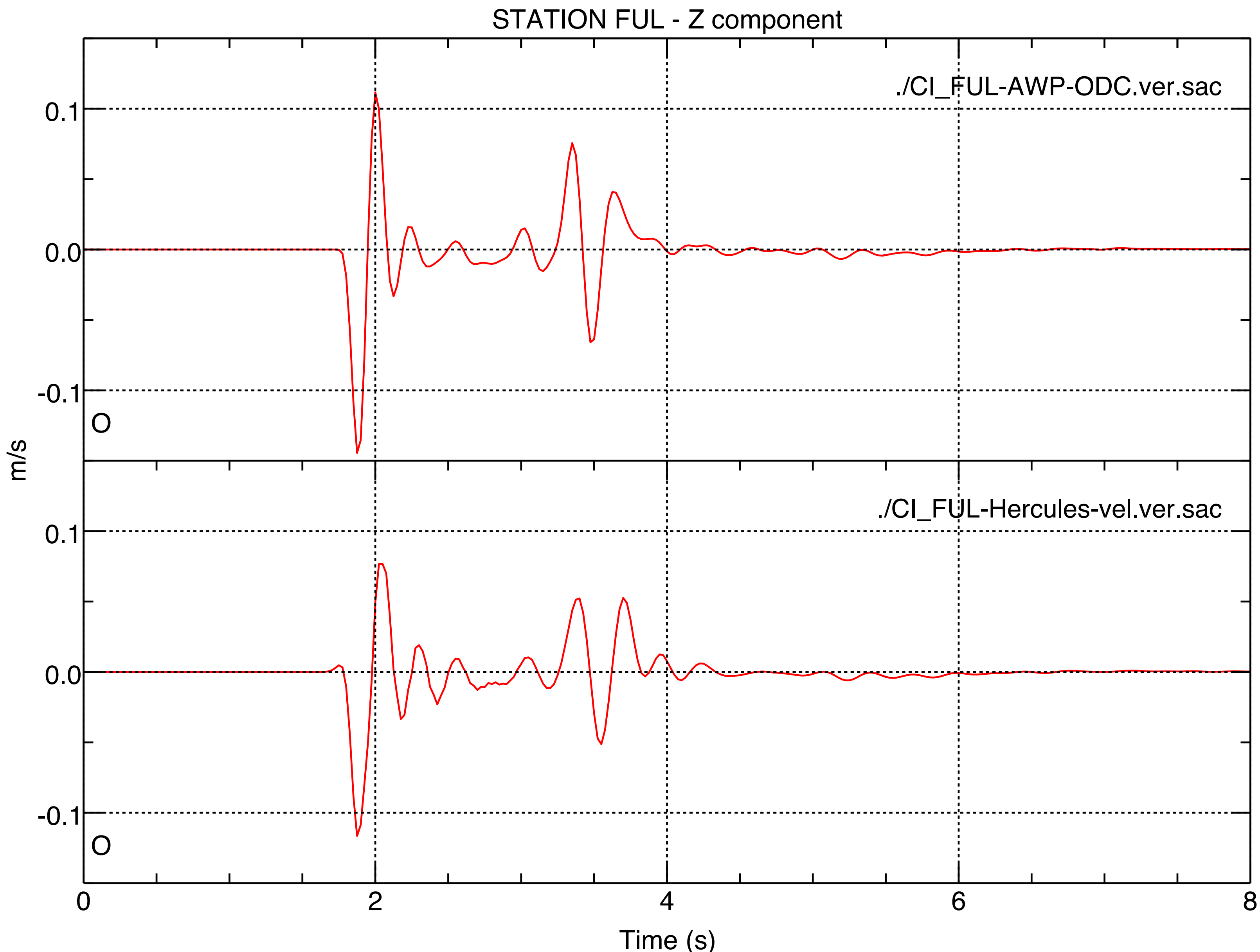
- Max Freq: 4Hz
- Min Vs: 500 m/s
- Number of cores used: 3060 Nodes * 32 = 97,920 Cores
- Time to complete simulation: 10 hours 30 minutes
- Estimated Cost: 32,000 Node Hours
- Simulated time: 100 s
- Total elements : 97,920,000,000
- Number of time steps : 100,000
- Spatial Discretization: 20 m

Hercules Blue (FE) Waters 4Hz Simulation

- Max Freq: 4Hz
- Min Vs: 500 m/s
- Number of cores used: 300 Nodes * 32 = 9,600 Cores
- Time to complete simulation: 11 hours 5 minutes
- Estimated Cost: 3,300 Node Hours
- Simulated time: 100 s
- Total elements : 6,178,209,792
- Number of time steps : 40,000
- Spatial Discretization Minimum: 10.9863 m
- Spatial Discretization Maximum: 87.8906 m

May 2015 4Hz Simulation Comparison AWP-ODC (FD) versus Hercules (FE)

Southern California Earthquake Center



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Los Angeles Times

LOCAL / L.A. Now

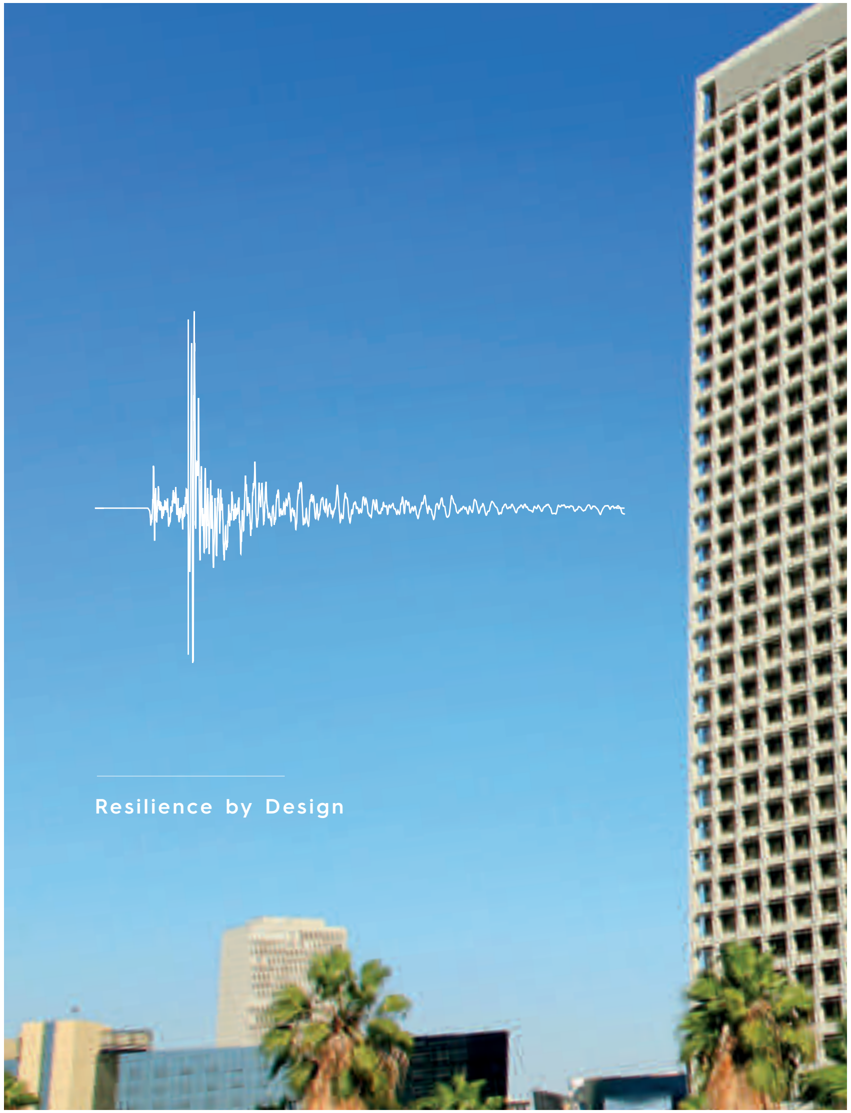
This article is related to: Hurricane Sandy (2012)

L.A. becomes first U.S. city to enact quake safety standards for new cellphone towers

"The Los Angeles plan requires new freestanding cellphone towers to be built to the same seismic standards as public safety facilities. Cellphone towers are currently built only strong enough to not collapse and kill people during a major earthquake. They're not required to be strong enough to continue working.."

- **Los Angeles Times 8 May 2015**

Resilience By Design
City of Los Angeles Earthquake Preparedness Plan (2015)



Resilient By Design
City of Los Angeles Earthquake Preparedness Plan (2015)

Strengthen Our Buildings

The most obvious threat from earthquakes is physical damage to vulnerable buildings. Soft story and concrete buildings built before the implementation of Los Angeles' 1976 revision of the building code pose a significant risk to life in strong earthquake shaking.

Fortify our Water System

The water system is the utility most vulnerable to earthquake damage, and that damage could be the largest cause of economic disruption following an earthquake. Portions of the system are more than a century old and vulnerable to many types of damage. Lack of water would impede recovery and the long-term loss of a water supply could lead to business failure and even mass evacuation. Developing a more resilient water system is imperative for the future of Los Angeles.

Enhance Reliable Telecommunications

Modern society and economic activity are dependent on telecommunications, including cell phones and Internet access. The Northridge earthquake occurred prior to these services being widely available, so we do not have direct experience with their vulnerabilities. We can, however, use the experiences in other countries and in other disasters to inform the efforts needed to protect vital communications systems.

Seismic Hazard versus Seismic Risk

- **Seismic hazard** refers the probability that an earthquake will cause ground motions exceeding a given threshold in a given geographic area, within a given window of time.

- **Seismic risk** refers to the potential damage from earthquake to a building, system, or other entity.


traditional bamboo house in
the Colombian Andes
Let’s make a difference…
working together

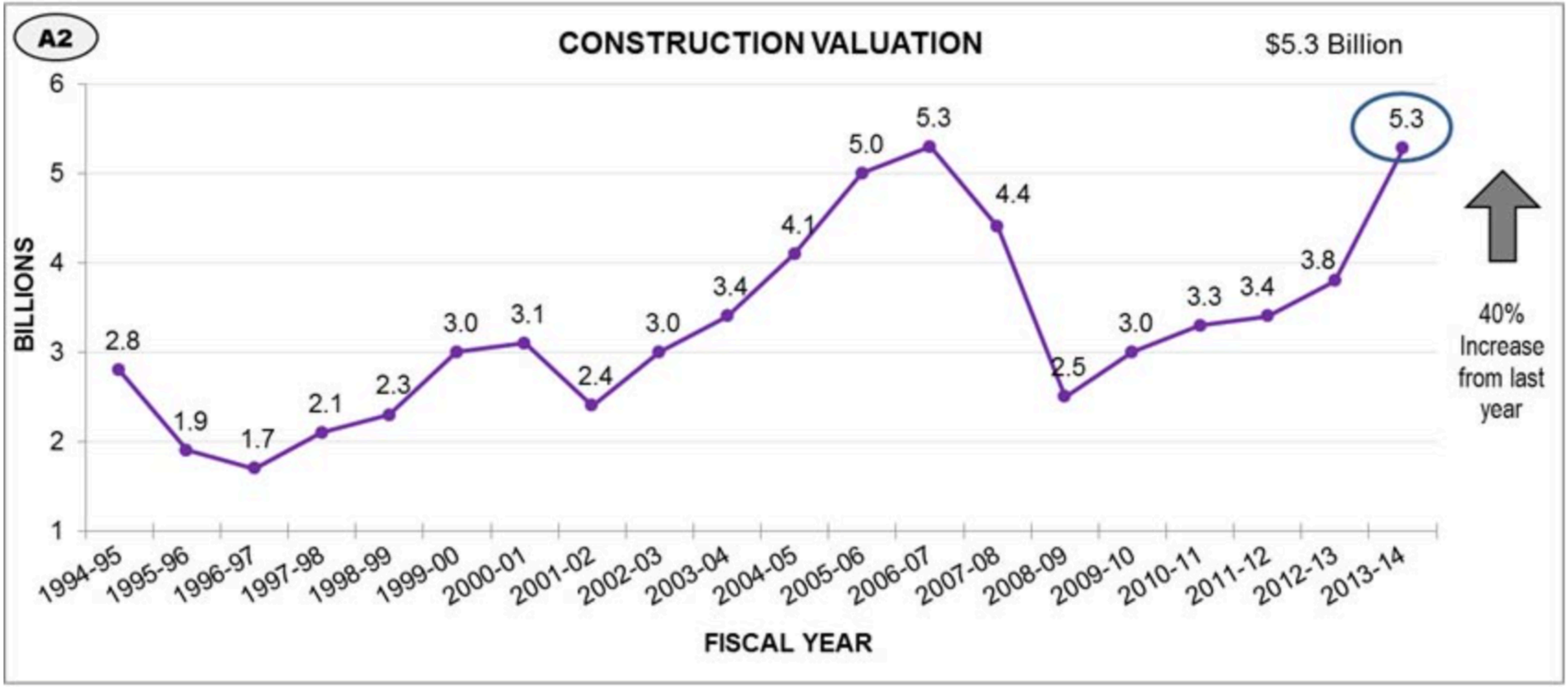
Blue Waters Impact on the Real World

Building Engineers are asking SCEC for higher frequency ensemble simulations. The path from Blue Waters to real-world seems like:

1. SCEC uses Blue Waters to calculated improved peak ground motion estimates for southern California
2. Improved peak ground motions estimates are used to calculate maximum credible ground motions (at different frequencies) for all sites in a region of interest.
3. ASCE engineers include improved maximum credible ground motions and publish updated building code recommendations.
4. Public authorities (such as City of Los Angeles) reference ASCE codes in their laws, ordinances, regulations.
5. Cell Towers engineers building new towers in Los Angeles using improved maximum credible ground motions during construction
6. Blue Waters results contribute to a safer environment

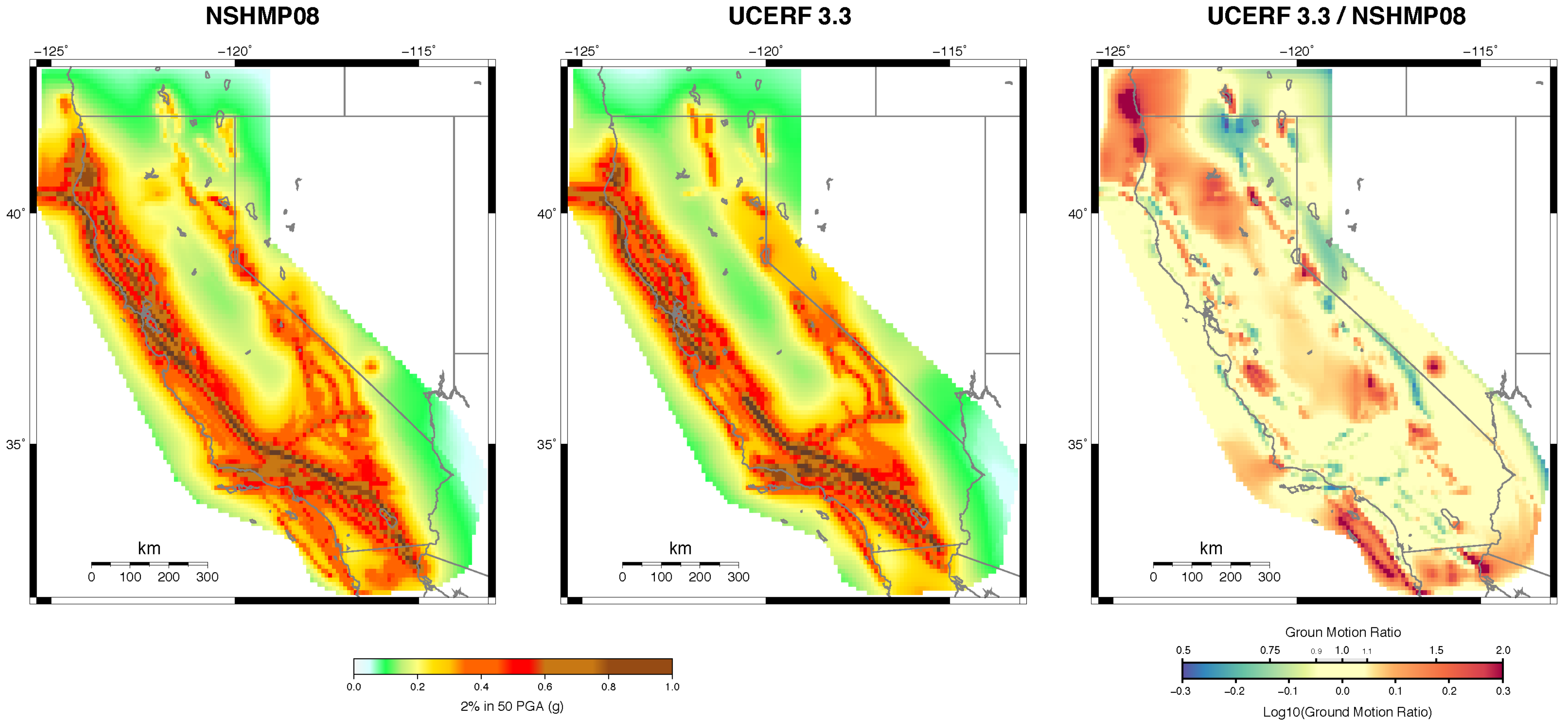
Blue Waters Impact on the Real World

City of Los Angeles issued 5.3B of construction permits in 2014

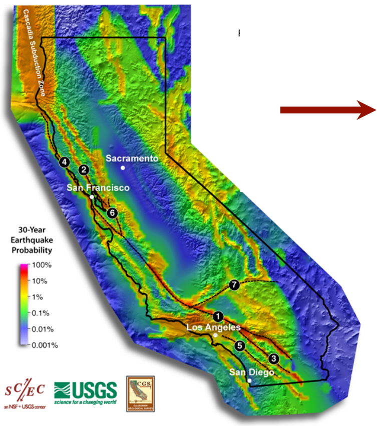


UCERF3.3 Ground Motion Map (2% in 50 yrs. 1Hz)

Maps of California ground motion implied by the 2008 NHSMP source model and UCERF3, and the ratio of the two. Ground motion is measured as the spectral acceleration at 1Hz with a 2% probability of being exceeded in 50 yrs.



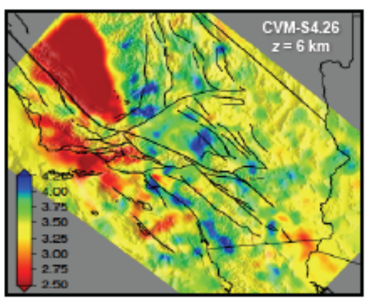
CyberShake Workflow



Uniform California Earthquake Rupture Forecast

UCVM → **AWP-ODC** → **SeisSynth** → *data transfer* → **Data Product Generation**

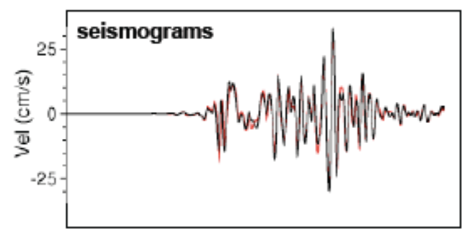
UCVM
Mesh generation
1 job per site
MPI, 320 cores



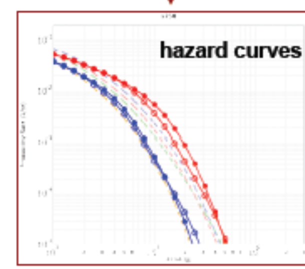
Full-3D tomographic model of S. California

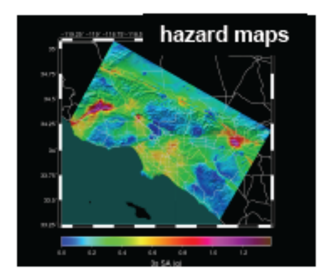
AWP-ODC
SGT computation
2 jobs per site
MPI, 10k CPUs or 100 GPUs

SeisSynth
Post-processing
415,000 jobs per site
serial

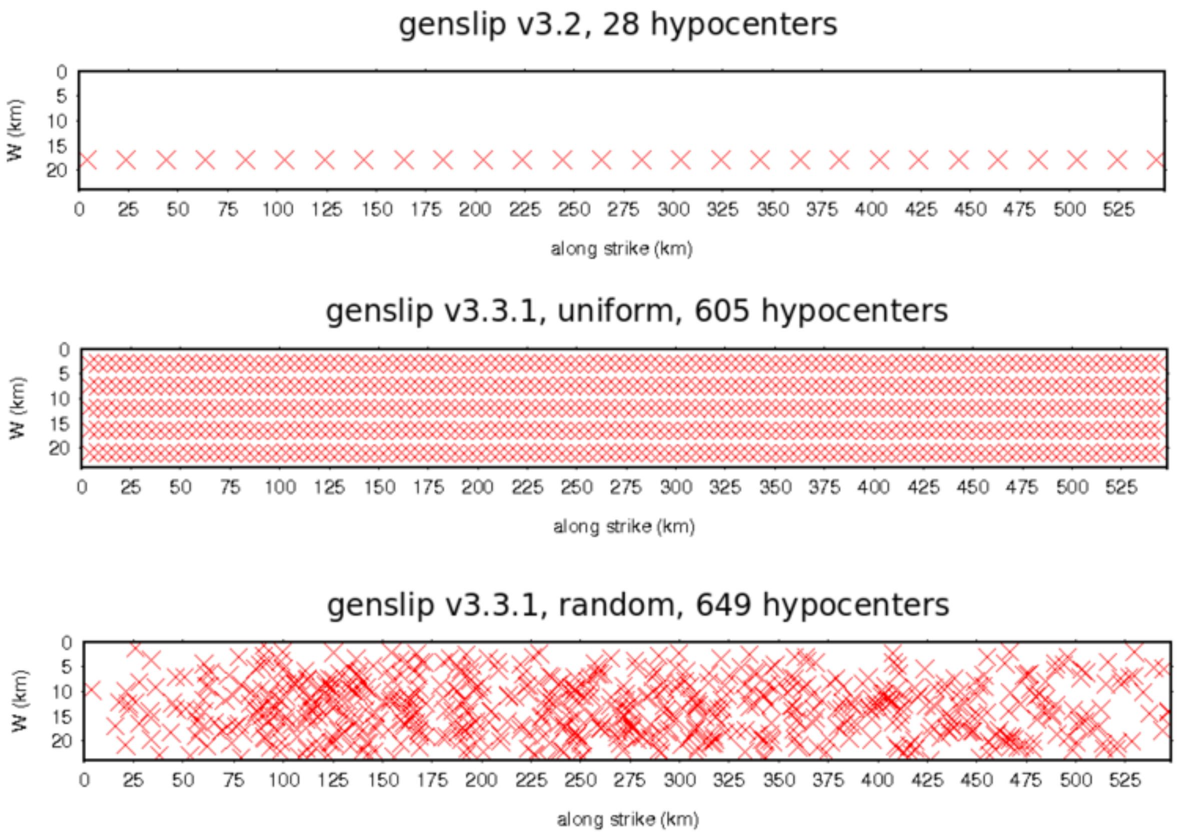


Data Product Generation
Populate DB, construct queries
4 jobs per site





CyberShake Rupture Generator Updated in 2014



CyberShake Rupture Generator that created rupture variations was changed from simple hypocenter spacing model to (top) to regular (center) and random (bottom). Center being used for first Los Angeles area 1Hz CyberShake model.

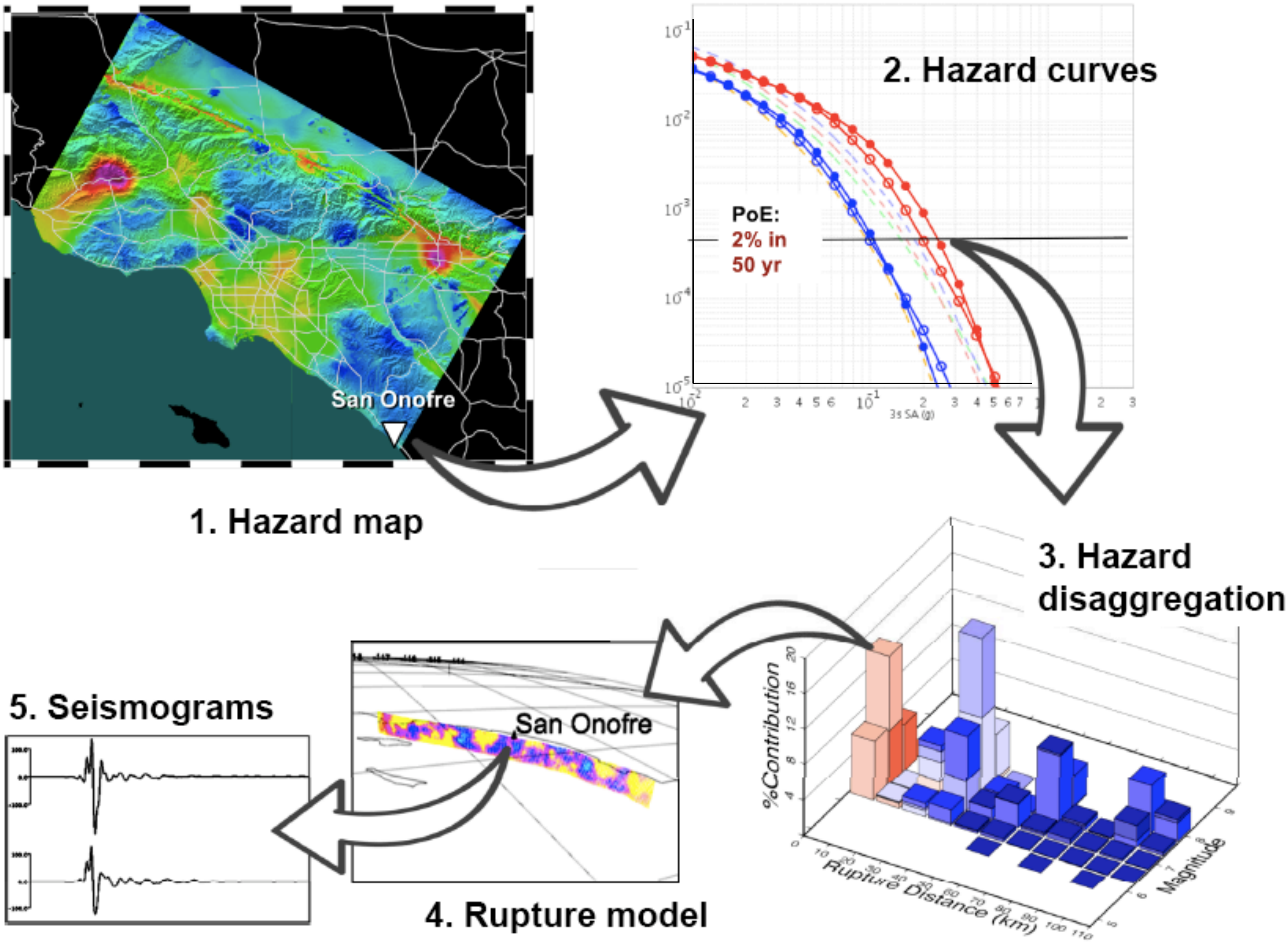
May 2015 UGMS Meeting

- CyberShake Study 15.4
  - UCERF2
  - No Background Seismicity
  - 3D Velocity Model: CVM-S4.26
  - Min Vs: 500 m/s
  - Velocity Meshing: 100m
  - Fault Meshing: 200m
  - Rupture Generator: genslip v3.3.1 (Graves & Pitarka 2014)
  - Maximum Frequency: 1.0Hz
  - PSHA 2.0s, 3.0s, 5.0s, 10.0s curves
  - RotD100 2.0s, 3.0s, 4.0s, 5.0s, 7.5s, 10.0s curves

New Computational Results For May 2015

- Current CyberShake 15.4 Study using NSF and DOE Computers
  - Los Angeles area Hazard Model based on 336 sites at 1Hz
  - Estimated 40M Computer Hours
  - Estimated 1PB+ temporary data split between Blue Waters and Titan
  - Estimated 11TB persistent data at SCEC
- Current Status: Preliminary results for 168 of 336 (50%) Sites Completed

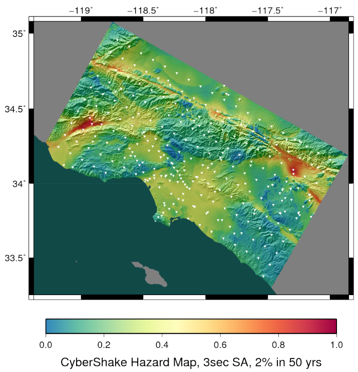
CyberShake Platform: Physics-Based PSHA

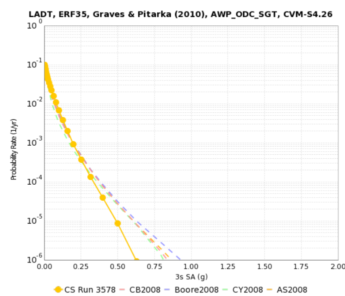


Southern California Earthquake Center

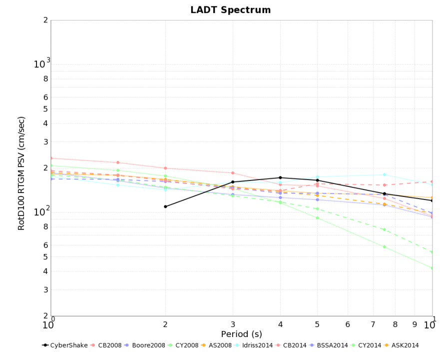
CyberShake 14.2 Probabilistic Hazard Model Products

CS 14.2 PSA3.0 Hazard Model (286 sites)

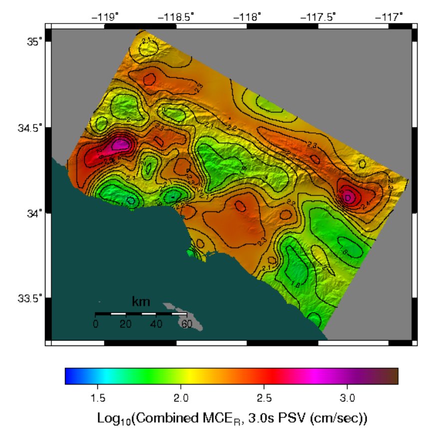




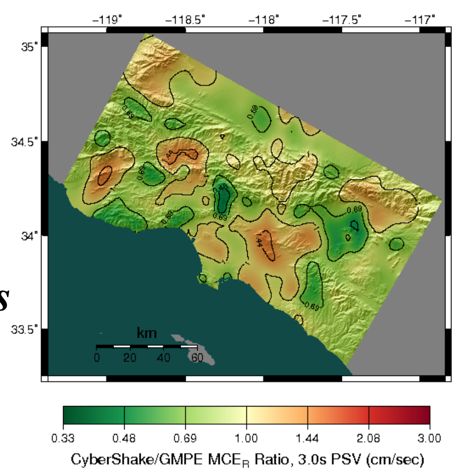
CS 14.2 RotD100 3.0s Probabilistic Hazard Curve (LADT)



CS 14.2 RotD100 3.0s Probabilistic, Deterministic, Combined, Overall MCER Curves (LADT)



CS 14.2 RotD100 3.0s Probabilistic, Deterministic, Deterministic Lower Limit, Combined MCER Contour Maps (286 Sites)



GMPE Comparison Maps Ratio (CS 14.2/ NGA-2) RotD100 3.0s (286 Sites)

Risk-Targeted Maximum Considered Earthquake Response Spectra (MCER) at 14 Southern California Sites

SCEC Meeting Program (November 3, 2014)

10:00 Welcome and Attendee Introductions (Tom Jordan)

10:10 Introductory Remarks & Meeting Agenda (C.B. Crouse)

Study Sites [edit]

We are calculating MCER results for 14 sites, available in a KML file Image to the right shows the location of the MCER 2014 study sites. These sites can be plotted using the following KML file:

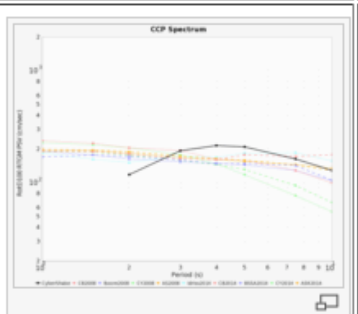
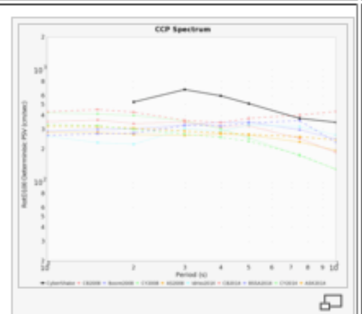
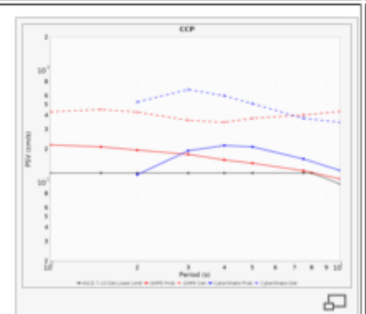
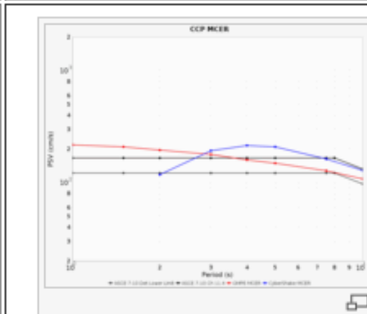
- MCER 2014 Study Sites (Google Earth KML Format). (KML file)

Near surface information about these sites includes Vs30, Z1.0, Z2.5 Values. These values are used in GMPE calculations for these sites. Site names, locations, and near surface values are listed in the following file.

- Site List with Vs30 Information (CSV File)

Results [edit]

Plots for each of the 14 sites are available in the following table.

Site	Full name	Probabilistic MCER	Deterministic MCER	Combined MCER results	Overall MCER results
CCP	Century City Plaza				

Risk-Targeted Maximum Considered Earthquake Response Spectra (MCER) at 14 Southern California Sites

SCEC Meeting Program (May 4, 2015)

10:00	Welcome and introductions	Thomas Jordan
10:15	Introductory Remarks and Meeting Agenda	C.B. Crouse
10:30	New Code Cycle (Project 17, BSSC Issue Teams, ASCE 7 SSC)	C.B. Crouse

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SCEC UGMS Committee Meeting 4

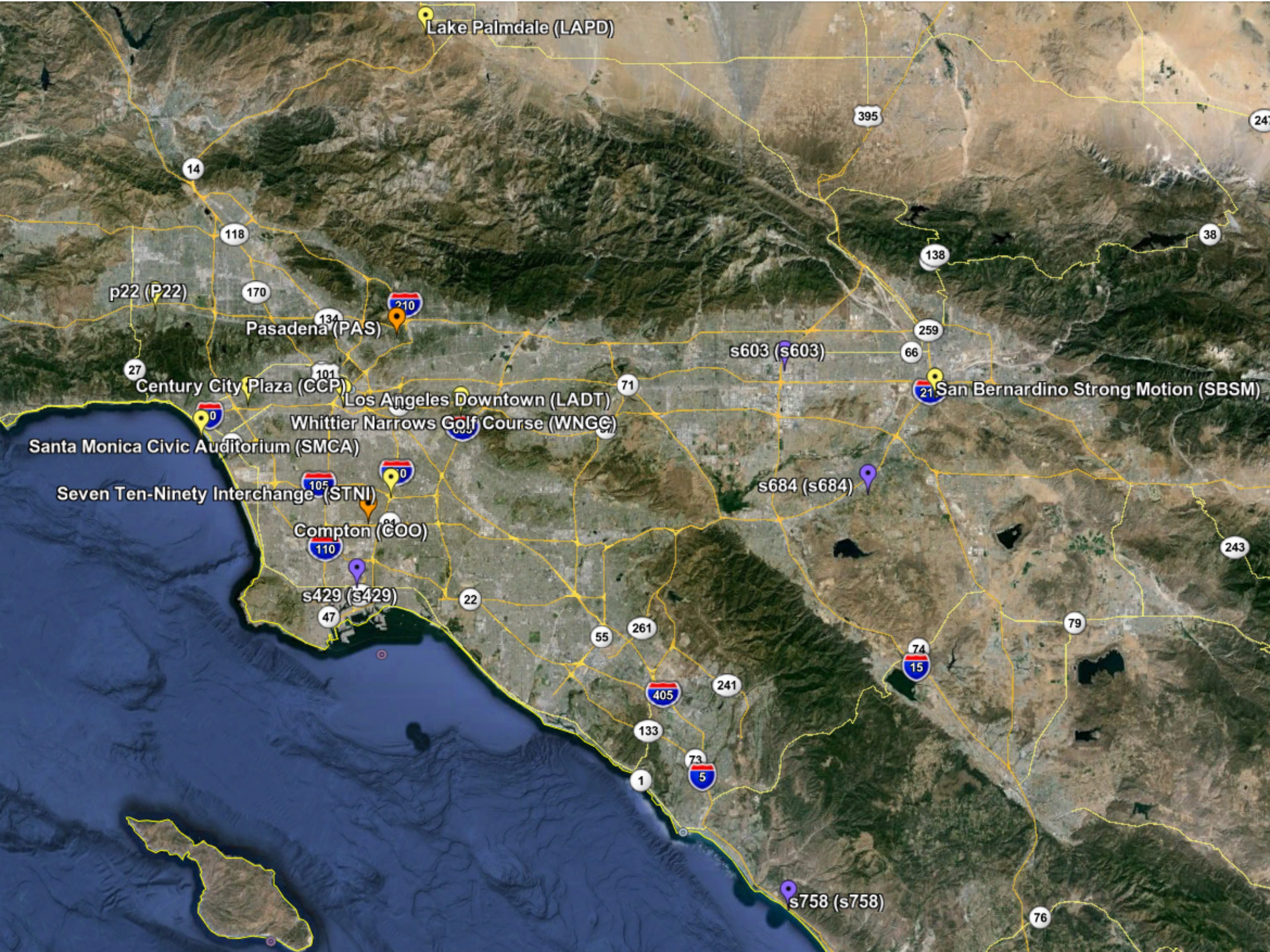
SCEC Committee for Utilization of Ground Motion Simulations Meeting 4
Organizers: C.B. Crouse (AECOM) and Tom Jordan (SCEC/USC)
Date: Monday, May 4, 2015 (10:00-15:30)
Location: SCEC Media Room (ZHS 165), USC, Los Angeles, CA
Participants: 24 (by invitation only)

an NSF+USGS center

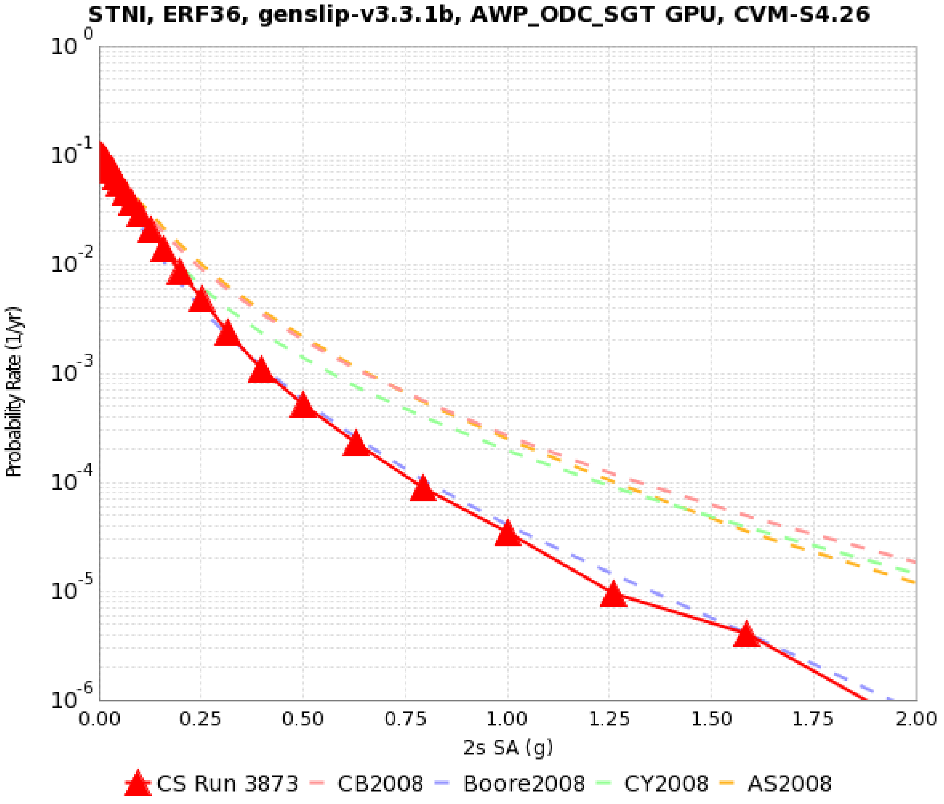
Contents [hide]

Agenda

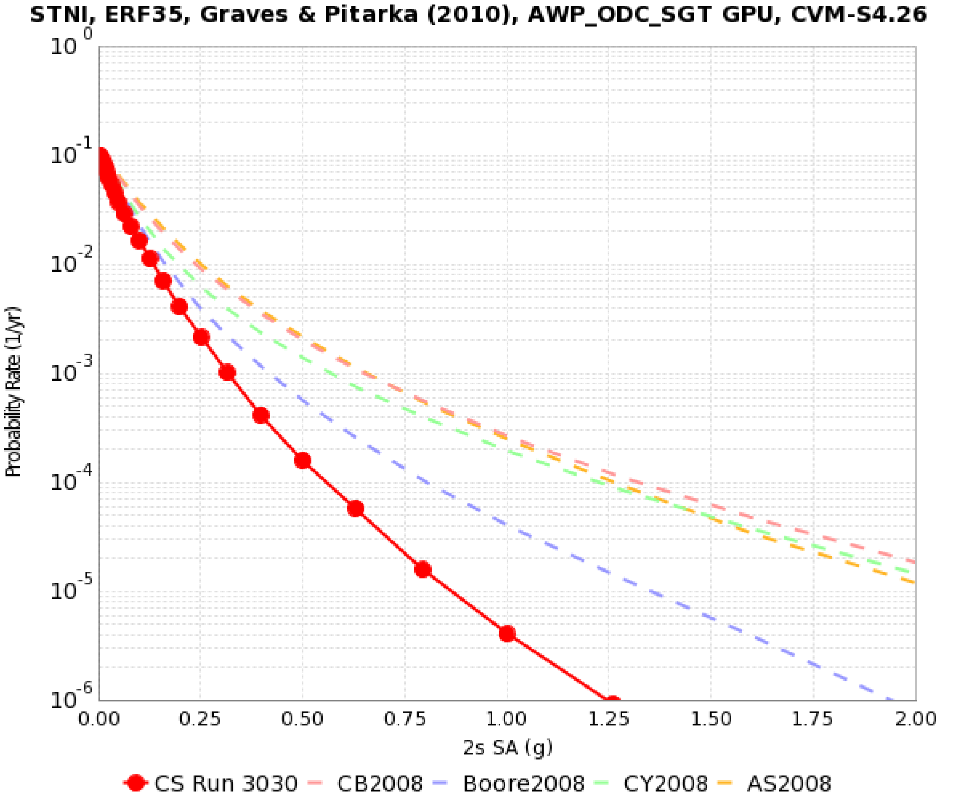
Presentation slides may be downloaded by clicking each title. PLEASE NOTE: Slides are the author's property. They may contain unpublished or preliminary information and should only be used while viewing the talk.


Lake Palmdale (LAPD)
p22 (P22)
Pasadena (PAS)
s603 (s603)
San Bernardino Strong Motion (SBSM)
Century City Plaza (CCP)
Los Angeles Downtown (LADT)
Whittier Narrows Golf Course (WNGC)
Santa Monica Civic Auditorium (SMCA)
Seven Ten-Ninety Interchange (STNI)
s684 (s684)
Compton (COO)
s429 (s429)
s758 (s758)

STNI Curves, 2 sec



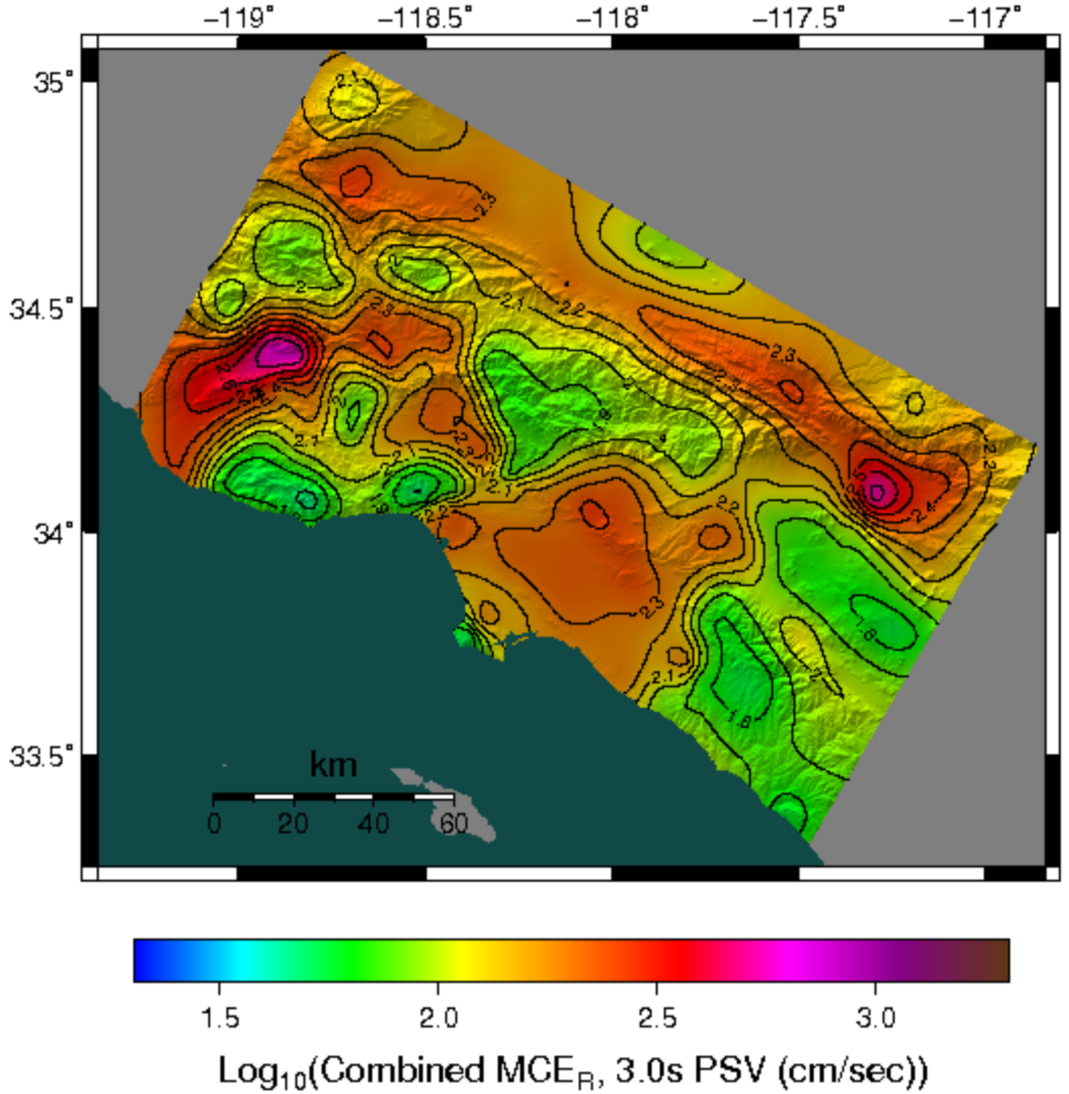
Study 15.4
(1 Hz)



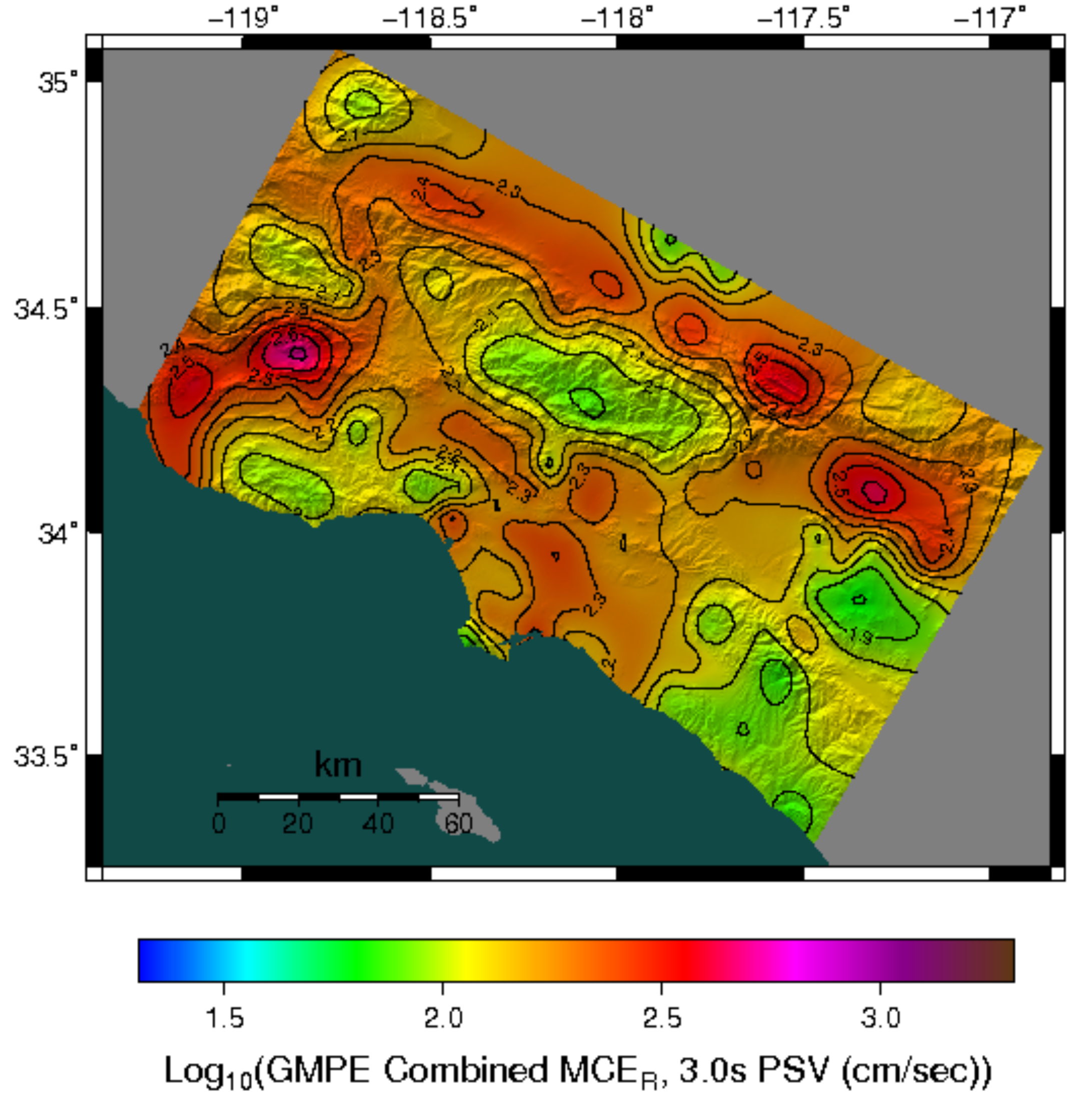
Study 14.2
(0.5 Hz)

1 Hz simulation (Study 15.4) reduces effect of roll-off due to filtering

CyberShake 14.2 Combined MCER Results
3s RotD100 (286 Sites)

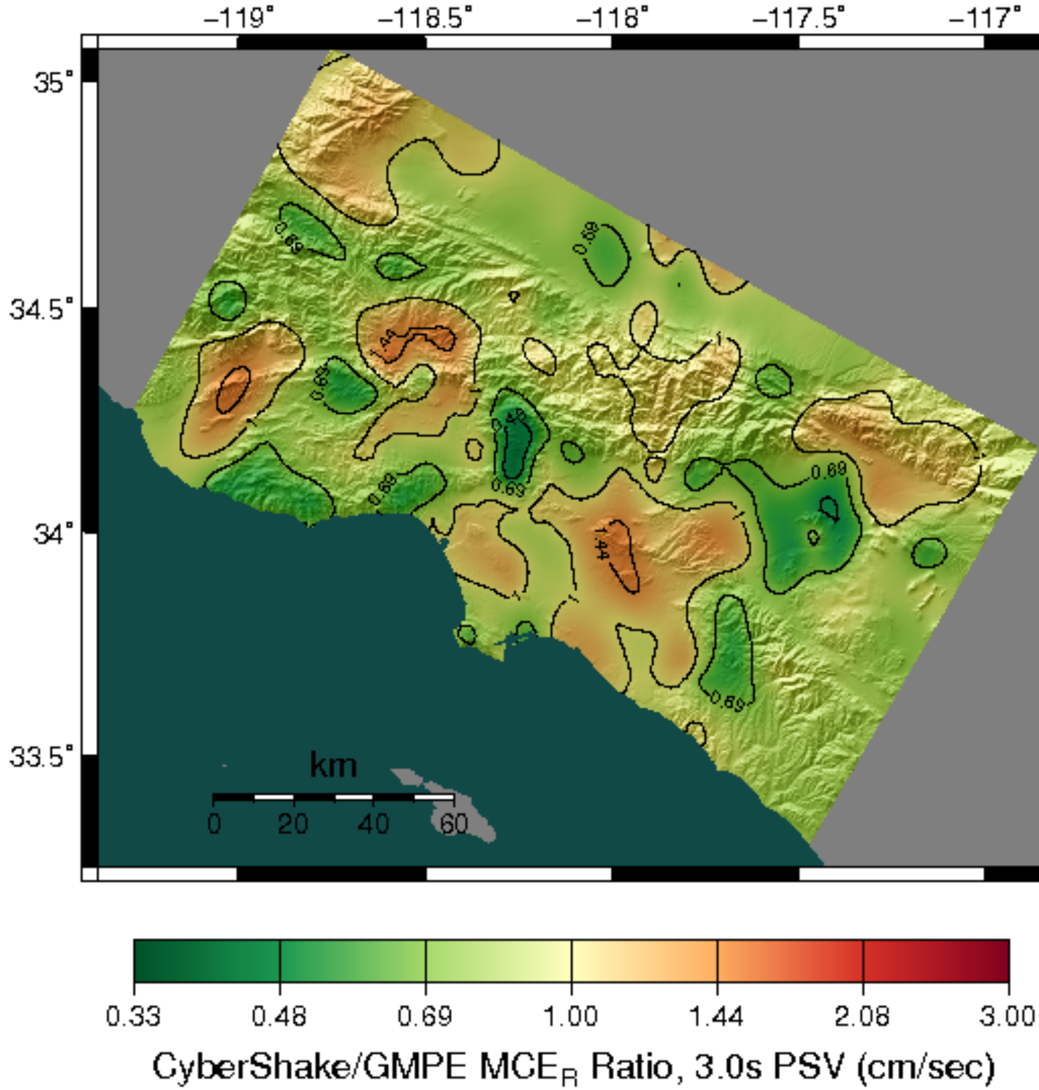


GMPE (NGA-2) Combined MCER Results
3s RotD100 (286 Sites)



Southern California Earthquake Center

GMPE Comparison Map
Ratio (CyberShake 14.2 / NGA-W2) MCER Results
3s RotD100 (286 Sites)



Conclusions

This describes how Blue Waters can have an impact on the real world.

It can be done. But it's not done.

1. **To make this happen we need continued support for supercomputer centers.**
2. **We need continued support for high performance scientific software developers.**
3. **We need continued support for scientific research programs including geoscientific research.**
4. **We need multi-disciplinary collaborations on practical problems.**

End

Various IMR types (subclasses)

IMT, IML(s)

Site(s)

Rupture

Intensity-Measure Relationship

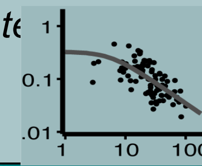
List of Supported IMTs

List of Site-Related Ind. Params

$$\text{Prob}(IMT \geq IML \mid Site, Rup)$$

Classic IMRs

Gaussian dist. is assumed; mean and std. dev. computed from various paramete



AKA:

"attenuation relationship"

Multi-Site IMRs

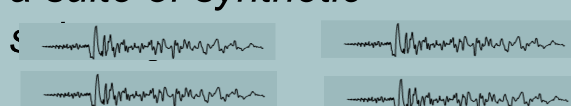
compute joint prob. of exceeding IML(s) at multiple sites

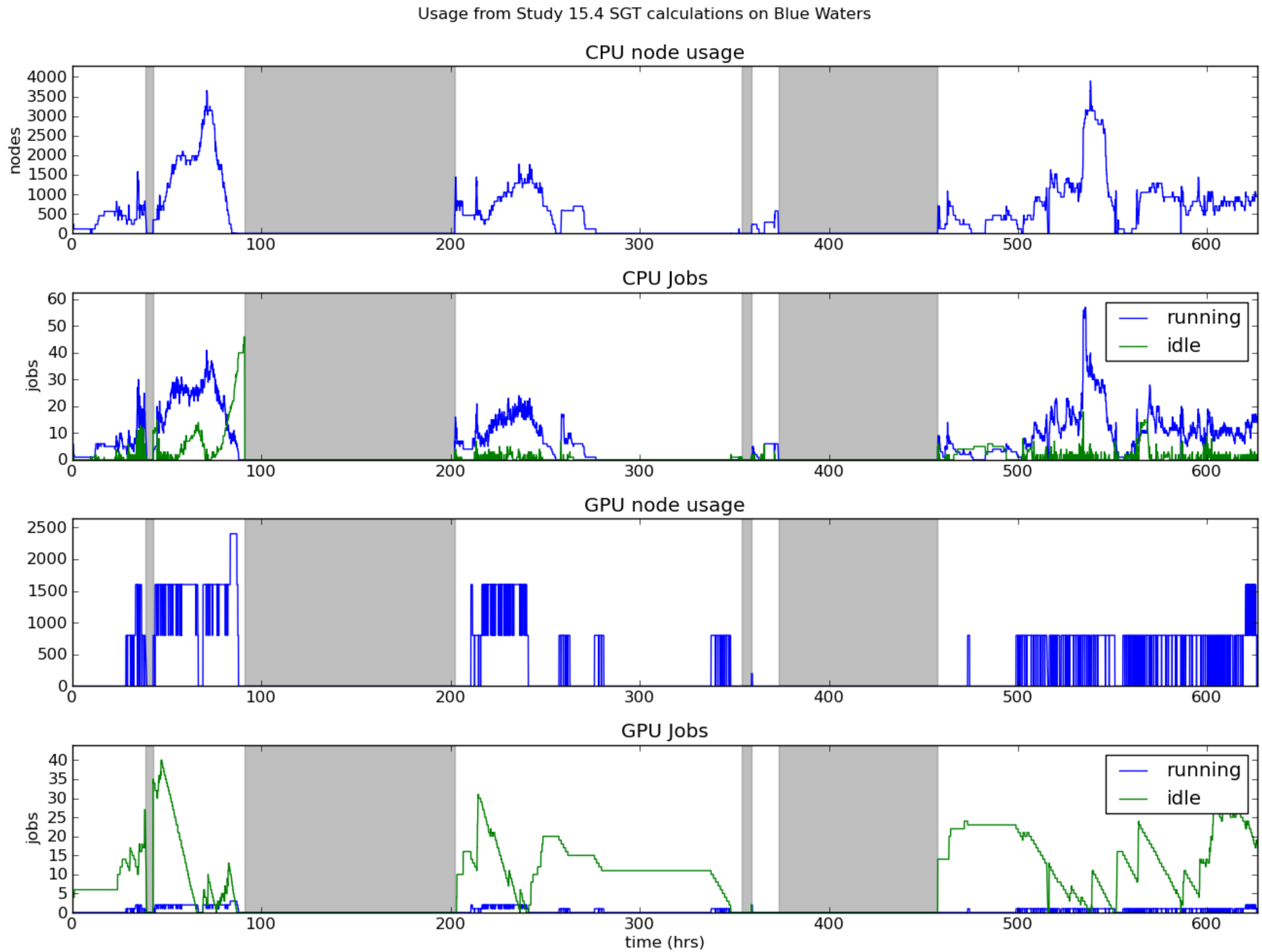
Vector IMRs

compute joint prob. of exceeding multiple IMLs

Simulation IMRs

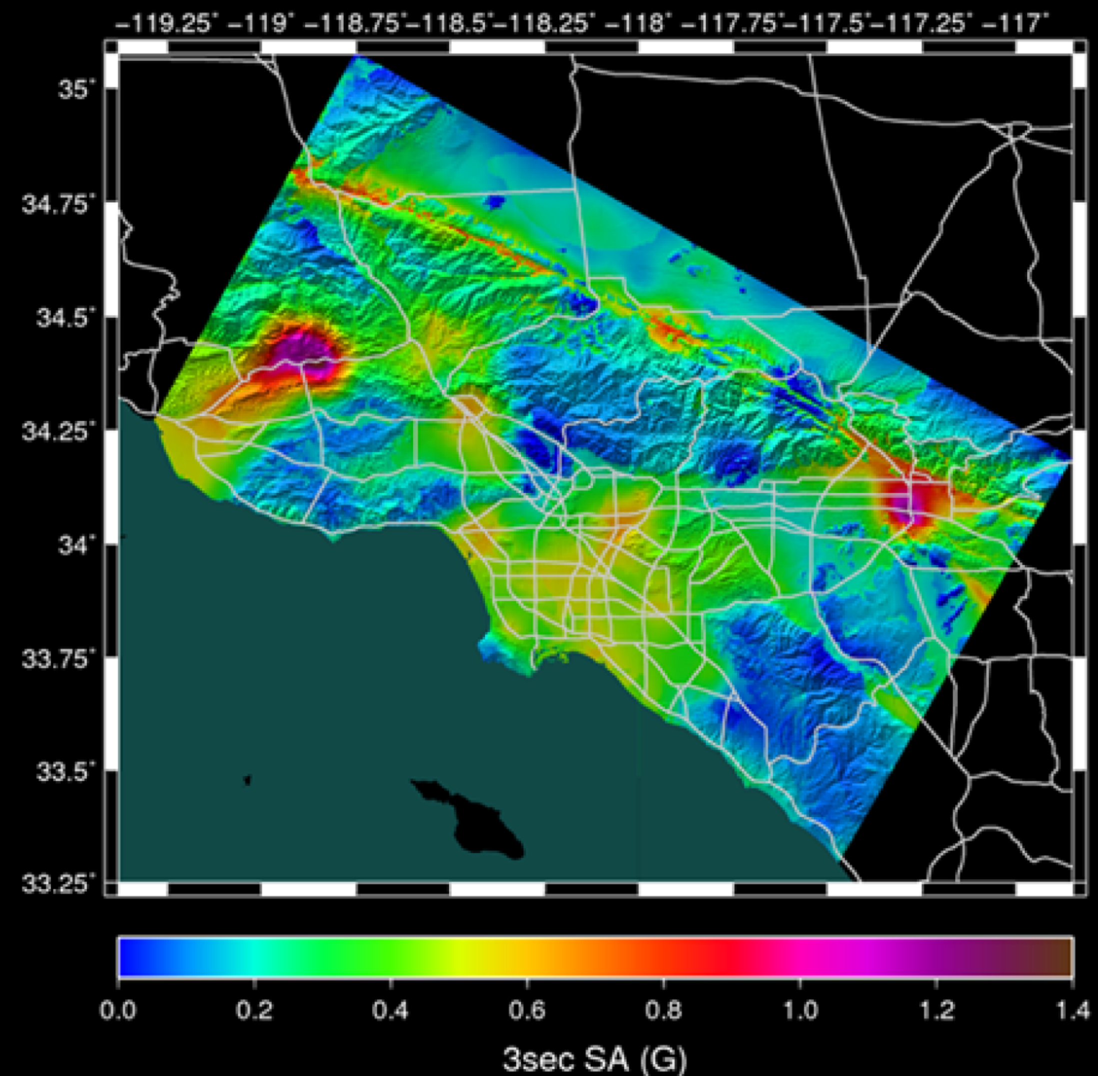
exceed. prob. computed using a suite of synthetic





Usage from Study 15.4 SGT calculations on Blue Waters
CPU node usage
nodes
CPU Jobs
jobs
running
idle
GPU node usage
GPU Jobs
time (hrs)

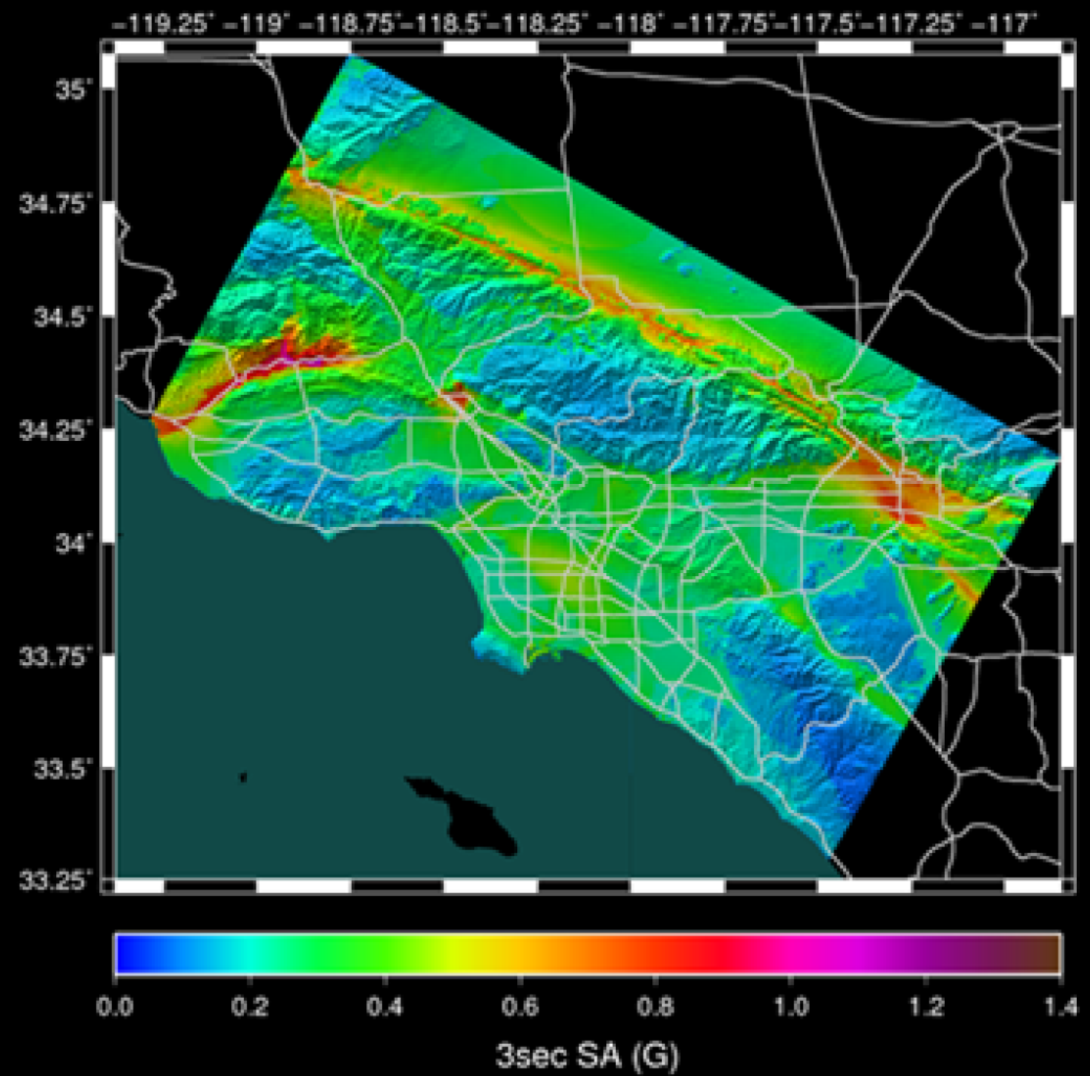
Los Angeles Region Hazard Map, 2% in 50-yr S_a(3 sec)
Graves et al. (2010) CyberShake Simulations



Graves et al. (2010) – Fig. 9

S C/E C

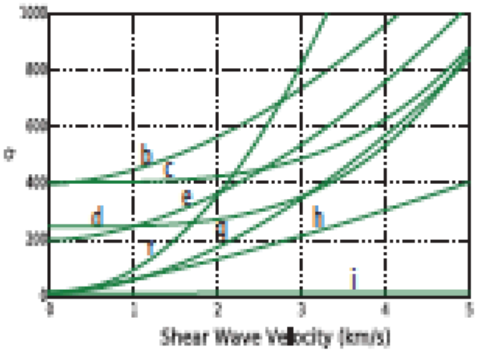
Los Angeles Region Hazard Map, 2% in 50-yr S_a(3 sec) Campbell & Bozorgnia (2008) NGA eqn.



Graves et al. (2010) – Fig. 9

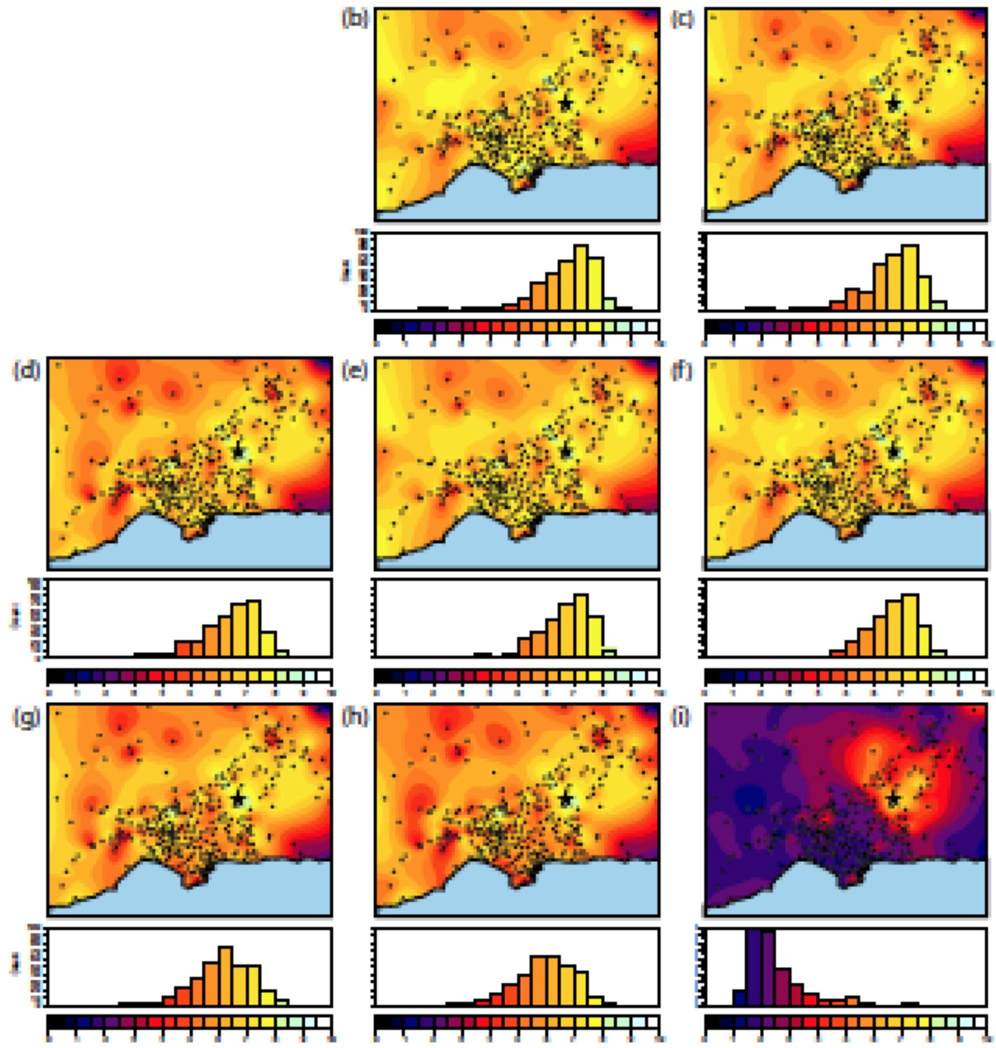
SCEC

Hercules Simulations Evaluate Qs-Vs Relationships
Goodness of Fit Evaluation Using Chino Hills Earthquake

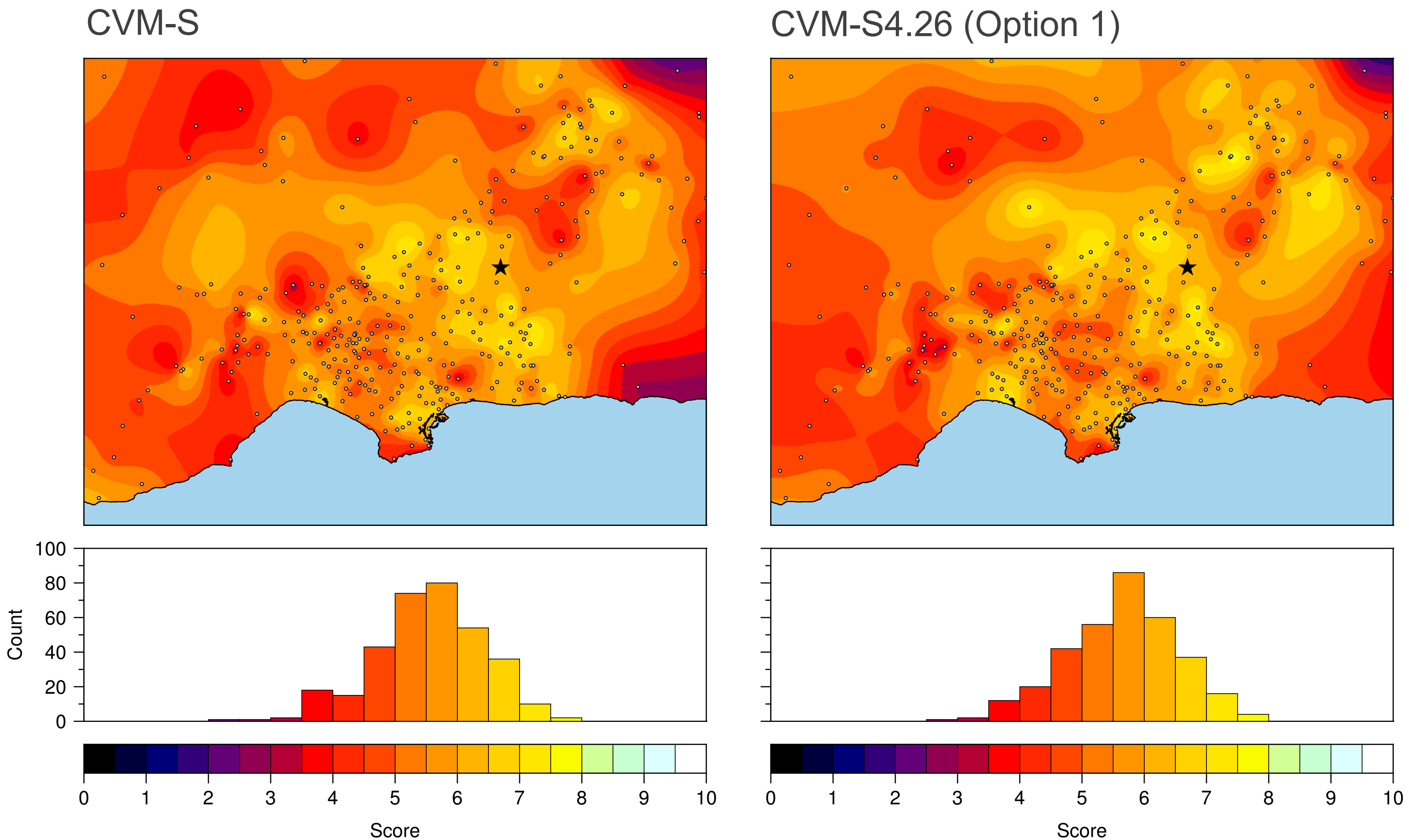


$$Q(V_s) = c + \alpha V_s^{\beta}$$

	C	α	β
a	700	2	2.8
b	400	48	1.77
c	400	2	3.4
d	250	2.4	3.45
e	200	48	1.77
f	10.5	80	2.1
g	10.5	48	1.77
h	10.5	48	1.301
i	10.5	1.5	0.5



Improvements beyond inversion f_{max} with respect to the base model (0–4 Hz)



Los Angeles Earthquake Preparedness

"If architects built buildings like programmers build programs, the first woodpecker that came along would destroy civilization."

Software Aphorism

November 2014 UGMS Meeting

- CyberShake Study 14.2
  - UCERF2
  - No Background Seismicity
  - 3D Velocity Model: CVM-S4.26
  - Min Vs: 500 m/s
  - Velocity Meshing: 200m
  - Fault Meshing: 1000m
  - Rupture Generator: genslip v3.2 (Graves & Pitarka 2010)
  - Maximum Frequency: 0.5Hz
  - PSHA 3.0s, 5.0s, 10.0s curves
  - RotD100 3.0s, 5.0s, 10.0s curves

Resilient By Design
City of Los Angeles Earthquake Preparedness Plan (2015)

ASCE 7-16 MINIMUM DESIGN LOADS FOR BLDGS AND OTHER STRUCTURE

SHARE

Purpose: To define magnitudes of loads suitable for the design of buildings and other structures, including dead loads from the weight of construction materials and fixed installations, live loads caused by the user, and environmental loads such as those which arise from the effects of wind, snow, and earthquakes. Develop loading criteria for assuring safety, serviceability, and integrity which are applicable to a wide class of construction technologies.

COMMITTEE MEMBERS

Ronald O Hamburger, P.E., F.SEI
Chair

James Gregory Soules, P.E., S.E., F.SEI, F.ASCE
Vice-Chair

CyberShake Study 14.2 Hazard Map